Journal of Tropical Forest Science 34(1): 11–23 (2022)
https://doi.org/10.26525/jtfs2022.34.1.11

EFFECTS OF TREE SPACING AND FORKING ON THE MODIFICATION OF WOOD DENSITY IN A TRIAL PLANTATION OF *TACHIGALI VULGARIS* FOR ENERGY IN AMAZONIA

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Submitted May 2020; accepted February 2021

The study investigated the intra-stem and inter-stem variations of wood basic density in *Tachigali vulgaris*, influenced by different planting spacing and the occurrence of forking in a trial carried out in Pará State, Brazil. The experiment was performed in a randomised block design, arranged in a split-plot scheme, where plot effect was constituted by planting spacing (4.5, 6.0, 7.5, 9.0, 10.5 and 12.0 m^2) and forking, as the effect of subplot (forked or not forked). The wood basic density increased from narrower to wider planting spacings. The wood basic densities in planting spacings of 9 m (0.517 g cm^{-3}) and 12 m (0.529 g cm^{-3}) were 16.9 and 19.4% higher compared to the lowest planting spacing of 4.5 m^2 (< 0.500 g cm^{-3}). Forking reduced wood density by almost 7% and promoted a wider variation within the stem. Forked stems decreased basic density towards the base-top direction. The findings suggested that, 87-months-old wood of *T. vulgaris* is suitable for energy purposes, and recommended for the establishment of homogeneous plantations in Brazilian Amazonia.

Keywords: Energy forest, biomass, tree vital area, Amazonia tree charcoal, stem characteristics

INTRODUCTION

Brazil is a leader in wood productivity and is one of the most important countries in the global forestry sector (Bonassa et al. 2018). Its planted forests increased significantly in the past years, and currently cover 9 million hectares of which 6.97 million are of *Eucalyptus* (77%), 1.64 million of *Pinus* (18%) and 0.39 million of other species, such as rubber, acacia, teak and parica (IBÁ 2020). The same report points out that 14% of the total volume of *Eucalyptus* wood planted in Brazil is destined for charcoal production. On the other hand, energy forests with *Eucalyptus* species in northern Brazil are incipient, and studies with native Amazonian species are necessary to establish plantations to match the local energy demand (Farias et al. 2016).

In this context, *Tachigali vulgaris*, a leguminous tree species, native and endemic to Brazil, seems to be a useful option to compose energy forests. It exhibits a high growth rate, symbiotic association with *Rhizobium* bacteria and high biomass production (Costa et al. 2015, Silva et al. 2021). The wood properties of this species are similar or even superior to those of consolidated commercial species in the energy and steel sector, such as *Eucalyptus* species. Literature reports that the basic density of *T. vulgaris* wood ranges from medium to high (0.496 g cm^{-3} to 0.716 g cm^{-3}). Besides, it has a higher heating value suitable for energy purposes varying from 19.16 MJ kg^{-1} to 20.14 MJ kg^{-1} (Oliveira et al. 2008, Orellana et al. 2018).

Initial planting spacing is among the silvicultural practices that most affect the establishment of forest stands. The number of trees planted per hectare has direct and indirect implications on interspecific competition, diameter growth, canopy and branch formation and development, biomass production, wood quality, management and harvesting costs, and consequently, on final product quantity and quality (Rocha et al. 2015, Ribeiro et al. 2017, Eufrade-Junior et al. 2018). The planting spacing also influences the basic density of wood (Erasmus et al. 2018). Forking is a biomechanical process in which the secondary stems originate from a primary (parental) stem and typically forms two or more stems with similar diameters (Slater & Ennos 2015). There is not enough research available to prove the causes of forking in the main trunk of forest species. However, some authors suggest that this process is associated with genetic and environmental factors (pest attack and disease), or interaction between these factors (Resende & Fantini-Júnior 2001, Ennos & Van Casteren 2010). Forking is believed to be a limiting factor that compromises the application of wood for some purposes because it changes the shape of trees, promotes variability in the technological properties of wood, and increases reaction wood production (Mattheck & Vorberg 1991, Özden et al. 2017).

It is believed that, if forking negatively influences wood density, the productive and energy losses are substantial, since it implies less wood mass and energy stored per unit of volume (Özden et al. 2017, Silva et al. 2021). Low-density woods will also cause high transport and storage costs (Amirta et al. 2016). Other consequences are related to the derived charcoal properties, particularly lower bulk density and reduced mechanical strength (Loureiro et al. 2019). Thus, there is a need to study the effects of forking on wood basic density, especially for energy purposes.

Therefore, the objectives of this study are: (i) to investigate and find the optimal planting spacing that provides denser wood (ii) to investigate the effects of forking on wood basic density (iii) to investigate the trend of within-stem variation pattern of *T. vulgaris* wood basic density and (iv) to investigate the forking effect on the variation pattern of basic density. Thus, the study raises four hypotheses: (i) the wood basic density of *T. vulgaris* increases in wider spacings, (ii) the forked stems produce lower density wood, (iii) the variation pattern of the wood basic density in the stem of *T. vulgaris* tends to decrease towards the base-top direction and (iv) the decrease in basic density in the longitudinal direction of the stem is also predicted in forked trees.

