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Wood density of forest species in integrated crop-livestock-forest system in the Brazilian Amazon: challenges and opportunities for *Bertholletia excelsa*, *Dipteryx odorata*, and *Khaya grandifoliola*

Densidade da madeira de espécies florestais em sistema integrado lavoura-pecuária-floresta na Amazônia Brasileira: desafios e oportunidades para *Bertholletia excelsa*, *Dipteryx odorata* e *Khaya grandifoliola*

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ABSTRACT

Wood density is the physical property directly related to the timber potential of a species and influences the environmental service of carbon storage and sequestration. Therefore, the objective of this study was to evaluate the wood density at different moisture levels (apparent, anhydrous, and basic) of the species *Bertholletia excelsa*, *Dipteryx odorata*, and *Khaya grandifoliola* in a young forest stand cultivated in an integrated crop-livestock-forest system. The Technological Reference Unit, established in 2010, highlighted the necessity for management interventions by 2021 to prevent excessive shading and eliminate phenotypically undesirable species. Material samples were harvested at five heights along the commercial stem to analyze wood density (anhydrous, apparent, and basic). Our results revealed that *D. odorata* had the highest densities (0.99, 0.91, and 0.83 g/cm^3), while *B. excelsa* and *K. grandifoliola* displayed lower densities (0.68, 0.61, 0.55 g/cm^3 and 0.61, 0.56, 0.51 g/cm^3, respectively). Notably, *D. odorata* exhibited an increasing basic density from base to top, while *K. grandifoliola* demonstrated greater homogeneity along its stem. The presented results provide robust technical support to inform decision-making on the use of native and exotic species in integrated production systems, as well as emphasizing the potential of the crop-livestock-forest system as a sustainable production practice.

Keywords: young forest plantations; physical properties of wood; bioeconomic potential; Pará.

RESUMO

A densidade da madeira é a propriedade física diretamente relacionada ao potencial madeireiro de uma espécie e influencia o serviço ambiental de armazenamento e sequestro de carbono. Portanto, o objetivo deste estudo foi de avaliar a densidade da madeira em diferentes níveis de umidade (aparente, anidra e básica) das espécies *Bertholletia excelsa*, *Dipteryx odorata* e *Khaya grandifoliola* em um povoamento florestal jovem cultivado em um sistema integração lavoura-pecuária-floresta. A Unidade de Referência Tecnológica, estabelecida em 2010, destacou a necessidade de intervenções de manejo até 2021 para evitar sombreamento excessivo e eliminar espécies fenotipicamente indesejáveis. Amostras de material foram colhidas em cinco alturas ao longo do tronco comercial para analisar a densidade da madeira (anidra, aparente e básica). Nossos resultados revelaram que *D. odorata* apresentou as maiores densidades (0,99, 0,91 e 0,83 g/cm^3), enquanto *B. excelsa* e *K. grandifoliola* apresentaram densidades menores (0,68, 0,61, 0,55 g/cm^3 e 0,61, 0,56, 0,51 g/cm^3, respectivamente). Notavelmente, *D. odorata* exibiu um aumento na densidade básica de base para o topo, enquanto *K. grandifoliola* demonstrou maior homogeneidade ao longo de seu tronco. Os resultados apresentados fornecem suporte técnico robusto para informar a tomada de decisões sobre o uso de espécies nativas e exóticas em sistemas de produção integrados, além de enfatizar o potencial do sistema integração lavoura-pecuária-floresta como uma prática de produção sustentável.

Palavras-chave: plantios florestais jovens; propriedades físicas da madeira; potencial bioeconômico; Pará.

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INTRODUCTION

The Brazilian Amazon has 497,222 km^2 of degraded area (PRODES, 2024). As an alternative to reduce these areas, rural properties have adopted the integrated crop-livestock-forest (CLF) production system, providing greater food security and environmental sustainability, being considered a nature-based solution (Balbino et al., 2011; Martorano et al., 2021a; Nwaogu and Cherubin, 2024). The CLF involves combining agricultural, livestock, and forestry activities within the same area through intercropping, rotation, or succession (Brasil, 2013; Monteiro et al., 2024). The CLF system spans approximately 17 million hectares across Brazil (ILPF Network, 2021).

Several forest species are used in CLF systems in the Amazon (Behling et al., 2021; Santana et al., 2023; Souza et al., 2024), as the component that remains in the system the longest, being responsible for a large part of the carbon accumulation in the soil and aboveground biomass (Kohl et al., 2017). Therefore, for silvicultural techniques to be disseminated and proper management to occur, information on the characteristics and uses of the species is necessary. Among the species used in CLF, the following stand out: *Bertholletia excelsa* Humn. & Bonpl. (Amazon nut) and *Dipteryx odorata* (Aubl.) Willd. (Cumaru), both native to the Amazon, and the exotic *Khaya grandifoliola* C. DC. (African mahogany). *Bertholletia excelsa* is a hyperdominant species, reaching 50 m in height, valued for its nuts and by-products (oils, bran) that contribute to local economies, although it is protected from timber exploitation by law (Brasil, 2006; Wadt et al., 2023; Souza JP et al., 2023). *Dipteryx odorata*, a climax species from the Fabaceae family, reaches 35 m and is valued for its durable wood and seeds containing coumarin, used in various industries (Herrero-Jáuregui et al., 2011; Silva-Neto et al., 2023). *Khaya grandifoliola*, from the Meliaceae family, is a large African tree that reaches 30–35 m in height. Its timber is highly valued internationally for its excellent quality, making it a sought-after material for furniture, construction, and musical instruments (Ribeiro et al., 2017; Reis et al., 2019). Beyond its commercial applications, *K. grandifoliola* also holds significant importance in traditional medicine and modern pharmacological studies, particularly for its antimalarial properties. This dual role as a commercial and medicinal resource emphasizes the importance of sustainable management and further research to optimize its benefits (Mukaila et al., 2021).

