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Sampling strategies along the tree stem to determine the basic density of *Eucalyptus* wood

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: There is a need to find a simpler sampling strategy that still maintains the accuracy of the results. This work aimed to assess different sampling strategies for measuring the basic wood density of *Eucalyptus* clones along the tree trunk.

Results: The basic wood density of most *Eucalyptus* clones was affected by the sampling strategy employed. The average density varied between samples, ranging from 476.69 to 449.61 Kg m^{-3}. In this study, the base positions generally showed lower density averages. Traditional sampling best represented the variation trend in Composite sampling due to their similar behavior. Depending on the clone and sampling methodology, the diameter at breast height represented 91.85 to 99.74% of the overall average stem. All adjusted equations were significant, allowing the basic density to be estimated through smaller sampling regions along the tree trunk. When the goal is to evaluate the property at four sample points, the best model corresponds to the heights in the upper half of the stem, which are the higher regions.

Conclusion: The analyzed base-top sampling strategies did not show significant differences between them, except for the one that only considered the diameter at breast height, which underestimated the basic density value of the wood. Sampling Removal of extremes effectively estimated the average density when considering all clones as a single material, which is the best strategy for measuring basic density under the conditions in the present study. Sampling positions at 50% of the tree's commercial height were more associated with the basic density.

Keywords: Commercial height; Mathematical models; Wood quality.

HIGHLIGHTS

Basic density is highest in central positions along the *Eucalyptus* trunk.
The 75% height best represents the average trunk density of *Eucalyptus*.
DBH sampling underestimates density.
Removal of extreme values was more representative of the average basic density of the tree.

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INTRODUCTION

Basic density is a crucial factor in determining wood quality and is widely recognized for its significant influence on operational and economic performance in the forestry sector (Boschetti et al., 2020). Density serves as a significant factor in various industrial processes, such as cellulose pulp production, where it informs about chip impregnation and specific consumption (Queiroz et al., 2004). The denser the wood, the better the performance in terms of weight in the production of charcoal (Loureiro et al., 2021). The impact of density can also be noted in Medium Density Fiberboard (MDF) panel manufacturing, affecting pressing and fiber contact (Maloney, 1989). The Brazilian timber industry faces a major challenge in determining the basic density of eucalyptus wood by sampling from the bottom to the top, as this characteristic can fluctuate throughout the height of the trunk. The differences may vary depending on the species, genetic makeup, tree age, growth conditions, increment, and management strategies applied (Boschetti et al., 2020). Therefore, the determination of wood density can be affected by factors such as variability, sample type, and analysis method.

Studies on the density of eucalyptus wood in Brazil often use disc sampling. This method involves taking samples at specific positions, such as the base (0%), 25%, 50%, 75%, and 100% of the tree's commercial height, or at the diameter breast height (DBH) position. The use of DHB as a fixed point for determining basic density has been established for many decades. Madern (1965) regarded DBH as the standard position for this determination, as it was already an international standard in forestry management.

When it comes to the diversity of timber uses and species, there is no agreement on the best sampling positions to estimate the average density of trees. This is because their behavior is being studied using a variety of sampling techniques, making it challenging to come to a clear conclusion. There is no specific standard method for determining basic density in Brazil. For instance, NBR 14660 (Associação Brasileira de Normas Técnicas – ABNT, 2004) focuses on producing samples for chemical analysis and does not cover sampling strategies for trees. To accurately assess a batch of wood for the basic density of discs and chips, NBR 11941 (ABNT, 2003) specifies that sampling must be conducted following NBR 14660. Besides that, specifies that it is imperative to ensure that the portions accurately represent the received sample for other evaluations.

Collecting samples at different heights of the tree requires time, money, and labor, both for field work and for analyzing in the lab. In this context, there is a need to find a simpler sampling strategy that still maintains the accuracy of the results. Investigating various sampling patterns and their results helps to determine if a smaller number of samples produces satisfactory results.

From this perspective, under the hypothesis that simplified sampling strategies are as effective as traditional methods for estimating the average basic density of wood of *Eucalyptus* clones, while maintaining precision and reducing operational costs, the objective of this study was not only to evaluate several sampling techniques along the tree stem but also to identify which one most effectively represents the basic wood density of *Eucalyptus* clones in comparison to the traditional method.

MATERIAL AND METHODS

Study area, sampling, and wood characterization

The study focused on four different eucalyptus clones (C1, C2, C3, and C4), all at the age of six years, from a commercial plantation belonging to a company that produces MDF panels in the municipalities of Lençóis Paulista e Agudos, both in the state of São Paulo, Brazil (Table 1). These clones consisted of two hybrids of *Eucalyptus urophylla* and *Eucalyptus grandis* (C1 and C2), along with individual *Eucalyptus grandis* (C3) and *Eucalyptus urophylla* (C4) trees.

The collection sites in Lençóis Paulista and Agudos had an average temperature of 21.5 and 22.2ºC and precipitation of 1485 and 1411 mm per year, respectively, between 2016 and 2022. The planting spacing was 3.00 x 1.90 m for C1, C2, and C3 and 3.00 x 2.00 m for C4, with the same silvicultural management applied to all clones.

Five trees were collected per clone, based on the average planting diameter determined by the forest inventory, excluding the first two borderlines. Furthermore, a minimum diameter of 5 cm was adopted to determine the commercial height. From eight positions on the stem, 3.50 cm thick discs were taken, along with a sample at the diameter at breast height (DBH) position, measured at 1.30 m from the ground. The sampled positions were divided into seven sampling strategies (Table 2).

The basic wood density was determined using one 45° wedge in each position (Figure 1) following the procedures outlined in NBR 11941 (ABNT, 2003).

Table 1: Growth characteristics of commercial eucalyptus clones at 6 years of age planted to produce MDF panels.

Clones	Climate	Area (ha)	Altitude (m)	Total height (m)	Commercial height (m)	DBH_{wb} (cm)
C1	Cfa	14.42	737	25.33	22.22	19.12
C2	Cfa	41.53	625	26.10	23.58	17.28
C3	Cfa	10.62	619	27.02	24.44	17.60
C4	Cfa	10.19	644	24.78	22.92	14.04

In which: Climate: according to Koppen classification; DBHwb: diameter with bark at 1.30 meters from the ground.

Table 2: Sampling strategies for the eucalyptus wood discs used in the study.

