Research, Society and Development, v. 10, n. 10, e558101019004, 2021
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v10i10.19004

Effect of soil type on mean annual increment, wood anatomy and properties of 33-year-old *Corymbia citriodora* (Hook.), K. D. Hill, & L. A. S. Johnson

Efeito do tipo de solo no incremento médio anual, anatomia e propriedades da madeira de *Corymbia citriodora* (Hook.), K. D. Hill, & L. A. S. Johnson, de 33 anos de idade

Efecto del tipo de suelo sobre el incremento anual medio, la anatomía y las propiedades de la madera de *Corymbia citriodora* (Hook.), K. D. Hill y L. A. S. Johnson, de 33 años

Received: 08/02/2021 | Reviewed: 08/13/2021 | Accept: 08/16/2021 | Published: 08/18/2021

Willyam de Lima Vieira
ORCID: https://orcid.org/0000-0003-0707-5382
Universidade Estadual Paulista, "Júlio de Mesquita Filho, Brazil
E-mail: willyamvieira84@gmail.com
Erick Phelipe Amorim
ORCID: https://orcid.org/0000-0002-8964-0770
Universidade Federal de São Carlos, Brazil
E-mail: erick.amorim95@hotmail.com
Caio Corsato Correa
ORCID: https://orcid.org/0000-0001-6892-5251
Universidade Estadual Paulista "Júlio de Mesquita Filho", Brazil
E-mail: corsatocaio@gmail.com
Fábio Minoru Yamaji
ORCID: https://orcid.org/0000-0002-0908-8163
Universidade Federal de São Carlos, Brazil
E-mail: fmyamaji@ufscar.br
Miguel Luiz Menezes Freitas
ORCID: https://orcid.org/0000-0001-8882-0908
Instituto de Pesquisas Ambientais, Brazil
E-mail: miguellmfreitas@yahoo.com.br
Adriano Wagner Ballarin
ORCID: https://orcid.org/0000-0002-1517-739X
Universidade Estadual Paulista, "Júlio de Mesquita Filho", Brazil
E-mail: awballarin@fca.unesp.br
Mario Tomazello-Filho
ORCID: https://orcid.org/0000-0002-9814-0778
Universidade de São Paulo, Brazil
E-mail: mtomazel@usp.br
Iraê Amaral Guerrini
ORCID: https://orcid.org/0000-0002-1336-0318
Universidade Estadual Paulista "Júlio de Mesquita Filho", Brazil
E-mail: iguerrini@fca.unesp.br
Marcio Rossi
ORCID: https://orcid.org/0000-0002-2360-2042
Instituto de Pesquisas Ambientais, Brazil
E-mail: rossi.10@uol.com.br
Eduardo Luiz Longui
ORCID: https://orcid.org/0000-0002-7610-9147
Instituto de Pesquisas Ambientais, Brazil
E-mail: elongui@sp.gov.br

Abstract

This study aimed to determine the effects of physical, chemical and water-holding capacity of Quartzarenic Neosol, Red Latosol and Red Nitosol on tree growth, physicomechanical properties and anatomical features of wood from 33-year-old *C. citriodora* plantations. More clayey soils with higher water availability, such as Red Latosol and Red Nitosol, increased the mean annual increment and heartwood percentage. In more sandy soils, such as Quartzarenic Neosol, density increased, but the size and diameter of fibers and vessels decreased, and both fiber cell wall thickness and frequency of vessels and rays increased. Wood shrinkage and mechanical properties did not differ between soils. We observed a gradual increase in the anatomical, physical and mechanical characteristics in the pith-bark direction. The uniformity index showed that Quartzarenic Neosol and Red Latosol soils produced more homogeneous woods. We concluded that soil texture and water availability influenced tree growth, anatomical properties and wood density.

Keywords: Adaptability; Forest improvement; Forest management; Provenance test; Wood quality.

Resumo

Este estudo teve como objetivo determinar os efeitos da capacidade física, química e de retenção de água do Neossolo Quartzarênico, Latossolo Vermelho e Nitossolo Vermelho sobre o crescimento arbóreo, propriedades físico-mecânicas e características anatômicas da madeira de plantações com 33 anos de *C. citriodora*. Solos mais argilosos e com maior disponibilidade hídrica, como o Latossolo Vermelho e o Nitossolo Vermelho, aumentaram o incremento médio anual e a porcentagem de cerne. Em solos mais arenosos, como o Neossolo Quartzarênico, a densidade aumentou, mas o tamanho e o diâmetro das fibras e vasos diminuíram, e a espessura da parede celular da fibra e a frequência dos vasos e raios aumentaram. A retração da madeira e as propriedades mecânicas não diferiram entre os solos. Observamos um aumento gradativo das características anatômicas, físicas e mecânicas no sentido medula-casca. O índice de uniformidade mostrou que os solos de Neossolo Quartzarênico e Latossolo Vermelho produziram madeiras mais homogêneas. Concluímos que a textura do solo e a disponibilidade de água influenciaram o crescimento das árvores, as propriedades anatômicas e a densidade da madeira.

Palavras-chave: Adaptabilidade; Melhoramento florestal; Manejo florestal; Teste de procedência; Qualidade da madeira.

Resumen

Este estudio tuvo como objetivo determinar los efectos de la capacidad física, química y de retención de agua de Quartzarenic Neosol, Red Latosol y Red Nitosol sobre el crecimiento de los árboles, las propiedades fisicomecánicas y las características anatómicas de la madera de plantaciones de 33 años de *C. citriodora*. Suelos más arcillosos con mayor disponibilidad de agua, como Red Latosol y Red Nitosol, aumentaron el incremento medio anual y el porcentaje de duramen. En suelos más arenosos, como Quartzarenic Neosol, la densidad aumentó, pero el tamaño y el diámetro de las fibras y los vasos disminuyeron, y aumentaron tanto el grosor de la pared celular de las fibras como la frecuencia de los vasos y los rayos. La contracción de la madera y las propiedades mecánicas no difirieron entre los suelos. Observamos un aumento gradual de las características anatómicas, físicas y mecánicas en la dirección médula-corteza. El índice de uniformidad mostró que los suelos Quartzarenic Neosol y Red Latosol produjeron maderas más homogéneas. Concluimos que la textura del suelo y la disponibilidad de agua influyeron en el crecimiento de los árboles, las propiedades anatómicas y la densidad de la madera.

Palabras clave: Adaptabilidad; Mejoramiento forestall; Manejo forestall; Ensayo de procedencia; Calidad de la madera.