Wood density is the physical property directly related to the timber potential of a species and also influences its environmental service of carbon storage and sequestration (Schulz et al., 2019; Santos et al., 2021; Romero et al., 2024). In this context, density can be determined at different moisture levels, namely: anhydrous (measured after the wood is dried, indicating the density without any moisture content); apparent (measured with moisture content at field levels, representing the density in its natural state); and basic (often considered the most stable measure, as it represents density in its oven-dry state based on the volume of the wood when it is saturated with water) (Rezende and Escobedo, 1988). It is important to note that basic density is the most commonly cited in the literature for determining the use of woody material, as it reflects the maximum fiber saturation level (Oliveira et al., 2019).

The wood density of planted trees is influenced by soil treatments involving chemical inputs like Nitrogen, Phosphorus, and Potassium (NPK), as well as factors such as tree spacing, growth rates, and climatic conditions (Ferreira et al., 2019; Lima et al., 2024; Rocha et al., 2020). Additionally, density variations occur both radially and longitudinally as trees mature (Hsing et al., 2016) and are further affected by species-specific traits, taxonomic group, and stand age (Sette Junior et al., 2012; Wassenberg et al., 2015). Accounting for these density variations along the stem is essential for accurate forest biomass estimation, as disregarding this systematic source of error can lead to substantial inaccuracies in biomass estimates, particularly in intercropped systems like CLF systems.

There is a lack of studies on the evaluation of longitudinal wood density in young stands within integrated production systems. However, the understanding of density variations along the trunk in young trees is limited, despite its importance for accurate biomass estimates, carbon stock assessments, and sustainable wood utilization strategies (Bonfatti Júnior et al., 2023; Momolli et al., 2024; Pimenta et al., 2024).

Longitudinal density profiles can vary significantly, influencing wood quality and applications, especially in species cultivated in high-density plantations, where competition and environmental conditions affect growth patterns (Zhang et al., 2021). Addressing this research gap is essential for advancing integrated production models aimed at biodiversity conservation and supporting the local economy. Therefore, the objective of this study was to evaluate the wood density at different moisture levels (apparent, anhydrous, and basic) of the species *B. excelsa*, *D. odorata*, and *K. grandifoliola* in a young forest stand cultivated in a CLF system.

MATERIALS AND METHODS

Characterization of the study area

The study was carried out at the Technological Reference Unit (TRU), located on the Nossa Senhora de Aparecida farm in a partnership between the Brazilian Agricultural Research Corporation (Embrapa Amazônia Oriental) and the rural producer, under contract nº. 22500.10/0039. The TRU is in the municipality of Mojuí dos Campos, between the geographical coordinates 02°38’11” S and 54°56’13” W, which is 37 km from the center of Santarém (BR 316/ Santarém-Cuiabá), a commercial hub in the western region of Pará.

The altimetry of the study area is representative of the “Santareno Plateau,” characterized by an average elevation of 153 m above sea level (Cortes et al., 2020). This region features small depressions between valleys that create streams, which eventually flow into the Tapajós River (Cândido et al., 2023). The predominant soil in the region is classified as yellow latosol, characterized by a medium to very clayey texture, deep drainage, and good water retention. The vegetation is primarily composed of dense ombrophilous dryland forest (Guerreiro et al., 2017).

The predominant climate typology is Am_3 according to the adaptation of the Köppen methodology proposed by Martorano et al. (1993), indicating that there are months with rainfall of less than 60 mm and annual rainfall ranging from 2,000 to 2,500 mm, with the wettest period occurring from December to May, concentrating 80% of the rainfall volume, and the least rainy (20%) from June to November (Martorano et al., 2021b).

When observing the water deficiency map with values ranging from 120 to 180 mm (readily available water [RAW] = 300 mm), it indicates that these are conditions of average soil water stocks for adult plants (Figure 1). According to Costa et al. (2018), the study area is influenced by average temperatures of 26.5°C and, in terms of climatic averages, the maximum temperature varies between 30.5 and 32.0°C and the minimum between 21.0 and 22.5°C.

The history of the TRU was detailed by Silva et al. (2018) and is currently established as a livestock-forestry (LF) system, as noted by Cândido et al. (2023). In this system, the forest species *B. excelsa*, *D. odorata*, and *K. grandifoliola* have been growing for 11 years without irrigation. These species are arranged in eight rows, spaced 7 m apart with a row distance of 5 m, and covering a total area of 0.92 hectares.

Figure 2 shows the data collection carried out in the field, depicting forest plantations, a thinned tree, and 5 cm thick sections (disks) extracted from each tree according to commercial height at the following relative positions on the tree: base (0%), 25, 50, 75, and top (100%) of commercial height (Ramalho et al., 2019). It is important to note that the material collection took place between September and November 2021, which is typically the driest period in the Amazon region, minimizing the potential impact of rainfall on the data collected (Longo et al., 2020).