MATERIALS AND METHODS

Study site

The study was carried out in a 5.6 hectares 87-months-old trial plantation of *T. vulgaris*. The study was conducted by the research teams of Brazilian Agricultural Research Corporation (Embrapa), Federal Rural University of Amazonia (UFRA) and other partners. The experimental planted forests are located in the production area of Jari Celulose SA company, district of Monte Dourado, Almeirim town, mesoregion of the lower Amazon, State of Pará, Brazil (Figure 1).

According to Köppen's classification, the region's climate is Am-type, with intermediate characteristics between Af and Aw, whose rainfall regime defines a short dry season between August and December and a rainy season between January and July (Figure 2). The mean annual rainfall recorded is 2.300 mm, and the mean annual temperature is 26.8 °C. The soil of the area is classified as Alic Yellow Latosol type, with medium sandy texture (Castro et al. 2018).

Experimental design

The experimental design was randomised blocks, composed of 3 blocks, each divided into 6 plots, with dimensions of 60 × 51 m (3,060 m^2 $plot^{-1}$). The experiment was arranged in a split-plot scheme, in which the plots consisted of six inter-tree spacing (4.5, 6.0, 7.5, 9.0, 10.5 and 12.0 m^2), randomly distributed in each block and subplots of the two forking levels (forked or not forked). The values of useful area per plant and tree density per hectare are shown in Table 1.

Data collection

Each plot (3,060 m^2 $plot^{-1}$) presents a permanent plot with 49 trees measured annually to monitor growth (regardless of spacing, 49 trees were measured). In this study, the dendrometric data were not used. The useful area of these permanent plots was: 220.5 m^2 (spacing 4.5 m^2), 294.0 m^2 (spacing 6.0 m^2), 367.5 m^2 (spacing 7.5 m^2), 441.0 m^2 (spacing 9.0 m^2), 514.5 m^2 (spacing 10.5 m^2) and 588.0 m^2 (spacing 12.0 m^2).

Figure 1 Location and characteristics (stand, canopy, stem and disk) of *Tachigali vulgaris* 87-months old trial stand in Monte Dourado district, Almeirim town, Pará, Brazil

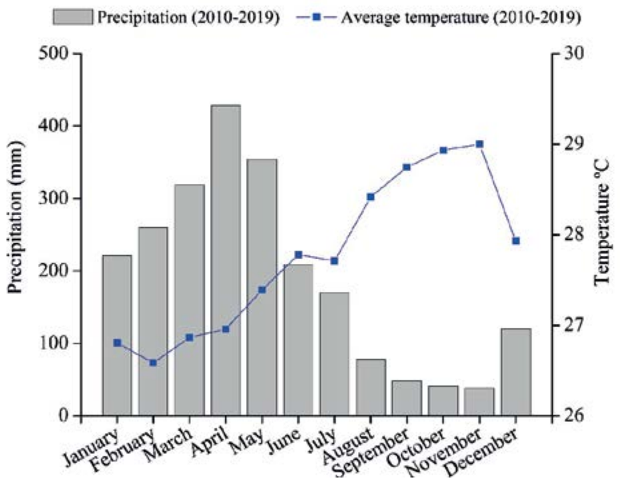

Figure 2 Climogram of the Almeirim town, Pará, Brazil

Table 1 Useful area per plant and tree density per hectare of *Tachigali vulgaris* 87-months-old trial stand in Monte Dourado district, Almeirim town, Pará, Brazil

Treatment	Initial planting spacing (m)	Useful area (m^2 $tree^{-1}$)	Initial density (tree ha^{-1})
1	3.0 × 1.5	4.5	2222
2	3.0 × 2.0	6.0	1666
3	3.0 × 2.5	7.5	1333
4	3.0 × 3.0	9.0	1111
5	3.0 × 3.5	10.5	952
6	3.0 × 4.0	12.0	833

Forking was typical in the studied area and appeared in all planting spacings. Aiming at a more precise representation of the types of stems that occured naturally in the trial plantation, forked trees were sampled in all planting spacing. The sampled trees were felled outside the permanent plots, avoiding the border of the plantations. The trees, free from diseases or pest attacks and visually representative of the plantation, were selected. For data collection, 3 trees were felled per treatment and per block, totaling 54 randomly sampled trees, 23 with non-forked stems, and 31 with forked stems.

In the field, the commercial height (h) of the felled trees was measured from the base up to a diameter of 5.0 cm with bark. A 5 cm-thick cross-section samples (disks) were obtained in the longitudinal position, 0%, and diameter at breast height (DBH) of 25, 50, 75 and 100%, based on the commercial height of non-forked and forked stems (Figures 3 and 4). Subsequently, all disks were sectioned into 4 wedges, and two of the opposite wedges were used to determine the wood basic density.