Strategies	Positions sampled along the commercial height (%)	Justification
DBH	DBH	Stem region adopted as a reference for measurements and field collections; in Brazil, 1.30 m from the ground.
Traditional	0, DBH, 25, 50, 75, and 100	Commonly used to analyze the density in the base-top direction of the stem.
Removal of extremes	DBH, 25, 50, and 75	Elimination of sampling extremes, the base, and the top.
Alternative 1	0, 50, and 100	Used to evaluate wood for solid products, in which the aim is to preserve as many logs as possible.
Alternative 2	12.5, 37.5, and 62.5	Elimination of extremes and average positions between other positions in traditional sampling.
Alternative 2+DBH	DBH, 12.5, 37.5, and 62.5	Alternative 2 with the addition of DBH.
Composite	0, DBH, 12.5, 25, 37.5, 50, 62.5, 75, and 100	Combination of all collected positions, which becomes the most representative for the entire stem.

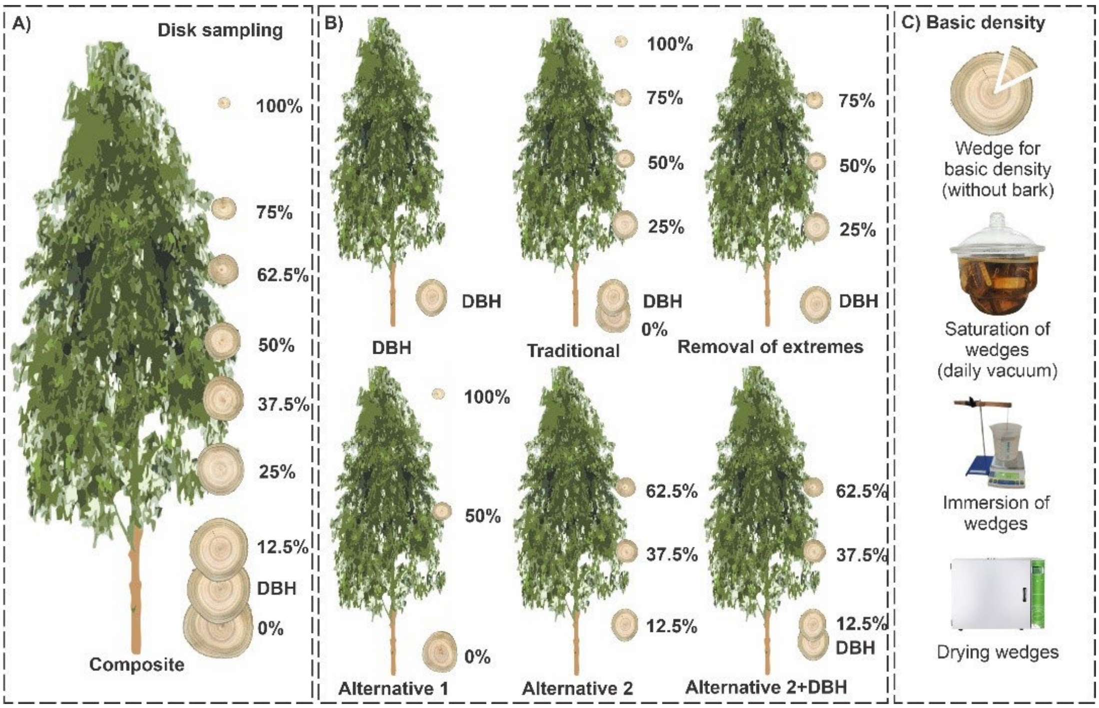

Figure 1: A) Complete (composite) sampling conducted in the field; B) Proposals for sampling strategies for measuring basic density; C) Procedures for determining basic density.

Data analysis

The analyses were conducted using R Studio software version 4.0.2 (R CORE TEAM, 2020). The study was designed in a completely randomized design (CRD). The Shapiro-Wilk test was used to verify normality and the Levene test was used to verify homogeneity of variances. For statistically significant factors identified by the F test of analysis of variance (ANOVA), the Scott-Knott test was employed. For all mean comparison tests, a 5% significance level was considered. The range of variation in basic density was calculated by finding the absolute difference between the maximum and minimum values in each situation analyzed.

Composite sampling was used as a standard because it is the most representative sampling strategy for the entire stem when adjusting regression models. The average basic density of the tree was estimated using multiple regression analysis, adjusted by the Exhaustive Search method (Leaps package). This method tests all combinations of variables and provides the best estimation for the dependent variable. The nine positions along the stem and the sampling strategies were used as independent variables. A comparison was made between the obtained combinations, and the most effective models were selected.

RESULTS

Sampling strategies for determining basic density

The basic wood density of most eucalyptus clones was affected by the sampling strategy employed. The average density varied between samples, ranging from 476.69 to 449.61 Kg m^{-3} (Table 3).

The sampling strategies varied for each clone under study: C1 - the density obtained at the DBH position was only similar to the sampling of Alternative 1. In contrast, the others did not show significant differences. C2 - only the density obtained at the DBH position showed a significant difference. C3 - the density obtained at the DBH position was only similar to Alternative samplings 3 and 4. C4 - was the only clone that showed no variation in basic density based on the sampling strategy. The overall behavior of the average basic density, across all clones in the study, was similar to C2, except for the sampling at the DBH position which differed from the others.

When evaluating the four clones, the Traditional, Removal of extremes (with the elimination of extremes), and Composite (nine sampling points) methods showed similar averages, indicating a similarity between these sampling methods. The basic density obtained from Alternative 1 (0%, 50%, and 100%) showed the highest value for most clones under study, except for C1, which indicates a decrease in density in the extreme regions sampled in the trees of this clone. There was a decrease in basic density in the DBH region for all clones, so the sampling carried out only in this position had the lowest absolute values. Alternative sampling 3 presented a higher average density value within clone C1; in Alternative sampling 4, the density was higher for clone C2. The sample standard deviation was higher for Alternative 1 and lower for DBH (Table 3).

Sampling strategies with nine relative positions along the stem were like those with six or even three sampling positions. Despite the lack of a significant difference in average basic density among the 4 clones, there was a definitive variance in Kg m^{-3} between the two strategies (Table 4). When analyzing the general average, there was a proximity of values between most sampling strategies, except when comparing Alternative 2+DBH (DBH, 12.5%, 37.5%, and 62.5%) and DBH with the other strategies, as showed a greater discrepancy (absolute values) to the other means. However, only the DBH has a significant difference.

