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Variation in the Basic Density of Woods Produced in the Brazilian Semiarid Region Subjected to Different Irrigation Regimes

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Abstract: The present work aimed to evaluate the wood of fourteen genetic materials (nine species, between native and exotic, and five clones of *Eucalyptus*) cultivated under two post-planting irrigation regimes in the Brazilian semiarid region. For each genotype, six trees (11 years old) were selected and subjected to two initial irrigation regimes (up to 12 months and up to 36 months) after planting. Discs of different stem heights were taken: 0% (base), breast height (DBH), 20%, 40%, 60%, 80%, and 100%. Samples were extracted along the radial axis of each disk at three regions (the pith-adjacent region, intermediate region, and bark-adjacent region). Samples were subsequently saturated in water to determine their density via the water displacement method. The irrigation systems caused changes in the pattern of radial and longitudinal variation in the clones regarding the proportion of woody material in the stem. Among the native species, Angico stood out with a high density and little juvenile wood, and Pau d'arco, with a low density and a high rate of juvenile wood. Among the exotic species, Nim presented a high density and a low rate of juvenile wood, and Chichá presented a high rate of juvenile wood and a low density. In the *Eucalyptus* hybrids, VE38 stood out with a high density. Overall, there was an influence from irrigation management, observed with greater intensity in exotic species for Mahogany and Acacia and for the VE41 and AEC1528 clones of *Eucalyptus*. The values of basic densities in the trees varied from 0.35 to 0.85 g·cm^{-3}. There was good adaptation of native and exotic species and clones to the planting area in the Semiarid region.

Keywords: wood quality; water scarcity; forest plantations; variation of density

1. Introduction

The cultivation of forests in the Brazilian semiarid region is mainly intended for producing firewood for the energy sector and roundwood for producing stakes and posts. In the region, there is still a predominance of traditional and predatory agricultural practices and the lack of an established production chain for timber forestry products. These factors and climate specificities limit development opportunities for forestry investment projects [1]. Despite this, the demand for wood and wood products is also growing in these areas [2], which indicates the need to carry out more studies that seek not only to evaluate alternatives for the expansion of forestry in the semiarid region but also to analyze the quality and potential of the wood produced by such plantations.

Among several works referring to the determination of the physical and mechanical properties of forest species [3–5], few investigate the behavior of the technological characteristics of wood when subjected to the effects environmental issues in areas that are not yet commercially exploited or that evaluate the influence of different irrigation management techniques (necessary for areas with reduced rainfall levels) on the quality of the wood produced. Most studies are restricted to investigating the parameters of growth and initial development of tree species [6]. Along these lines, the climate of the Brazilian semiarid region is characterized by water insufficiency due to irregularly distributed rainfall and its intense irregularity in time and space, periodically causing the occurrence of prolonged droughts [7].

The choice and improvement of forestry sources are carried out to provide raw materials with high efficiency for different industries. Analyses of its properties estimate wood quality since it is possible to benefit from and allocate it appropriately for use through the knowledge of these characteristics [8].

Density is one of the main properties evaluated in wood. According to Müller [9], this property presents a good relationship with other characteristics, such as mechanical resistance and stiffness, in addition to being determined from a simple test [10,11]. This property varies according to the position of the wood in the trunk, both longitudinally (base–top) and radially (pith–bark), which also causes changes in the other correlated properties. The variation in these two axes is influenced by anatomical, chemical, and physical differences that occur along the stem and is explained by changes in fiber length, proportions of cell types, cell diameter, cell wall thickness, and lignin, among others. These are, in turn, conditioned by genotype factors, tree age [12], and environmental conditions [13].

Local factors also influence the basic density of wood from commercial forest species. Therefore, they should be considered an essential parameter in assessing wood quality to support the forestry and processing industries and manage forest plantations to expand possible species use [14].

At this juncture, it becomes crucial to promote research of this nature as a subsidy to expand the number of areas that meet the requirements of silvicultural practices necessary for forestry production, assuming that some of the native and exotic tree species and clones of *Eucalyptus*, established in the semiarid region, present wood with potential for industrial supply. Therefore, this work aimed to evaluate the basic density of wood from different forest species cultivated under different irrigation regimes in the semiarid region, more precisely in the Marco furniture hub, located in the state of Ceará.

2. Materials and Methods

2.1. Selected Species

Fourteen species were selected: four native, five exotic, and five *Eucalyptus* clones, aged approximately 11 years and established in the semiarid region of Brazil (Table 1). These were cultivated in a managed plot of the Baixo Acaraú Irrigated Perimeter (longitude: 03°06′02″ S, latitude: 40°04′06″ W and altitude of 56 m above the sea level) (Figure 1). According to the Köppen–Geiger classification, the region's climate is type Aw' (tropical with a dry winter), with a rainy season between January and April and a dry season between May and December [15]. The average annual precipitation is approximately 1000 mm, with an average annual temperature of 28 °C, which can vary between 23 °C and 34 °C, and an average annual relative humidity of 70% [16]. The relief is reasonably flat, with generally deep, well-drained soils of medium or medium/light texture and very permeable [17].

Table 1. Species selected for technological characterization.

Common Name	Scientific Name	Classification	Ht (m)	DBH (cm)
Angico	*Anadenanthera colubrina* (Vell.) Brenan	Native	13.31	16.12
Jatobá	*Hymenaea courbaril* L.	Native	9.99	10.14
Pau d'arco roxo	*Handroanthus impetiginosus* (Mart. Ex DC) Mattos	Native	18.88	20.63
Sobrasil	*Colubrina glandulosa* var. Reitzii	Native	13.57	14.48
Mogno-africano	*Khaya grandifoliola C. DC.*	Exotic	11.63	13.43
Acácia	*Acacia mangium* Willd.	Exotic	20.48	28.06
Chichá	*Sterculia foetida* L.	Exotic	13.23	16.41
Nim	*Azadirachta indica* A. Juss	Exotic	10.88	15.58
Teca	*Tectona grandis* Linn. F	Exotic	13.73	15.96
GG 702	*Eucalyptus urophylla S. T. Blake*	*Eucalyptus* clone	29.48	27.45
GG 680	*E. urophylla* × *E. grandis*	*Eucalyptus* clone	28.60	24.02
VE 41	*E. urophylla* × *E. grandis*	*Eucalyptus* clone	33.27	35.86
VE 38	*E. urophylla* × *E. camaldulensis*	*Eucalyptus* clone	29.86	31.25
AEC 1528	*E. urophylla* × *E. grandis*	*Eucalyptus* clone	26.59	28.03

Ht = total height; DBH = diameter at breast height.

