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GREEN WOOD DENSITY ESTIMATES AT DIFFERENT AGES AND ASSORTMENTS FOR *Pinus taeda* L.

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Resumo

Estimativa da Densidade Verde da Madeira de Pinus taeda L. em diferentes idades e sortimentos. Um fator relevante a se considerar no setor florestal é a precificação da madeira, onde geralmente as empresas florestais mensuram a madeira em toneladas por meio da pesagem dos caminhões. No entanto, essa abordagem genérica pode resultar em estimativas imprecisas pois não leva em consideração fatores que podem afetar o valor da densidade verde. Assim, o objetivo foi compreender a variação da densidade verde da madeira em diferentes idades e sortimentos de povoamento de *Pinus taeda* L. A pesquisa foi desenvolvida na fazenda Lageado Grande no município de Bituruna, estado do Paraná, em povoamentos de *P. taeda* com idades de 11, 15 e 19 anos em espaçamentos 3 m x 2 m, 2,5 m x 2,5 m e 2,5 m x 2,5 m, respectivamente. O delineamento estatístico utilizado para avaliação do teor de umidade, densidade básica e densidade verde, foi o DBC em arranjo fatorial de três idades (11, 15 e 19 anos) em diferentes sortimentos. Na avaliação do teor de umidade inicial, densidade básica e a densidade verde, todas as variáveis foram influenciadas pela idade e pelo tipo de sortimento. Os valores de teor de umidade diminuíram com o avanço da idade, enquanto a densidade básica aumentou. Já a densidade verde aumentou com o aumento da idade e diminuiu com o aumento das classes de sortimento. Os resultados indicaram que para a determinação do fator de conversão de peso para volume utilizando a densidade verde recomenda-se considerar as variações identificadas entre idades e sortimentos para obter estimativas mais precisas.
Palavras-chave: densidade básica, teor de umidade, conversão de unidades de massa.

Abstract

Fair timber pricing is crucial in the forest sector. Usually, the company buying wood measures timber in tons by weighing trucks at the factory. However, this approach can result in inaccurate estimates because it does not take into account factors that may affect green density. Thus, the objective of this study was to understand the variation in wood green density at different ages and assortments of *Pinus taeda* L. stands. The research was developed at the Lageado Grande farm in the municipality of Bituruna, state of Paraná, in *P. taeda* stands aged 11, 15, and 19 years planted in the 3 m x 2 m, 2.5 m x 2.5 m, and 2.5 m x 2.5 m spacing, respectively. We assessed moisture content, basic density and green density in a factorial randomized block design testing levels of age (11, 15, and 19 years) in different assortment classes. We found that initial moisture content, basic density, and green density were affected by age and assortment. Moisture content decreased with increasing age, and basic density increased. Green density increased with increasing age and decreased with increasing assortment. The results indicated that to determine the weight-to-volume conversion factor using green density, it is recommended to consider ages and assortments to obtain more accurate estimates.
Keywords: basic density; moisture content; mass unit conversion.

INTRODUCTION

Planted forest sector in Brazil plays an important role in the economy, providing essential resources for various other sectors, for example, construction, furniture, pulp and paper, and energy (MAXIMO *et al.*, 2022). These plantations are composed of a species of the *Pinus* genus by 19%, corresponding to 1.9 million hectares. In 2022, the total forest area of plantations in Brazil reached 9.94 million hectares, 0.3% increase compared to previous year, 2021, which can be explained by pine species rapid growth, high yield, and short rotation (IBÁ, 2023). *Pinus taeda* is one of the most cultivated species, due to its unique characteristics such as fast growth, high productivity, versatility, resistance to pests and diseases, and broad applicability. It is cultivated in many countries, which makes its wood widely available on the market at affordable prices compared to other species (CAVALI *et al.*, 2020).

Wood trade and pricing are normally done based on wood volume, being individual tree volume considered the building blocks composing stand volume (BONAZZA *et al.*, 2022; NICOLETTI *et al.*, 2021). Stand volume is a crucial variable in the forestry sector, as its monitoring provides relevant information for forest management, harvest planning, wood pricing, project economic evaluation, and research data (MALINDZAKOVA *et al.*, 2021; NICOLETTI *et al.*, 2021). Volume also indicates forest potential and site quality.