Measurement of the wood basic density

The wood basic density was determined according to NBR 11941-02 that describes volume determination by water immersion method (ABNT 2003). Two opposite wedges were used from the disks of each within-stem sampling position. The mean wood basic density was calculated from the arithmetic mean of the opposite wedge. Then, the woods were classified as low (< 0.5 g cm^{-3}) or medium (> 0.5 g cm^{-3}), according to Csanády et al. (2015).

Statistical analysis

The basic wood density data were tested for the assumptions of independence by Durbin-Watson test, homogeneity of variance by Bartlett test, and normality of residuals by Shapiro-Wilk test, considering 5% level of significance. Univariate variance analysis was performed using a randomised block design in a split-plot scheme (Equation 1). The analysis of variance (ANOVA) and the F-test (at the level of 10% significance) revealed the statistical effect of planting spacing and forking on basic density of the wood. When there was a significant statistical effect of the planting spacing factor by F-test, simple linear regression models were fitted.

$$Y_{ikj} = \mu + S_i + \beta_j + \varepsilon_{ij} + ST_k + (S \times ST)_{ik} + \varepsilon_{ikj} \quad (1)$$

where Y_{ikj} is the basic density of the i-th level of spacing factor, in the k-th level of the factor stem type, in the j-th block; μ is a general constant of the model; S_i is the effect of the

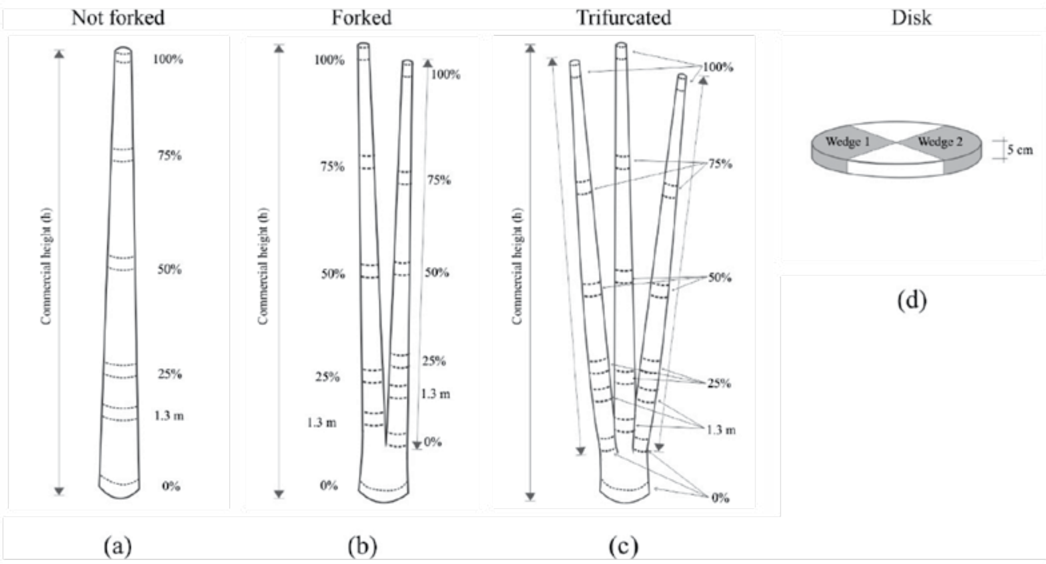

Figure 3 Sampling scheme of not-forked (a), forked (b) and trifurcated (c) stems along the height, and wedged disks sectioning (d)

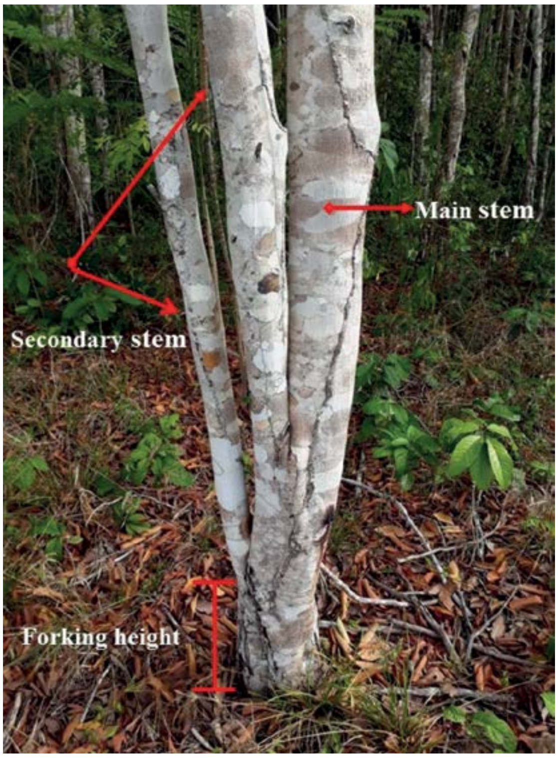

Figure 4 Illustration of main and secondary stems and forking height of *T. vulgaris* 87-months-old trial stand