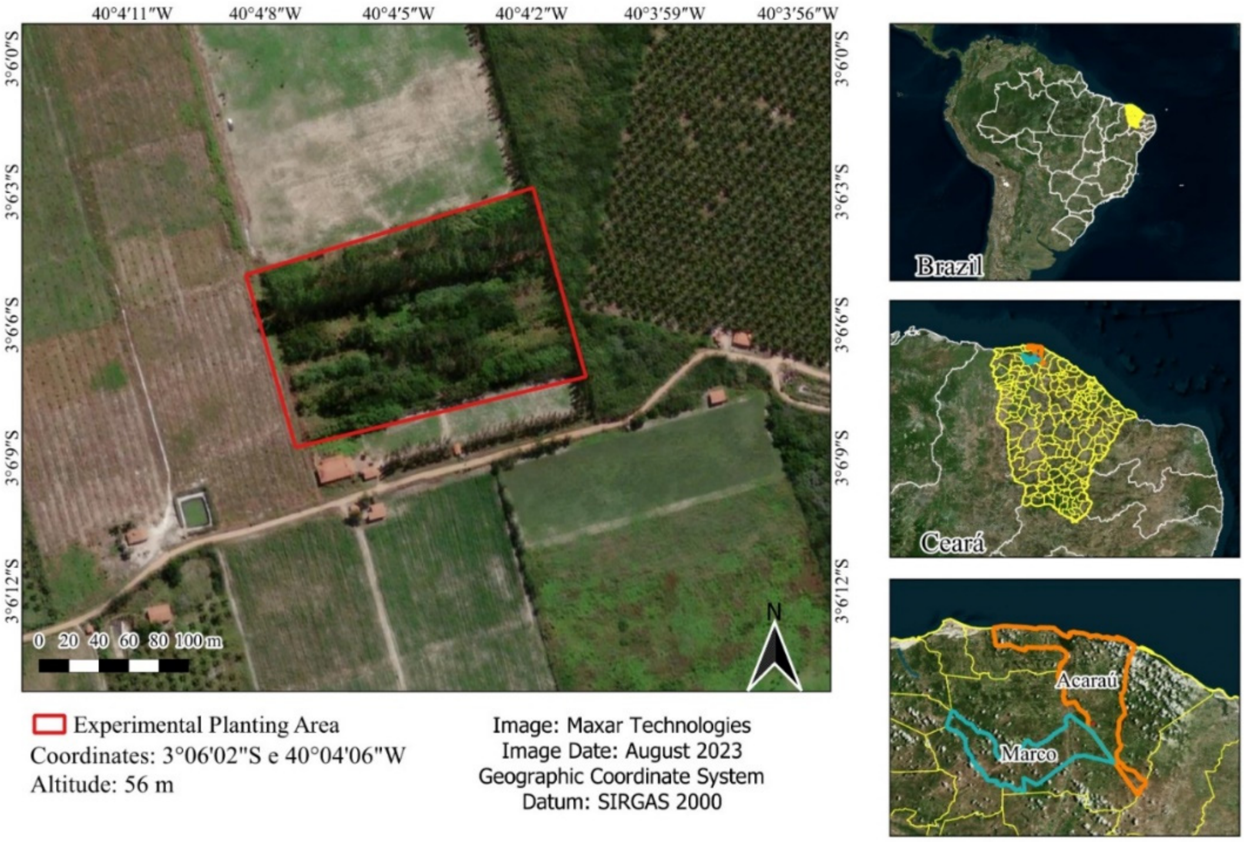


Figure 1. Location of the experimental area in the region of Marco—CE, Brazil.

2.2. Conducting Plantings

The planting of the species was carried out in three lines, with each line consisting of 15 plants. A 3 × 2 m spacing was adopted, with 3 m between rows and 2 m between plants in the row, with the first and third rows being used as a border. All species and clones were initially subjected to the micro-sprinkler irrigation system for 12 months. After this period, part of the experiment was conducted without irrigation, and the other part remained with continuous irrigation until 36 months.

Systematic thinning equivalent to 50% of the individuals was carried out four years after planting the clones. For native and exotic species, after the same period since the experiment was set up, selective thinning equivalent to 30% of the individuals was carried out. Such procedures resulted in increased spacing to optimize the performance of the remaining individuals. Thus, the experimental design of the implemented area consisted of 14 genetic materials and 2 irrigation managements.

2.3. Sampling of Selected Species

Six individuals (3 for each type of irrigation) of each native and exotic species and the five Eucalyptus clones were collected approximately 11 years after planting. To ensure greater quality and reliability in the results, samples with good phytosanitary conditions and an absence of knots and bifurcations were selected up to the commercial height of their trunk. The sampling also considered the two management conditions that trees were subjected to, one with irrigation for up to 12 months and the other for up to 36 months after planting.

Discs 5 cm thick were cut along the trunk at positions corresponding to 0% (base), DBH, 20%, 40%, 60%, 80%, and 100% of the total height (Figure 2a). The samples were prepared for the physical analysis of the wood using $\frac{1}{4}$ wedges of each disc (Figure 2b). From each fraction, three samples with irregular shapes and sizes were taken in the radial direction (close to the pith, intermediate, and close to the bark).

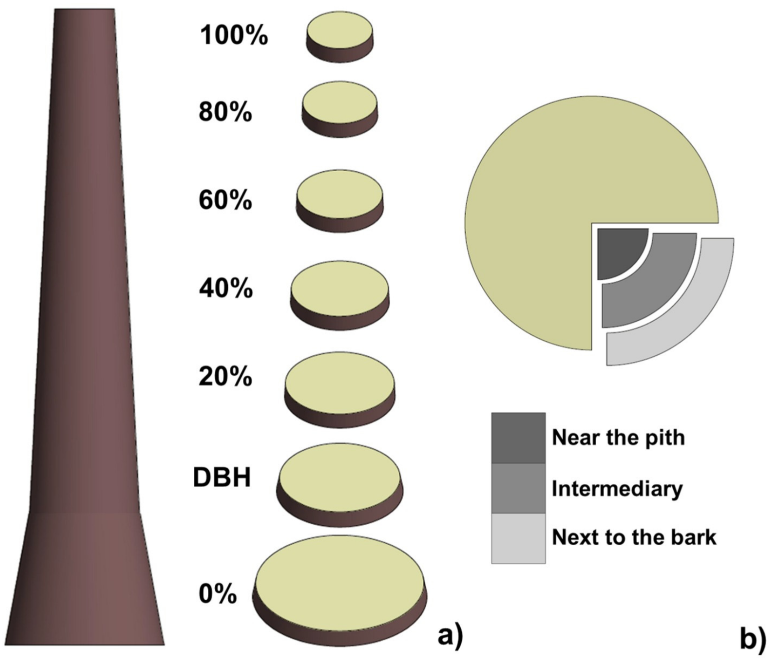


Figure 2. Sampling scheme: (**a**) representation of the distribution of discs in the axial direction of the trunk; and (**b**) representation of the wedges (in the radial direction) of the discs.

2.4. Determination of Basic Density

The wedges obtained from the discs of each species were submerged in water for 14 days until the cell walls were completely saturated (fiber saturation point—PSF) to obtain the saturated volume of the specimens. The saturated samples had their volume determined by the water displacement method (immersion method), according to procedures described by Vital [18] and standard NBR 11941 [19]. Then, the samples were placed in the oven at

103 ± 2 °C until they reached a constant mass. The relationship between dry mass and saturated volume obtained the basic density.

$$Db\left(\text{g}\cdot\text{cm}^{-3}\right) = \frac{Ps}{V\ (displaced)} \tag{1}$$

where, Db = basic density in g·cm^{-3}; Ps = dry mass of the sample; V = volume of liquid displaced.

2.5. Analysis of Results

The data were tabulated considering the different variations in the radial and axial directions of the stem. Results were organized and interpolated to achieve the distribution of tree density along the stem. Images were generated that identified density variation within the trees. The software used was AutoCAD version 2021 to sketch the tree-shaped figure; ArcMap version 10.5 to add the basic density values to their respective points in the tree and promote color differentiation in the intervals of the studied variable; and CorelDraw, 2021 versions, to organize and improve the quality of images. The variables considered were: species/clones with fourteen levels and two post-planting irrigation regimes (up to 12 months and up to 36 months).

A multivariate analysis was conducted to verify the similarity regarding the density parameter between the different treatments evaluated (species and irrigation time). The procedure adopted was using dendrograms, adopting the Ward method, where the percentage of 20% dissimilarity was established for comparison purposes.

The average density of the tree was determined, considering the proportionality of the volume represented by each wedge, as Vital [18] recommended, following the procedures observed in Equation (2) and Figure 3. The volume of each segment of the tree (logs) was determined by the Smalian method.

$$\rho = \frac{\Sigma_{di} \times V_i}{V} \tag{2}$$

where: d_i = average density of the discs; V_i = volume that each disc represents; V = total volume of the tree.

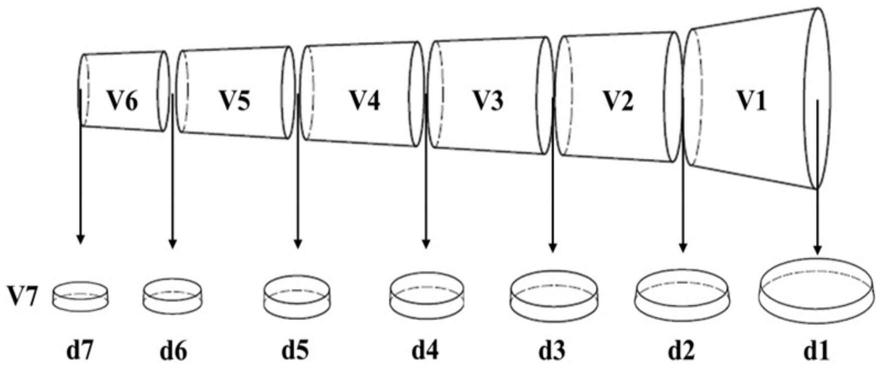


Figure 3. Disc collection positions (d_i) and their respective volumes (V_i) used to determine the weighted basic density of the tree (adapted from [18]).

Tree density values were compared using descriptive statistics (average and standard deviation). The values obtained were used to classify the wood, categorizing them according to Zaque et al. [20] (Table 2).

Table 2. Classification of the basic density of wood from fourteen forest species in the region of Marco—CE, Brazil.