In 2021, trees were felled to ensure the full functioning of the integrated production system, considering the maintenance of the tree component with the best phenotypic characteristics to also provide light penetration to the grasses in each plot. The plantations had 200 trees of *B. excelsa* (25 individuals per row), 240 trees of *D. odorata* (30 individuals per row), and 264 trees of *K. grandifoliola* (33 individuals per row). The system was being used practically as a rest area for zebu cattle (*Bos indicus* Linnaeus), which, during sunshine hours, used the tree plots only as a refuge/shelter/harbor for animal comfort, as the pastures were underperforming due to the denseness of the trees. The animals predominantly use 7.3 ha with grasses (*Panicum maximum* Jacq.) that intersperse the plots. It is important to emphasize that these differences between the numbers of individuals in the plots are caused by the losses inherent in consolidating an experimental unit in a CLF system.

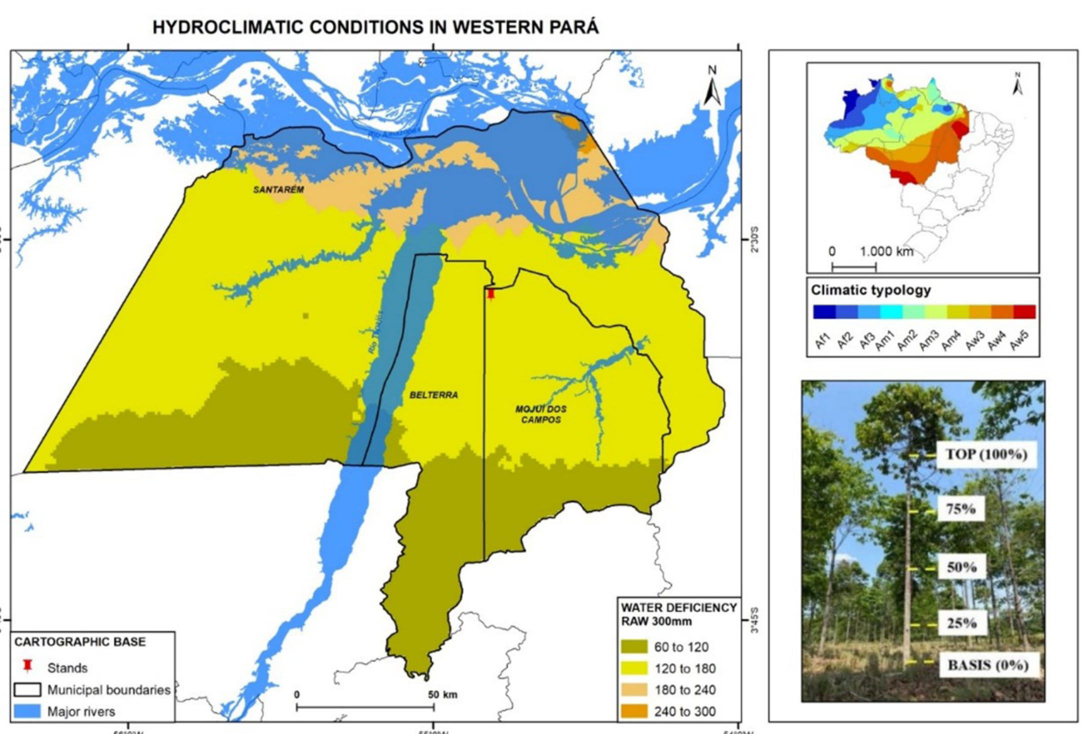

Figure 1 – Map containing information on the location of Nossa Senhora de Aparecida farm, Mojuí dos Campos (PA), and data from 2021 on the climatic typology of the surroundings, annual rainfall, and cartographic base.

Data collection

A diameter distribution of the trees was carried out, as demonstrated in the diameter classes, to guarantee the representation of trees at all sizes, in accordance with the values presented in Table 1.

In the Wood Technology Laboratory at the Federal University of Western Pará, a wedge-shaped sample corresponding to 1/8 of the disk was taken from each disk, and the bark was discarded (Gendvilas et al., 2022). The wedges were identified, weighed on a precision balance (with an accuracy of 0.005 g), and organized into mesh bags containing five samples from each tree. The samples were immersed in a water tank until they reached full saturation, after which the green volume of the samples was determined.

The sample material was then kept in a forced-air oven at 60°C until it reached 0% humidity, to remove the water by capillarity. Figure 3 presents a summary of the ten methodological steps of the work.

After recording the saturated mass, dry mass, saturated volume, and dry volume, the apparent, anhydrous and basic densities were obtained, according to Equations 1, 2, and 3, respectively.

$$\rho\ apparent = \frac{m_{12}}{V_{12}} \quad (1)$$

Where:

ρ apparent = apparent density ($g.cm^{-3}$);

m_{12} = mass of wood at 12% moisture content (g); and

V_{12} = volume of wood at 12% moisture content (cm^3).

