Influence of fertilization and water deficit on the density and anatomical characteristics of eucalyptus grandis wood

Influência da fertilização e do déficit hídrico na densidade e características anatômicas da madeira de eucalyptus grandis

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Mariana Pires Franco
PhD in Sciences, Forest Resources
Institution: Universidade Estadual Paulista (UNESP)
Address: R. Geraldo Alckmin, 519, Itapeva – SP, CEP: 18409-010
E-mail: ma.pires@hotmail.com

Maria Fernanda Felippe Silva
Graduation Student in Industrial Wood Engineering
Institution: Universidade Estadual Paulista (UNESP)
Address: R. Geraldo Alckmin, 519, Itapeva – SP, CEP: 18409-010
E-mail: mff.silva@unesp.br

Glaucia Aparecida Prates
PhD in Production and Systems Engineering
Institution: Universidade Estadual Paulista (UNESP)
Address: R. Geraldo Alckmin, 519, Itapeva – SP, CEP: 18409-010
E-mail: g.prates@unesp.br

Lesley Carina do Lago Attadia Gali
PhD in Administration
Institution: Faculdade de Ciências Agrárias e Veterinárias da Universidade Estadual Paulista (FCAV - UNESP)
Address: Via de Acesso Professor Paulo Donato Castellane, s/n, Vila Industrial, Jaboticabal – SP, CEP: 14884-900
E-mail: lesley.attadia@unesp.br

José Cláudio Caraschi
PhD in Chemistry
Institution: Universidade Estadual Paulista (UNESP)
Address: R. Geraldo Alckmin, 519, Itapeva – SP, CEP: 18409-010
E-mail: j.caraschi@unesp.br

Antônio Francisco Savi
PhD in Mechanical Production Engineering
Institution: Universidade Estadual Paulista (UNESP)
Address: R. Geraldo Alckmin, 519, Itapeva – SP, CEP: 18409-010
E-mail: antonio.savi@unesp.br

Gilles Chaix
PhD in Integrative Biology
Institution: CIRAD, UMR AGAP Institut and UMR AGAP Institut
Address: Avenue Agropolis, 34398, Cedex 5, Montpellier, France
E-mail: gilles.chaix@cirad.fr

Mario Tomazello Filho
PhD in Agronomy
Institution: Universidade de São Paulo, ESALQ, Departamento de Ciências Florestais
Address: Av. Pádua Dias, 11, Piracicaba – SP, CEP: 13418-900
E-mail: mtomazel@usp.br

ABSTRACT
The expansion of plantations may be compromised by climate change, altering the frequency and intensity of precipitation. This study aimed to evaluate the influence of potassium and sodium fertilization and water deficit on the apparent density property and anatomical characteristics of *Eucalyptus grandis* wood. Six treatments varying in fertilization and rainfall incidence were evaluated. Apparent density testing was conducted via X-ray, while the anatomical features of fibers and vessels were examined through image analysis using a polarized light microscope. Cartography was also performed to map the density variation along the trunk in longitudinal and radial directions. Trees without fertilization exhibited higher apparent density, whereas those with partial rain exclusion displayed less homogeneous wood. Overall, treatments involving potassium and sodium showed no significant difference between them and resulted in a thinner secondary wall. The results indicate that water deficit and fertilization methods significantly impact wood properties.

Keywords: wood quality, drought effects, apparent density, anatomical properties, potassium, sodium.

RESUMO
A expansão das plantações pode ser comprometida pelas mudanças climáticas, alterando a frequência e a intensidade da precipitação. Este estudo teve como objetivo avaliar a influência da fertilização de potássio e sódio e o déficit hídrico na propriedade de densidade aparente e nas características anatômicas da madeira de Eucalyptus grandis. Foram avaliados seis tratamentos, variando na fecundação e na incidência de chuvas. O teste de densidade aparente foi realizado através de raio-X, enquanto as características anatômicas das fibras e vasos foram examinadas através de análise de imagem usando um microscópio de luz

polarizada. A cartografia também foi realizada para mapear a variação de densidade ao longo do tronco em direções longitudinais e radiais. Árvores sem fertilização exibiam maior densidade aparente, enquanto aquelas com exclusão parcial de chuva exibiam madeira menos homogênea. No geral, os tratamentos envolvendo potássio e sódio não apresentaram diferença significativa entre eles e resultaram em uma parede secundária mais fina. Os resultados indicam que o déficit hídrico e os métodos de fertilização impactam significativamente as propriedades da madeira.