To ensure fair trade, it is essential to determine wood volume accurately, which can be done by applying tree scaling methods, in which the trunk is sectioned into logs to be measured. There are several methods for calculating volume employing this technique, for example, Smalian, Huber, and Newton (MACHADO; FIGUEIREDO FILHO, 2014). To determine the most accurate scaling method for measuring tree volumes, it is essential to test them across a wide range of forest conditions, considering different species, ages, clones, site, management practices, etc. Those stands and site attributes impact tree architecture, taper, and consequently, volume determination accuracy (LIMA, 2015). Therefore, it is crucial to employ a reliable scaling method ensuring precision in determining tree volumes while minimizing errors with a lower sampling intensity, saving sampling time, and labor resources.

Another crucial factor in the forestry sector is wood pricing. While producers sell their wood in volume - cubic meters, as it is the response variable from forest inventories, in industry, companies will measure wood bought in tons by weighing the trucks entering the manufacturing plant. To convert this mass unit, most companies adopt an average conversion factor, usually assuming that one ton is equivalent to one cubic meter (MACHADO; FIGUEIREDO FILHO, 2014; WEGGLER *et al.*, 2012). However, this generic approach can lead to inaccurate estimates as it does not take into account factors that can affect green density values (BONAZZA, 2022). According to Bonazza *et al.* (2022), green density can vary depending on species, tree age, growth conditions, moisture content, storage time, and even among different wood assortments. Given that green density plays an important role in forest management and logistical planning (FOELKEL, 2015), its accurate determination is essential, as mass directly affects transportation costs, vehicle load capacities, and the final value of the product (BONAZZA *et al.*, 2022).

Therefore, considering the importance of calculating wood green density to facilitate conversion between volume and mass units towards fair wood commercialization and pricing, this research aims to improve green density determination. By deepening the understanding of green density variations across different ages and assortments, we hope to contribute to sustainable forest management and the optimization of wood resource use. Thus, the objective of this study was to understand the variation in green wood density across different ages and assortments for *Pinus taeda* L. stands. We hypothesized that there is no difference in green density according to age and assortment.

MATERIAL AND METHODS

Log volume measurement, weighing, and disc extraction

Data was collected at Fazenda Lageado Grande, in Bituruna, Parana (PR), Brazil, in *Pinus taeda* L. stands at ages of 11, 15, and 19 years, with active harvesting operations. The stands selected were T011, T007, and T038 at ages of 11 (1st thinning), 15 years (2nd thinning), and 19 (clear-cut), respectively. Assortment (S) standard size considered by the company was used in this study. Each assortment class had 60 logs sampled, resulting in a sample of 180, 240, and 300 logs at ages of 11, 15, and 19, respectively, totaling 720 logs.

Logs of different ages were sampled from different wood piles within the forest and/or on the roadside (Figure 1). Logs were removed from the piles and scaled following Huber, Smalian, and Newton techniques. These methods were employed because they are widely accepted in the forestry literature, ensuring accurate wood volume measurements. Besides, the forest company staff are used to those methods, which optimize data collection with greater precision. Following volume measurement, the logs were weighed using a digital scale with a 500-kilogram (kg) load capacity suspended on a tripod connected to a generator (Figure 2). The logs were labeled in the field according to assortment and stand age. Following log volume measurement and weighing, three cm-thick discs were cut to have their wood density determined, resulting in 180 discs at age 11, 240 at age 15, and 300 at age 19, totaling 720 discs.

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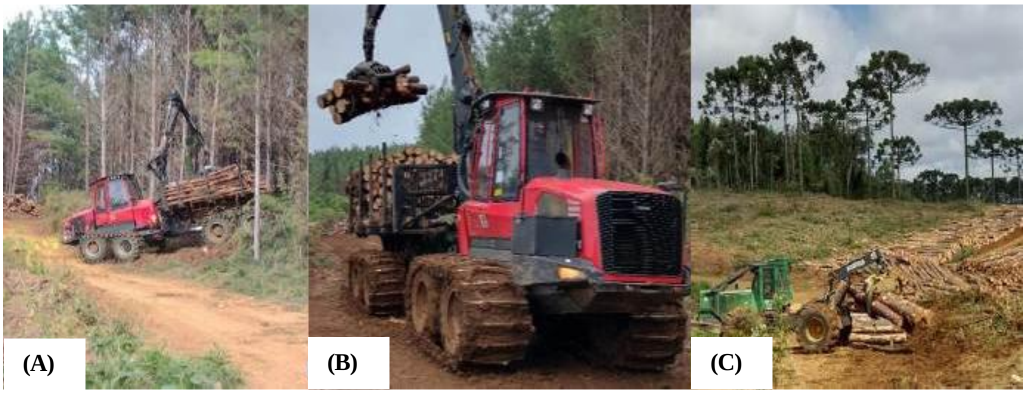