1. Introduction

Eucalyptus and *Corymbia* species have been planted for decades in Brazil, especially as raw material for paper and pulp, but also for use as material for energy and lumber. *Eucalyptus* and *Corymbia* plantations occupy 6,97 million hectares of planted tree area in Brazil, and the largest planted areas are located in the states of Minas Gerais (28%), São Paulo (17%) and Mato Grosso do Sul (16%) (Ibá, 2020). The gender *Corymbia* includes 113 species, mostly in endemic, tropical, arid and semi-arid areas of northern Australia (Butler et al., 2017). In Brazil, *C. citriodora* plantations were started with a view to physiological adaptation, growth and wood utilization for charcoal production. Over time, objectives of plantations were expanded in order to produce sawmill wood, energy and exploration of leaves for essential oil extraction (Vitti & Brito, 1999).

Knowledge of plantation site characteristics, such as temperature and precipitation, as well as texture, chemical and soil water-holding capacity, is essential to understand how these characteristics can influence productivity and wood quality. In Brazil, most *Corymbia* plantations occur in Latosols (Gonçalves et al., 1997; Silveira et al., 2001). In general, *Corymbia* plantation productivity and wood quality are related to soil physical properties (Pereira et al., 2019), degree of soil acidity (Hong et al., 2019), water availability (Bordron et al., 2019; Ployet et al., 2019), and availability of mineral nutrients (Castro et al., 2020).

In general, Quartzarenic Neosols occur in approximately 6% of the Brazilian territory (Embrapa, 2019a). These soils are pedogenetically poorly evolved soils with absence of subsurface diagnostic horizons. They are young soils and have a predominance of characteristics inherited from original material. Latosols are the most representative soils in Brazil and represents about 39% of total area of the country wich are highly pedogenetically developed soils, highly weathered and with no deep clay increment. Nitosols have low occurrence in Brazil with approximately 1.5% of occurrence, but they occupy an important area in the state of São Paulo. These are clayey soils, lacking textural gradient and structure (Embrapa, 2019a). In the State of São Paulo, proportions are as follows: Quartzarenic Neosols 2.26%, Latosols 38.42% and Nitosols 1.46% (Rossi, 2017).

Recently, Souza et al. (2020) concluded that for the establishment of productive commercial stands of *C. citriodora*, the selection should correspond to the best genotypes selected across the complete deployment area, corresponding to genotypes fit to be used in different soil types. In order to complement plant selection, which will produce better wood quality. In the present study, we investigated growth, physicomechanical properties, and anatomical features of 33-year-old *C. citriodora* (formerly *Eucalyptus citriodora* Hook.) (Walter, 2020) in the three soil types described above.

We emphasize that soil classification is obtained from evaluation of morphological, physical, chemical and mineralogical data of soil profile. Environmental aspects of the profile site, such as climate, vegetation, relief, source material, water conditions, external soil characteristics and soil-landscape relationships, are also used (Santos et al., 2018). More specifically, this study aimed to determine the effects of physical, chemical and water-holding capacity of Quartzarenic Neosol, Red Latosol and Red Nitosol on tree growth, physicomechanical properties and anatomical features of wood from 33-year-old *C. citriodora* plantations. We hypothesized that trees growing in sandy and less nutrient-rich soils presented a slower growth owing to water and nutritional restrictions. We further reasoned that these trees would have denser wood with larger cell wall proportion and smaller cell lumen diameter and, consequently, higher physicomechanical values when compared to trees growing in more clayey and nutritionally rich soils. Such differences will determine wood quality and its potential uses.

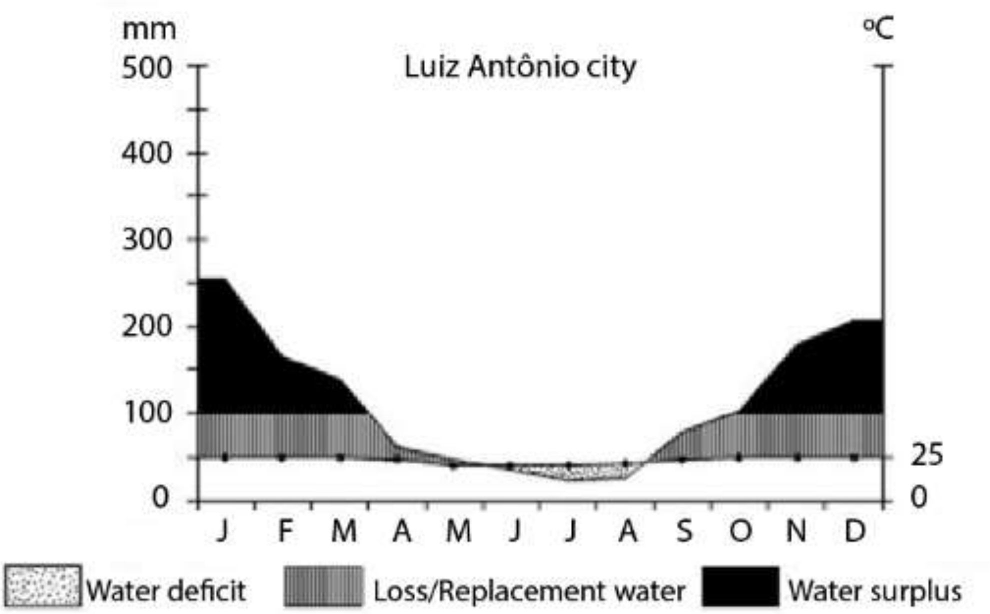
2. Methodology

2.1 Provenances of the seeds, planting area and sampling

In 1982, *C. citriodora* seeds of open-pollinated plants were collected in commercial plantations in Pederneiras State Forest, located in Pederneiras City, São Paulo State, Brazil (22°27′S, 48°44′W, elevation 500 m), where the climate is CWa in the Köppen-Geiger classification. In 1983, a progeny test was established with 56 progenies at the Luiz Antonio Experimental Station (LAES) in Luiz Antônio City, São Paulo (21º40’S, 47º49’W, elevation 550 m) (Gurgel-Garrido et al., 1997), where the climate is Aw (Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura – CEPAGRI, 2019). The average annual rainfall is 1,365 mm, and average annual temperature is 21.7º C, with the warmest months occurring in January, February and March and the coldest months in May, June and July. Luiz Antônio's climate diagram is presented in Figure 1.