Palavras-chave: qualidade da madeira, efeitos da seca, densidade aparente, propriedades anatômicas, potássio, sódio.

1 INTRODUCTION

The global climate change, resulting from human activities such as the use of fossil fuels, agriculture, and land use changes, is expected to intensify in the future, affecting various segments of the forest-based production chain in Brazil and around the world. (Quevedo *et al.* 2021; IPCC, 2022).

The Brazilian territory has 7.5 million hectares of areas with *Eucalyptus* plantations (IBÁ, 2023). This significant area with plantations demonstrates the importance of planted forests in meeting the demand of both national and international industries for wood products and reducing pressure on natural forests.

The country's economic activity is closely related to natural resources and, therefore, is dependent on climatic conditions. This dependency underscores the interest in approaching studies that involve the interaction between water deficit and fertilization as a means to minimize this issue.

In water deficit situations, trees have several mechanisms to reduce water loss, such as stomatal control or adaptations in the flexibility of leaf cell walls through osmotic adjustments (Morgan 1984, Arndt *et al.* 2008, Reich 2014). One of the mechanisms involves the use of solutes, especially potassium and sodium, to minimize the effects of water scarcity (Taiz and Zeiguer 2009). Furthermore, trees can adjust root and leaf architecture, adapt the anatomy of vessels and/or fibers in the xylem. (Fonti *et al.* 2013; Battie-Laclau *et al.* 2014, Christina *et al.* 2017).

As a result, understanding the processes and interactions between the availability of fertilizers and water in the functioning of eucalyptus stands is crucial for maintaining forest productivity and devising new silvicultural management methods, such as the selection of genotypes adapted to global climate change, necessary for expanding forest plantations (Almeida *et al*. 2010, Atkinson *et al.* 2011, Lachenbruch and McCulloh 2014, Christina *et al.* 2015, Christina *et al.* 2017).

Therefore, the present work aims to evaluate the influence of water deficit and potassium and sodium fertilization on apparent density properties and the anatomical characteristics of fiber and vessel dimensions in *Eucalyptus grandis* wood.

2 EXPERIMENTAL

2.1 MATERIALS

2.1.1 Study Area

The experiment was installed at the Itatinga Experimental Station of the University of São Paulo, São Paulo state, Brazil (23°02 S, 48°38 W). The climate, according to Köeppen, is characterized as humid mesothermal (Cwa). The mean annual temperature and rainfall is 19.9° C and 1360 mm, respectively. The study was conducted on a hilltop with a 3% slope at an altitude of 850 m. The soils are very deep ferralsols (> 15 m) on Cretaceous sandstone, Marília formation, Bauru group, with a clay content ranging from 14 to 23%.

2.2 METHODS

2.2.1 Experimental Plantation Description

The experiment was a split-plot design installed in June 2010 with a highly productive clone of *Eucalyptus grandis* well established in commercial plantations by Suzano Company (Brazil). The trees were organized in six treatments (three types of nutrient supply and two water regimes) replicated in three blocks. The whole-plot factor was the water regime 37% throughfall reduction (− W) and no throughfall reduction (+W), while fertilization was considered as the split-plot factor potassium addition (+K), sodium addition (+Na), and control (C). Thus, these were the treatments analyzed:

• +K + W: 0.45 mol K m- 2 applied as KCl and no throughfall reduction,

• +Na + W: 0.45 mol Na m- 2 applied as NaCl and no throughfall reduction,

• C + W: control, without K and Na fertilization, and no throughfall reduction,

• +K – W: 0.45 mol K m- 2 applied as KCl, and 37% throughfall reduction,

• +Na – W: 0.45 mol Na m- 2 applied as NaCl, and 37% throughfall reduction,

• C – W: control, without K and Na fertilization, and 37% throughfall reduction.