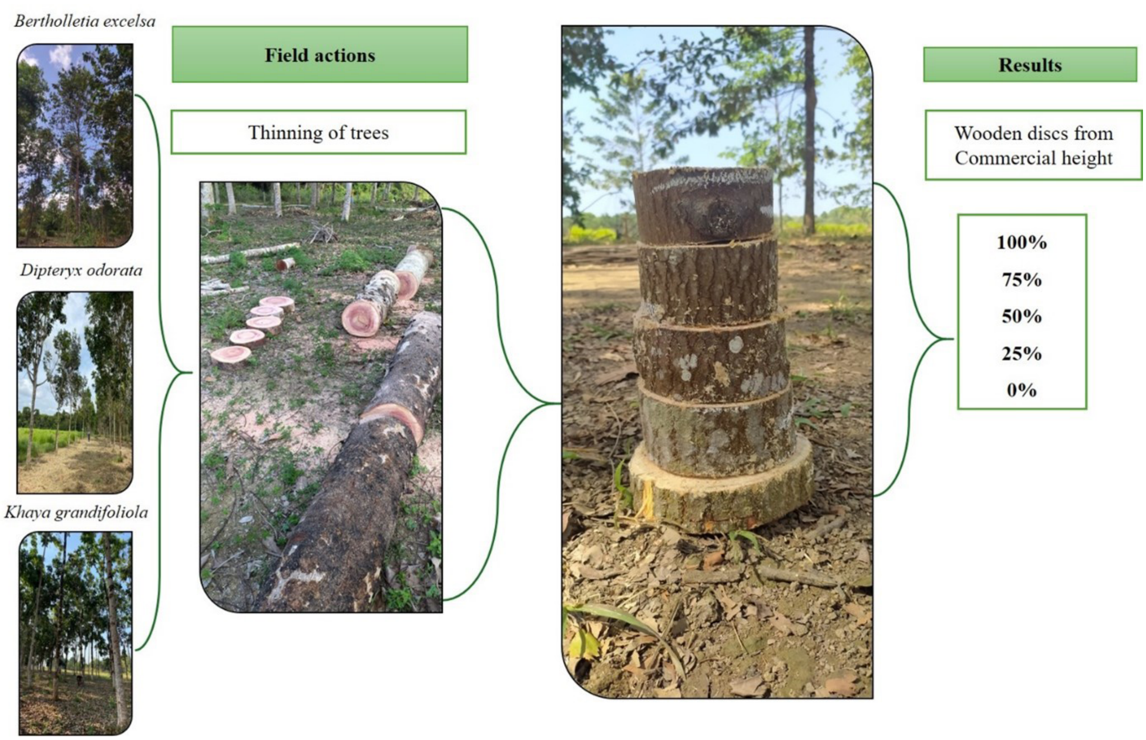

Figure 2 – Field activities, highlighting the thinning and collection of discs to obtain the wood density of *Bertholletia excelsa*, *Dipteryx odorata*, and *Khaya grandifoliola*.

Table 1 – Number of trees collected according to the diametric class (in centimeters) of the selected individuals.

Bertholletia excelsa							
	6 ≤ DBH < 11	11 ≤ DBH < 16	16 ≤ DBH < 21	21 ≤ DBH < 26	26 ≤ DBH < 31	DBH ≥ 31	Total
n	5	4	5	5	5	5	29
Dipteryx odorata							
	6 ≤ DBH < 9	9 ≤ DBH < 12	12 ≤ DBH < 15	15 ≤ DBH < 18	18 ≤ DBH < 21	DBH ≥ 21	Total
n	5	5	4	5	2	3	24
Khaya grandifoliola							
	12 ≤ DBH < 17	17 ≤ DBH < 22	22 ≤ DBH < 27	27 ≤ DBH < 32	DBH ≥ 32	Total	
n	5	5	4	5	5	24	

DBH: diameter at breast height.

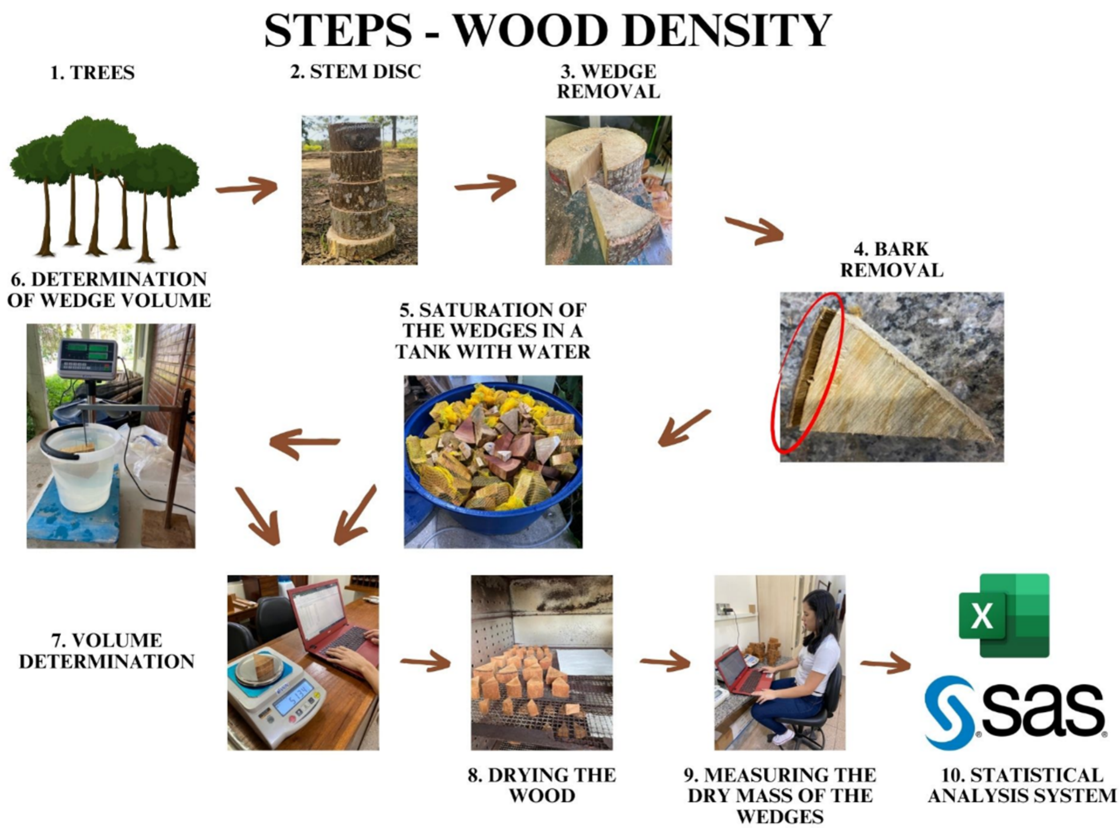

Figure 3 – Methodological scheme for obtaining the wood densities of *Bertholletia excelsa*, *Dipteryx odorata*, and *Khaya grandifoliola*.