The planting was established with the same design - spacing 3 × 2 m with one external border row of the same species without fertilization - in three different soil types: Quartzarenic Neosol (RQ), Red Latosol (LV), and Red Nitosol (NV) (Embrapa, 2019b). The correspondence between the adopted classification (SiBCS) and WRB/FAO Soil Taxonomy are as follows RQ - Arenosols/Quartzipsamments; LV - Ferralsols/Oxisols; and NV - Nitisols/Oxisols - Kandic (Embrapa, 2019a).

Figure 1. Climate diagram according to Walter (1986) from the Luiz Antônio, SP planting area and tree collection. Averages obtained from January/2005 to September/2015.



Source: CIAGRO - Integrated Center for Agrometeorological Information (http://www.ciiagro.sp.gov.br/).

In 2008, the LAES team determined height, DBH (diameter at breast height - 1.30 m from the ground), and stem shape, using a grading system with values ranging from one (worst grade, crooked trunks) to five (best grade, straighter trunks) and survival. In 2015, the same measurements were made, but competition among trees was added. The 2008 and 2015 information served as a basis to select 18 trees (one from each of the 18 best progenies), the tallest and/or largest in diameter, for each type of soil, totaling 54 trees.

Selected trees were felled in 2016, and from each tree, a disc at the base of trunk for heartwood and sapwood percentages and uniformity index and a 1-meter long log at the region immediately below breast height for physical, mechanical and anatomical investigations were sampled. From logs, we obtained a central board (5 cm thick), and from these boards, we cut three specimens with cross section of 50 x 50 mm². Three radial positions were established: the nearest part of trunk center, designated as pith, a middle position, and a position close to the bark, designated as bark. Specimens for anatomical features were taken to the laboratory, and for physicomechanical properties, they were conditioned to equilibrium in a climate-controlled room under 65% of relative humidity and 21ºC (approximately 12% EMC – Equilibrium Moisture Content). After acclimatization, specimens in nominal dimension were prepared according to the ASTM D 143 secondary method (Astm, 2007).

2.2 Soil sampling and analysis

We performed physical and soil water retention analyses according to Embrapa (1997). We collected samples at depths between 0-20 cm at three points within plantation, and then we mixed samples to prepare a composite sample. We repeated the same procedure for each soil type. For texture analysis, we determined the percentages of sand, clay and silt. We also determined soil water retention content and soil bulk density with a volumetric cylinder, using three samples of each soil type.

Air-dried soil samples were analyzed for phosphorus (P); aluminum (Al); H+Al; aluminum saturation (m%); the basic cations, including potassium (K), calcium (Ca), and magnesium (Mg); sum of the bases Ca, Mg and K (SB); pH; base saturation

(V%); the micronutrients boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn); cation exchange capacity (CEC) and total organic carbon (O.M.). Soil analysis was carried out according to the procedures described by Raij et al. (2001).

2.3. Mean annual increment

From 54 trees, we measured DBH (diameter at breast height, 1.3 m from the ground) with a caliper and height with a Vertex IV hypsometer. For conversion of cylindrical volume to real volume (m^3), we used the average from factors per species since tree volumes were calculated based on the formula proposed by Scolforo (1993). Then we used the equation $Vcylindrical = 0.0000785398163 * DBH^2 * H$ (Eq. 1). Next, the volume per hectare was calculated according to 3 x 2 m spacing by multiplying the number of plants by the average tree volume, and, finally, the volume per hectare per year was calculated by dividing the volume per hectare by age of planting (33 years, 1983-2016).

2.4. Physical properties

Wood density at 12% EMC was determined according to Glass and Zelinka (2010). Specimens 2 cm × 2 cm × 3 cm were conditioned at constant temperature (21°C) and moisture content (65%), and in these conditions, the mass was determined using an analytical balance. The volume was calculated by the product of their dimensions obtained with a micrometer.

Volumetric shrinkage was obtained from the same samples as those used for basic density (ABNT, 1997). The samples were saturated in water, and their dimensions were measured with a caliper (accuracy = 0.001mm), taking three measurements per direction. After oven-drying at 105 ± 3°C, we determined the dry volume of each sample. Volumetric shrinkage (as a percentage) is the difference between initial saturated and oven-dried volume divided by the initial volume.

One radial strip of each disc was obtained with a parallel circular saw (1.7 mm thick) and conditioned in a climate room (20°C, 60% relative humidity, 24 h) (Amaral & Tomazello Filho, 1998). These samples were scanned in a collimated X-ray source (25 kV), using a QTRS-01X tree-ring analyzer (Quintek Measurement Systems Inc., Knoxville, TN, USA) at a resolution of 80μm (QMS, 1999) to obtain a density profile. Punctual values of wood density along the radius were compiled to calculate the uniformity index of the xylem.

The uniformity index (Echols, 1973) numerically quantifies the dispersion around the average density of punctual density values of the wood along the region evaluated. Using the histogram of punctual densities and taking the class that contains the average, or reference class, and its contiguous classes (upper and lower) with weight 1, the other classes are assigned incremental weights (2, 3, 4), which increase as they move away from the reference class. 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 (reference and its two contiguous classes) and a uniformity index of 100. As the index increases, wood uniformity decreases. In this study, for all trees in each soil type, frequency classes with amplitude of 50 $kg.m^{-3}$ were used (Cherelli et al., 2018).

2.5 Mechanical properties

Mechanical characterization was carried out with the following tests: compression strength parallel to grain ($\sigma c \parallel$) and modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending (three-point test). These tests were performed in a computer-controlled 300kN electromechanical testing machine (INSTRON/EMIC, Paraná, Brazil). Deformations in bending were evaluated using a mechanical extensometer (accuracy = 0.01mm).

All variables of the mechanical tests were adopted according to NBR7190 (ABNT, 1997). Compression tests were performed on 20mm x 20mm x 60mm specimens and bending tests on 20mm x 20mm x 460mm specimens and a span length of 420mm. Both tests used a loading speed of 10MPa/min. Initial results of strength and elastic properties (modulus of elasticity) were corrected to the Equilibrium Moisture Content - EMC (12%), using a conversion coefficient of 3% (of variation per 1% of variation in the MC) for strength properties and 2% for elastic properties.

In the Brazilian standard NBR 7190 (ABNT, 1997), the characteristic value of compression strength parallel to the grain is used to classify the wood in the system of strength classes, guiding the choice of the most suitable species for structural projects (Eufrade Junior et al., 2015).

2.6 Anatomical analysis

Corymbia citriodora wood is characterized by presenting color differences between heartwood (reddish) and sapwood. We polished the base surface of each disc with sandpaper and measured percentages of heartwood and sapwood with a ruler.