An individual plot measured 864 m², with 144 trees at a spacing of 2 m x 3 m. K and Na supply were applied in a single dose 3 months after planting. At the same time of planting, standard fertilization applied in the region was used except K. Trees were fertilized with 75 kg ha^{-1} of P_2O_5, 80 kg ha^{-1} of N ($NH_4(SO_4)_2$), and 20 kg ha^{-1} of FTE BR-12 (micronutrient source) applied close to the pits. Moreover, 2000 kg ha^{-1} of dolomitic limestone was broadcast on the soil surface (Chambi-Legoas et al., 2021). The 37% throughfall reduction in the – W plots was performed using clear greenhouse plastic panels mounted on wooden frames at a height varying between 0.5 m and 1.6 m (Battie-Laclau et al., 2016) and covering 37% of the plot area (Figure 1) and installed in September 2010 (3 months after planting).

Figure 1. Overall view of the experiment, where (A) +W treatments and (B) -W treatments

Source: Own authorship.

2.2.2 Tree Selection

Based on forest inventories carried out every six months in the experimental area. The wood samples were obtained in May 2015, when the trees turned 5 years old. According to the annual inventory of trees, the sampled trees were distributed in four to nine diametric classes (one tree per diametric class). Extreme classes were not sampled.

Thus, three trees were selected by fertilization treatment and water regime, totaling 54 trees (9 trees per treatment) randomly sampled. A log of 20 cm length was cut from the positions base, breast height, 25, 50, 75 and 100% of total height for a complete sampling of trees.

2.2.3 Wood Apparent Density by X-Ray Microdensitometer

Wood density profiles were obtained for all sampled positions. The samples were prepared in a rectangular sections bark-to-bark with 2 cm width, pith-centered. After, each sample was glued to wooden supports. Then, using a parallel double circular sawing equipment, a wood slice with 1.8 cm thickness was transversally cut from each section. The samples were conditioned in a climatic chamber (20° C, 60% HR) for 48 h, with 12–15% wood moisture content. Thereafter, using the Faxitron MX-20 Cabinet X-Ray Imaging System equipment (Faxitron X-Ray Corporation, Lincolnshire, IL, USA) were obtained the X-ray images of the wood samples. X-ray images were verified in R software with the X-ring package (Campelo et al., 2019), where a calibration curve was adjusted from known density values and thicknesses of a step-wedge recorded in each image. The wood density profile was obtained using the calibration curve, based on the grayscale value of pixels and the thickness of the sample.

To construct the cartography of the variation in apparent wood density in the radial (pith-bark) and longitudinal (base-top) directions of the tree trunk, the radial profiles of apparent density of wood samples from the positions base, breast height, 25, 50, 75 and 100% of total height were used the R software. The initial creation script being based on the work of Franco (2014). It was proposed to map the variation in apparent density to better understand the effect of treatments on the entire tree. To interpolate the data obtained and generate the cartographic maps, kriging was used, considered a good data interpolation methodology, which uses tabular data and its geographic position to calculate the interpolations (LANDIM, 2006).

2.2.4 Fibers and Vessels Features

The anatomical characterization was carried out by determining the dimensions of fibers and vessels. Radial sampling of 0, 50 and 100% of the DBH discs was carried out and rectangular samples measuring 2 cm x 2 cm x 2 cm were removed. The determination of fiber dimensions at each radial position was carried out using Franklin's method for maceration (Franklin, 1945). To measure vessels, sections of 10–15 µm thickness from the transverse surface of the samples were cut on a sliding microtome (Leica SM 2010 R). Histological slides were obtained, as stated by the standard wood anatomy techniques (Johansen, 1940). After, the digital images were captured with a digital camera (Axio Cam MRC-Zeiss) integrated into a microscope (Zeiss Axio Scope A1) (Chambi-Legoas et al., 2021). The images acquisition for fiber length, vessel density, and vessel area was at 25x magnification. Images for vessel diameter were acquired at 40x magnification, and images for thickness, diameter, and lumen diameter of fibers were acquired at 100x magnification (Iawa Committee, 1989). Fiber features were measured for at least 35 fibers for each sample and radial positon. The fiber thickness was calculated as half of the difference between the fiber diameter and fiber lumen diameter (Chambi-Legoas et al., 2021). The diameter (µm), density (vessels.mm^{-2}) and occupied areas (%) of the vessels were measured over the entire area of the histological section. Measurements were performed using the ImageJ software version 1.52a (Schneider et al., 2012).