The amplitudes between the sampling strategies varied from 27.09 to 0.28 Kg m^{-3}. The highest value was between DBH and Removal of extremes, and the lowest value was between Removal of extremes and Alternative 1. In general, the most significant differences were observed when comparing the basic density at the DBH position with other sampling strategies.

When comparing the average basic density in the DBH sampling with the Composite sampling (Table 4), there is an underestimation of up to 5% of this property. The average density values for Removal of extremes (DBH, 25%, 50%, and 75%) and for Alternative 1 (0%, 50%, and 100%) were similar, just like those for Traditional and Composite. In this study, the base positions (0%, DBH, and 12.50%) generally showed lower density averages when considering the variation tendency from the base to the top of the stem for all sampling strategies (see Figure 2).

The trend in base-to-top basic density variation for the sampling strategies was similar, except for clone C2. The clones generally show a decrease in basic density from the base up to 12.5% of the commercial height, followed by an increase in this property up to 75%, and then a further

Table 3: Average basic wood density (Kg m^{-3}) of Eucalyptus clones in the different sampling strategies.

Sampling strategies	Clones				Average clone density
	C1	C2	C3	C4	
DBH	453.38 B (20.34)**	461.32 B (17.77)**	440.09 B (20.18)**	443.64 A (16.31)**	449.61 B (19.19)**
Traditional	474.03 A (36.07)	501.74 A (43.78)	466.37 A (24.91)	455.11 A (26.98)	474.31 A (37.57)
Removal of extremes	486.54 A (25.21)	502.25 A (33.39)	463.94 A (26.73)	454.05 A (21.99)	476.69 A (32.71)*
Alternative 1	466.75 B (43.00)	505.67 A (50.78)*	474.95 A (26.41)*	458.29 A (31.43)*	476.41 A (42.14)
Alternative 2	490.85 A (22.03)*	501.91 A (32.52)	452.15 B (20.20)	445.19 A (25.50)	472.52 A (34.89)
Alternative 2+DBH	481.48 A (26.87)	491.76 A (34.22)	449.13 B (20.37)	444.8 A (23.14)	466.79 A (33.13)
Composite	479.63 A (32.81)	501.79 A (40.00)	461.63 A (24.18)	451.8 A (26.63)	473.72 A (36.61)

*highest average between strategies; **lowest average between strategies. Values in parentheses represent the standard deviation. Means followed by the same capital letter vertically do not differ statistically, according to the Scott-Knott test at a significance level of 5%.

reduction of 100% for the more representative Composite sampling. At the 12.5% position, the average density was the lowest at 449 Kg m^{-3}, while at the 75% position, it was the highest at 496 Kg m^{-3}. The density at the 100% position (top) was lower than that found in the central regions of the stem length, but still higher than at the 0% position. The elimination of sampling points resulted in an inadequate representation of density patterns in certain locations. This was due to the increased distance between sampling positions, which failed to capture any changes in density along the stem.

Traditional sampling best represented the variation trend in Composite sampling due to their similar behavior. Due to the elimination of sampling at the extremes, Removal of extremes did not capture the lowest average density at the base and top, only representing the continuous increase of this variable along the stem, as well as Alternative 2. Alternative 1 exhibited a sudden increase in density at 50% of the tree's height, while Alternative 2+DBH indicated a tendency for densities to increase from the basal region onwards.

Composite sampling, with larger sample points, divided the positions along the stem into two groups after applying the Skott-Knott test. The first group, with higher density, included positions from 25% to 100% of the commercial height, while the other positions (0%, DBH, and 12.5%) belonged to the lowest density group.

Traditional sampling showed higher and statistically similar densities at the 75% and 50% positions. Removal of extremes was the only strategy to form three distinct

Table 4: Range of variation in the average basic wood density between sampling strategies for all clones.

Sampling strategies	Δ	Sampling strategies	Δ	Sampling strategies	Δ
DBH x Removal of extremes	-27.09	Alternative 1 x Alternative 2+DBH	9.62	Alternative 1 x Composite	2.70
DBH x Alternative 1	-26.81	Traditional x Alternative 2+DBH	7.52	Traditional x Removal of extremes	-2.38
DBH x Traditional	-24.70	Alternative 2+DBH x Composite	-6.92	Traditional x Alternative 1	-2.10
DBH x Composite	-24.11	Alternative 2 x Alternative 2+DBH	5.73	Traditional x Alternative 2	1.79
DBH x Alternative 2	-22.92	Removal of extremes x Alternative 2	4.17	Alternative 2 x Composite	-1.19
DBH x Alternative 2+DBH	-17.19	Alternative 1 x Alternative 2	3.89	Traditional x Composite	0.60
Removal of extremes x Alternative 2+DBH	9.90	Removal of extremes x Composite	2.98	Removal of extremes x Alternative 1	0.28

Δ = the absolute difference between sampling strategies (Kg m^{-3}).