We cut small pieces of wood from each sample for maceration using Franklin's method (Berlyn & Miksche, 1976). Wood fragments were stained with aqueous safranin and mounted temporarily in a solution of water and glycerin (1:1). Samples of 2 cm^3 were softened in boiling water and glycerin (4:1) for 1 hour. From these samples, transverse and longitudinal sections 20μm in thickness were obtained with a sliding microtome. Sections were bleached with sodium hypochlorite (60%), washed thoroughly in water, and stained with 1% safranin (Johansen 1940). Measurements followed the recommendations of the IAWA Committee (Iawa, 1989). Quantitative data are based on at least 25 measurements for each feature from each tree, thus fulfilling statistical requirements for the minimum number of measurements. Anatomical measurements were obtained using an Olympus CX 31 microscope equipped with a camera (Olympus E330 EVOLT) and computer image analysis software (Image-Pro 6.3).

2.7 Data analysis

We initially undertook descriptive statistical analysis and used Box Plot graphics to detect and exclude. We assumed values 1.5 times higher than the 3rd quartile and values 1.5 times lower than the 1st quartile. Normality tests were performed to check the distribution of data, and when a normal distribution was not observed, data were square root-transformed. Then, a parametric analysis of variance (one-way analysis of variance (ANOVA)) was performed. When a significant difference was observed, Tukey's test was used to identify pairs of significantly different means. We analyzed the radial variation within the same tree and also three radial positions together, comparing the results in the three soil types.

3. Results and Discussion

3.1 Soils

We found differences in soil texture according to granulometry analyses in the three soil types. RQ has 52% coarse sand, 41% fine sand, 4% clay and 3% silt. LV has 40% coarse sand, 41% fine sand, 16% clay and 3% silt. NV presented the lowest amount of coarse sand (6%), fine sand (13%) and the largest amount of clay (52%) and silt (29%) (Table 1).

Table 1. Physical attributes of three soil types (0-20 cm layer) of 33-year-old *Corymbia citriodora* plantings.

Soils	Sand			Clay	Silt	Soil texture
	Coarse	Fine	Total			
	(g.kg^{-1})					
RQ	515	415	930	43	27	Sand
LV	399	413	812	158	30	Sandy loam
NV	65	130	195	519	286	Clay

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV).Source: Authors.

For chemical attributes, we observed differences among pH, organic matter, macronutrients and micronutrients, and base saturation. We noticed that the most acidic pH is in LV and that organic matter is higher in NV. LV and RQ have high Al3 +, but low phosphorus, potassium, calcium and magnesium values. Sulfur has average reference values for all three soil types. On the other hand, micronutrients present difference between LV, with high values, and NV, with low values, for copper. In both soils, iron presents high values, and manganese and zinc low values. NV has high values for all macronutrients and micronutrients. According to the reference values, the base saturation (V%) is very low for LV and low for RQ and NV soils (Table 2). RQ has higher soil density, while NV has lower soil density (Table 3).

Table 2. Soil pH, organic matter and mineral nutrients of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	pH	**O.M.**	**P**	**Al^{3+}**	**H+Al**	**K**	**Ca**	**Mg**	**S**	**SB**	**CTC**	**m%**	**V%**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
Soils	$CaCl_2$	g.dm^{-3}	mg.dm^{-3}					––– mmol$_c$.dm^{-3} –––								––– mg.dm^{-3} –––		
RQ	4.1	7	3	6	29	0.4	2	1	7	3	32	64	9	0.15	0.2	88	0.5	0,1
LV	3.8	10	4	10	56	0.4	2	1	6	3	59	75	5	0.20	1.4	68	0.9	0,1
NV	4.6	24	96	1	92	6.1	62	13	7	81	173	1	47	0.26	14.6	49	94.8	4,4

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). Total organic carbon (O.M.); phosphorus (P); aluminum (Al); H+Al; potassium (K), calcium (Ca), magnesium (Mg); sulfur (S); sum of the bases Ca, Mg and K (SB); cation exchange capacity (CEC); aluminium saturation (m%); base saturation (V%); boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn). Source: Authors.

The areas are characterized by sandy (RQ), medium (LV) and clayey (NV) soils with no physical impediment to water infiltration into the soil and different water-holding capacity (Table 3). Clay soils have higher water-holding capacity (Table 3) compared to medium and sandy soils. This results from higher clay contents, the well-developed block structure and higher percentage of micropores in NV. Additionally, Rossi et al. (2005) show that clay mineral typology also influences this soil's water-holding capacity. According to Brady and Weil (2010), clay soils have higher water-holding capacity at a given potential than that of sandy soils.

The mean values of soil water-holding capacity in field capacity after natural drainage range from 0.09 $dm^3.dm^{-3}$ in RQ to 0.33 $dm^3.dm^{-3}$ in LV. This higher water retention in the evaluated matric potentials always occurs in NV (Table 3), but it does not reflect differences in the available water data (0.04MPa) since available H2O = FC-PWP. Rossi et al. (2005) report that total soil water reserve (water retained under matric potentials below the permanent wilting point) can be used by native forest vegetation and correlated with variations in vegetation. On the other hand, available soil water also depends on plant properties, such as roots depth; analyses in the present study were fixed on 20cm of surface layer.

NV is a soil with variable fertility according to its origin; however, our experimental site in the state of São Paulo has high fertility Nitosol (Morais et al., 2010; Rossi, 2017). RQ and LV had low saturation values per base (9 and 5 V%, respectively), classified as dystrophic soils, following the Brazilian Soil Classification System (Embrapa, 2018), and NV (47 V%) almost presented a eutrophic soil classification (higher than 50%).

Table 3. Average retained water and soil density of 33-year-old *Corymbia citriodora* in three soil types (0-20 cm layer).

	Retained water ($dm^3.dm^{-3}$)								
	Tension (MPa)								Soil density
Soils	Saturado	0.003	0.006	0.01	0.03^{FC}	0.1	0.5	1.5^{PWP}	($kg.dm^{-3}$)
RQ	0.43	0.33	0.22	0.13	0.09	0.07	0.06	0.05	1.85a
LV	0.53	0.39	0.29	0.19	0.14	0.12	0.10	0.10	1.70b
NV	0.63	0.47	0.44	0.38	0.33	0.31	0.29	0.29	1.51c

Quartzarenic Neosol (RQ); Red Latosol (LV); Red Nitosol (NV). FC = field capacity, PWP = permanent wilting point. Source: Authors.