Basic Density ($g \cdot cm^{-3}$)	Classification
≤0.40	Very light
0.41 a 0.55	Light
0.56 a 0.75	Moderately heavy
0.76 a 0.95	Heavy
≥0.96	Very heavy

Source: Zaque et al. [20].

3. Results and Discussion

3.1. Native Species

Figure 4 represents the variation in density in the radial and axial directions of the stem of four species native to Brazil, located in an experimental plantation in the semiarid region under two different irrigation systems. In the radial direction, a tendency towards lower values was observed in the pith region for all species at all heights tested. In contrast, the highest values remained in the peripheral region of the trunk. In the axial direction, the highest density values were concentrated in the basal region of the trees for the species of *C. glandulosa* and *A. colubrina*, while *H. impetiginosus* had higher density at the top of the tree. *H. courbaril*, on the other hand, was denser in the intermediate positions, close to 60% of the height. Nogueira and Castro [21] found a similar result when evaluating the wood of *Mimosa tenuiflora*, in which the average values of basic density remained in the lower and central proportions of the trunk of this species (base area and 50% to 75%), suggesting a more significant amount of heartwood in these regions of the trunk to explain this result.

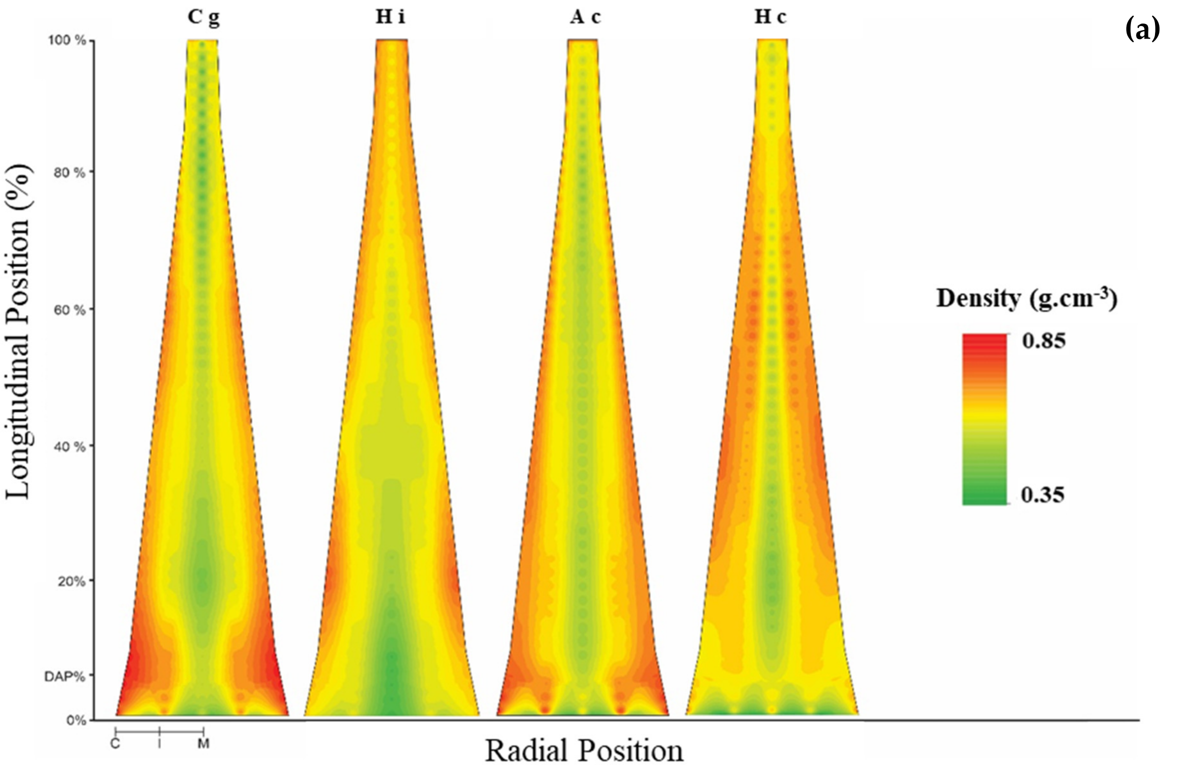
The tendency to increase basic density in the pith-bark direction, as occurred in native species, is considered a standard for most forest species and is related to the differentiation in the thickness of the fiber walls and the types of cells that make up the woody material [22,23].

There was variation in the density distribution pattern with the proportion of more and less dense wood in the trunk along the stem when comparing the different species. However, when comparing them individually and under the two irrigation systems, it was noted that there was an increase in basic density values when irrigated for 12 months after planting.

In the species *C. glandulosa*, the highest proportion of dense wood was present from the base to close to a height of 20%, reaching from the bark region to the intermediate area of the stem, followed by a thin layer also in the bark area until reaching 80% of the total height. The greatest representation of less dense wood was concentrated from a height of 20% close to the bark region and intensely throughout the trunk region from 80% of the total height. This behavior was observed when subjected to the two irrigation regimes, as shown in Figure 4.

For *H. impetiginosus*, the highest density was located in the bark region at a height above DBH up to 35%, being more significant in trees subjected to the irrigation system up to 36 months after planting (Figure 4b). However, maintaining the same pattern in the distribution of the evaluated parameter. There was a greater proportion of less woody material in the region, corresponding to 40%, and more intensely in the pith region, from the base to above 20% of the height. After this position, the variation in density for the two treatments remained stable until the total height.

In the species *A. colubrina*, the distribution of density values occurred similarly in the two irrigation regimes used. The highest densities were concentrated in the bark peripheral region from the base's height to the 80% position. Specific points with greater intensity and higher density values were observed in the irrigation regime of up to 12 months (Figure 4a), especially from the base region to the DBH. Lower density values were found in the base height region, the intermediate areas, and the bark of the trunk.



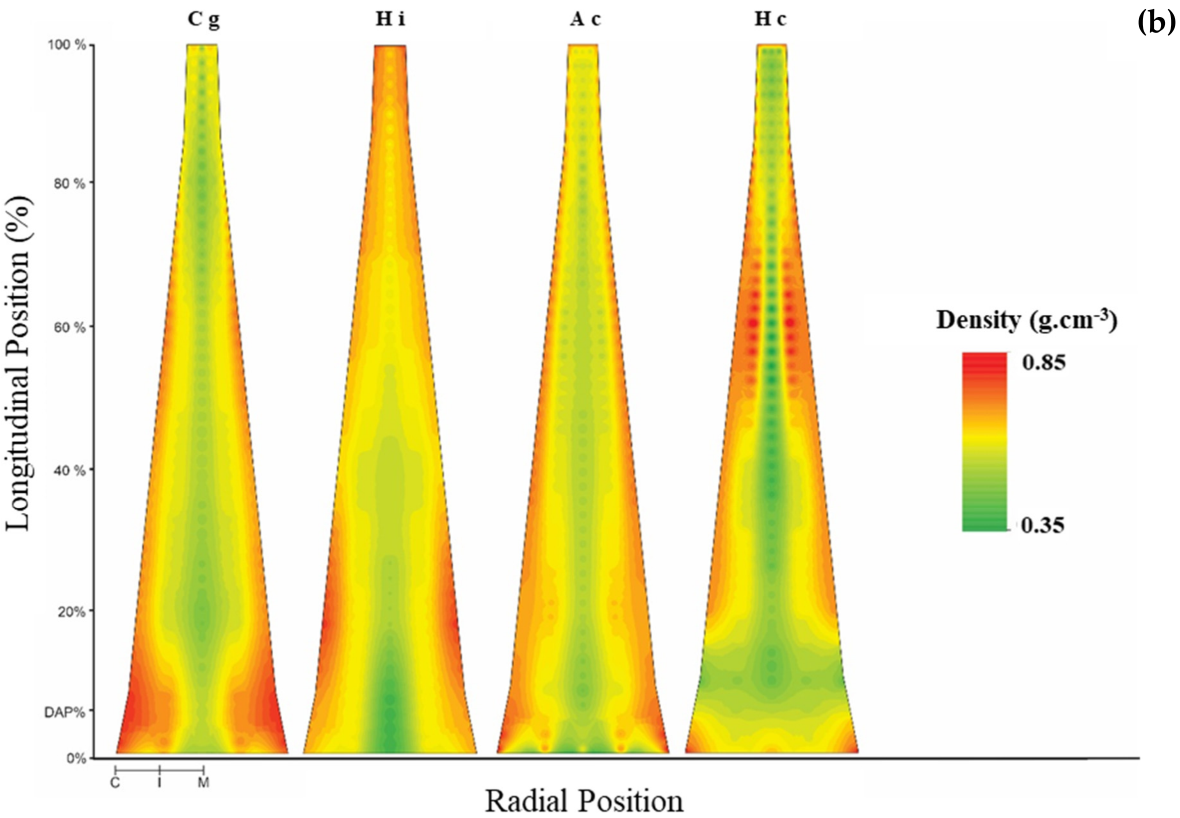


Figure 4. Variation in the basic density of wood of four native species in the region of Marco—CE, under irrigation regimes up to 12 months (**a**) and 36 months (**b**) after planting. C—bark; I—intermediate position; M—pith. Identification of the analyzed species represented by the letters: A c—*A. colubrina*; C g—*C. glandulosa*; H c—*H. courbaril* e H i—*H. impertiginosus*.