$$\rho\ anhydrous = \frac{m_0}{V_0} \quad (2)$$

Where:
ρ anhydrous = anhydrous density ($g.cm^{-3}$);
m_0 = dry mass of wood at 0% moisture content (g); and
V_0 = volume of wood at 0% moisture content (cm^3).

$$\rho\ basic = \frac{m_s}{V_{sat}} \quad (3)$$

Where:
ρ basic = basic density ($g.cm^{-3}$);
m_s = dry mass (g); and
V_{sat} = saturated volume (cm^3).

Once the anhydrous, apparent, and basic densities had been obtained, it was necessary to apply the weighted average, based on the diameter of each sample, to make the data more robust and reliable, according to Equation 4 (Downes et al., 1997).

$$\rho = \frac{1}{2}\left\{\frac{(\rho_0+\rho_{25})*(\rho_0^2+\rho_{25}^2)+ \ldots\ldots(\rho_{75}+\rho_{100})*(\rho_0^2+\rho_{25}^2)}{d_0^2+d_{100}^2+2*(d_{25}^2+2)*(d_{25}^2+d_{50}^2+d_{75}^2)}\right\} \quad (4)$$

Where:
ρ = weighted density ($g.cm^{-3}$);
ρ_2 to ρ_{100} = wedge density from base (0%) to top (100%) at commercial height ($g.cm^{-3}$); and
d_0 to d_{100} = disk diameter from base (0%) to top diameter (100%) at commercial height (cm).

Data analysis

Two experimental designs were considered:

Experimental design 1, to verify the difference between the types of density in the species, in which: Sampling universe – forest species (*B. excelsa*, *D. odorata*, and *K. grandifoliola*); treatments – type of density (apparent, anhydrous, and basic); replications – samples (wedges) collected from the stem, based on weighted density (Equation 4).

Experimental design 2, to verify the difference in basic density along the stem of the species, in which: Sampling universe – forest species (*B. excelsa*, *D. odorata*, and *K. grandifoliola*); treatments – collection positions on the stem (0, 25, 50, 75 and 100%); replications – samples (wedges) collected from the stem.

Data was subjected to statistical assumptions, such as normality of the data (Shapiro-Wilk test), homogeneity of variances (Levene's test), and checking for outliers (Grubbs's test). Subsequently, analysis of variance and Tukey's test were employed to compare the means, with a significance level of 5%. When necessary, the Box-Cox optimal power method was applied to transform the variables (Box and Cox, 1964). In addition, the basic density data along the stem was analyzed through multivariate statistics, represented graphically by dendrogram and confidence ellipse of the means, using the free statistical software SAS (Statistical Analysis System, 2023).

RESULTS AND DISCUSSION

Differences in types of densities and their implications for crop-livestock-forest

The average values found for the density (ρ) of apparent, anhydrous, and basic wood from the CLF forest component shows a decreasing tendency. In *D. odorata*, the values were ρ apparent 0.99, ρ anhydrous 0.91, and ρ basic 0.83; for *B. excelsa*, ρ apparent was 0.68, ρ anhydrous 0.61, and ρ basic 0.55; and in *K. grandifoliola*, ρ apparent was 0.61, ρ anhydrous 0.56; and ρ basic 0.51, in $g.cm^{-3}$. The species that presented the highest value for diameter at breast height (DBH) was *K. grandifoliola*, with an average of 32.18 cm, followed by *B. excelsa*, with 20.92 cm, and *D. odorata* with 13.86 cm (Table 2). This information reflects important implications for understanding wood's physical properties and its application in the CLF system.

In this context, apparent density is generally associated with the strength and stiffness of wood (Christoforo et al., 2020). In the CLF system, where trees coexist with annual crops and pastures, apparent density is an essential metric for evaluating timber potential, with D. odorata having the highest apparent density (0.99 $g.cm^{-3}$). According to Bamber et al. (1982), the increase in apparent density is due to changes in the morphology of the fibers, with an increase in the cell wall fraction.

Anhydrous density refers to the density of wood that is completely dry, without any moisture content (Altgen et al., 2023). This type of density is relevant for the use of wood in industrial applications. *D. odorata*, which has an anhydrous density of 0.91 $g.cm^{-3}$, can be used to provide wood with good strength, suitable for structural use, including applications that may reduce the cost of external inputs on the property (Silva-Neto et al., 2023).

Table 2 – Apparent, anhydrous, and basic densities (mean values and standard deviations ±) and wood of the forest components (diameter at breast height) present in the crop-livestock-forest system.

