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Article

Bark volume and thickness in teak trees with different spacings

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Abstract - The bark in some forest species may represent a significant volume of the trunk, demanding the use of efficient methods to estimate bark volume indirectly through equations. The aim of this study was to evaluate bark volume and thickness in teak (*Tectona grandis*) trees planted at different densities. Volume data were used to evaluate the percentage of bark in different portions of the trunk. Averages were compared by the Tukey test ($p < 0.05\%$) and regression analysis (polynomial model) was used to predict bark thickness along the trunk. The effect of spacing on bark thickness was compared by the model identity test. The percentage of bark in more densely planted teak trees was higher. The percentage of bark decreases from the base to the top of the tree trunk, with an average volume of green bark reaching 24% to 30% of the total volume. Increasing spacing promotes higher absolute average bark thickness.

Volume e espessura de casca em árvores de teca em diferentes espaçamentos

Resumo - A casca em algumas espécies florestais pode representar um volume significativo do fuste, o que sugere a utilização de métodos eficientes de estimativas de casca de forma indireta por meio de equações. O objetivo do trabalho foi avaliar o volume e a espessura de casca em árvores de *Tectona grandis* implantadas em diferentes densidades de plantio. Foram usados dados de cubagem para avaliar a porcentagem de casca em diferentes porções do fuste. As médias foram comparadas pelo teste de Tukey ($p < 0,05$) e também se empregou análise de regressão (modelo polinomial), para se estimar a espessura da casca das árvores ao longo do fuste. O efeito do espaçamento na espessura da casca foi comparado com o teste de identidade de modelos. O percentual de casca das árvores de teca é maior nos espaçamentos mais adensados. A porcentagem de casca vai diminuindo da base para o topo do fuste das árvores, sendo que em média o volume de casca verde chega a apresentar valores entre 24% a 30% do volume total. O aumento do espaçamento promove maior espessura média de casca das árvores.

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Introduction

Native to the wetlands of the Indian subcontinent and Southeast Asia (Firmino et al., 2012), the demand for *Tectona grandis* L. f. (teak) wood for luxury applications is increasing, such as quality furniture and shipbuilding (Husen & Pal, 2007). Making furniture with panels of young teak wood has become popular and has more accessible prices. In addition, Dégbe et al. (2018) report the use of teak in traditional medicine in West Africa.

Wood is the main commercial product from teak cultivation, reaching high prices on the international market. The bark is considered a residue by industry and can be left in the field if the wood is peeled at the time of mechanized harvest or discarded as part of the wood residues during log processing. However, commercial interest in teak bark may be stimulated due to recent discoveries of its potential uses.

According to Baptista et al. (2013), tree bark is a resource of great potential for use, since it is available on a large scale from forestry operations and industrial processing. Tree bark has structural and chemical complexity, which makes it suitable for use in biorefineries. The grinding and fractionation of teak bark by particle size can be used to selectively enrich the fine fractions in soluble materials. Another potential use of teak bark is the extraction of substances that inhibit the methicillin-resistant bacteria *Listeria monocytogenes* and *Staphylococcus aureus* (Neamatallah et al., 2005). Patil et al. (2011) reported that teak bark powder has excellent adsorption capacity for the removal of methylene blue dye from aqueous solutions. Moreover, Dégbe et al. (2018) reported that the ethanolic extract of teak bark showed an inhibitory effect on *Toxoplasma gondii*, a parasitic protozoan responsible for toxoplasmosis.

The cultivation of teak for timber production is notoriously profitable, and the development of new commercial uses for materials which are currently considered waste, such as bark, could enable even more profit for producers. However, according to Drescher et al. (2010), it is important to manage the crop correctly, so that profitable cultivation is guaranteed, based on information produced from technical criteria.

Bark thickness can be estimated indirectly using equations that estimate thickness from the diameter, bark, and trunk height at the sampling point, as well as tree diameter at 1.3 m above ground level (DBH), and total height (Li & Weiskittel, 2011; Kitikidou et al., 2014). Previous research on teak used a function of tree diameter to estimate bark thickness along the trunk (Cordero & Kanninen, 2003; Tewari & Mariswamy, 2013). However, studies on other species show that bark thickness varies according to age, region, spacing, and management regime (Laasasenaho et al., 2005; Brooks & Jiang, 2009; Stängle et al., 2015). Thus, it is important to know the bark thickness and content of teak trees, since bark studies on this species are rare in the literature, especially studies that address different planting densities and the use of more flexible mathematical models, such as the polynomials.

In this context, it is important to generate dendrometric knowledge about teak bark, enabling more accurate forest inventories. Our hypothesis is that the spacing influences the thickness and the volume of the bark in teak trees. The aim of this study was to evaluate bark volume and thickness in *T. grandis* trees planted with different spacings.

Material and methods

Study area

The experimental area was a teak stand in the Instituto Federal de Mato Grosso (IFMT) (16°11'S, 57°40'W), in Cáceres, Mato Grosso State, Brazil. The climate, by the Köppen classification system, is Awi (tropical savannah with wet summer and dry winter), presenting a tropical rainy climate, with two well-defined seasons, a rainy period from October to March and a dry period from April to September. The average temperature varies from 24 °C to 26 °C, the total annual precipitation is 1,320 mm and the altitude is 117 m (Alvares et al., 2013; Nunes et al., 2016). The relief is flat with soil classified as Typical Dystrophic Yellow-Red Oxisol (Passos et al., 2006).

Teak trees were planted in December 1998 (4 ha). The seedlings were planted in four spacings: 3 m × 2 m, 4 m × 2 m, 5 m × 2 m and 6 m × 2 m in a randomized block design, with three blocks.