Concerning the species *H. courbaril*, the most significant proportion of wood with a high basic density occurred in the intermediate region and close to the bark, between 50 and 70% of the total height of the stem in the two irrigation systems, with greater intensity in the regime up to 36 months after planting. In trees with irrigation for up to 36 months, the regions with lower density occurred throughout the range between DBH and 20% and between 80 and 100% of height. While those in treatment with irrigation up to 12 months, had lower density in the range close to 0% of height and in the DBH pith up to 70% of height. The highest proportion of less dense wood occurred in both treatments in the pith and intermediate regions along the entire stem, particularly from the 40% position up to the maximum height.

Modes et al. [24] explain that the decrease in basic density in the base–top direction, as in the case of the species A. colubrina and *C. glandulosa*, can occur due to the greater quantity of juvenile wood present in the apical zone of the trees, formed by thick and thin branches, unlike *H. impetiginosus* and *H. courbaril*, which increased as the height increased, with a concentration of less woody material at the base and center of the stem. In his research with the species *Memecylon lateriflorum*, Ohemeng et al. [25], states that in humid ecological zones, the base of the tree tends to have a higher density value when compared to the intermediate and top parts.

The similarity analysis of these results (Figure 5) indicated that for the native species *H. impetiginosus* and *A. colubrina*, the effects of the two irrigation systems on the basic density variable remained the same. The proximity based on evaluating the relative Euclidean distance between these two species also allows us to corroborate this result. As for the species *H. courbaril* and *C. glandulosa*, when subjected to different irrigation systems (12 and 36 months after planting), they showed divergent behaviors, indicating the influence of irrigation on the basic density of the wood of these species.

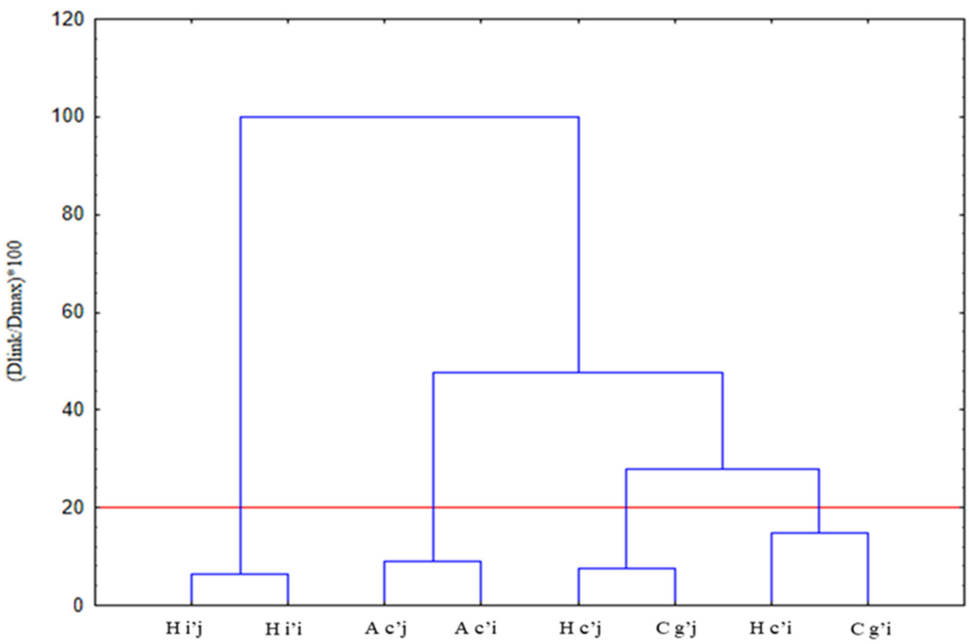


Figure 5. Dendrogram of the influence of irrigation management on the basic density of four native species native from Brazil, established in the region of Marco—CE. Identification of the analyzed species represented by the letters: A c—*A. colubrina*; C g—*C. glandulosa*; H c—*H. courbaril* e H i—*H. impertiginosus.* The letters "i" and "j" represent irrigation time adopted for each area, with "i" equivalent to 36 months, and "j" equivalent to 12 months.

It is also evident the dissimilarity in behavior between the species *H. impetiginosus* under the influence of the two-irrigation management with the other groups presented, especially with the species *H. courbaril* and *C. glandulosa*, indicating different responses to the variable under study even subject to the same conditions environmental. In the group of native species, the plant species is mentioned as an influential factor on density, considering that the different anatomical elements and their proportions, once genetically conditioned to each tree, differentiate them from other species by presenting their specific weights [26].

The average values of basic density of wood of the four native species evaluated for the two different irrigation management conditions (12 and 36 months) can be seen in Figure 6. Considering data determined in this study and the parameters cited by Zaque et al. [20], the basic density of the wood of the species *H. impetiginosus* is considered light, and the species *C. glandulosa*, *A. colubrina* and *H. courbaril* are classified as moderately heavy. When considering the general average of the wood of the native trees evaluated, the highest basic density was found in the species A. colubrina in both treatments (12 and 36 months), followed by the species *H. courbaril* and *C. glandulosa*, both under the irrigation regime for up to 12 months. When choosing the correct wood for a given use, one must consider the technological characteristics, their properties, and the respective levels required to perform satisfactorily. Density is an important quality index but cannot be used in isolation [27].

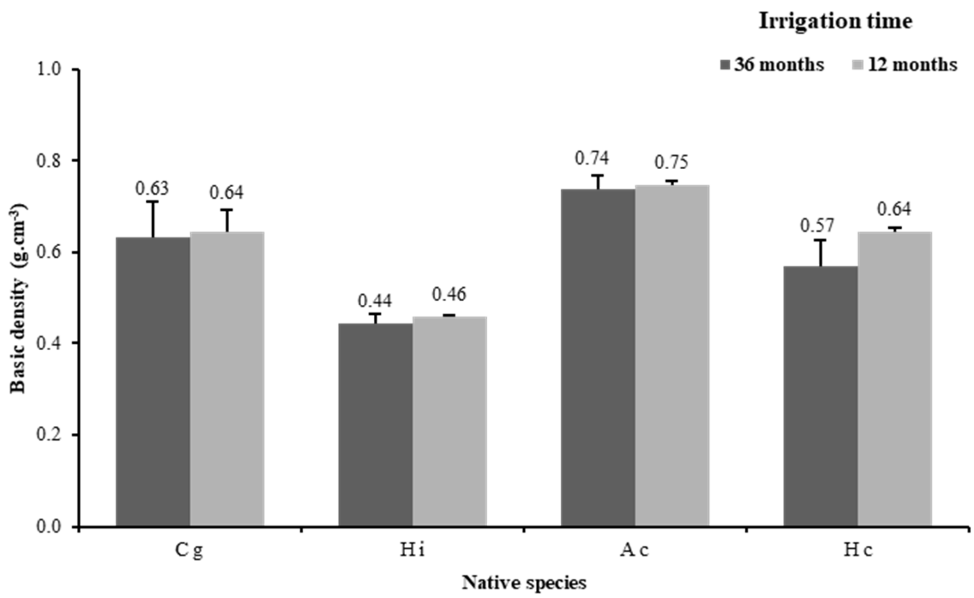


Figure 6. Basic density in four native species of wide occurrence cultivated in two irrigation regimes, implemented in the region of Marco—CE. Identification of the analyzed species represented by the letters: A c—*A. colubrina*; C g—*C. glandulosa*; H c—*H. courbaril* e H i—*H. impertiginosus*.