2.2.5 Data Analysis

The statistical analysis was performed using SAS Enterprise Guide 7.1 (SAS Institute Inc., Cary, NC, USA). Outliers and heterogeneity of variance were measured. Differences between treatments and blocks were tested using analysis of variance, in completely randomized blocks for the split-plot experimental device, when the six treatments were compared. The normal distribution of residuals was verified using the Kolmogorov-Smirnov test. When differences between treatments were detected at a 5% significance level, the Student-Newman-Keuls test was used to compare treatment means.

3 RESULTS AND DISCUSSION

The results show a significant difference between the average apparent density of control (C) trees in relation to those fertilized with K and Na, independently of the throughfall situation. It is possible to observe that the average apparent density values between fertilized trees are very similar, and in trees with throughfall exclusion, the difference is less than 0.002 g/cm³. The C trees had the highest apparent density values compared to fertilized, regardless of the the throughfall situation, corroborating with the results of Chambi-Legoas *et al.* (2021). The minimum and maximum wood apparent density values for all treatments varied between 0.320 and 0.340 g/cm³ and 0.860 and 0.880 g/cm³, respectively. This amplitude of variation in apparent density observed allows to conclude that there is an alternation of growth bands in the wood of the trees studied (Table 1).

Table 1. Apparent density of *Eucalyptus grandis* wood for each treatment

Treatment	Apparent density ($g.cm^{-3}$)		
	Mean	Minimum	Maximum
C/+A	0,570 a* (0,016)	0,386 a (0,027)	0,866 a (0,037)
Na/+A	0,539 b (0,020)	0,356 bc (0,020)	0,865 a (0,030)
K/+A	0,543 b (0,022)	0,323 b (0,040)	0,875 a (0,022)
C/-A	0,567 a (0,014)	0,370 ab (0,023)	0,881 a (0,018)
Na/-A	0,547 b (0,026)	0,348 bc (0,054)	0,879 a (0,013)
K/-A	0,545 b (0,020)	0,335 b (0,040)	0,881 a (0,031)
*Note: Means followed by the same letter, vertically, do not differ from each other by the Tukey test at a 5% significance level. Values in parentheses indicate the standard deviation.			