3.2 Mean annual increment

Dendrometric data from 54 trees of 33-year-old *C. citriodora* trees is presented in table 4. Tree height did not vary among soil types. RQ trees presented the smallest diameters at breast height and, consequently, the lowest volume per tree (Table 5 and Figure 2). In our study, plantations are in the same area and therefore under the same rainfall regime; therefore, soil water retention is crucial for availability to trees. RQ presented the lowest water retention, which explains the lower volumetric growth of trees compared to the volumetric growth of trees in LV and NV soils with higher water retention capacity. Although RQ and LV may be considered nutrient-poor soils, LV has slightly higher cation exchange capacity, but very low base saturation. In LAES, we observed a water deficit between June and August, which possibly explains the lower tree volume in RQ since this type of soil has low water retention capacity.

Variations in soil types are determinants of forest productivity (Fisher and Binkley, 2000). In our study, we found differences in grain size, chemical composition and water-holding capacity among the three soil types. In general, NV values were higher compared to those of RQ and LV. This might be attributed to soil source materials in that NV has a basaltic origin, while RQ has a sandstone origin, and LV also has a probable origin in sandstone, but may contain some basalt. Another determining factor is water availability, a key resource for tree productivity in *Eucalyptus* plantations (Stape et al., 2010).

Table 4. Dendrometric data of 33-year-old *Corymbia citriodora* trees. DBH = diameter at breast height (1.3 m from the ground).

	Quartzarenic Neosol		Red Latosol		Red Nitosol	
Tree	Height (m)	DBH (cm)	Height (m)	DBH (cm)	Height (m)	DBH (cm)
1	20.5	14.0	23.0	14.0	27.5	20.5
2	27.0	20.0	32.9	32.0	20.6	14.5
3	18.2	11.0	21.7	16.0	33.0	27.0
4	22.8	16.0	30.5	27.0	20.0	21.5
5	23.5	14.5	18.6	14.0	22.5	13.0
6	21.4	13.0	18.0	19.5	23.0	26.5
7	23.0	18.0	20.2	13.0	23.7	16.0
8	19.2	10.5	26.5	24.0	29.4	25.0
9	21.5	23.0	27.3	24.0	17.4	15.0
10	21.0	15.0	24.0	19.0	25.5	16.0
11	20.4	16.0	25.4	17.5	24.4	16.0
12	20.3	16.0	29.0	22.0	18.7	12.5
13	25.0	18.5	25.0	22.5	24.6	18.0
14	14.8	9.0	9.0	23.0	22.1	17.5
15	31.6	18.5	26.2	15.5	21.0	14.0
16	26.0	22.0	23.0	16.0	16.4	12.0
17	23.3	16.0	23.7	18.5	25.0	16.0
18	20.0	14.0	16.1	12.0	26.2	24.5

Source: Authors.

Table 5. Silvicultural data and mean annual increment of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
Height (m)	14(22.1a)31*	9(23.3a)32	16(23.3a)33
DBH (cm)	9(15.8b)23	12(19.4a)32	12(18.0a)27
Tree volume (m^3)	0.217b	0.356a	0.307a
Volume per hectare ($m^3.ha^{-1}$)	361.67	593.33	511.67
Mean annual increment ($m^3.ha^{-1}.year^{-1}$)	10.96	19.14	16.50

Minimum (mean) and maximum values for DBH. Height and tree volume are presented. In the same row, distinct letters differ statistically ($P < 0.05$) by Tukey’s test. *Maximum and minimum values. Source: Authors.

Figure 2. Overview of *Corymbia citriodora* plantations in the three soil types. A. Quartzarenic Neosol. B. Red Latosol. C. Red Nitosol.

Source: Authors.

According to Forrester et al. (2010) and White et al. (2014), homogeneous *Eucalyptus* plantations have high water use efficiency, and this is reflected in their ability to produce more wood. According to Amazonas et al. (2018), low water amount in soil can decrease water potential in xylem and force plants to close stomata to avoid water loss, which, in turn, leads to a decrease in photosynthetic rate and, consequently, a decrease in growth and biomass.

Gava and Gonçalves (2008) studied the influence on *Eucalyptus grandis* wood in three soil types: Red Latosol, Yellow Red Latosol and Quartzarenic Latosol. The authors reported that soil physical attributes, especially clay content, in direct relationship to available water amount, was the one that most affected wood productivity and quality. Similar results occurred in our study because *C. citriodora* showed lower mean annual increment in Quartzarenic Latosol, but higher mean annual increment in Red Latosol.

Other authors have reported the influence of macro- and micronutrients on tree growth in different species. Harris et al. (1978) found that deficiencies in nitrogen and phosphorus restrict trunk and branch diameter, but have much less influence on trunk height growth in *Pinus radiata*. In our study, according to soil fertility (layer 0-20 cm) for *Eucalyptus* plantations (Castro et al., 2010), RQ and LV soils have low organic matter and phosphorus values, while in NV, values are medium and high, respectively.

Studying wood formation of *Populus tremula* and *P. tremuloides* trees in relation to amount of sodium and potassium, Fromm (2010) reported a decrease in wood increment when these species grow with low amounts of K+ or Ca2+. RQ and LV soils have low potassium and calcium contents, and NV values are medium and high, respectively. Biagiotti et al. (2017) studied the effect of potassium fertilization on *C. citriodora* during the first two years of plant life and concluded that up to nine months of fertilization promoted higher growth in height, while 12 months of fertilization promoted greater growth in diameter and biomass. At 24 months, no response to potassium fertilization was observed, suggesting a higher nutrient requirement in the initial growth phase. According to Cunha et al. (2019), the cycling of nutrients N, P, K Ca, and Mg in long rotation *C. citriodora* planting is important in maintaining forest productivity.

Smith et al. (2009) compared the effects of Ca^{2+} fertilization on calcium concentration in *Picea rubens* wood at two sites with different initial levels of Ca^{2+} in the soil. The authors found higher amounts of calcium in the wood in higher soil concentrations, evidencing interrelated processes between soil and tree chemistry and confirming that calcium cycle plays a key role in the health and productivity of *P. rubens* forests in northeastern USA. Studying water efficiency use in tree species with calcium and phosphorus fertilization in abandoned pastures in Brazilian Amazon, Silva et al. (2008) reported a significant effect on photosynthesis rate. In contrast to isolated phosphorus, trees growing in plots fertilized with phosphorus and calcium increased photosynthesis, indicating that calcium is an important limiting nutrient in secondary pasture succession. The effect of boron amount on soils with different textures (clay and sand) in *C. citriodora* showed an increase in volume per hectare in clayey soil and water availability (Pinheiro et al., 2019).