i-th level of spacing factor, fixed effect; β_j is the effect of the j-th block, fixed effect; ε_{ij} is the experimental error between the i-th level of spacing factor and the j-th block (error a); ST_k is the effect of k-th level of stem type factor, fixed effect; $(S \times ST)_{ik}$ is the effect of the interaction of the i-th level of the spacing factor with the k-th level of stem type, fixed effect; ε_{ikj} is the experimental error between i-th level of spacing factor and the j-th block and k-th level of stem type factor (error b), assumed to be normally and independently distributed with average 0 and variance σ^2.

The basic density variation along the stem longitudinal direction was initially analysed using descriptive statistics (average and standard deviation) and later, through polynomial regression models. All statistical analyses were performed in R Language version 3.4.3. A statistical package was used for the Shapiro-Wilk and Bartlett tests, lmtest for the Durbin-Watson test, and ExpDes for ANOVA (Zeileis & Hothorn 2002, Ferreira et al. 2012, R Core Team 2017).

RESULTS

Wood basic density under different planting spacings

Wood basic density data of *T. vulgaris* met ANOVA's basic assumption of independence (p-value = 0.276900), homogeneity of variance (p-value = 0.726200), and normality of residuals (p-value = 0.218500) of the statistical model. The F-test revealed significant effect of planting spacing (p-value = 0.056626) and forking (p-value = 0.001755) on basic density, at 10%

Table 2 Variance analysis summary for *Tachigali vulgaris* wood basic density from 87 months old trial stand in Monte Dourado district, Almeirim town, Pará, Brazil

Variation source	FD	Basic density (g cm^{-3})		
		MS	Fc	Pr (> Fc)
Planting spacing	5	0.005319	3.1742*	0.056626
Block	2	0.000472	0.2819	0.760158
Error a	10	0.001676		
Forking	1	0.012063	16.0169*	0.001755
Planting spacing*Forking	5	0.001352	1.7954^{ns}	0.188295
Error b	12	0.000753		
Total	35			
CVe^1			8.24	
CVe^2			5.52	

FD: freedom degree, MS: mean square, Fc: F calculated value (the value obtained from the ratio of the square mean of each factor, by the square mean of the residuals), CVe^1: experimental coefficient of variation for split (%), CVe^2: experimental coefficient of variation for sub-split (%), *: significant at 10% of probability, ^{ns}: non-significant at 10% of probability

probability level. Variance analysis revealed that factors were independent, with no interaction effect, as well as no block effect (Table 2).

Regarding the planting spacing factor, there was a positive effect on wood basic density, with an increasing trend in the wider planting spacing, except for 10.5 m^2 spacing, as verified by the linear model equation fitted to estimate density as a function of spacing ($R^2 = 0.74$, Fc =11.71, p-value = 0.0065) (Figures 5 and 7). Wood basic densities ranged from 0.443 g cm^{-3} to 0.529 g cm^{-3}, with the lowest value in 4.5 m^2 spacing (0.443 g cm^{-3}) and the highest values in 9.0 m^2 and 12.0 m^2 spacings (0.517 g cm^{-3} and 0.529 g cm^{-3}, respectively). Increases of 16.9 and 19.4%, respectively, were observed for wider planting spacings, 9.0 m^2 and 12.0 m^2, compared to the 4.5 m^2 spacing (Figures 5 and 7).

Effect of forking on basic density

There was no significant effect on the interaction between planting spacing and forking, meaning all spacings showed similar stem type effect. Forked stems showed the

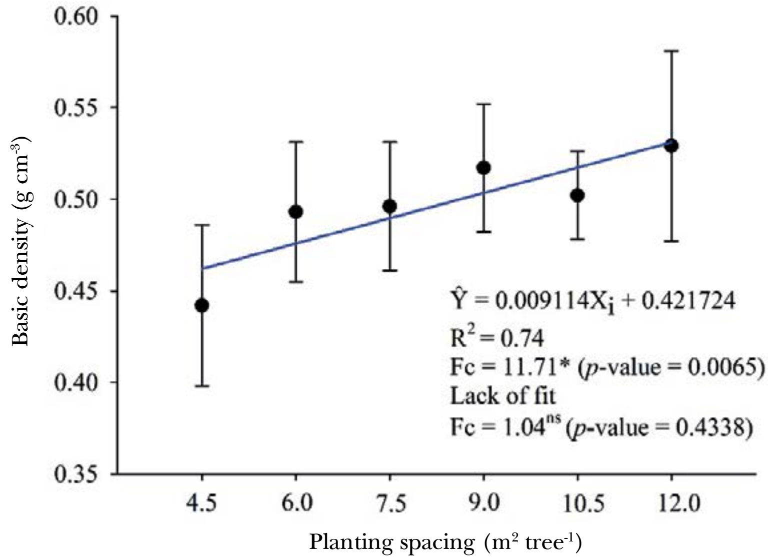

Figure 5 Increasing of wood basic density in function of planting spacing of *Tachigali vulgaris* 87-months-old trial stand