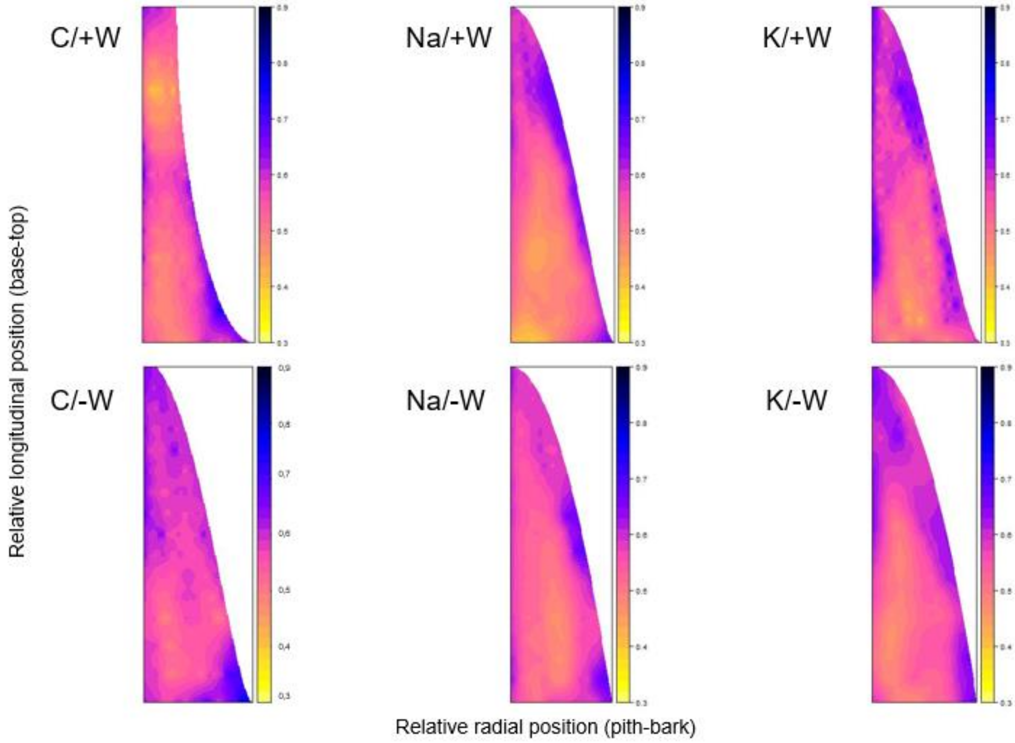
Source: Own authorship.

The average wood apparent density values of all eucalyptus trees obtained (0.550 g/cm³) are similar to those found by other authors. The genetic material and site conditions are the major factors that cause differences in apparent density values. Furthermore, higher proportions of juvenile wood in relation to adult wood in this age group, causing these differences (Hills; Brown, 1984).

It is also possible to infer that, considering that the C trees without throughfall exclusion are already in a stress condition as its received the minimum of nutrients for growth and, in the C/-W treatment, they suffered a “second” stress with the throughfall exclusion, the apparent density values reflect the unfavorable condition for growth, where trees may present thickening of the cell wall, reduced lumen diameter and accumulation of axial parenchyma, reflecting high density values (Drew *et al*., 2011; Rosner *et al*., 2014).

The amplitude of radial variation of the average apparent density is 0.539 to 0.567 g/cm³ for the six treatments. The pattern of variation in the apparent density of *E. grandis* is less consistent in the longitudinal direction compared to the radial direction (Figure 2). Lower density values were observed in the region close to the pith, more pronounced in the Na/+W treatment and higher values closer to the bark, notable in the C/-W treatment. In the longitudinal direction, it is possible to verify that the variation in apparent density was greater in C trees, followed by trees fertilized with K and Na. Furthermore, density varies more pronouncedly in the regions corresponding to the base, DBH and 25% of the total height in the six treatments. In positions 50, 75 and 100% of total height this variation is also observed, however, less pronounced. It is also possible to observe that, regardless of the treatment, there is a pattern of variation in density, which decreases to a certain point and then increases to the top of the tree. This pattern of density variation in the base-to-top and pith-to-bark directions is described in detail by Panshin and Zeeuw (1970).

Figure 2. 2D model of apparent density variation along the trunk



Source: Own authorship.

The cartography obtained allowed to visualize how wood properties respond to fertilization, but mainly to the water availability factor; It is possible to state that the throughfall exclusion implied in trees that produced less homogeneous wood, that is, the variation in apparent density within the tree is greater. In this sense, it must be considered that this characteristic can influence the final use of the wood.

3.1 FIBERS FEATURES

The largest fibers were found in the wood of trees fertilized with K, without throughfall exclusion, being this treatment statistically different from the C treatment with and without throughfall exclusion, and statistically equal to Na treatment (Table 2). Regarding width, treatments with K and Na were statistically equal, independently of the throughfall exclusion. The same occurred for the fiber wall thickness. The diameter of the fiber lumen assumed the highest value in trees fertilized with Na, in a situation of throughfall exclusion. It is remarkable that the highest average values of fiber width and lumen diameter obtained were observed in fibers that received the application of Na in a situation of throughfall exclusion.