Figure 1. Harvesting and log piles were sampled according to assortment class at ages of 11 (A), 15 (B), and 19 (C).

Figura 1. Colheita das toras a serem amostradas de acordo com o tipo de sortimento aos 11 (A), 15 (B) e 19 (C) anos de idade.

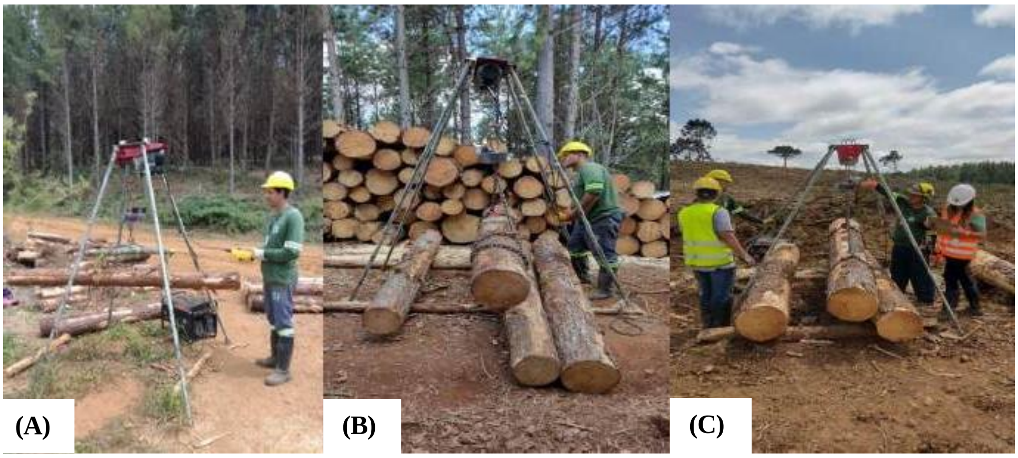

Figure 2. Log weighing in the roadside following the first thinning at age 11 (A), second thinning at age of 15 (B), and final harvest at age 19 (C).

Figura 2. Pesagem de toras na área de operação do primeiro desbaste na idade de 11 anos (A), segundo desbaste na idade de 15 anos (B) e corte final na idade de 19 anos (C).

The different number of discs on each treatment was due to the different assortment yielded at each age: three assortments in the first thinning, four in the second thinning, and five in the final cut. Each disc was labeled according to the operation and assortment size (Table 1).

Table 1. Coding describing the discs according to operation and assortment class.
Tabela 1. Códigos utilizados para identificação dos discos no campo conforme operação e sortimento.

Assortment	TTL (cm)	Forest Operation		
		1º Thinning	2º Thinning	Clear Cut
1	6-13	$1TH_1A_n$	$2TH_1A_n$	CC_1A_n
2	13-18	$1TH_2A_n$	$2TH_2A_n$	CC_2A_n
3	18-23	$1TH_3A_n$	$2TH_3A_n$	CC_3A_n
4	23-33	-	$2TH_4A_n$	CC_4A_n
5	> 33	-	-	CC_5A_n

Legend: TTL: thinned tip log; 1TH – First thinning; 2TH – second thinning; CC – Clear Cut; $A_{1...5}$ – Assortment 1 to 5; $_n$ – log 1 to 60.

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After cutting the discs, wet weight was measured using a scale (Figure 3A and 3B). Next, samples were taken to the Forest Management Laboratory to be stored, at the Center-West State University (Universidade Estadual do Centro-Oeste -UNICENTRO), Irati campus (Figure 4C).