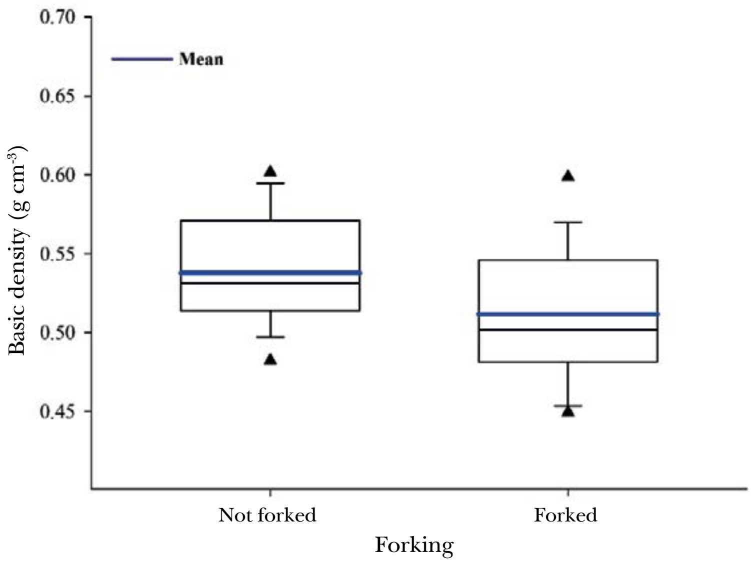

Figure 6 Data distribution of wood basic density in not forked and forked stems of *Tachigali vulgaris* 87-months-old trial stand

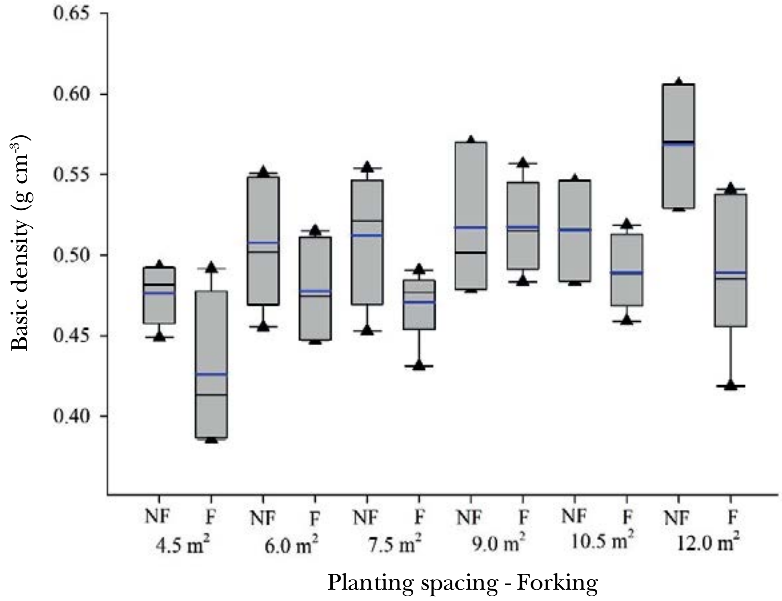

Figure 7 Data distribution of wood basic density per planting spacing and forking of *Tachigali vulgaris* 87-months-old trial stand

lowest mean wood basic densities in all planting spacings (Figures 6 and 7). The mean basic density in the forked stems (0.478 g cm^{-3}) was 7.18% lower than that of non-forked stems (0.515 g cm^{-3}).

Stem longitudinal variation of basic density

The adjusted polynomial model demonstrated that wood basic density reduced from the base to the top of the stem (Figure 8), resulting in within-stem variation patterns. It decreased to 0.204 g cm^{-3} (up to 4 m height) for the 4.5 m spacing, 0.208 g cm^{-3} (up to 8 m height) for the 6.0 m^2 spacing, and 0.188 g cm^{-3} (up to 8 m height) for 7.5 m^2 spacing (Figure 9). In the spacings of 9.0 m^2 and 12 m , decreases were 0.155 g cm^{-3} and 0.137 g cm^{-3}, both up to 8 m height.