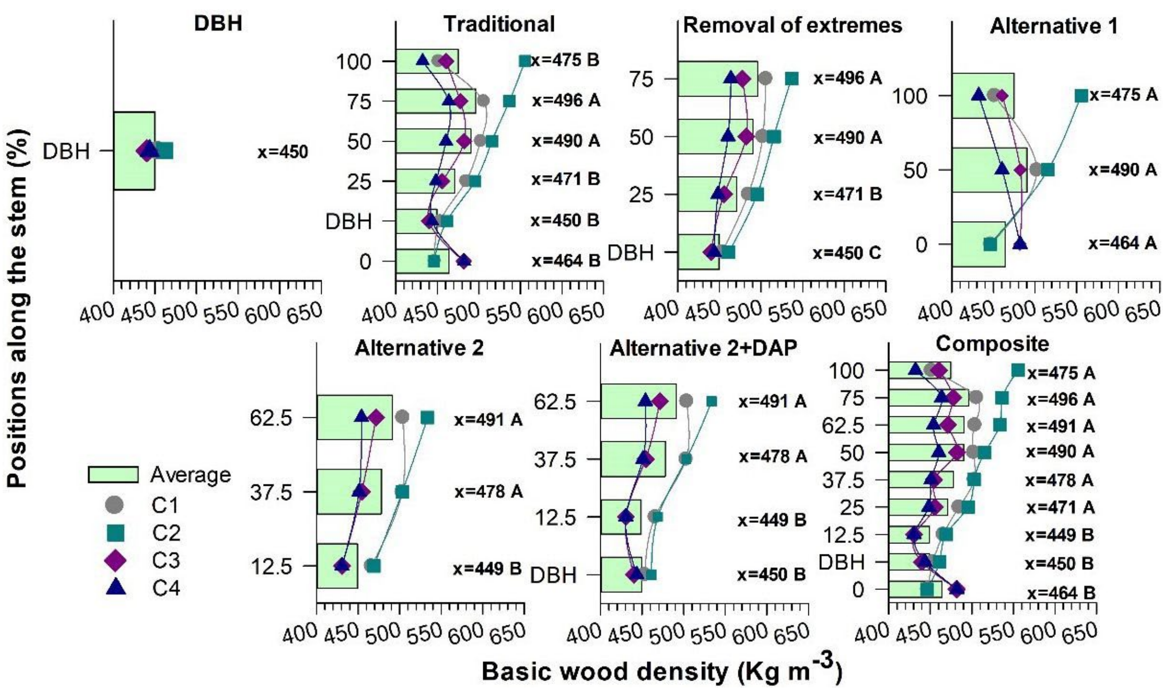

Figure 2: Trends in variation in basic wood density in the base-to-top direction of the commercial height for the clones studied within each sampling strategy.
X = average basic density in that relative position for all clones analyzed. Means followed by the same capital letter vertically do not differ statistically, using the Scott-Knott test at 5% significance.

groups based on the test used, with DBH having the lowest basic density. Alternative 1 did not show any statistically significant difference between the densities, but the highest value was observed at the 50% position. In Alternative 2, the positions of 37.5% and 62.5% were like each other, with higher averages, and different from 12.5%. When DBH is added to this sampling strategy in Alternative 2+DBH, this position becomes equal to 12.5%. In Composite sampling, clones C1 and C2, which are hybrids of *E. urophylla* x *E. grandis*, showed an increase in density from 0% up to 37.5%. The base-to-top variation in basic wood density was the same for clones C3 and C4.

Basic density at DBH height in relation to the tree average

The sampling strategies that included tree diameter at breast height (DBH) were compared, and the representativeness of DBH to the general average of the tree for each method was obtained (see Figure 3). Each clone showed different behavior, but there was little difference observed between the various sampling strategies.

Depending on the clone and sampling methodology, the DBH represented 91.85 to 99.74% of the overall average stem, with a difference of 1.17 to 40.93 Kg m^{-3} from the values obtained by the methods. In Traditional sampling, the density at the DBH position was 97.48% of the average for clone 4, with a difference of 11.47 Kg m^{-3}. C2 had a lower representativity, with a density difference of 40.42 Kg m^{-3} compared to the overall average. In Removal of extremes sampling, the DBH density corresponded better for clone C4 and worse for clone C2, with a difference of 10.41 Kg m^{-3} and 40.93 Kg m^{-3}, respectively.

The density obtained at DBH for clone C4 in Alternative 2+DBH sampling corresponded to almost 100% of the clone average, with a difference of around 1 Kg m^{-3}, indicating that it is a representative sampling position of the general average of the trees for this clone. In the Composite sampling, the density at the DBH position for clone C4 was also representative, with 98.19% and a difference of approximately 8 Kg m^{-3}.

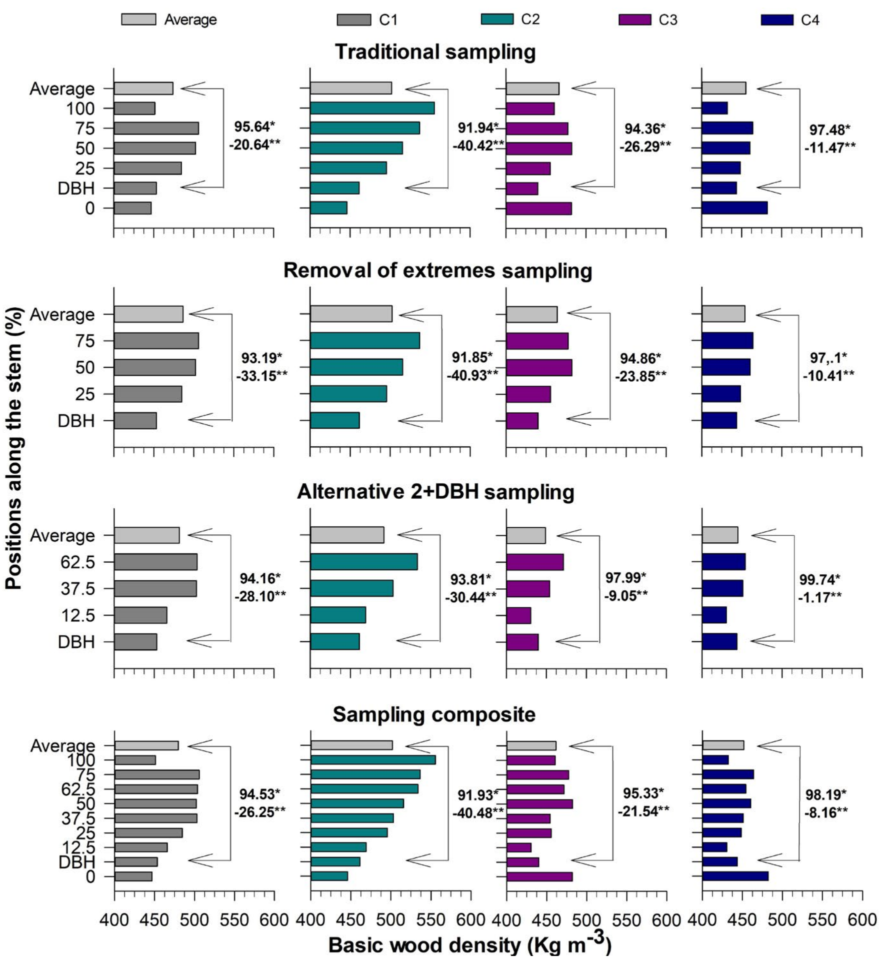

Figure 3: Wood basic density values determined in different sampling positions.
The arrow compares the values obtained at the DBH position with the overall average of the clones. *Percentage of basic density obtained in DBH considering the general average as 100%. **Absolute difference between the basic density (Kg m^{-3}) obtained in DBH and that calculated by the overall average of the clone.

When it comes to C1, the DBH aligned more closely with the average of the tree when using traditional sampling techniques, but there was a variation of approximately 21 Kg m^{-3}. The closest approximation for C2, C3, and C4 occurred in Alternative strategy 4, with a difference of 30, 9, and 1 Kg m^{-3}, respectively.