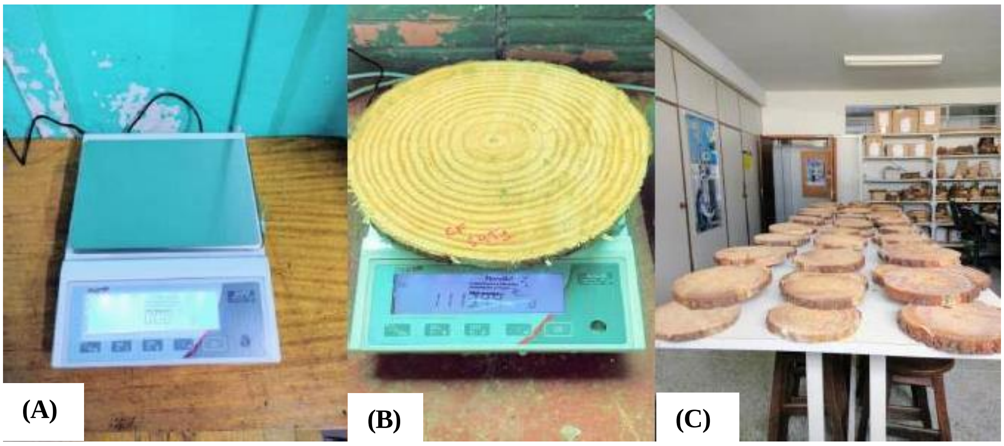

Figure 3. Wet weight determination (A and B) and storage room in the Forest Management Laboratory (C).
Figura 3. Determinação da massa úmida (A e B) e armazenamento no Laboratório de Manejo Florestal (C).

Moisture content and basic density

Disc moisture content was obtained according to the COPANT Standard 461/1972, in the field. Next, the discs were taken to the Forest Management Laboratory, where discs were labeled according to the operation and age. The discs were immersed in water for one month. Water was replaced every three days. Next, bark was removed, and the discs were weighed every third day until weight stabilized in three consecutive measurements.

Dick volume was determined using the hydrostatic balance method, with a one-decimal-place scale with a minimum capacity of 8,000 g. Container plus water weight was disregarded, as the scale was tared. The discs were hung by a nail and fully submerged, without contact with the container sides and bottom, so that the top of the disc was leveled with the water surface. The first reading after submersion was recorded in grams. The scale was tared each time a new disc was inserted, and the water was replaced after 15 discs were weighed. After determining the volume, the discs were placed in an oven at 103 ± 2 °C for twenty-four hours. Next, the discs were weighed every three days until their mass stabilized. The weight was recorded.

Data analysis

The experiment was set as a factorial experiment within a randomized block design. The factors considered were: Factor 1 – stand age, and Factor 2 – assortments, distributed across six blocks, 10 logs per block. Age consisted of three levels (11, 15, and 19 years), while assortments had different levels according to age (three assortment sizes at age 11, four assortment sizes at age 15, and five assortment size at age 19, as previously described). The variables evaluated were: IMC – initial moisture content (%); p – basic density (g/cm³); Gd – green density (t/m³). Initial moisture content was calculated using Equation 1 (BONAZZA *et al.*, 2022)

$$IMC_i = \frac{m_u - m_s}{m_s} x100 \quad (1)$$

where: *IMCi*: initial moisture content (%); m_u: green wood weight (g) and; m_s: dry wood weight (g).

Basic density was calculated according to COPANT Standard 461/1972 – Method for determining basic specific mass, calculated by dividing the dry mass of the sample at 0% moisture content and its saturated volume (2). Each log had its green density calculated using its volume and mass as in 3 (BONAZZA *et al.*, 2022). The volume was calculated using the three methods (Huber, Smalian, and Newton).

$$p = \frac{m0\%}{vsaturated} \quad (2)$$

$$Gd = \frac{m}{v} \quad (3)$$

where: *p*= basic wood density (g.cm^{-3}); $m_{0\%}$= dry disc mass at 0% of moisture; $v_{saturated}$= disc volume; *Gd*= green density (t.m^{-3}); *m*= green log mass (t) and *v*= Log volume (m³).