Basic density positively influences energy density. The greater the mass per volume, the greater the thermal energy released during burning. Therefore, materials with high values of basic wood density above 0.52 g·cm^{-3} are recommended for energy purposes [28]. Most species met this criterion, except for *H. impetiginosus* [29]. Carlos et al. [30], evaluating Angico cuttings produced under a management plan in the northeastern semiarid region, observed an average basic density of 0.90 g·cm^{-3}. For *C. glandulosa*, in a study area in Pará, Brazil.

3.2. Exotic Species

Acácia and Chichá followed the trend of increasing density from pith to bark (Figure 7). The species *K. grandifoliola*, *T. grandis*, and *A. indica* showed significant changes in this behavior, especially in the highest positions of the trees in both treatments. In the axial direction, there was a tendency for density to decrease in the base-to-top direction for the species *A. mangium*, *K. grandifoliola*, and *S. foetida* and an increase for *T. grandis* and *A. indica*.

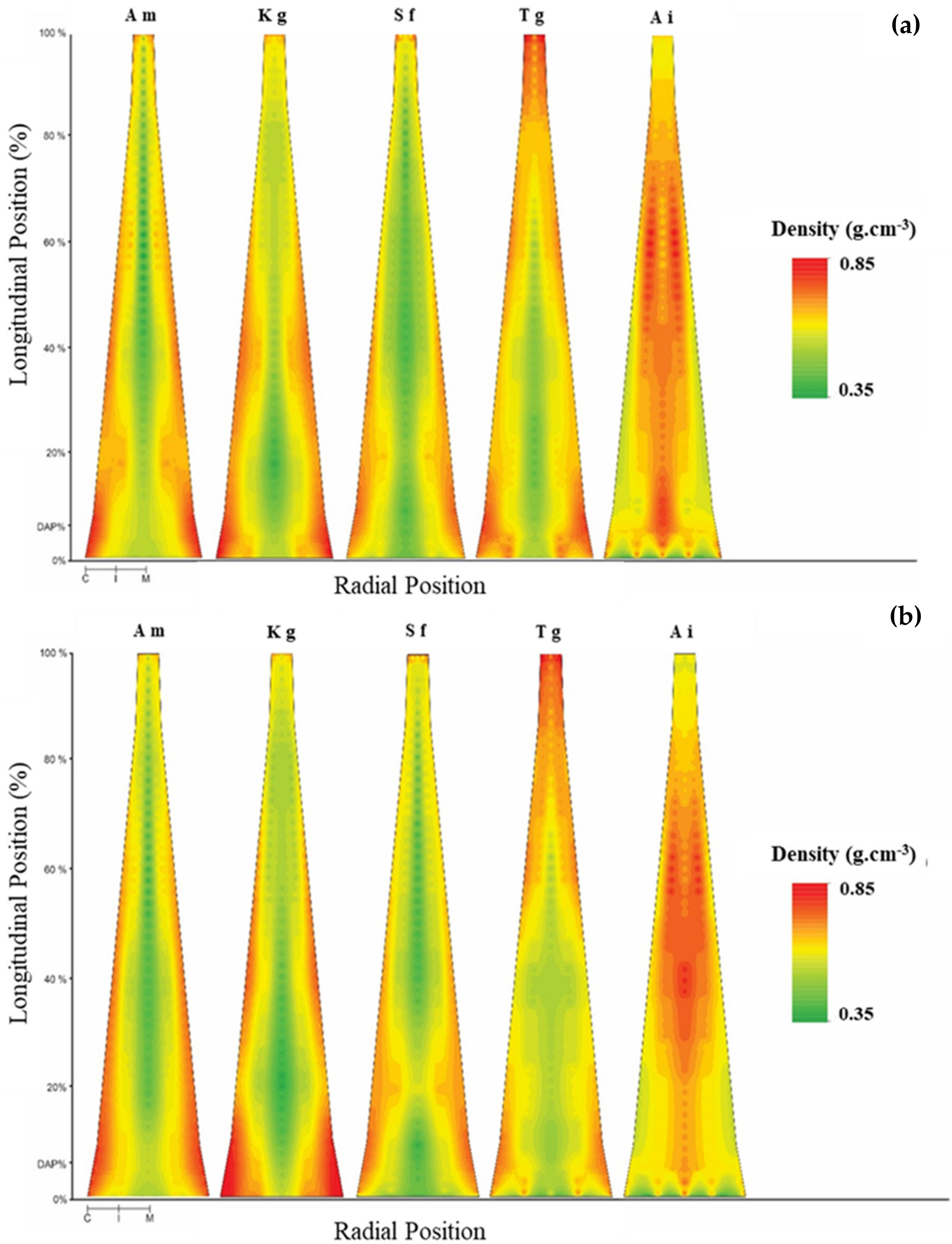


Figure 7. Variation in basic density of five species in the region of Marco—CE under irrigation regimes of up to 12 months (**a**) and 36 months (**b**) after planting. C—bark; I—intermediate position; M—pith. Identification of the analyzed species represented by the letters: A m—*A. mangium*; K g—*K. grandifoliola*; S f—*S. foetida*; T g—*T. Grandis*; A i—*A. indica*.

Analyzing the behavior of the species *A. mangium*, slight variation was observed in the two directions evaluated when the two treatments were compared. A slight increase in the proportion of denser wood close to the base of the tree occurred when subjected to management with longer irrigation times (Figure 7b). The proportion of less dense wood remained for both treatments in the pith region from the base to the top. As for the more woody material predominated in the bark region, significantly in the basal region, until a little higher than the DBH, decreasing its proportion as the height increased.

When formed during the vegetative period, wood cells are distinct because they have thin walls and large lumens, forming what is known as early wood, which, unlike the latewood developed at the end of the vegetative period, manifests thicker cells with smaller lumens. Plant individuals exhibit higher densities when there is a more significant amount of latewood. This is related to and explained by the fact that the direction of greater densities occurs in the region closest to the bark, where there is a greater amount of latewood and the growth and development of adult wood [18].

For *K. grandifoliola*, minor changes were observed regarding the pattern of basic density presentation in forest essences when subjected to the two irrigation regimes. In this species, the densest material was concentrated in the bark region and the basal part of the intermediate region, in greater proportion for the irrigated system up to 12 months after planting (Figure 7a). In both systems, the species showed lower densities in the pith region throughout the stem. As for *S. foetida*, the distribution pattern was similar for trees in both irrigation systems. However, there were significant differences in the proportion of more and less dense wood when subjected to different irrigation. In the system irrigated for 36 months (Figure 7b), there was a greater proportion of less dense material in the pith region close to the base.

Concerning *T. grandis*, the densest wood was found in the bark region at the base height up to the 10% position. Also, in all regions of the trunk, a little above the 60% position of the total height in both treatments. The highest proportion of less dense wood was concentrated in all regions of the trunk at positions of 20 and 40% of the height when subjected to the irrigated system up to 12 months after planting (Figure 7a). Intermediate values were maintained for irrigation up to 36 months (Figure 7b).

The species *A. indica* was the one that showed the most differentiated density distribution pattern compared to the others. The density pattern in this species was similar in both irrigation regimes. The lowest density was observed in the pith, intermediate, and bark regions at the base of the stem. The highest densities were observed in the intermediate and pith regions, between 25 and 75% of the height. The top region presented intermediate density values. Some minor variations in the radial distribution of the trunk in the base region of the trees, as occurred in the exotic species in this study, are suggested to be linked to the fact that some species respond more homogeneously when compared to others due to the species itself; that is, the genetic factor [31].

The behavior of the basic density of the species *A. mangium*, for example, differed from the results found by Gonçalves and Lelis [32] and Vale et al. [33] since in the work of these authors the species followed a trend of decreasing density up to half the height of the tree, followed by an increase up to the top. In this work, the decrease extended to the maximum height in both treatments. In the species *T. grandis*, there was an increase in basic density from a position close to 60%, practically half the height of the tree to the top in all regions of the trunk, and this may be related to greater resistance in this region caused by the insertions of branches [34].

It was possible to verify similarities between the species *A. indica*, *T. grandis*, and *S. foetida* when subjected to different irrigation regimes (12 and 36 months after planting), suggesting no variation in the basic density pattern of these woods when subjected to different conditions (Figure 8). The species *A. indica*, differed entirely from the other species under the different irrigation regimes (up to 12 and up to 36 months). Different behavior also occurred in the species *K. grandifoliola* and *A. mangium* when subjected to these two conditions, indicating the effect of irrigation on density. There were more pronounced similarities between the species *T. grandis* and *K. grandifoliola*, both under the influence of the irrigation system up to 36 months after planting, between the species *T. grandis* and *A. mangium* under the influence of the irrigation system up to 12 months after planting, and between the *S. foetida* group in the two irrigation regimes, and the *A. mangium* species irrigated for up to 36 months, all evidenced by the proximity between the species.