Adjust models to estimate the basic density of the wood

It was possible to adjust regression models to estimate the average basic density of the tree using the density obtained in each sampling strategy (Table 5).

The equations were estimated for each sampling method, considering the average basic tree density of all eucalyptus clones. All adjusted equations were significant, allowing the basic density to be estimated through smaller sampling regions along the tree trunk. The best fit was for Traditional sampling and the one with the lowest coefficient of determination was for sampling only in DBH. As the number of independent variables increased in the equation, the adjusted coefficient of determination also increased.

In seeking analysis and process optimization, Removal of extremes proved efficient for density estimation, explaining around 94% of the variations and using only four sample points. Despite using three sample points, Alternative 1 only accounts for 80% of the observed variations, emphasizing the impact of the base and top on the basic density.

In addition to the suggested strategies, it is possible to estimate the basic density using other sample positions analyzed in this work (see Table 6). When estimating density from a single sampling point, the 75% position was the most representative. With two points, in addition to 75%, there was an increase in the 62.5% position. And with three points, the positions of 50%, 62.5%, and 75% were considered. Among the nine positions evaluated, the least representative of the average tree density was the relative height of 37.5%.

Table 5: Linear regression equations, precision statistics for predicting the basic density of eucalyptus wood at 6 years, using sampling strategies as independent variables.

Sampling strategies	p-value	R²aj.	RMSE	Adjusted equation
DBH	0.02*	0.23	20.10	$BWD_{average} = 195.4156 + 0.6190 * BWD_{DBH}$
Traditional	0.72*	0.98	3.03	$BWD_{average} = 11.3243 + 0.0832 * BWD_{0\%} + 0.0947 * BWD_{DBH} + 0.3282 * BWD_{25\%} + 0.1413 * BWD_{50\%} + 0.2146 * BWD_{75\%} + 0.1071 * BWD_{100\%}$
Removal of extremes	0.03*	0.94	5.70	$BWD_{average} = 95.1379 - 0.0184 * BWD_{DBH} + 0.2265 * BWD_{25\%} + 0.1891 * BWD_{50\%} + 0.3779 * BWD_{75\%}$
Alternative 1	0.00*	0.80	10.30	$BWD_{average} = 227.9452 - 0.1117 * BWD_{0\%} + 0.4663 * BWD_{50\%} + 0.1454 * BWD_{100\%}$
Alternative 2	0.00*	0.89	7.54	$BWD_{average} = 146.6383 + 0.2530 * BWD_{12.5\%} - 0.0309 * BWD_{37.5\%} + 0.4651 * BWD_{62.5\%}$
Alternative 2+DBH	0.02*	0.89	7.59	$BWD_{average} = 120.4481 + 0.0922 * BWD_{DBH} + 0.2416 * BWD_{12.5\%} - 0.0456 * BWD_{37.5\%} + 0.4588 * BWD_{62.5\%}$

$R^2_{aj.}$: adjusted coefficient of determination; RMSE: root mean-square error (%); $DB_{average}$: estimated basic density of the tree (Kg m^{-3}); BWD_x%: basic wood density at the position indicated in the tree (Kg m^{-3}); *significant at 5% error probability.

Table 6: Linear regression equations, precision statistics for predicting the basic density of eucalyptus wood at 6 years, using sampling positions as independent variables.

Nº of positions	p-value	R²aj.	RMSE	Adjusted equation
1	0.00*	0.90	7.36	$BWD_{average} = 163.0525 + 0.6264 * BWD_{75\%}$
2	0.00*	0.95	5.16	$BWD_{average} = 154.5032 + 0.2939 * BWD_{62.5\%} + 0.3528 * BWD_{75\%}$
3	0.00*	0.97	4.13	$BWD_{average} = 128.8669 + 0.1587 * BWD_{50\%} + 0.2604 * BWD_{62.5\%} + 0.2808 * BWD_{75\%}$
4	0.00*	0.98	3.37	$BWD_{average} = 136.0949 + 0.1493 * BWD_{50\%} + 0.2245 * BWD_{62.5\%} + 0.2586 * BWD_{75\%} + 0.0548 * BWD_{100\%}$
5	0.00*	0.99	2.66	$BWD_{average} = 115.9645 + 0.1531 * BWD_{12.5\%} + 0.1366 * BWD_{50\%} + 0.1661 * BWD_{62.5\%} + 0.2185 * BWD_{75\%} + 0.0677 * BWD_{100\%}$
6	0.00*	0.99	2.10	$BWD_{average} = 82.1448 + 0.0646 *: BWD_{0\%} + 0.1504 * BWD_{12.5\%} + 0.1056 * BWD_{50\%} + 0.1975 * BWD_{62.5\%} + 0.2272 * BWD_{75\%} + 0.0689 * BWD_{100\%}$
7	0.00*	0.99	1.73	$BWD_{average} = 56.6260 + 0.0691 * BWD_{0\%} + 0.0754 * BWD_{DBH} + 0.1529 * BWD_{12.5\%} + 0.1146 * BWD_{50\%} + 0.1988 * BWD_{62.5\%} + 0.1852 * BWD_{75\%} + 0.0777 * BWD_{100\%}$
8	0.04*	1.00	1.12	$BWD_{average} = 27.4734 + 0.0808 * BWD_{0\%} + 0.0857 * BWD_{DBH} + 0.1371 * BWD_{12.5\%} + 0.1360 * BWD_{25\%} + 0.1157 * BWD_{50\%} + 0.1258 * BWD_{62.5\%} + 0.1665 * BWD_{75\%} + 0.0917 * BWD_{100\%}$

$R^2_{aj.}$: adjusted coefficient of determination; RMSE: root mean-square error (%); $DB_{average}$: estimated basic density of the tree (Kg m^{-3}); BWD_x%: basic wood density at the position indicated in the tree (Kg m^{-3}); *significant at 5% error probability.

When the goal is to evaluate the property at four sample points, the best model corresponds to the heights in the upper half of the stem, which are the higher regions. DBH only became a significant independent variable after seven sample points, reaching the 25% position, with eight sample points. The more positions included in the adjustment equation, the closer the model came to reality, but it was less cost-effective.

DISCUSSION

Sampling strategies for determining basic density

The connection between Traditional, Removal of extremes, and Composite sampling is explained by the three strategies sharing similar sampling positions. Composite sampling, which covers more sample positions, comes with increased collection costs, and requires more time to conduct density analyses. The average density obtained through Composite sampling of the four clones only differed from the measurement taken at the DBH. This indicates that using strategies with fewer sampling positions along the trunk to determine basic wood density can produce accurate results, conserve resources, and make better use of the trunk.