Although it is known that macro- and micronutrient contents influence tree growth, in our study, despite values classified as low in some nutrients, as discussed above, trees in LV did not differ in tree height, DBH or volume from NV trees. This suggests that amounts of macro- or micronutrients did not directly influence tree growth.

3.3 Physical and Mechanical properties

We observed a gradual increase of density at EMC from the pith to the bark in LV and NV soils, whereas in RQ soil, pith showed lower density, and no significant difference was noted between intermediate and bark positions. Among soil types, we observed lower density in NV and no significant differences between LV and RQ. In pith to bark variation for three soil types, volumetric shrinkage was higher in bark position, but pith and intermediate positions showed no significant differences. Among the soils, we did not find significant differences in volumetric shrinkage (Table 6).

We found a gradual increase of the compression parallel to the grain in LV and NV soils, while in RQ soil, we observed lower values in pith, but no difference between intermediate and bark positions. From MOE, we observed a gradual increase in LV and RQ soils, while in NV soil, we noticed higher MOE in bark. From MOR, we observed lower values in bark position only in RQ soil, but gradually increasing towards the bark. We did not find significant differences among the three types of soils for mechanical properties (Table 6).

According to the average values of the physical and mechanical properties, the wood of *C. citriodora* was grouped into resistance class 40, following the strength classes of standard NBR 7190 (Sales, 2004; Sales & Calil, 2005).

Table 6. Radial variation of physical and mechanical properties in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol				Red Latosol				Red Nitosol			
	pith	inter	bark	mean	pith	inter	bark	mean	pith	inter	bark	mean
ρ12	0.85b	0.93a	0.95a	0.91A	0.82c	0.93b	1.01a	0.92A	0.80c	0.85b	0.95a	0.87B
VS	15.03b	14.48b	16.40a	15.32A	14.42b	15.51b	17.24a	15.72A	13.67b	14.67b	16.32a	14.88A
fc0	51.11b	62.09a	65.48a	59.40A	49.54c	63.23b	72.75a	61.82A	48.35c	60.90b	69.52a	59.42A
MOE	11138c	13763b	17449a	14123A	10985c	15872b	19453a	15507A	12141b	13623b	18596a	14818A
MOR	82.62c	112.93b	134.43a	109.94A	79.68b	124.16a	139.20a	114.64A	98.87b	103.06ab	127.54a	110.27A

Density at 12% moisture content ρ12 = (g.cm^{-3}); VS = volumetric shrinkage (%); fc0 = compression parallel to the grain (MPa); MOE = modulus of elasticity (MPa); MOR = modulus of rupture (MPa). The comparison among radial positions is represented by lowercase letters, while the comparison among site soil types is represented by uppercase letters. In the same row, distinct letters differ statistically ($P < 0.05$) by Tukey's test.Source: Authors.

When we analyzed the radial variations of physical and mechanical properties, we found differences between innermost and outermost positions in all soil types. Vale et al. (1995) report that it is desirable for wood to have as homogeneous density as possible for better yield and quality in the final product. Based on this criterion, RQ tree wood was slightly more homogeneous in density and in general, as they varied less than LV and NV tree woods. One explanation would be the smaller tree diameter in RQ.

However, among soil types, we only observed differences in wood density. In a study with wood density of *Eucalyptus grandis* in three soil types (Red Latosol, Yellow Latosol and Quartzarenic Neosol), Gava and Gonçalves (2008) did not find differences. In the present study, we found lower wood density in NV, which has a higher amount of clay compared to RQ and LV. A similar result was observed by Rigatto et al. (2004) with *Pinus* species. They observed lower wood density from trees in clayey soils compared to other soils of different particle size compositions.

In addition to soil texture, its chemical composition can influence wood features. Ramanantoandro et al. (2016) studied the influence of soil types on trees from a Madagascar forest with differences in relief. The authors report that wood density is higher in poor ferralitic soils than in lowlands with iron-rich soils. Along the slope, they explained that soil is chemically poor, dominated by young, clayey soils that have poor structural stability and easily eroded.

In contrast, lowland soils are more fertile from soil nutrient accumulation by erosion. Thus, Ramanantoandro et al. (2016) suggest that tree growth is slower on poor soil, allowing wood to become denser. In our study, the relief is not a determinant of wood variations, since *C. citriodora* plantations are in flat locations. However, we still found a similar result. The nutrient-poor soils were RQ and LV, which, despite having iron content higher than NV, the highest wood densities occurred in RQ and LV trees when compared to wood from NV trees. Other authors have also found similar results with high density wood related to low soil fertility, e.g., Chave et al. (2006) who compiled data from more than 2400 Neotropical tree species. Hättenschwiler et al. (1996) and Kostiainen et al. (2004) in studies with conifers also reported a decrease in wood density with soil fertilization.

Sette et al. (2014a) describe the controversial effect of mineral fertilizers on *Eucalyptus* wood properties, indicating an increase and decrease in wood density. Studying the effect of potassium and sodium application on wood density of young *Eucalyptus grandis* trees, Sette et al. (2014b) and Castro et al. (2017) found lower density with lower fertilization. Barbosa et al. (2014) reported higher wood density in *Eucalyptus* spp. with lower NPK contents, while Sansigolo and Ramos (2011), in a study with *Eucalyptus grandis*, found a different result with lower wood density in soil with higher fertility. These results show a tendency toward higher wood density in less nutritional condition, although each situation should be analyzed in a more general context. This is one of gains to be emphasized in our study. Since plantations are in the same area, we are analyzing trees under the same temperature and precipitation regimes, even with the presence of microenvironments.

Arnaud et al. (2019) and Ployet et al. (2019) evaluated the effect of soil fertilization and water availability on wood density in *Eucalyptus grandis* submitted to treatments with and without potassium fertilization and with rain inclusion and exclusion. The authors observed that the presence of potassium and rainfall exclusion increased basic density when compared to the presence of potassium and rainfall. Our results showed very low K values and lower water availability in RQ and LV soils, but higher basic density values compared to NV soil with its higher fertility and higher water availability. This suggests that water availability was a major factor accounting for differences in basic density.