Fiber size and quality are affected by silvicultural practices such as fertilization and site quality (MacDonald and Hubert, 2002). Chambi-Legoas *et al*. (2021) explain that fertilization regimes significantly affected the characteristics of fibers and vessels. Regarding the high standard deviation values found for fiber length, Sette Junior (2010) explains that this is mainly due to the random effects of the residue, which are the main sources of variability and represent between 35.2 and 55.6% of the total variation. As described by Lousada (1999) and Sette Junior (2010), such random effects that cause these variations can occur due to fertilization treatments, basal area classes, the position of the disk on timber, natural variability the density of the wood, the age, or the rate of growth of the trees.

Table 2. Mean values of the length, width, wall thickness, and lumen diameter of *Eucalyptus grandis* wood fibers for each treatment

Treatment	Length (µm)	Width (µm)	Fiber wall thickness (µm)	Lumen diameter (µm)
C/+W	900,1 a* (195,2)	21,2 a (3,9)	3,5 a (0,8)	14,7 a (4,4)
Na/+W	883,7 b (166,3)	20,4 b (3,9)	3,2 b (0,7)	14,1 b (3,3)
K/+W	901,2 b (193,9)	20,8 b (4,7)	3,5 a (0,9)	13,8 b (4,6)
C/-W	854,3 ab (177,0)	20,9 a (4,0)	3,3 a (0,7)	14,3 a (3,3)
Na/-W	827,8 b (198,8)	21,4 b (3,9)	3,2 b (0,5)	15,1 b (3,6)
K/-W	839,7 b (194,3)	19,9 b (3,6)	3,1 b (0,5)	13,7 c (3,1)

*Note: Means followed by the same letter, vertically, do not differ from each other by the Tukey test at a 5% significance level. Values in parentheses indicate the standard deviation.

Source: Own authorship.

Similar results in the same experimental area for younger ages confirm the results obtained in our study (Castro *et al*., 2017; Chambi-Legoas *et al*., 2020; Chambi-*Legoas et al.*, 2021). In this sense, it can be inferred that the application of K and Na induced the formation of smaller secondary walls.

Higher wall thickness values in C trees (regardless of throughfall exclusion) show a direct relationship with the high-density values found in these trees. The width of the fibers is inversely related to the density, just as the diameter of the lumen is inversely related to the density which, in turn, is directly related to the thickness of the fiber wall. Thus, the greater the number of empty spaces, the lower the density of the wood. Furthermore, the exchange rate and the influence of external factors such as water availability, cause these differences observed in the results (Panshin and De Zeeuw 1970).

The analyzed fiber parameters, but mainly the fiber wall thickness, are variables involved in the wood formation processes. The dimensions of the fibers may depend on the turgor pressure inside the cell and on the auxins produced in the tree canopy, inducing greater plasticity of the cell wall through variations in microfibrillar angles in the different layers in the ultrastructure of wall (Larson, 1967; Zobel and Van Buijten, 1989). Therefore, greater turgor pressure and auxin concentration induce the formation of larger cells in the initial phase of cell division of the cambium. With this, it is understood that the application of fertilizers influences the results obtained for the fibers, since the turgor pressure and auxin can be altered. K and Na influence the greater or lesser turgor pressure and the formation of a greater leaf area in the tree canopy, that is, an area with a high concentration of auxins (Zobel and Van Buijtenem, 1989).

Because of trees synthesizing greater amounts of sugars through photo-synthesis, there is an increase in the biosynthesis of cellulose molecules, which will be incorporated as microfibrils in the secondary wall, increasing its thickness. Furthermore, differences in the transpiration pattern, which may occur due to treatments, are mainly related to variations in stomatal control, the extension of the root system and the leaf surface (Battie-Laclau *et al*., 2014).