The data was tested for normality and homogeneity of variance using the Shapiro-Wilk test ($p \geq 0.05$) and the Fligner-Killeen test ($p \geq 0.05$), respectively. Since the data did not follow normality, they were transformed using the Box-Cox method (Box & Cox, 1964). This technique is commonly applied to asymmetric distribution, allowing for reliable parametric tests. This approach ensured greater statistical robustness in comparing means across different treatments. After transforming data, the assumptions for analysis of variance (ANOVA) were reassessed, normality was confirmed, and an analysis of variance was performed. The statistical analysis was performed using R software (R Core Team, 2024), employing the 'ExpDes.pt' package for analysis of variance and the Shapiro-Wilk test, the 'stars' package to perform the Fligner-Killeen test (Pebesma & Bivand, 2023), and the 'MASS' package for data transformation using the Box-Cox method. Treatment means were compared using Tukey's test, with a significance level of 5%

RESULTS

The analysis of variance showed no significant effect for block, indicating consistency in data collection and environmental conditions. Age, assortment and their interaction were statistically significant. The results of Tukey's test for initial moisture content (IMC) (Table 2) showed that the highest values were observed in assortment S1 at all ages (11, 15, and 19 years). For the other assortments, IMC did not differ from each other within different ages (vertical analysis, capital letters). Average IMC values at age 11 were higher in all assortments compared to the other ages (15 and 19 years) (horizontal analysis, small letters). Average IMC values did not differ statistically at ages 15 and 19.

Table 2. Mean, standard deviation, and statistical analysis for initial moisture content in the interaction between age and assortment of *Pinus taeda* L. stands in Bituruna, Paraná.
Tabela 2. Valores médios, desvio padrão e análise estatística do teor de umidade inicial na interação entre idade e sortimento de *Pinus taeda* L. no município de Bituruna - Paraná.

Sortimentos	Initial Moisture Content (%)		
	Age		
	11 years	15 years	19 years
S_1 – (6-13 cm)	193.79 (± 37.79) Aa	160.96 (± 40.69) Ab	144.05 (± 40.87) Ab
S_2 – (13-18 cm)	158.50 (± 21.84) Ba	131.97 (± 37.55) Bb	116.44 (± 23.80) Bb
S_3 – (18-23 cm)	154.29 (± 35.70) Ba	127.35 (± 18.96) Bb	112.00 (± 34.24) Bb
S_4 – (23-33 cm)	---	123.19 (± 28.78) Ba	110.12 (± 21.43) Ba
S_5 – (> 33 cm)	---	---	100.96 (± 22.93) B

Capital letters (vertical assessment) compare assortment averages at ages; Small letters (horizontal assessment) compare age averages at assortment class. Same letters did not differ statistically, according to Tukey test at 5% significance.
Letras maiúsculas na vertical refere-se ao comparativo de médias das idades em cada nível de sortimento avaliado; letras minúsculas na horizontal referem-se ao comparativo de médias dos sortimentos em cada idade. Letras iguais não diferem estatisticamente entre si, pelo teste Tukey 5% de probabilidade de erro.

Tukey test for basic density (p) showed that at ages 11 and 15, assortment S1 had significantly lower basic density values compared to the other assortments. There was no statistically significant difference between the values of assortments S2 and S3 at ages 11 and 15 (Table 3). At age 19, average values of assortments S1 and S2 did not differ statistically, nor did S3 and S4 (vertical analysis). In the horizontal analysis, basic density values were higher at age 19 across all assortments, compared to ages 11 and 15. No statistically significant difference was found in the average basic density values between ages 11 and 15 for assortments S1, S2, and S3, as well as between ages 15 and 19 for assortment S4.

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Table 3. Mean, standard deviation, and statistical analysis of basic density and the interaction between age and assortment for *Pinus taeda* L. stands in Bituruna, Paraná.

Tabela 3. Valores médios, desvio padrão e análise estatística do teor de densidade básica na interação entre idade e sortimento de *Pinus taeda* L. no município de Bituruna - Paraná.