Considering the six planting spacings, wood basic density values of stem base ranged from 0.580 to 0.650 g cm^{-3}. The highest decrease in wood basic density was observed up to 8 m height, both for the broadest and narrowest planting spacings, with treatment 2 (6.0 m^2)

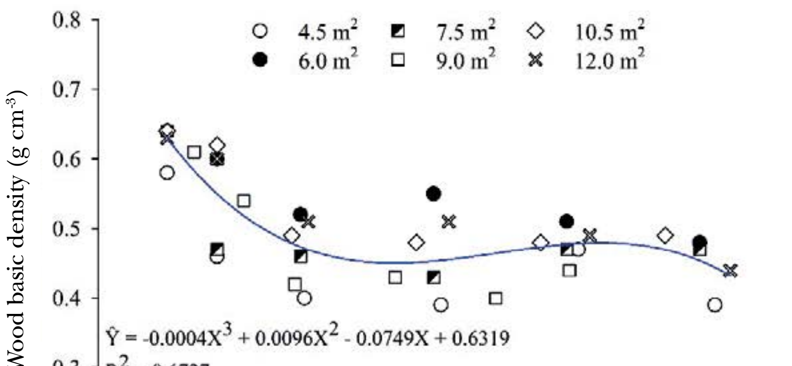

Figure 8 Longitudinal variation of the wood basic density of *Tachigali vulgaris* 87-months-old in six planting spacings

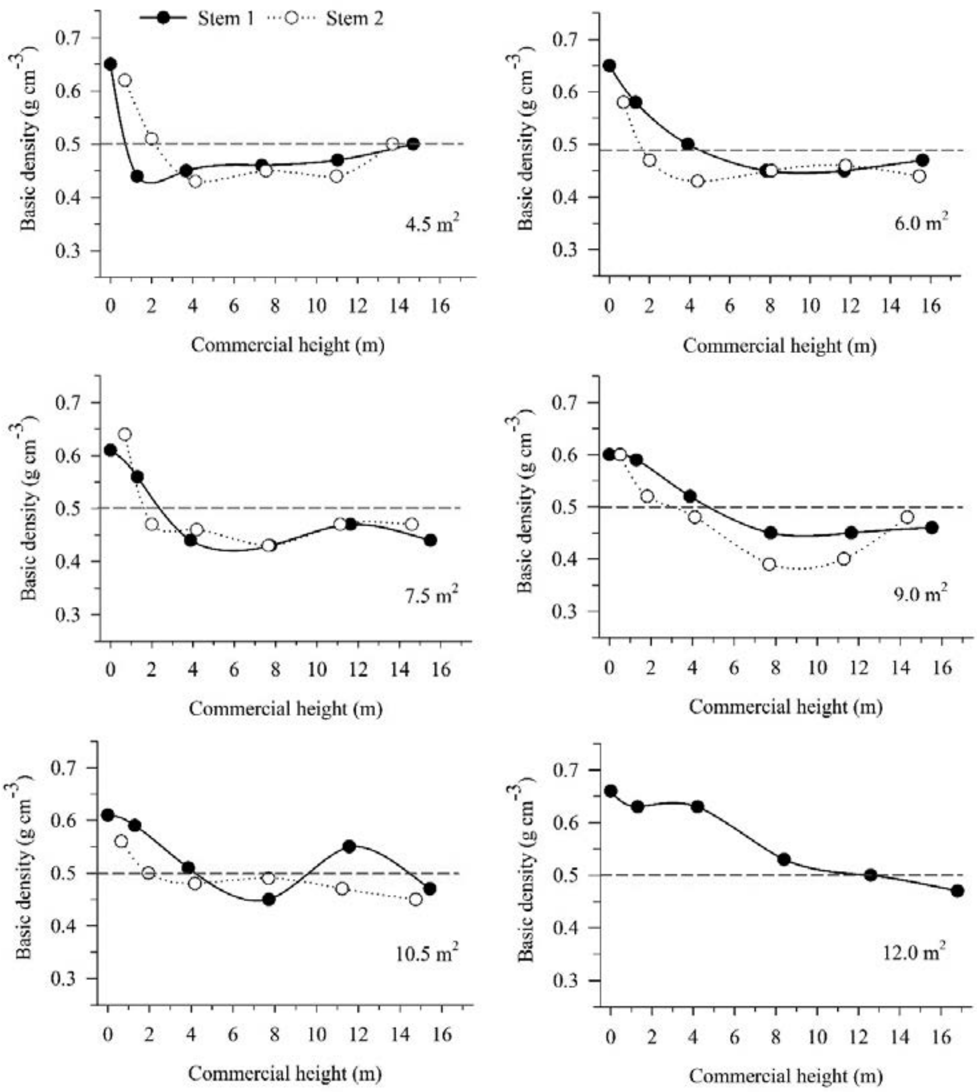

Figure 9 Longitudinal variation of the basic density of *Tachigali vulgaris* wood in the six analysed planting spacing

presenting the lowest basic density value (0.490 g cm^{-3}) at this height. Between 14 and 16 m heights, 4.5, 6.0, 9.0, 10.5 and 12.0 m^2 planting spacings presented wood basic density ranging from 0.450 to 0.490 g cm^{-3} (Figure 9). The 7.5 m planting spacing was the only one with wood basic density above 0.500 g cm^{-3} (0.570 g cm^{-3}) at stem top.