Studies relating soil attributes to wood density are more common, but some also related soil attributes to other properties. Lima and Garcia (2011), with *E. grandis* at 21 years old, observed radial variations in properties with increase in bark direction, corroborating our results with *C. citriodora*. Lima and Garcia (2011) also evaluated the effect of thinning and NPK fertilization at planting time and also at five years of planting on *E. grandis* wood at 21 years old. The authors observed a positive relationship between fertilization and compression parallel to the grain and modulus of elasticity, but found no significant relationship with shear strength and modulus of rupture. Haselein et al. (2002) observed an increase in modulus of elasticity and modulus of rupture with increasing soil fertilization in *Eucalyptus saligna* wood. As previously mentioned, our study showed that only wood density presented variations among soil types, while the other properties were not influenced. Thus, given that values of other properties are satisfactory for a given producer, our study indicates that wood properties, generally, do not change if seeds of this trees will plant in different soil types. High wood density and strength values are also suitable for use as lumber. According to Saranpää (2003), wood as a structural material generally has high density and strength, the same results we elucidated in *C. citriodora*.

In the present study, soil collections occurred when trees were adults, older than 30 years. Therefore, the relationships and inferences discussed here reflect the then current soil condition. We know that some studies indicate that *Eucalyptus* culture alters soil conditions. For instance, Leite et al. (2010) studied edaphic characteristics in Eucalyptus forested area, near pasture area, pasture area, *Eucalyptus* area near native forest area, and native forest area. In areas cultivated with Eucalyptus, the authors reported a reduction in exchangeable Ca^{2+}, Mg^{2+} and K^{+} levels; pH reduction; and increases in Al^{3+} and H + Al contents. In addition, increases in phosphorus nutrient content were found in areas cultivated with *Eucalyptus*. Thus, it is possible that some changes have occurred over time, but we do not have soil attributes before planting to compare with the current situation.

The uniformity index was higher in NV, but it differed between RQ and LV (Table 7). Thus, soil that would possibly put more stress on plants (RQ, which does not retain water) resulted in higher homogeneity. We suggest that RQ plants may not have experienced major water stress, apparently adapting well, growing less, but more homogeneously, than other groups. Cherelli et al. (2018), evaluating uniformity index in *C. citriodora*, *E. tereticornis* and *E. grandis*, aged 28, 35 and 18 years, respectively, observed that *C. citriodora* (UI = 187) did not differ from *E. tereticornis* (UI = 194), but was lower than *E. grandis* (UI = 267). The authors suggest that higher density of sapwood with mature wood characteristics may interfere with uniformity index. In the present study, denser wood from NV soil did not present the highest uniformity index.

Table 7. Uniformity index in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
Uniformity index	167b	177b	214a

In the same row, distinct letters differ statistically (P < 0.05) by Tukey's test. Source: Authors.

3.4 Anatomical features

We observed higher heartwood percentage and, consequently, lower sapwood percentage in LV and NV soils, respectively (Table 8).

Table 8. Heartwood and sapwood percentage in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol	Red Latosol	Red Nitosol
Heartwood (%)	57b	70a	71a
Sapwood (%)	43a	30b	29b

In the same row, distinct letters differ statistically (P < 0.05) by Tukey's test. Source: Authors.

Quantification of heartwood and sapwood percentages is also important in determining the quality of wood (Oliveira, 1997). According to Pereira et al. (2013), it is interesting that timber used in construction or furniture production has a higher heartwood percentage than sapwood since most sapwood is lost in wood cutting. An alternative would be sapwood treatment, which is permeable to chemicals that confer resistance to fungi and insects.

Wood from RQ trees has lower quality as RQ trees have lower heartwood percentage compared to wood from trees from LV and NV. However, according to Vieira (2003), in Rio Grande do Sul, *Eucalyptus* sapwood is used as external walls in rustic buildings, even though sapwood has low value-added products owing to faster degradation.

The increase in tree diameter in LV and NV soils was accompanied by increase of heartwood percentage, which was higher than that of RQ soil with low water availability and sandy texture. This result was observed in six-year-old *E. grandis* × *E. urophylla* clones that presented lower heartwood percentage in soils with low water availability (Barbosa et al., 2019). In 19-year-old *C. citriodora* in deep sandy loam soil, an increase in sapwood above 48% was observed, increasing gradually to the commercial height limit when compared to six other Eucalyptus species (Oliveira et al., 1999). In our study, wood from RQ soil presented 43% of sapwood, values close to those found by (Oliveira et al., 1999). Heartwood percentage in 20-year-old *C. citriodora* trees in India ranged from 74% to 84% at the trunk base (0.6 m) and 68% to 79% at the trunk top (6.6 m). In our study with 33-year-old trees, results showed that heartwood percentage in LV (70%) and LV (71%) soils is close to values found by the authors, regardless of height (Shashikala & Rao, 2009).

We found a gradual increase in pith to bark direction for fiber length in three soil types. Fibers with larger diameter occur in bark. Fiber lumen diameter gradually decreased toward the bark in the three soil types. Fiber wall thickness increased gradually from pith to bark in the three soil types. Longer fibers with wider diameter, larger lumen diameter, and thicker wall occurred in NV. Vessel diameter increased, and vessel frequency decreased from pith to bark in the three soil types. Larger vessels occurred in NV and narrower vessels occured in LV, with higher frequency in RQ and lower frequency in NV. Lower ray frequency occurred in pith position in the three soil types. Ray width gradually increased toward the bark in the three soil types. Among soil types, lower ray frequency occurred in LV with difference observed between RQ and NV. Ray width was larger in RQ and smaller in NV. Ray frequency decreased toward the bark in all three soil types. Higher frequency was observed in RQ, while LV and NV did not differ (Table 9).

Table 9. Radial variation of anatomical features in wood of 33-year-old *Corymbia citriodora* in three soil types.

	Quartzarenic Neosol				Red Latosol				Red Nitosol			
	pith	inter	bark	mean	pith	inter	bark	mean	pith	inter	bark	mean
FL	947c	989b	1037a	991B	901c	1014b	1071a	995B	905c	1065b	1099a	1023A
FD	15.5b	15.3b	16.2a	15.7B	14.8b	14.9b	15.4a	15.0C	16.0b	16.4b	17.0a	16.5A
FLD	4.8a	3.3b	2.7c	3.6B	4.4a	3.5b	2.9c	3.6B	6.1a	4.7b	4.0c	4.9A
FWT	5.3c	5.9b	6.7a	6.0B	5.2c	5.7b	6.2a	5.7B	4.9c	5.8b	6.5a	5.7A
VD	73c	90b	106a	90B	72c	87b	103a	88C	76c	94b	113a	95A
VF	19a	14b	11c	15A	16a	12b	10c	13B	13a	10b	8c	10C
RH	156b	167a	167a	163A	155b	161a	159a	159B	153b	168a	164a	162A
RW	11c	13b	15a	14A	11c	13b	15a	13B	11c	12b	14a	12C
RF	12a	11b	10c	11A	11a	10b	9c	10B	12a	10b	9c	10B

Fiber length (FL) µm; fiber diameter (FD) µm; fiber lumen diameter (FLD) µm; fiber wall thickness (FWT) µm; vessel diameter (VD) µm; vessel frequency (VF) nº. mm^{-2}; ray height (RH) µm; ray width (RW) µm; ray frequency (RF) nº. mm^{-1}. Difference between radial positions is represented by lowercase letters, while comparison between provenances is represented by uppercase letters. In the same row, distinct letters differ statistically ($P < 0.05$) by Tukey's test. Source: Authors.