Assortments	Basic wood density - p (g.cm³)		
	Age		
	11 years	15 years	19 years
S_1 – (6-13 cm)	0.31 (± 0.03) Bb	0.32 (±0.03) Cb	0.37 (± 0.06) Ba
S_2 – (13-18 cm)	0.33 (± 0.04) Ab	0.35 (± 0.07) Bb	0.38 (± 0.03) Ba
S_3 – (18-23 cm)	0.36 (± 0.07) Ab	0.36 (± 0.03) Bb	0.39 (± 0.07) Aa
S_4 – (23-33 cm)	---	0.38 (± 0.07) Aa	0.40 (± 0.05) Aa
S_5 – (> 33 cm)	---	---	0.41 (± 0.04) A

Capital letters (vertical assessment) compare assortment averages at ages; Small letters (horizontal assessment) compare age averages at assortment class. Same letters did not differ statistically, according to Tukey test at 5% significance

Letras maiúsculas na vertical refere-se ao comparativo de médias das idades em cada nível de sortimento avaliado; letras minúsculas na horizontal referem-se ao comparativo de médias dos sortimentos em cada idade. Letras iguais não diferem estatisticamente entre si, pelo teste Tukey 5% de probabilidade de erro.

To determine green density, green volume was measured using three scaling methods (Huber, Smalian and Newton). The analysis of variance showed no difference between the methods for block and age. There was a significant difference between assortments, and its interaction with age. Therefore, data was assessed for assortments and age according to the method.

Green density did not differ among assortments at age 11, indicating that at this age, same conversion factor can be applied to all assortments (Table 4). At age 15, assortments S1 and S2 were statistically not different, differing from S3 and S4, statistically not different. The same was observed for age 19, assortments S1 and S2, and S3 and S4, have the same conversion factor. Assortment S5 differed from the others, with the lowest green density value (vertical assessment).

Table 4. Mean, standard deviation, and statistical analysis for green density volume (with bark) calculated using Huber, Smalian, and Newton methods, in the interaction between age and assortment for *Pinus taeda* L. stands in Bituruna, Paraná.

Tabela 4. Valores médios, desvio padrão e análise estatística da densidade verde do volume com casca calculado pelos métodos de Huber, Smalian e Newton, da interação entre idade e sortimento de *Pinus taeda* L. no município de Bituruna – Paraná.

Assortments	Green density (t.m³) - Huber		
	Age		
	11 years	15 years	19 years
S1 – (6-13 cm)	0.98 (± 0.10) Ab	1.05 (± 0.22) Aa	1,06 (±0,15) Aa
S2 – (13-18 cm)	0.97 (± 0.09) Ab	1.00 (± 0.09) Aa	1,03 (± 0,06) Aa
S3 – (18-23 cm)	1.01 (± 0.13) Aa	0.97 (± 0.08) Ba	0,99 (± 0,08) Ba
S4 – (23-33 cm)	---	0.99 (± 0.12) Ba	0,94 (± 0,07) Bb
S5 – (> 33 cm)	---	---	0,92 (± 0,07) C
	Green density (t.m³) - Smalian		
S1 – (6-13 cm)	0,96 (± 0,10) Ab	1.02 (± 0.15) Aa	1.03 (±0.11) Aa
S2 – (13-18 cm)	0,93 (± 0,09) Ab	0.98 (± 0.08) Aa	1.01 (± 0.10) Aa
S3 – (18-23 cm)	0,92 (± 0,10) Aa	0.91 (± 0.11) Ba	0.95 (± 0.11) Ba
S4 – (23-33 cm)	---	0.91 (± 0.15) Ba	0.92 (± 0.09) Ba
S5 – (> 33 cm)	---	---	0.87 (± 0.09) C

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Assortments	Green density (t.m³) - Newton		
	Age		
		11 years	15 years
S1 – (6-13 cm)	0,97 (± 0,08) Ab	1.05 (± 0.23) Aa	1.04 (±0.11) Aa
S2 – (13-18 cm)	0,95 (± 0,07) Ab	0.99 (± 0.07) Ba	1.02 (± 0.06) Aa
S3 – (18-23 cm)	0,98 (± 0,10) Aa	0.94 (± 0.08) Ba	0.97 (± 0.07) Ba
S4 – (23-33 cm)	---	0.96 (± 0.13) Ba	0.93 (± 0.06) Ba
S5 – (> 33 cm)	---	---	0.90 (± 0.07) C

Capital letters (vertical assessment) compare assortment averages at ages; Small letters (horizontal assessment) compare age averages at assortment class. Same letters did not differ statistically, according to Tukey test at 5% significance

Letras maiusculas na vertical refere-se ao comparativo de médias das idades em cada nível de sortimento avaliado; letras minúsculas na horizontal referem-se ao comparativo de médias dos sortimentos em cada idade. Letras iguais não diferem estatisticamente entre si, pelo teste Tukey 5% de probabilidade de erro.