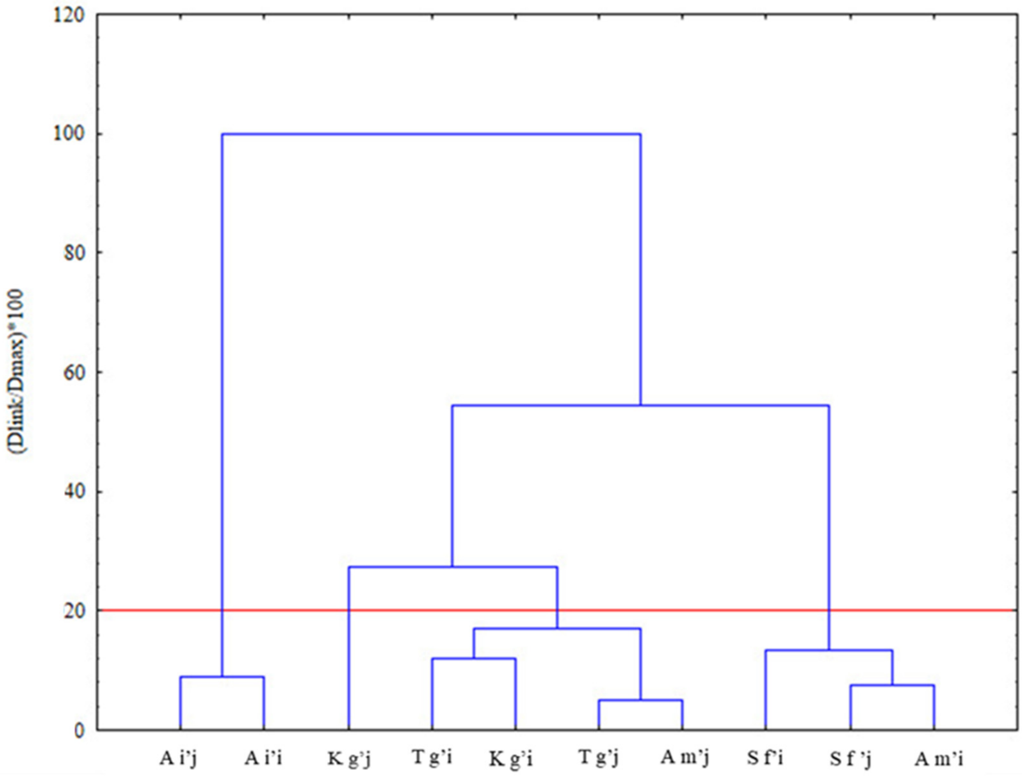


Figure 8. Dendrogram of the influence of irrigation management on the basic density of five exotic species, established in the region of Marco—CE. Identification of the analyzed species represented by the letters: A m—*A. mangium*; K g—*K. grandifoliola*; S f—*S. foetida*; T g—*T. Grandis*; A i—*A. indica*. The letters "i" and "j" represent irrigation time adopted for each area, with "i" equivalent to 36 months, and "j" equivalent to 12 months.

Factors that interfere with the variation in the basic density of wood are the soil and climactic conditions since, when associated with the genetic nature of the species, they can cause differentiation in the structural pattern of the different types of plant constituents: cells, fibers, vessels, rays, and the thickness of the cell walls, altering the anatomical characteristics of the individual, its development during planting, and the quality of the final product [35].

The average values of basic density of the four native species evaluated for the two different irrigation management conditions can be seen in Figure 9. In this group of species, according to Zaque et al. [20], only the species *A. indica* was classified with a moderately heavy basic density. All others were classified as light basic density woods. When evaluating the global average of native trees of each species, it was verified that the highest basic density was found in the species *A. indica* in both treatments, followed by the species *C. glandulosa* when subjected to irrigation conditions for less time (12 months after planting).

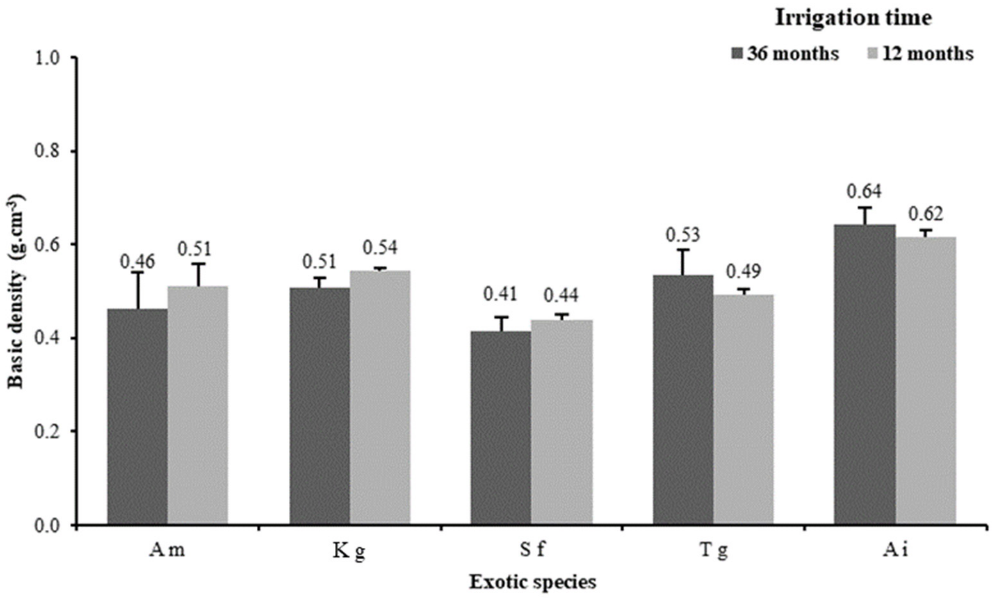


Figure 9. Basic density in five exotic species cultivated in two irrigation regimes, implemented in the region of Marco—CE. Identification of the analyzed species represented by the letters: Am—*A. mangium*; K g—*K. grandifoliola*; S f—*S. foetida*; T g—*T. Grandis*; A i—*A. indica*.

As for the global average of basic density, in a study with Nim (*A. indica*), Neves [36] found an average of 0.56 to 0.85 g·cm^{-3} of basic density, a value close to that found in this study (0.62 and 0.64 g·cm^{-3}, for irrigation of 12 and 26 months, respectively) classifying it as a moderately heavy wood. Carvalho [37], for *K. ivorensis*, observed a lower average basic density (0.47 g·cm^{-3}) than that found in this study and close to that found by Lima et al. [38], corresponding to 0.45 g·cm^{-3}.

3.3. Eucalyptus Clones

Figure 10 demonstrates a tendency for variation in the basic density of *Eucalyptus* clones implanted in the semiarid region, subjected to different irrigation conditions. Generally, a pattern of variation in the basic density of the species was observed in the radial and axial directions. In the radial region, there was a predominance of lower values in the pith region, increasing in the intermediate region constituted by the sapwood, with higher values in the bark region. In the axial direction, the wood presented high-density values in the base region up to 20% of the total height. Also noteworthy was the marked differentiation in the proportions representing the denser and less dense wood in the trees due to the irrigation system to which they were subjected as the height increased.

Concerning clone AEC1528 (*E. urophylla* × *E. grandis*), the most significant proportion of wood with high basic density occurred in the region closest to the bark, up to 50% of the total height of the stem in the irrigated system for up to 36 months. In contrast, a higher proportion occurred at the base up to DBH and between 20 and 70% of the total height in the irrigated system up to 12 months (Figure 10a). This phenomenon was also observed by analyzing the radial variation in the density of the wood from *E. saligna*, presenting a higher average density at the height of the DBH in the bark region [22], from *Pinus taeda* L. with different ages and higher average density in the outermost region [39], of Tauari (*Couratari oblongifolia* Ducke & R. Knuth.) with higher average density in the area between the pith and the bark and the bark [5], the same for the wood from Eucalyptus grandis and Eucalyptus saligna [40], and from *E. pellita* and *E. acmenioides* with an increase of 50% towards the bark [41].