Density ρ ($g.cm^{-3}$)	Species		
	Bertholletia excelsa	*Dipteryx odorata*	*Khaya grandifoliola*
Apparent	0.68 ± 0.05 a	0.99 ± 0.10 a	0.61 ± 0.06 a
Anhydrous	0.61 ± 0.03 b	0.91 ± 0.10 b	0.56 ± 0.04 b
Basic	0.55 ± 0.03 c	0.83 ± 0.06 c	0.51 ± 0.05 c
CV (%)	6.44	9.76	9.17
p-value	2.02 e^{-19}	3.20 e^{-07}	1.10 e^{-07}
DBH (cm)	20.92 ± 7.86	13.86 ± 4.70	32.18 ± 9.58

DBH: diameter at breast height; CV: coefficients of variation. Means followed by the same letter in the columns do not differ according to the Tukey's test at 5%.

Basic density is considered the most stable measure and reflects the relationship between dry mass and saturated volume of wood (ABNT, 2003). In the CLF system, basic density is important for long-term planning, as it provides a standard measure for comparing species and helps to understand the characteristics of wood over time and under environmental changes (Eloy et al., 2024). *K. grandifoliola*, with a basic density of 0.51 $g.cm^{-3}$, may be more suitable for areas where the focus is on fast growth and the production of lightweight wood for less demanding uses, while *D. odorata*, with 0.83 $g.cm^{-3}$, provides denser and more durable wood, suitable for long-term industrial or commercial use (Reis et al., 2019; Sousa et al., 2019).

The variability among species, expressed by the coefficient of variation (CV, %) and the mean DBH, allows for the selection of specific species for different functions within the system. The Shapiro-Wilk test values suggest that data for each density type are approximately normally distributed. Species with lower density variability, such as *B. excelsa* (CV = 6.44%), can provide greater predictability regarding biomass and carbon stock (Souza CR et al., 2023). On the other hand, the larger average DBH of *K. grandifoliola* (32.18 cm) indicates that this species can be used in a CLF system focused on the rapid production of biomass, benefiting systems with high harvest turnover and product diversification (Santos et al., 2020; Gomes et al., 2024).

The densities of the analyzed woods help select the most suitable species for the specific objectives of each CLF system, promoting a balance between productivity, sustainability, and the conservation of natural resources.

Analyze the longitudinal variation in wood basic density

Basic density is more commonly used in scientific research, as it represents wood in its maximum state of expansion, with moisture content above the fiber saturation point (approximately 30%). The International Association of Wood Anatomists (IAWA) considers basic wood density classification (Wheeler et al., 1989). This parameter provides a consistent measure for comparing wood density across species, as it excludes variations caused by moisture levels below the saturation threshold (Oliveira et al., 2019). For this reason, the basic wood density of forest species present in the CLF was analyzed in detail along the stem where a similar decay curve was observed across the three species, as shown in Figure 4.

The analysis of basic density along the stems of *D. odorata*, *B. excelsa*, and *K. grandifoliola* reveals distinct patterns with implications for forestry management. *D. odorata* exhibited the highest basic density near the ground (0%) at 0.88 g/cm^3, which gradually decreased along the stem (0.85, 0.80, and 0.77 g/cm^3 at 50, 75, and 100% of the stem, respectively), indicating that the densest wood is at the base, likely due to mature wood concentration. In *B. excelsa*, a significant density difference was observed only at the base (0.63 g/cm^3), suggesting that mass accumulates there to support the tree's structural and ecological roles. *K. grandifoliola*, an exotic species, showed uniform density distribution, with significant variation only between the base and the rest of the stem, making it a promising candidate for forestry crops in the region due to its consistent wood quality.

These findings align with previous studies indicating a general decrease in basic density from base to top, attributed to a shift from mature to juvenile wood (Hsing et al., 2016; Dimou et al., 2023; Romero et al., 2024; Momolli et al., 2024). The basic density of the wood evaluated in the present study is of fundamental importance, as it directly influences wood processing and utilization, as well as serves as a basis for estimating above-ground biomass and carbon stock (Silveira et al., 2013; Poorter et al., 2015). However, studies analyzing basic wood density along the stem of the species included in this research are limited (França et al., 2015; Momolli et al., 2024).

Latreille et al. (2018) evaluated the physical and mechanical properties of *Dipteryx alata* (Baru), a 10-year-old species in a monoculture that belongs to the same genus as *D. odorata* (Cumaru) and reported a basic density of 0.78 g.cm^{-3}; however, this study did not provide a detailed analysis along the stem. The basic density was observed to be lower than that found in the present study, with only a one-year age difference, indicating that the wood of *D. odorata* in our research is denser.

Lima et al. (2024) examined the wood properties of twenty Amazonian tree species with potential for commercial timber use and identified *D. odorata* as having the highest basic density among them, at 0.91 g.cm^{-3}. This high density contributes to the species' desirability on the market, making it one of the most heavily exploited in the Amazon (Honorio-Coronado et al., 2020). In addition to its value as a timber resource, *D. odorata* also shows potential for ecological benefits. Brasil-Neto et al. (2021) highlighted its suitability for reforestation efforts and its role in improving soil quality in degraded pastures in the Eastern Amazon. Together, these findings underscore the dual value of *D. odorata*, both economically and ecologically, offering sustainable opportunities for its cultivation in integrated systems in the Amazon (Lopes et al., 2023).

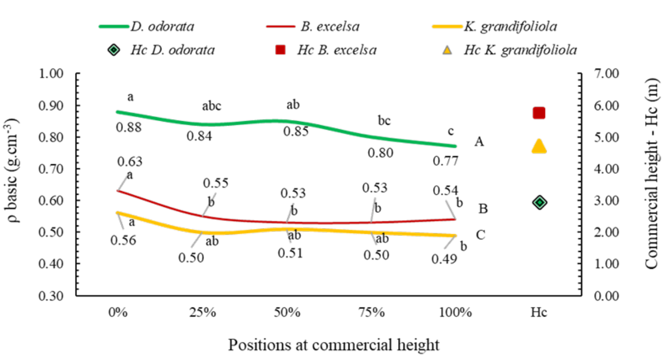

Figure 4 – Average profile of the variation in basic density along the stem of *Bertholletia excelsa*, *Dipteryx odorata*, and *Khaya grandifoliola* woods, between September and November 2021.