Each clone had distinct intrinsic characteristics based on factors such as growth conditions and age, but the difference in basic density among the evaluated genotypes was minor. For instance, C2, although the same hybrid as C1, exhibited different behavior compared to the others.

The most accurate representations of density variation along the stem were found in the Traditional and Composite sampling methods, with minimal difference in their average results. It is technically feasible to use the nationally adopted Traditional sampling method, compared to a method with 3 additional sampling points (12.5%, 37.5%, and 62.5%).

The higher basic density value obtained by Alternative 1 (0%, 50%, and 100%) compared to the other strategies can be justified by the absence of the positions of DBH and 12.5%, which showed the lowest averages. This strategy had the highest standard deviation among the other samples evaluated, showing the greatest variability in the positions of 0%, 50%, and 100% of the commercial height. This justifies Removal of extremes, which proposes the elimination of extremes. The low standard deviation found in the DBH is due to sampling only one position, resulting in greater data uniformity.

The current standards for determining the basic density of wood do not provide much information about sampling positions in the base-top direction of trees, such as NBR 14660 (ABNT, 2004) and NBR 11941 (ABNT, 2003). The differences between using DBH and other strategies suggest that DBH position alone is not a suitable choice for sampling the entire tree. The larger difference between the DBH and Removal of extremes reflects the impact of the sampling method on results, which can significantly affect the planning and operations of companies that rely on wood as a key resource for manufacturing reconstituted wood panels, cellulose pulp, and other products.

A good choice of sampling strategy is essential for more accurate results. The variability of wood properties along the stem is often overlooked and underestimated. The analysis conducted on a few trees or a single position to determine their trunk characteristics leads to overlooked estimates of the property analyzed across the entire population (Pádua, 2009).

The basic density of wood along the stem can vary due to a variety of factors such as species/genetic material, age of the tree, and environmental and practical considerations. These trends may be observed during evaluation and can also be affected by sampling and the method of determination used (Boschetti et al., 2020). The influence of sampling strategies is demonstrated here.

The decrease in density in the DBH region has also been noted by Oliveira et al. (2021) and Nornberg et al. (2023). According to the literature, there is a lack of studies explaining the decrease in basic density from the base to the DBH, as well as the positioning of maximum commercial height. It is possible to suggest that there is a relationship with the formation of wood or even with the growth conditions of these individuals, and further investigation into this impact is necessary. In certain genetic compositions, the density at the DBH level may be comparable to that of the base. However, the behavior of each clone differs, as this study found a range of 1.17 to 40.93 Kg m^{-3} in the density in the DBH of the tree.

In this study, all clones except C2 showed a lower density at the top compared to the base. However, these values were lower than the averages found in the central regions of the stem length, a behavior also observed by Oliveira et al. (2021) and Magalhães et al. (2020). By adding more sampling points in the lower areas of the trunk, this decrease becomes even more noticeable (Pádua, 2009). However, it is not economically or functionally beneficial to increase the sample number. Rather, the focus should be on finding ways to reduce it without sacrificing accuracy and representativeness.

The variation observed for the eucalyptus clones in the Composite sampling was comparable to the results obtained by Pádua (2009) for *E. grandis* x *E. urophylla* at 6 years old. Nevertheless, the decrease in density occurred from the base to 25% of the commercial height. Rocha et al. (2024) observed a 100% decrease in density at the DBH for *E. urophylla* at 7 years old. Nornberg et al. (2023) confirmed a decrease in density from the base to DBH, with a maximum increase of 66% and a subsequent decrease of up to 100% from the commercial height for *E. saligna* at 8 years old.

In most cases, the basic density of young eucalyptus wood follows a trend of decreasing up to 50% of its height, then increasing from that point onwards, regardless of any changes in the top regions. (Hsing et al., 2016). The apical areas of eucalyptus trees exhibit higher density as a result of bearing the weight of the crown and undergoing mechanical stress, according to Sette Junior et al. (2012). The top portion may have lower density due to its role in supporting and being affected by wind movement, but it possesses greater elasticity (Panshin e Dezeeuw, 1980).

The base tends to have wood with higher density and mechanical resistance due to the tree's support function, but this is not always the case. In this study, the lower basic density in the basal regions could be related to the rapid initial growth conditions. This does not rule out the possibility that it is young wood, which means it has a large amount of juvenile wood. The variation in the basic density of wood along the stem is mainly due to differences in the wood's anatomical structure, including the thickness of the cell wall of the fibers and the diameter of the vessels (Moutinho et al., 2016).

The adoption of simplified sampling strategies, such as Removal of extremes, enables forestry management companies to optimize costs and time while maintaining accuracy in determining the basic wood density, particularly in fast-growing commercial plantations. This approach can be integrated into forestry management software to automatically calculate density based on reduced data sets, facilitating the application of technologies such as LiDAR for estimating wood volume and quality. Future research should investigate the applicability of these strategies across different forest species, management systems, and environmental conditions, assessing the influence of climatic variations and soil characteristics on their effectiveness.

Basic density at DBH height in relation to the tree average

The DBH led to an underestimation of the basic density. However, it is commonly used for sampling in the forestry sector due to its reference height, ergonomic nature, easy accessibility, and better operational efficiency, to represent the properties of the tree's wood as a whole. Most wood assessments in this region are conducted with the tree standing. Therefore, it is important to have the average basic density values of the tree and its diameter at breast height (DBH) to calibrate mathematical models for estimating basic density using non-destructive techniques such as the increment auger, Pilodyn, Resistograph, and Near Infrared Spectroscopy.

Although the basic density in the DBH corresponded to more than 90% of the average in all clones and samples, the absolute difference between this position and the actual average density of the tree showed relatively high values in most situations. The DBH seems to have the least variation compared to other clones, with only C4 showing smaller differences. This suggests that the DBH represents the average of this specific clone, with no statistical difference between the average density of the sampling methods.

Melo et al. (2024) observed changes in the average tree trunk DBH in two different climatic conditions in her study. This indicates that both the type of tree and growth factors influence sampling strategies. Some tree species maintain a consistent wood density in their diameter at breast height, which creates a more uniform and versatile wood suitable for various purposes (Oliveira et al., 2005).

The sampling at DBH is a practical and ergonomic approach for non-destructive simulations in the forestry sector, but its use as the sole sampling point for the tree's average density must be complemented by adjustments with statistical models. Future research should investigate the impact of tree age on the relationship between DBH density and average density, in order to verify the behavior of the density measured at DBH as representative of the average stem density.