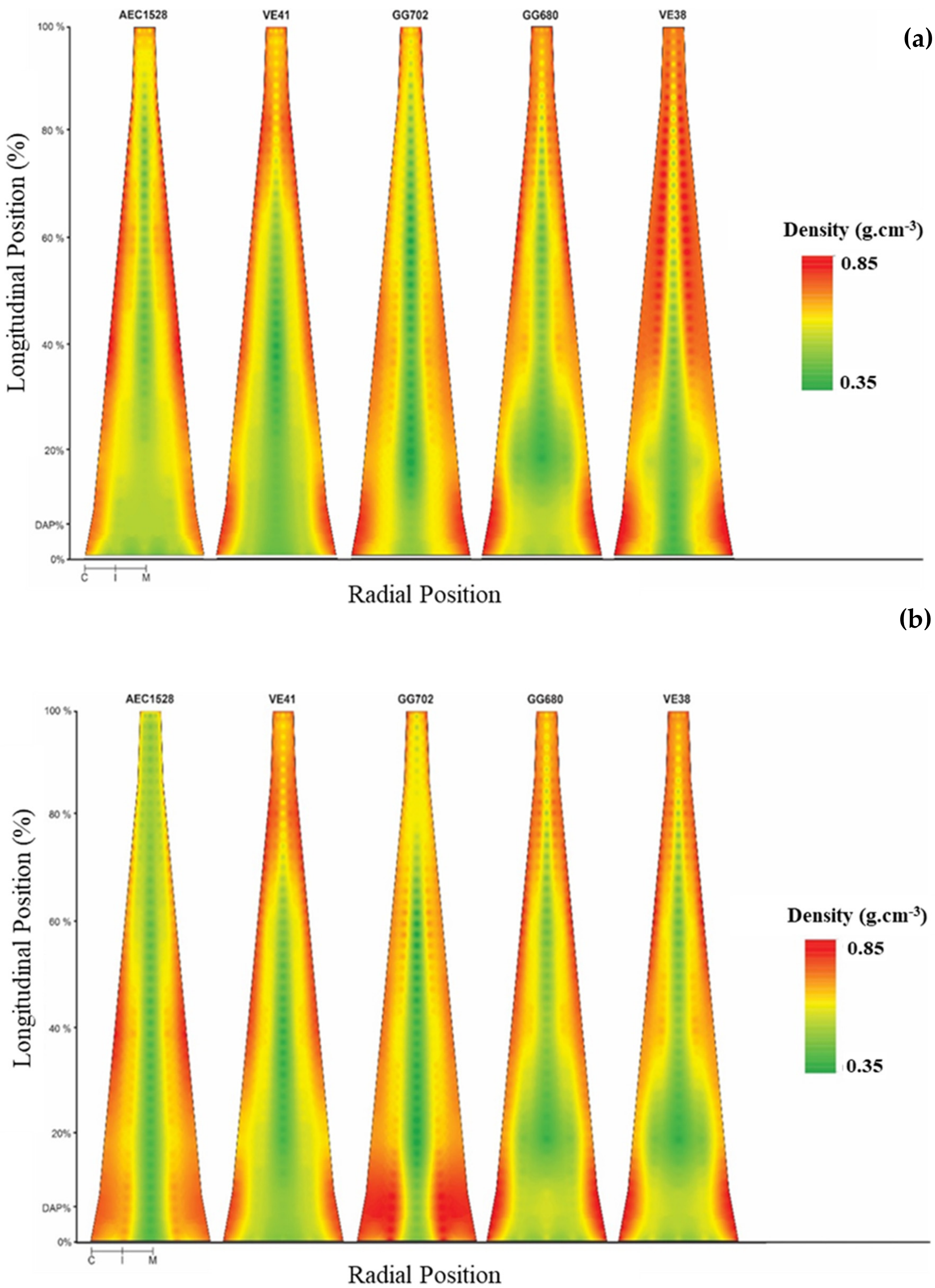


Figure 10. Variation in the basic density of wood from five Eucalyptus clones in the region of Marco—CE, under irrigation regimes of up to 12 months (**a**) and 36 months (**b**) after planting. C—bark; I—intermediate position; M—pith. Identification of analyzed clones represented by letters and numbers: AEC1528—*E. urophylla* × *E. grandis*; VE41—*E. urophylla* × *E. grandis*; GG702—*E. urophylla*; GG680—*E. urophylla* × *E. grandis*; VE38—*E. urophylla* × *E. camaldulensis*.

In trees with irrigation for up to 12 months, it was noted that the base area up to 20% of the height comprises the most significant proportion of less dense material, which denotes the difference in the clone's behavior under different irrigation conditions. Clone VE41 (*E. urophylla* × *E. grandis*) showed similar behavior in both irrigation systems. The highest density values occurred in the peripheral region of the base, up to approximately 35% of the height. In clone VE41 (*E. urophylla* × *E. grandis*), based on the values observed, some authors suggest that this pattern of distribution of higher densities in the base-to-top direction in both regimes occurs because this region is the most suitable for insertion of lateral branches where recurrent changes in the anatomical structure occur [10].

Regarding the density pattern of clone GG702, the highest densities occurred at a position close to 20% of the height, presenting wood with a density of 0.67 g·cm^{-3} in the bark and intermediate regions in the irrigated system up to 36 months. In clone GG680 (*E. urophylla* × *E. grandis*), the variation in basic density behaved similarly when subjected to both irrigation systems. A higher proportion of woody material was found between the base positions up to 20% of the height in the bark and intermediate section of the stem, with a maximum density of 0.65 g·cm^{-3} in this region. The highest proportion of less dense wood occurred from the base to 40% of the height. After this point, the presence of denser wood was again observed in the peripheral region of the trunk, and an increase in the proportion of wood with greater density up to the maximum height of the clones.

The highest density values were obtained in the area corresponding to the base, DBH, and close to the height of 20% of the trees, with a recurrent increase or stabilization of these values when reaching percentages from 35% height to the total height. Evaluating a clonal hybrid of *E. urophylla* × *E. grandis*, Gonçalves et al. [42] found an increasing trend in the basic density of wood depending on the height of the base and crown, similar to what was significantly found in clone VE38 (*E. urophylla* × *E. camaldulensis*) when cultivated with irrigation for up to 12 months. Evaluating adult trees of *E. globulus*, Gominho et al. [43] found that the external heartwood had a higher basic density, especially in the lower part of the stem, corroborating the results found in all clones studied in this work in the two irrigation regimes after planting.

For clone VE38 (*E. urophylla* × *E. camaldulensis*) subjected to irrigation for up to 36 months (Figure 10b), the highest density values were found in an extreme portion of the bark, from the base of the trunk to close to the 20% position reaching maximum values of 0.70 g·cm^{-3}. The clones subjected to irrigation for up to 12 months (Figure 10a) demonstrated greater densities from the base to close to 20% of the height in the external region of the stem. It also presented a significant proportion of high densities from a position close to 40% of the height to the total height, with maximum density values seen especially in the intermediate region of the trunk. In this irrigation regime, the differentiation of density behavior in the radial position of the stem is evident, especially at the base.

The different models of axial variation in wood density presented are like those already shown in studies with species of the genus *Eucalyptus*. In this species, there may be a uniform decrease in height, stabilization of the base up to the 20% position, followed by an increase of up to 75%, and a decrease and stabilization at the top, not following a uniform pattern of variation [44].

From the dendrogram of Eucalyptus clones (Figure 11), it was found that only clone VE41 (*E. urophylla* × *E. grandis*) showed similar behavior when subjected to different irrigation systems (12 and 36 months after planting), demonstrating the non-significant effects of irrigation on the basic density of this progeny. In addition, there was similarity in a group formed by clones VE38 (*E. urophylla* × *E. camaldulensis*) (irrigated for 12 months after planting) and GG702 (*E. urophylla*) (irrigated for 36 months after planting) and in another composed of clones GG608 (irrigated for 12 months) and GG702 (*E. urophylla*) (irrigated for 12 months). Dissimilarity was observed for the other clones evaluated, pointing to the effect of irrigation on basic density, especially between clone VE41 (*E. urophylla* × *E. grandis*) and clone AEC1528 (*E. urophylla* × *E. grandis*) in the two irrigation systems. The distance between clones indicates more significant differentiation in the behavior of basic density when comparing them.