Uppercase letters compare the basic density between species and lowercase letters compare the basic density along the stem of each species. Letters indicate the differences between the means of each collection position and the uppercase letters highlight the differences between species. Geometric shapes refer to the commercial height of each species.

The basic wood density of *B. excelsa* in native forests of the Brazilian Amazon is 0.62 g.cm^{-3} (Fearnside, 1997), a value similar to that observed in the present study, where the species is in a juvenile phase, located in a recovery degraded area. The *B. excelsa*, although prohibited from commercial harvesting in Brazil (Brasil, 2006), can enhance the economic and ecological value of integrated systems. When present in these systems, *B. excelsa* provides additional products for commercialization, such as seeds, which have established national and international markets, and contributes to carbon storage strategies (Vieira et al., 2022; Souza AO et al., 2023). This versatility adds further value to integrated systems, strengthening the case for including native species with high ecological value in sustainable cultivation practices.

Momolli et al. (2024) conducted a detailed characterization of wood density in *K. grandifoliola* cultivated in monoculture with a planting spacing of 30 x 30 cm, at 9.5 years of age. They observed that the species exhibited a basic density ranging from 47.8 to 55.9 g.cm^{-3}, with a decrease in density along the stem. In the middle positions (25, 50, and 75%), no significant differences in density were observed. The trees displayed an average commercial height of 5.7 m and a mean DBH of 21.3 cm. All characteristics were like those of *K. grandifoliola* in our study, except for DBH, which was greater in the present study, with a value of 32.18 cm, likely due to the wider spacing used.

The combination of native and exotic species for the recovery of degraded areas is established in Law No. 12,651/2012, known as the "New Forest Code" (Brasil, 2012). This legal instrument provides support for the use of species like *K. grandifoliola* in the restoration of legal reserves. The law facilitates the incorporation of agroforestry and other sustainable practices into environmental regularization programs, both on titled rural properties and areas with land tenure, thereby promoting both ecological restoration and sustainable production.

In this context, the basic density values analyzed in the study are fundamentals for understanding the potential of these species for both restoration and sustainable production. Considering the basic density values analyzed along the stem, Figure 5 confirms there is a similarity between *B. excelsa* and *K. grandifoliola* woods, as they form a single clade from the cut at 25% of the commercial stem. On the other hand, *D. odorata* has a distinct basic density characteristic, which differs from those of the other two species analyzed in this study.

As wood density is the result of the relationship between two physical quantities, mass and volume, this property makes it possible to group similar species, assign uses and applications, infer the quantification of carbon stored in forests, and confirm this in planted forests (Romero et al., 2024). Therefore, despite the species having distinct densities, it is possible to group them, with *B. excelsa*, and *K. grandifoliola* classified as medium-density wood, while *D. odorata* is characterized as heavy-wood, according to the IAWA classification (Wheeler et al., 1989). This highlights the importance of choosing species based on their wood properties, as defined by legal frameworks, to achieve both ecological and economic goals in CLF systems.

In addition to these wood properties, trees contribute significantly to long-term carbon sequestration, both in biomass and in the soil (Waring et al., 2020, Reis et al., 2021). For example, in Paragominas, a municipality in Pará where integrated systems are widely used, improvements in soil properties have been observed, as the increase in organic matter has contributed to higher CO_2 stocks in the more superficial layers of the soil profile (Fernandes et al., 2019). Therefore, the selection of species like *B. excelsa* and *K. grandifoliola* not only increases wood production and its economic value but also contributes to the enhanced sequestration of carbon in both biomass and soil, further supporting the sustainability goals of CLF systems (Souza CR et al., 2023; Momolli et al., 2024).

Figure 6 presents the canonical discriminant analysis highlighting the differences between the basic densities of the three species. Canonical variable 1 separates *D. odorata* from the other two species, primarily due to its higher values at the 25% (10.92) and 75% (5.10) positions of the commercial stem. Therefore, the overall graphical analysis indicates that the three species are distinct according to the two canonical variables, as the 95% confidence ellipses do not intersect, reinforcing the separation of *D. odorata* in terms of basic density of wood along the stem.

D. odorata, despite its high basic wood density, which makes it highly valuable in the timber market, also presents significant bioeconomic potential due to the production of coumarin, a compound found in its seeds and widely used in the fragrance and food industries (Sousa et al., 2022). *B. excelsa*, being a species with prohibited timber use (Brasil, 2006), is primarily noted for its non-timber products, such as fruits and seeds, which have been traded for many decades by the traditional Amazon population (Souza AO et al., 2023; Medeiros et al., 2024). Therefore, promoting sustainable practices that consider both the ecological and bioeconomic potential of these species will ensure their long-term survival and contribution to Amazonian ecosystems. The CLF system offers an opportunity to raise awareness of the broader ecological roles of these species and their potential to drive sustainable practices, particularly in the use of non-timber products and environmental services.