Average green density (Gd) values did not differ statistically between assortments S1 and S2 at ages 15 and 19, but differed from those at age 11. For assortment S3, all ages showed statistically not different average values, as did the assortment S4 at ages 15 and 19. No statistical differences were observed in green density values among the volume measurement methods evaluated, suggesting the use of Huber method for volume determination and green density calculation, since it is the most straightforward method for field data collection and showed the lowest coefficient of variation (CV%). This method provided more consistent estimates, and it is the easiest one to perform in the field, making it ideal for forestry operations.

DISCUSSION

The analysis of variance showed significant differences between ages and assortments, and its interactions to moisture content, basic and green density, which corroborates with Bonazza *et al.* (2022). Highest moisture values were observed in the S1 (6 – 13 cm) in all ages (11, 15 and 19), as shown by Bonazza *et al.* (2022), who also found high moisture content for young *P. Taeda* wood, which is common to young trees built with juvenile tissue.

Basic density had an inverse trend compared to moisture, which had values increasing with age, which was also found by Bonazza *et al.* (2022), who showed that increasing late wood with increasing age resulted in cells with reduced lumen and higher density. Sousa *et al.* (2007) described lower density in juvenile tissue due to shorter tracheids with thinner cells, also corroborating lower densities at young ages. Bonazza *et al.* (2022) observed significant differences between assortments. On the other hand, the results in this study showed low significance for basic density in the different assortments over different ages. These disagreements among the studies could be explained by stand attributes and wood variability.

Wood density is related to wood characteristics, for example, cellulose yield, physical and mechanical paper resistance, coal yield, and quality etc. To understand these variations is important to optimize wood harvesting and transportation, and to apply new technologies allowing wood conversion between wood volume and mass, so wood trade is fairer and more flexible (BONAZZA *et al.*, 2022). Some forest companies consider a factor of 1 to convert wood weight to volume, meaning one cubic meter equals one ton of wood, without considering age, assortment, and after-harvesting time (Machado; Figueiredo Filho, 2014; BONAZZA *et al.*., 2022).

Green density was related to age/sorting in this study, as observed by Bonazza *et al.* (2022). Green density increased with age and decreased with the increase in assortment size, meaning higher moisture content in younger and smaller-diameter logs. Bonazza *et al.* (2022) suggest that green density is strongly related to the initial moisture content, which explains the observed variability. The authors also found that older wood tends to exhibit higher green density values. Furthermore, within each age, it was found that green density increased as the log diameters decreased, reflecting the higher water content and lower basic wood density. The study from Bonazza *et al.* (2022) showed that different green densities exist for different assortments and ages, enforcing the need for stratifying conversion factors to wood mass and volume for higher precision.

This study was conducted at a single location, which may limit the extent the results to other regions and management conditions. However, this research provides a relevant contribution to the forestry sector by demonstrating the influence of age and assortment on the green wood density, which impacts conversion from volume to mass. Therefore, the results indicate that applying a single green density value, without considering age and assortment size may lead to inaccurate pricing, affecting both producers selling and industries buying wood. Thus, by adopting different coefficients, it is possible to enhance wood value determination and improve planning of logistical costs associated with transportation, providing support for more efficient and sustainable forest resource management.

CONCLUSIONS

- Moisture content decreased with age, while basic density increased with age. Green density increased with age and decreased with increasing assortment size. Therefore, age and assortments significantly affected moisture basic and green density for *P. taeda* wood.
- To better employ green density precisely, age and assortments should be considered.
- If variability is significant, it is preferable to use specific values for each age and assortment class, as is the case with the smaller assortments at all ages and assortment five at age 19. For ages 15 and 19, it is possible to use the same green density conversion factor
- Our results showed that green density differed according to age and assortment.

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