Any changes in radial direction, tree growth, and wood properties among soil types should be determined by anatomical variations. In terms of radial variation, our results are in agreement with Baas et al. (2004) and Lachenbruch et al. (2011), who outline the changes from pith to bark, including increase in fiber length and wall thickness, negative relationship between vessel diameter (increase) and vessel frequency (decrease), and increase in ray dimensions.

Comparing among soils in the present study, longer fibers, larger diameter and larger lumen diameter occurred in NV and smaller diameter fibers in LV. Thicker wall fibers occurred in RQ. In a study with *Betula pubescens* in forest and peat-like soil (high organic matter content), Loustarinen et al. (2017) found larger and fewer cells in forest soils compared to peat-like soil where plants showed high growth rates and decrease in wall / lumen of fiber in adult wood. Oliveira et al. (2012) studied the wood of 64-month-old *Eucalyptus grandis* natural hybrid clone wood grown in different municipalities of the states of Espírito Santo and Minas Gerais with different edaphoclimatic characteristics. The authors found longer and larger diameter fibers in a region with sandy loam soil (authors' classification) compared to latosol regions. Lupi et al. (2012) investigated the effect of soil nitrogen increase on *Picea mariana* wood in boreal forest in Canada. The authors reported only an increase in tracheid wall thickness in initial wood of treated trees.

Over a period of two years, Vilotić et al. (2015) studied the dimensions of *Paulownia elongata* fibers with and without addition of macronutrients (N, P, K, Ca and Mg) and micronutrients (Fe, Mn, B, Zn, Cu). In plants in control soil (without fertilization), the authors reported that fibers were longer than those in plants in fertilized soil. In this case, fertilizer treatment interfered negatively with fiber length. In our study, *C. citriodora* fibers were longer in NV, soil with higher amounts of macro- and micronutrients, compared with the other two soil types.

In our study, larger vessels occurred in NV and narrower in LV. In a study with *Copaifera langsdorffii* with differences in vegetation type and soil attributes, Longui et al. (2014) found narrower vessels in trees on stony soils with low water retention and poorer nutrients. Oliveira et al. (2012) found vessels with larger diameters and frequency in latosol regions, compared with clayey soil in *Eucalyptus grandis*. It will be recalled that our results showed larger diameter vessels in NV with more clayey soil. Not only the texture, but soil chemical composition also influences the wood. Studying wood formation of *Populus tremula* and *P. tremuloides* trees in relation to the amount of sodium and potassium, Fromm (2010) reported a decrease in cambial activity and vessel diameter when these species grow in low amounts of K+ or Ca2+. This may have occurred in our study since *C. citriodora* wood vessels in RQ (90 µm) and LV (88 µm) trees were narrower than those found in LV wood (95 µm) where K and Ca contents were respectively RQ and LV = 0.4 and 2 mmolc/dm3 and NV = 6.1 and 62 mmolc/dm3. However, it is noteworthy that trees in LV presented the largest increments, even with narrower vessel diameter. Vessel diameter is positively related to water conduction; therefore, if water is available, more suitable conditions exist for photosynthetic efficiency (Hacke et al., 2005). The results of vessel density might help explain this variation, or in the case of trees we analyzed, significant differences between vessel diameters are not sufficient to imply significant differences in water conduction, photosynthesis and, consequently, growth rate.

Lower ray frequency occurred in LV with no difference between RQ and NV. Ray width was larger in RQ soil and smaller in NV soil. When observing ray dimensions (multiplying the height by the width), we notice that RQ presents bulker rays than the trees growing in the other two soil types. For *Copaifera langsdorffii* in the previously noted study, Longui et al. (2014) also found wider rays in trees in stony soils with low water retention and poorer nutrients. The authors suggested that higher ray volume in this context could confer greater potential for starch reserves, which may be important owing to the lower photosynthetic rate of *C. langsdorffii* plants with little soil water availability. In our study, a similar situation occurred with *C. citriodora* trees in RQ soil with lower water retention capacity, potentially interfering with photosynthesis, recalling trees with smaller diameter and smaller increment in RQ. In a study with *Eucalyptus grandis*, Oliveira et al. (2012) found bulker rays in a region with clayey soil compared with latosol regions.

We did not measure the proportion of axial parenchyma, but it may also play an interesting role in the results, especially since Loustarinen et al. (2017) found an increase in axial parenchyma in *Betula pubescens* wood in peat-like soil (high organic matter content) compared to forest soils. In our study, we observed an inverse association between organic matter content, decreasing from NV, LV to RQ, and ray volume was smaller in LV and higher in RQ.

4. Conclusion

We concluded that different physical, chemical and water properties of three soil types influenced the physical, mechanical and anatomical properties of *Corymbia citriodora* wood. Our results corroborate findings in the literature, more clayey soils with higher water availability, such as Red Latosol and Red Nitosol, increased the mean annual increment and heartwood percentage. In more sandy soils, such as Quartzarenic Neosol, density increased, but the size and diameter of fibers and vessels decreased, and both fiber cell wall thickness and frequency of vessels and rays increased. A more fertile, clayey soil condition with higher water availability influenced the formation of less homogeneous and dense woods. Wood shrinkage and mechanical properties did not differ between soils. We observed a gradual increase in the anatomical, physical and mechanical characteristics in the pith-bark direction. The uniformity index showed that Quartzarenic Neosol and Red Latosol soils produced more homogeneous woods. Although no differences were noted in mechanical properties among soils, average values of these properties wood was graded into higher strength classes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Dirceu de Souza and Israel Luiz de Lima for fieldwork (Forestry Institute - IF), as well as Ailton de Lima Lucas (UNESP - Botucatu), Sonia Regina Godoi Campião and Juraci de Andrade Barbosa (Forestry Institute - IF) for laboratory assistance. We also thank the Programa de Pós-Graduação em Ciência Florestal da Faculdade de Ciências Agronômicas - FCA/UNESP (https://www.fca.unesp.br/#!/pg-ciencia-florestal) for support in development of this study.

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