3.2 VESSELS FEATURES

The diameter of the vessels was statistically greater in the wood of trees fertilized with K, regardless of the condition of throughfall exclusion (Table 3). The C treatment with partial exclusion of rain had the lowest average value of tangen-tial diameter of vessels. Regarding the percentage of area occupied by the ves-sels, a statistical difference was observed in the C/-W and K/-W treatments, but a small variation was observed, from 13.3 to 14.7%, among all treatments evalu-ated. The frequency of vessels assumes higher values in control trees, regard-less of rainfall conditions, followed by trees fertilized with Na and K. These results make clear the inverse relationship between frequency and vessel diameter.

Table 3. Mean values of the tangential diameter, percentage of occupied area and frequency of *Eucalyptus grandis* wood vessels for each treatment

Treatment	Tangential diameter (μm)	Percentage of occupied area (%)	Frequency (nº.mm^{-2})
C/+W	96,6 a*(12,8)	14,5 a (1,3)	17,2 a (2,3)
Na/+W	103,5 a (13,8)	14,7 a (1,8)	14,2 b (2,2)
K/+W	111,7 b (11,7)	14,7 a (2,2)	11,7 c (2,1)
C/-W	95,3 a (12,8)	13,3 b (1,2)	16,8 a (2,0)
Na/-W	101,4 a (14,1)	13,8 a (1,4)	13,5 b (1,5)
K/-W	110,6 b (13,8)	13,3 b (2,2)	11,8 b (1,7)

*Note: Means followed by the same letter, vertically, do not differ from each other by the Tukey test at a 5% significance level. Values in parentheses indicate the standard deviation.

Source: Own authorship.

The characteristics of the vessels were quite responsive to the treatments. Fertilized trees have few vessels and large diameters, compared to C trees. Similar effects have been reported in the literature, demonstrating that in the wood of *Eucalyptus* species trees, water limitation in the soil leads to a decrease in the tangential diameter and an increase in the frequency of vessels (Baas; Schweingruber, 1987). Trees in drought conditions presented two main strategies to improve water transport efficiency, being (i) increasing the area corresponding to sapwood and (ii) altering the anatomical structures of the vessel elements. The smaller vessels, more grouped and numerous vessels are formed in the wood of trees under drought conditions and reduced precipitation which can compromise the water conductivity of the wood or lead to embolism. Therefore, it is understood that the increase in the frequency of vessels and the decrease in their tangential diameter constitutes an adaptation of the plant in response to water deficit to compensate for the loss of water transport capacity (Searson *et al*., 2004).

E. grandis trees show rapid responses to adverse climatic conditions resulting in a significant reduction in growth in arid regions and, in this case, water availability is one of the most important factors that alters the anatomical structure of the wood, demonstrating high plasticity of the species (Battie-Laclau *et al*., 2014, Battie-Laclau *et al*., 2014, Battie-Laclau *et al*., 2016). The increase in the tangential diameter of the vessels, from a physiological point of view, results in a significant increase in hydraulic conductivity. Battie-Laclau *et al.* (2014), in the same experimental area as the present study, observed that, regardless of the water regime, fertilization with K induced twice the value of sap flow, in relation to control trees, resulting in greater hydraulic efficiency and greater water consumption by trees. In this way, it can be understood that the wood of *Eucalyptus* trees fertilized with K and Na has vessels with a larger tangential diameter, providing greater upward transport of mineral sap, meaning greater photosynthetic activity and biomass production.

4 CONCLUSIONS

The induced water deficit in tree planting and the various forms of potassium and sodium fertilization influenced the property of apparent density and the anatomical characteristics of *Eucalyptus grandis* wood.

The control trees exhibited higher values of apparent density due to the thickening of fiber walls resulting from adverse growth conditions. There was no significant difference between potassium and sodium fertilization.

Wood density, especially in treatments with partial rain exclusion, showed a less homogeneous behavior along the trunk.

Overall, the fiber dimensions in the treatments with potassium and sodium fertilization showed no statistically significant difference between them. Fertilization induced the formation of a secondary wall with smaller dimensions.

Regarding the vessels, an inverse relationship between vessel frequency and diameter was notable. The treatments, with and without rain exclusion, fertilized with potassium, showed significantly larger tangential vessel diameters, followed by the sodium-fertilized treatments and the control treatment.

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