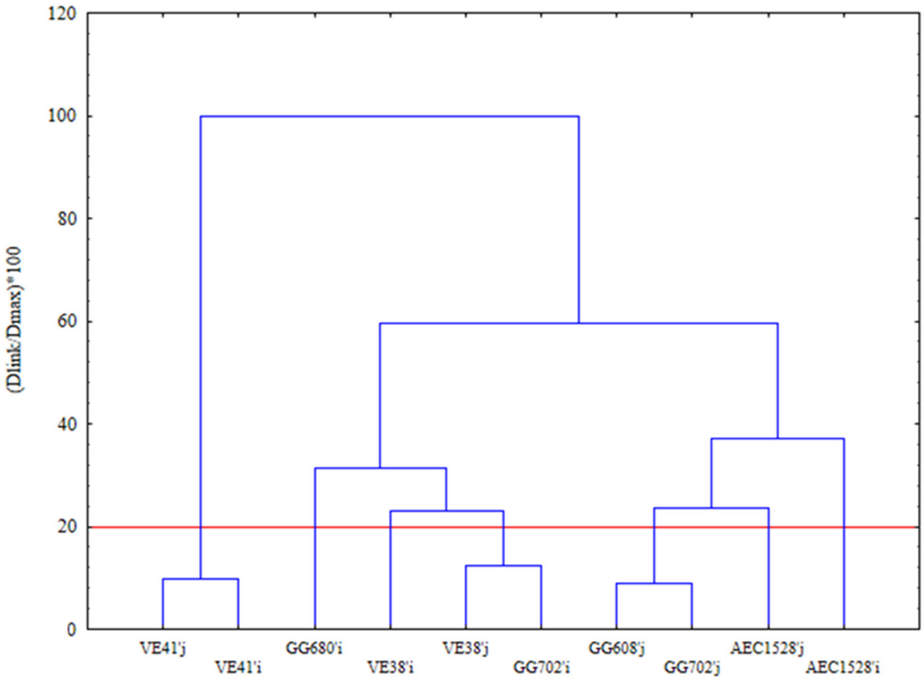


Figure 11. Dendrogram of the influence of irrigation management on the basic density of five Eucalyptus clones, implemented in the region of Marco—CE. Identification of analyzed clones represented by letters and numbers: AEC1528—*E. urophylla* × *E. grandis*; VE41—*E. urophylla* × *E. grandis*; GG702—*E. urophylla*; GG680—*E. urophylla* × *E. grandis*; VE38—*E. urophylla* × *E. camaldulensis*. The letters "i" and "j" represent the irrigation time adopted for each area, with "i" equivalent to 36 months, and "j" equivalent to 12 months.

Drew et al. [45], when testing *E. globulus* in two irrigation conditions, observed that the basic density of the wood of the individuals increased in response to the reduction in water availability, as occurred with clones VE41 (*E. urophylla* × *E. grandis*) and GG680 in this study. This same author suggests that trees employ different physiological processes and morphological strategies under different irrigation regimes to deal with environmental conditions, such as the increased quantity of fibers with smaller radial diameters in non-irrigated crops. The increase in density under conditions of high temperatures, characteristic of the semi-arid climate, is a trend considered by other authors for species of this genus and is related to the reduction in the lumens of the xylem vessels and an increase in the thickness of the cell wall [46].

Rocha et al. [11], evaluating the effect of irrigation on four *Eucalyptus* hybrids in locations with different climate patterns, found that in drier locations, the trees had higher basic density, demonstrating differentiation in different water availability conditions. A similar result was found by Moulin et al. [47] evaluating two one-year-old clones of the *E. grandis* × *E. urophylla* hybrid and a seven-year-old clone of *E. grandis* × *E. camaldulensis* in systems with and without irrigation.

The average values of basic wood density of the clones evaluated under the two different irrigation management conditions (12 and 36 months after planting) can be seen in Figure 12. According to Zaque et al. [20] the clones GG680 and VE41 (*E. urophylla* × *E. grandis*) were classified with light basic density wood, whereas clones AEC1528 (*E. urophylla* × *E. grandis*), GG702 (*E. urophylla*) and VE38 (*E. urophylla* × *E. camaldulensis*) with moderately heavy basic density woods. Clone VE38 (*E. urophylla* × *E. camaldulensis*) presented a higher average density compared to the others, followed by AEC1528 (*E. urophylla* × *E. grandis*) and GG702 (*E. urophylla*).

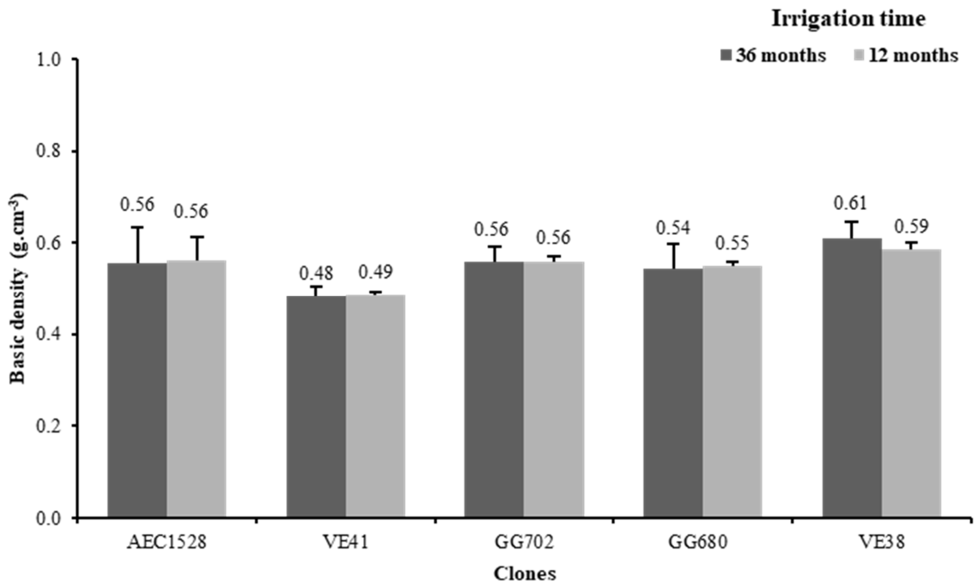


Figure 12. Basic density (g·cm^{-3}) in five Eucalyptus clones cultivated in two irrigation regimes, implemented in the region of Marco—CE. Identification of analyzed clones represented by letters and numbers: AEC1528—*E. urophylla* × *E. grandis*; VE41—*E. urophylla* × *E. grandis*; GG702—*E. urophylla*; GG680—*E. urophylla* × *E. grandis*; VE38—*E. urophylla* × *E. camaldulensis*.

In the case of the evaluated clones, it was found that although there was a change in the basic density distribution pattern along the stem due to irrigation conditions, there was a positive adaptation to the environmental conditions under which the forest provenances were tested, maintaining wood densities typical of the usual forest formations. Emphasizing that species of the *Eucalyptus* genus in question, can vary between 0.40 and 1.20 g·cm^{-3} in density [48].

The basic density values obtained in this study corroborate the use of wood from the species produced in the semiarid region since the plant species maintained the expected results. It also directly contributes to mitigating the effects of deforestation of natural vegetation and reduces logistics costs by expanding planting areas [49].

4. Conclusions

In this work, the influence of two irrigation regimes on the wood density of native and exotic species and *Eucalyptus* clones, all cultivated in the Brazilian semiarid region, was evaluated. There was a difference in the behavior of basic density between the species studied and the *Eucalyptus* hybrids. The density distribution in the trees in the radial and axial directions varied, mainly about the proportion of woody material presented in each region of the trunk. In the radial direction, the trend towards increasing density predominated in the pith-bark direction, and in the axial direction, the highest density values were located in the region from the base to the DAP.

The influence of irrigation management was observed with greater intensity in the exotic species *K. grandifoliola* and *A. mangium*, and among the Eucalyptus clones VE41 *(E. urophylla* × *E. grandis*) and AEC1528 (*E. urophylla* × *E. grandis*). *H. courbaril* and *C. glandulosa*, when subjected to different irrigation systems (12 and 36 months after planting), showed divergent behaviors, indicating the influence of irrigation on the basic density of the wood of these species. The groups with the greatest proximity and a high similarity percentage for the evaluated variable were found in native species, especially for *H. impetiginosus* and *A. colubrina* in both treatments.

The species studied were well adapted to the planting area. The wood evaluated presented basic densities within limits pre-established in other studies, categorized as wood with light or moderately heavy density, and can be recommended for different uses, from charcoal production to simple civil construction and furniture making.

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Data Availability Statement: Raw data were generated at the Brazilian Agricultural Research Corporation—Embrapa and at the UFERSA (Brazilian Universities). Derived data supporting the findings of this study are available from the corresponding author upon request.

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