The exploratory analysis of the data through descriptive techniques showed that the secondary stems exhibited a variation of the wood basic density pattern, similar to that of the main stems. In the first planting spacing (Figure 9), a sharper decrease in wood basic density appeared in the first 8 m height. On the broader planting spacings (9.0, 10.5 and 12 m^2), there was a smoother decreasing trend in wood basic density from the base to the top, especially in the 10.5 m one (± 0.024 g cm^{-3}) (Figure 9).

Wood basic density classification

The narrowest planting spacings, except 6.0 m , presented more low-density trees. The 4.5 m planting spacing stood out with 100% low-density trees, while the three widest planting spacings presented 56% of mean-wood-density trees and 44% of low-wood-density trees (Figure 10). Regarding forking, the classification revealed that 68% of forked stems were of low-wood-density and 32% were of mean-wood-density, while the trees with non-forked stems had 41% low-wood-density and 59% mean-wood-density (Figure 10).

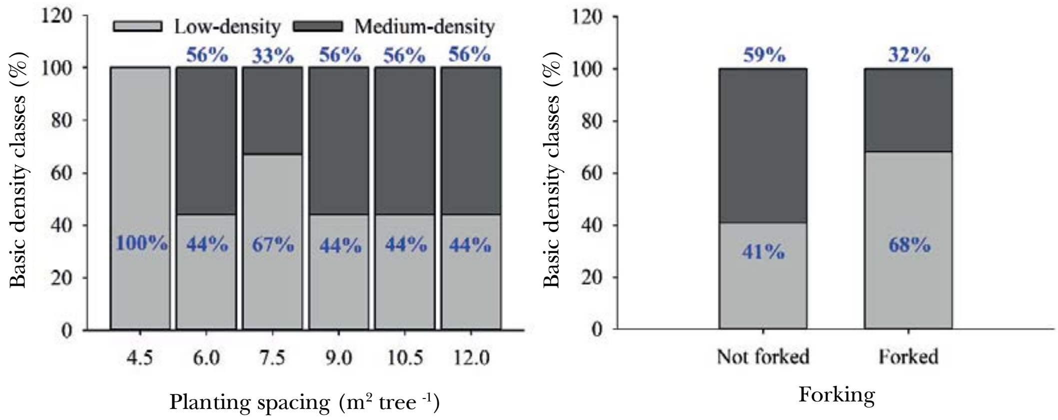

Figure 10 Proportions of trees by each basic density classification per planting spacing (A) and stem type (B) of *Tachigali vulgaris* 87-months-old trial stand

DISCUSSION

Wider planting spacings produced denser wood confirming the first hypothesis, the wood basic density of *T. vulgaris* was higher in wider planting spacings. Previous studies corroborate this finding (Rocha et al. 2016, Moulin et al. 2017). This behavior possibly relates to the lowest interspecific competition in wider spacings leading to the early formation of mature wood, increasing the mature to juvenile wood proportion and consequently the wood basic density, compared to narrower spacings (Oliveira et al. 2017). In wider spacings, the lowest interspecific competition for sunlight improves interception, distribution and light capture in response to increases in leaf area, foliar angle and orientation, caused by the largest vital area available for tree canopy development (Liu et al. 2016). Consequently, photosynthetic efficiency is boosted by increasing photoassimilate substance fixation, as well as water and nutrient absorption and utilisation (Ren et al. 2017). During wood anatomical elements formation and development, the plant requires a vast amount of photoassimilate substances, such as polysaccharides (cellulose, hemicelluloses and pectin) and monosaccharides (glucose, galactose, mannose and xylose), to create and expand cell wall, the primary regulator of wood basic density (Yamamoto et al. 2012). Thus, higher resource availability to wood increases cell wall width, and consequently, wood basic density.

The *T. vulgaris* is a highly efficient species in the use of photosynthetic, photochemical and nutrient resources, and consequently, in height and diameter growth (Guimarães et al. 2018). Although correlation tests were not performed, wood and growth attributes are likely positively related, considering the outstanding photosynthetic performance of the species.

The wood basic density behavior under different planting densities is affected by several factors, including tree age, which directly interferes with cambial activity, environmental conditions of the stand sites (soil and climate), silvicultural practices, genetic characteristics of each species, and juvenile to mature wood proportions (Zobel & Sprague 1998, Carson et al. 2014).

The spacing of 12.0 m^2 stood out for producing denser wood and required fewer planted trees (0.529 g cm^{-3} and 833 trees ha^{-1}, respectively) compared to 9.0 m planting spacing (0.517 g cm^{-3} and 1111 trees ha^{-1}, respectively). The 9.0 m^2 spacing was reported as the most suitable by Tonini et al. (2018), who evaluated the influence of spacing on biomass production in a 70-months-old *T. vulgaris* plantation. The authors recommended 9.0 m spacing for commercial plantations of *T. vulgaris* for energy purposes because it provided higher biomass allocation per trunk, desirable wood features and fewer planted trees, which reduces implantation costs.