Adjustment of models to estimate the basic density of wood

The density obtained from different sampling techniques, when used to adjust mathematical models for calculating the mean basic density of trees, aligns with the idea proposed by Rocha et al. (2024) that DBH may not be the most suitable sampling position. The significant regressions have demonstrated the possibility of accurately estimating the average basic density of a tree by using the density obtained from sampled positions along the stem, as long as these positions are representative of the tree's overall average. This was proven by Oliveira et al. (2018) and Nornberg et al. (2023).

Traditional sampling provided a better fit because it had more sampling points, which better captured the density variation in the base-top direction of the stem. The goal when estimating density is to achieve the highest coefficient of determination and reduce sample points. Therefore, Removal of extremes was found to be a feasible option. Following Rocha's et al. (2024) research, this alternative involves cutting off the ends of the stem. She concluded that the most common position among all the clones studied was between DBH and 75% (similar to Removal of extremes), as it provides the most accurate representation of the tree's average basic density and volume.

The limited accuracy of Alternative 1 in estimating the average density of the clone can be attributed to significant fluctuations at the base and top of the stem, leading to inconsistent density readings that do not truly represent the entire stem. Although the DBH does not represent the basic density of the tree, it still serves as a convenient and practical sampling point. In some cases, such as collecting radial cores or using non-destructive analysis equipment like resistograph, Pilodyn, or others, sampling in more apical positions becomes unfeasible and risky. In such situations, it is preferable to adopt mathematical models to estimate this property.

Understanding how density varies along the vertical axis of a tree trunk can help us accurately estimate the overall variability of the tree based on just one sample point. This can ultimately reduce the effort and costs associated with sampling wood from various positions along the trunk (Rocha et al., 2024).

When examining these materials with young eucalyptus wood, it is recommended to use Removal of extremes sampling as it provides the most accurate density estimate by utilizing positions at DBH, 25%, 50%, and 75%. This results in fewer sampling points and minimal difference compared to Composite. It is possible to estimate the density of the tree trunk with high precision using a small number of sample discs, if the proposed equations include specific and strategic positions on the trunk, as proven in this study.

Based on the non-significant regression of DBH for the studied eucalyptus clones, it is not advisable to use this parameter in statistical models for predicting clone density. However, it should be noted that as these are young materials, their density may still increase with age. Even though the second half of the stem displays a higher correlation with the wood's basic density, it is not a feasible option for operation due to its non-invasive approach to preserving the primary section of the stem (with a larger diameter).

The equation obtained from the 75% position yielded an excellent coefficient of determination, indicating that estimating density based on a single sampling point is not straightforward. Nornberg et al. (2023) could not identify a single sampling point for estimating the density of *E. saligna* wood at 8 years of age. They pointed out that sampling only at the height of the DBH, while practical, is not recommended as it underestimates the average wood density. The authors also concluded that when estimating wood density using two sampling points, it is best to do it at the DBH regions and 33% of the commercial height. Additionally, three points should be added at the 66% position, which is close to the 75% found in this study.

In a study of native species in Minas Gerais, Oliveira et al. (2018) determined that the most accurate way to estimate stem wood density with a single disc is to take measurements at the midpoint of the main stem. For two discs, measurements should be taken at 25% and 75% of the height, and for three discs, at 0%, 50%, and 100% of the height. The estimated equation suggests that the final strategy proposed by Oliveira et al. (2018) is not suitable for the material in this study. This stresses the importance of considering the genetic material and its origin when developing calibration curves for non-destructive analyses.

When examining the positions involved in Traditional sampling, Pádua (2009) discovered that the basic density measured at 1.10 and 1.50 m above the ground showed the strongest correlations with three sampling strategies evaluated for *E. grandis* x *E. urophylla* at 6 years. Couto et al. (2012) concluded that positioning the commercial height at 70% was the most appropriate way to represent the average basic density of *Eucalyptus* sp clones at 3.5 years old. Meanwhile, Rocha et al. (2024) found that the ideal sampling position for estimating basic density for *Corymbia* and *Eucalyptus* clones at 7 years is at a relative height of 25%. The variations in results are caused by differences in clones, age, origin, sampling methods, and statistical approaches used in each study.

The basic density, which is more closely related to positions halfway up the tree, may be affected by the decrease in density in the lower trunk regions observed in the clones, especially in the DBH region. This discrepancy caused these positions to diverge from the tree's overall average. In a practical setting, it is important to consider both the strong relationship between the height of the sample and the average tree density, as well as the ease of accessing the point for non-destructive collection (Downes et al., 1997) and ensuring the maximum preservation of the stem.

Companies that use eucalyptus wood as raw material can adopt the proposed models to accurately adjust the basic density from a few sample points, resulting in reduced operational costs and optimized laboratory analysis time. Governments and forest certification institutions can apply these methodologies to standardize wood quality assessment, promoting sustainable practices and enhancing competitiveness in the international market. It is recommended to validate these models on a larger scale, including commercial plantations under different climatic and edaphic conditions, as well as incorporating anatomical and chemical wood analyses to explore more complex relationships between wood properties and their industrial applications.

CONCLUSION

The analyzed base-top sampling strategies did not show significant differences between them, except for the one that only considered the diameter at breast height (DBH), which underestimated the basic density value of the wood. The basal (0 to 12.5%) and apical (100%) positions for most clones (except C2) had lower density values compared to the central positions of the stem height.

The amplitude between sampling strategies was relatively high in some situations, especially when comparing the DBH with the other six sampling strategies. This emphasizes the importance of studying the differences not just from a statistical perspective but also from an operational angle, projecting the data on an industrial scale. The DBH region aligns best with the average density found for Alternative 2+DBH (DBH, 12.5, 37.5, and 62.5%); however, it does not represent the position that most accurately estimates the average basic density.

The sampling Removal of extremes (DBH, 25, 50, and 75%) provided an effective estimate of the average density when considering all clones as a single material. This is the best strategy for measuring basic density under the conditions described in the present study. Sampling positions at 50% of the tree's commercial height were more associated with the basic density. The optimal sampling position for estimating the basic density of the tree using just one disk was 75%. It was 62.5% and 75% for two discs, and for three discs, the positions should be 50%, 62.5%, and 75% of the commercial height.