One of the main challenges for both species is ensuring their ecological function within the Amazon. In light of this, further research is needed to better understand the dynamics of nut production, its rela-

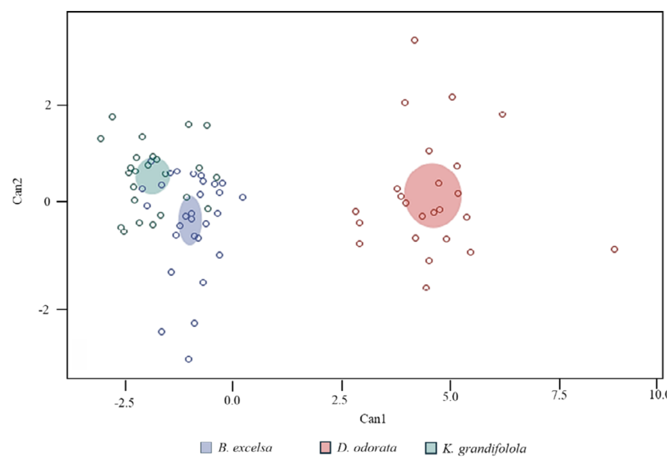

Figure 6 – Confidence ellipses for the vector of means (95%), according to the first two canonical (Can1 and 2) discriminant variables between the basic densities along the stem of the species *Bertholletia excelsa*, *Dipteryx odorata*, and *Khaya grandifoliola*, considering the densities obtained along the commercial stem.

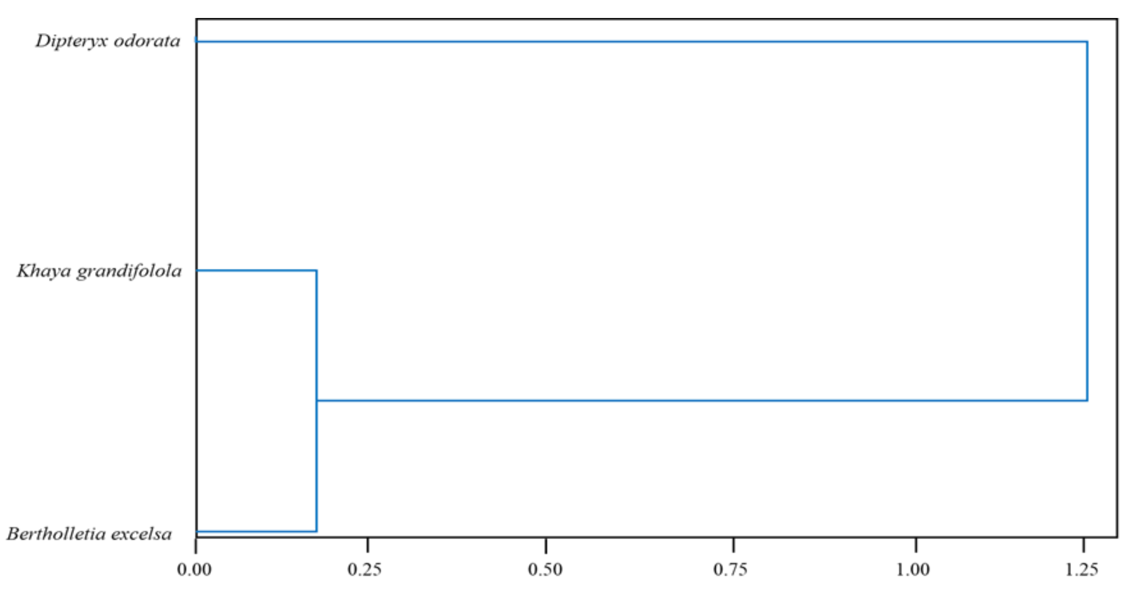

Figure 5 – Dendrogram using the average linkage method between the two native species and the exotic (*Bertholletia excelsa*, *Dipteryx odorata*, and *Khaya grandifoliola*) comparing the densities obtained along the commercial stem, in an integrated production system in Mojuí dos Campos (PA).

tionship with environmental factors, coumarin levels, and the ecological implications of its harvest.

CONCLUSION

The presented results provide robust technical support to inform decision-making regarding the use of native and exotic species in integrated production systems:

- *Dipteryx odorata* is the species with the highest wood density, particularly at the base of the commercial stem, making it a highly valued species in the timber market. However, to capitalize on these opportunities and mitigate potential risks, it is essential to implement adaptive management strategies that recognize species-specific differences and promote sustainable forestry practices;
- *Bertholletia excelsa* exhibited a consistent basic density along the commercial stem and was distinguished by the highest commercial height among the species evaluated. While it demonstrates clear timber potential, its characteristics suggest high efficiency in providing environmental services, such as carbon sequestration, playing a significant role in climate change mitigation;
- *Khaya grandifoliola* exhibited the largest DBH and the lowest density. The variation in basic density is nearly homogeneous along the commercial stem, a characteristic that indicates the wood's ease of workability for furniture manufacturing.

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Authors' contributions

Santos, L.E.: conceptualization, data curation, formal analysis, investigation, methodology and, writing — original draft. **Dias, C.T.S.:** data curation, formal analysis, investigation, methodology, software, supervision, validation, visualization and, writing — original draft. **Araújo, E.J.G.:** writing — review & editing. **Cândido, A.C.T.F.:** writing — review & editing. **Fernandes, P.C.C.:** writing — review & editing. **Silva, A.R.:** Conceptualization, writing - review & editing. **Oliveira, A.H.M.:** writing — review & editing. **Moutinho, V.H.P.:** methodology, validation, writing — review & editing. **Martorano, L.G.:** conceptualization, methodology, validation, formal analysis, investigation, visualization, writing — review & editing.

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