Forking has negative interference on wood basic density

The forked stems showed lower density wood than non-forked stems, confirming the harmful effect of forking in the second hypothesis. The result possibly relates to the lower investment in the production of photoassimilates to create and expand cell walls, culminating in lower density wood formation (Figures 6, 7 and 11). Forked trees are more susceptible to external environmental agents, such as strong winds. Therefore, the wood invests more photoassimilates resources in developing the main stem rather than the secondary stem as a possible mechanical support strategy of the tree (Slater & Ennos 2013). Overall, *T. vulgaris* trees get forked between 0.5 and 0.7 m height (Figure 4), very near to tree base, where wood basic density values are higher, a possible biomechanical strategy taken by *T. vulgaris* trees from the stem base.

Secondary stems present an adaptive strategy that allows the formation of a secondary layer of tissue in the junction region between the main stem and secondary stem, ensuring improved mechanical support to the main stem and consequently reducing the risks of tree falling (Dahle & Grabosky 2010). Increased wood basic density in the junction region of the stems explains the reduction of basic density in the secondary stem, which is probably due to higher photoassimilates resources investment in the forking base to make the tree support possible (Özden et al. 2017).

Another important finding concerned the percentage of forked stems, classified as low-density (68%), which is higher than the percentage found in non-forked stems (41%). Trees of low-density wood occur in the narrower spacings, for which basic density varies more than wider spacings. The results confirm the negative interferences of forking on reducing basic density and within-stem variation pattern.

Goulart et al. (2012) reported basic density of 0.448 g cm^{-3} (stem) and 0.452 g cm^{-3} (branch) in the evaluation of *Stryphnodendron adstringens*. The low density in branches is related to the higher juvenile wood proportion found in the secondary stem, compared to main stem, as the main stem has older cambial. The higher juvenile wood proportion in the secondary stem explains the lower basic density.

Wood basic density in *Tachigali vulgaris* decreases from the base to the top

Higher wood basic density values found in the stem base of *T. vulgaris* compared to stem top are consistent with the within-stem variation pattern, widely verified for tree species (Wassenberg et al. 2014, Longuetaud et al. 2017). It was observed that the basic density of *T. vulgaris* wood decreased from the base up to 4 m, more sharply in the smaller spacings (4.5 m^2 and 6.0 m^2). The strong influence of spacing on density variation patterns, especially in the narrower spacings, caused a wide individual variation, which is probably related to reducing density in these spacings. This means, low-density trees show a more extreme basic density within-stem variation than denser wood trees.

The higher wood basic density in the stem base is related to cambial age, comprising all growth rings and higher mature wood proportion, besides a higher percentage of heartwood (Firmino et al. 2019). On the other hand, on the top of the tree, wood basic density is lower due to higher juvenile wood proportion, characterised by a wider variation in fibre length, cell wall thickness and fraction, resulting in lower density wood (Hébert et al. 2016). The wide intra-stem variation of the wood basic density caused by the different planting spacing suggests a strong influence on the heterogeneity of the genetic material. The stand has a seminal origin, and no genetic improvement has been carried out for this species so far. Besides, the wide variation in wood basic density within the stem of *T. vulgaris* can be used as a parameter to select trees with more uniform wood basic density, which is a desirable characteristic for charcoal production.

Finally, the effect of forking on the basic density variation pattern was not evident in this study, suggesting that forking interferences are not concentrated on a specific within-stem position, but uniformly distributed along the stem.

Tachigali vulgaris has appropriate wood density for energy purposes

For energy purposes, specifically for charcoal production, wood basic densities ranging from medium to high (> 0.500 g cm^{-3}) are desirable. In this research, *T. vulgaris* wood showed basic density ranging from 0.443 g cm^{-3} to 0.529 g cm^{-3}, superior to those verified by Silva et al. (2018) for the woods of two 7-years-old clonal hybrids of *E. grandis* x *E. urophylla* (0.440 g cm^{-3} to 0.500 g cm^{-3}).

The use of wood with high basic density culminates in charcoal with a higher bulk density and better mechanical resistance, which is desirable for the steel industry (Vieira et al. 2019). Denser woods also have a higher energy density, which is the energy stored in a given volume of wood (Simetti et al. 2018).

CONCLUSIONS

The *T. vulgaris* 87-months-old wood showed desirable quality for energy purposes, and is recommended for establishing homogeneous plantations in Brazilian Amazonia. The planting spacing affects the wood basic density, producing denser and within-stem uniform wood, from narrower to wider planting spacings. Forking increases the proportion of low-wood-density trees with a wider within-stem variation. The forked trees presented a decreasing trend of the basic density from the base to the top. The *T. vulgaris* trees branch off near the base of the stem, which may suggest a biomechanical support strategy for the stem. Finally, further investigations should be carried out to avoid forking and elucidate the interferences of this phenomenon in the quality and productivity of *T. vulgaris* wood and charcoal.

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