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REFERENCES

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS - ABNT. NBR 14660: Madeira – Amostragem e preparação para análise. São Paulo: ABNT, 7 p., 2004.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS - ABNT. NBR 11941: Madeira - determinação da densidade básica. Rio de Janeiro: ABNT, 6 p., 2003.

BOSCHETTI, W.T.N.; VIDAURRE, G.B.; SILVA, J.G. M. Qualidade da madeira de eucalipto proveniente de plantações no Brasil. Vitória: EDUFES, Densidade e sua variação na madeira de eucalipto, p. 132-170, 2020. http://repositorio.ufes.br/handle/10/11606

COUTO, A.M.; PROTÁSIO, T.P.; REIS, A.A.; et al. Amostragens longitudinais alternativas para a determinação da densidade básica em clones de *Eucalyptus* sp. *Floresta e Ambiente*, v. 19, n. 2, p. 184-193, 2012. https://doi.org/10.4322/floram.2012.022

DOWNES, G. M.; HUDSON, I. L.; RAYMOND, C. A.; et al. Sampling plantation eucalypts for wood and fiber properties. Hobart: CSIRO; 1997. 177 p.

HSING, T. Y.; PAULA, N. F.; PAULA, R. C. Características dendrométricas, químicas e densidade básica da madeira de híbridos de *Eucalyptus grandis* x *Eucalyptus urophylla*. *Ciência florestal*, v. 26, n. 1, p. 273-283, 2016. https://doi.org/10.5902/1980509821119

LOUREIRO, B. A.; ASSIS, M.R.; MELO, I. C. N. A.; et. al. Rendimento gravimétrico da carbonização e caracterização qualitativa do carvão vegetal em clones de híbridos de *Corymbia* spp. para uso industrial. *Ciência Florestal*, v. 31, n. 1, p. 214-232, 2021. https://doi.org/10.5902/1980509836120

MADERN, J.H. The heritability of wood density. *In*: IUFRO, MEETING SECTION 41. Melbourne, v. 2, p. 1-20, 1965.

MAGALHÃES, L. G. S.; LIMA, A. P. L.; LIMA, S. F.; et. al. Densidade básica da madeira de clones de eucalipto em diferentes espaçamentos. *Brazilian Journal of Development*, v. 6, n. 4, p.19435-19445, 2020. https://doi.org/10.34117/bjdv6n4-202

MALONEY, T. M. Modern particleboard & dry process fiberboard manufacturing. San Francisco: Miller Freeman, 1989. 672 p.

MELO, A.B.; SILVA, P. H. M.; ARAUJO, S. L.; SILVA, J. G. M.; FERRAZ, A. V.; ROCHA, SMG.; ALMEIDA, MNF.; ARAUJO, M.; GODINHO, T.; CASTOR NETO, TC.; MOULIN, JC.; VIDAURRE, GB. Productivity and wood quality traits of *Corymbia* and *Eucalyptus* species in two soil water deficit sites. *Industrial Crops & Products*, v. 219, 119141, 2024. https://doi.org/10.1016/j.indcrop.2024.119141

MOUTINHO, V. H. P.; TOMAZELLO FILHO, M.; BRITO, J. O.; et. Al. Influence of the wood physical properties on the charcoal physical and mechanical properties. *Scientia Forestalis*, v. 44, n. 111, p. 557-561, 2016. DOI: 10.18671/scifor.v44n111.02.

NORNBERG, L. V.; CARDOSO, G. V.; FERNANDES, M. A. M.; et. al. Otimização de pontos amostrais ao longo do fuste pra determinação da densidade básica da madeira de *Eucalyptus saligna*. *Nativa*, v. 11, n. 1, p. 128-133, 2023. https://doi.org/10.31413/nativa.v11i1.15068

OLIVEIRA, G. M. V.; MELLO, J. M.; SCALON, J. D.; et al. Amostragem de discos e uso de equações para estimar a densidade básica da madeira em diversas fitofisionomias. *Ciência Florestal*, v. 28, n. 4, p. 1615-1626, 2018. https://doi.org/10.5902/1980509835127

OLIVEIRA, J. T. S.; HELLMEISTER, J. C.; TOMAZELLO FILHO, M. Variação do teor de umidade e da densidade básica na madeira de sete espécies de eucalipto. Revista Árvore, v. 29, n. 1 p. 115-127, 2005. https://doi.org/10.1590/S0100-67622005000100013

OLIVEIRA, R. A.; BATISTELA, G. C.; SIMÕES, D.; PADOVANI, C. R. Aplicação de modelos lineares de efeitos mistos para avaliar a densidade básica da madeira de duas espécies e um híbrido de *Eucalyptus*. *Scientia Forestalis*, v. 49, n. 129, p. e3201, 2021. https://doi.org/10.18671/scifor.v49n129.03

PÁDUA, F. A. Amostragem para avaliação da densidade básica da madeira de um híbrido de *Eucalyptus grandis* W. Hill ex Maiden x *Eucalyptus urophylla* S. T. Blake. 2009. 99 p. Tese (Doutorado em Ciência e Tecnologia da Madeira) – Universidade Federal de Lavras, Lavras, 2009.

PANSHIN, A. J.; DEZEEUW, C. Textbook of wood technology: structure, identification, properties, and uses of the commercial woods of the United States and canada. 4.ed. New York: New York: McGraw-Hill, 1980. E-book, 722 p.

QUEIROZ, S. C. S.; GOMIDE, J. L.; COLODETTE, J. L.; et. al. Influência da densidade básica da madeira na qualidade da polpa Kraft de clones hibrídos de *Eucalyptus grandis* W. Hill ex Maiden x *Eucalyptus urophylla* S. T. Blake. Árvore, v. 28, n. 6, p. 901-909, 2004. https://doi.org/10.1590/S0100-67622004000600016

ROCHA, S. M. G.; BARROS JUNIOR, U. O.; OLIVEIRA, L. J.; et. al. Association between the anatomical features and the natural drying of young wood from hybrid *Corymbia torelliana* and *Corymbia citriodora* clones. *European Journal of Wood and Wood Products*, v. 82, p. 1901-1912, 2024. https://doi.org/10.1007/s00107-024-02134-7

SETTE JUNIOR, C. R.; OLIVEIRA, I. R.; TOMAZELLO FILHO, M.; YAMAJI, F. M.; LACLAU, JP. Efeito da idade e posição de amostragem na densidade e características anatômicas da madeira de *Eucalyptus grandis*. Revista Árvore, v. 36, n. 6, p. 1183-1190, 2012. https://doi.org/10.1590/S0100-67622012000600019