Pruning was performed at 9, 14, and 22 months after planting (Passos et al., 2006). None of the plots underwent thinning and trees were 15-years old at the time of evaluation. According to Silva et al. (2016), the average survival was high (> 90%).

Sampling and data collection

Before selecting the trees, an inventory for each experimental block in the stand was performed. Surveys were carried out along the central lines of each plot, avoiding the edge effect. Diameter at 1,30 m height (DBH) was measured and five classes of DBH were then defined, each with a 5 cm amplitude. Ten trees were selected per treatment in each block, totaling 30 trees per spacing distance. Sampling considered all diametric classes, with the number of trees sampled proportional to the frequency observed in the population of each spacing as shown in Figure 1. The trees were randomly chosen in each class.

The trees were harvested, and their diameter measured at a height of 0.15 m (height of stump), 1.30 m, and then every 2 m until the first fork. From this point measurements were made every 1 m on the main (thicker) bifurcation, until a minimum diameter with bark of approximately 5 cm was reached. At each measurement point, the bark thickness was measured at two opposite points on the trunk with the Swedish trunk meter, which is widely used to allow rapid bark observations at low cost and with no cross-cut on the trunk (Stängle et al., 2015). Thus, the bark thickness was averaged, and the volumes of each tree with and without bark were calculated by the Smalian method. Table I summarizes the descriptive statistics of the main dendrometric variables of the sampled trees.

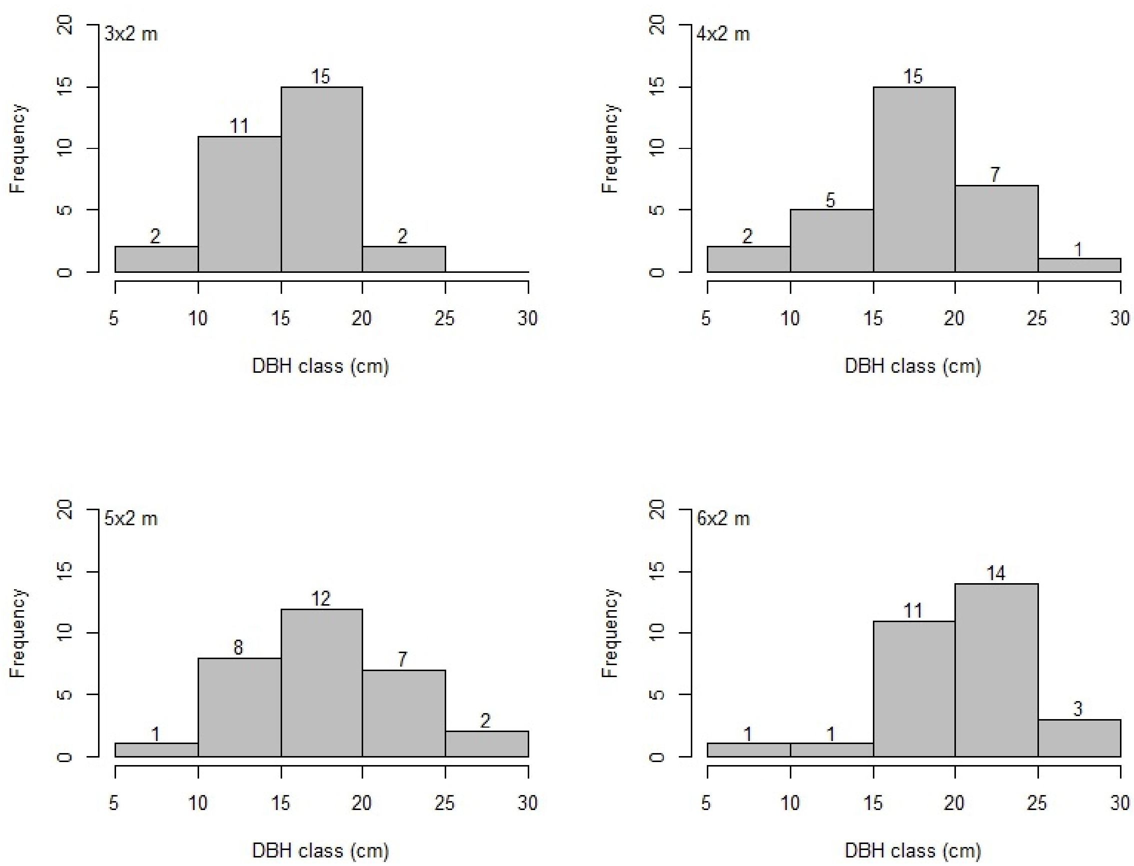

Figure 1. Number of sampled *Tectona grandis* trees, by diameter class and spacing in Cáceres, Mato Grosso, Brazil. DBH: diameter at 1.3 m above ground level.

Table 1. Descriptive statistics of dendrometric variables of *Tectona grandis* at different tree spacing.

Spacing (m)	Variables	Average	Standard deviation	Minimum	Maximum
3 × 2	DBH	15.29	3.60	7.50	22.25
	TH	15.84	1.92	10.3	19.10
	TVb	0.1218	0.0646	0.0165	0.2885
	TV	0.0878	0.0501	0.0097	0.2177
4 × 2	DBH	17.27	3.90	8.55	25.25
	TH	13.98	2.18	12.15	20.50
	TVb	0.1681	0.0848	0.0302	0.4083
	TV	0.1215	0.0660	0.0184	0.3172
5 × 2	DBH	17.58	4.64	6.50	26.05
	TH	16.02	1.77	10.30	19.10
	TVb	0.1773	0.0933	0.0106	0.4087
	TV	0.1280	0.0741	0.0033	0.3295
6 × 2	DBH	20.42	3.89	9.10	26.55
	TH	17.35	1.33	14.00	19.45
	TVb	0.2365	0.0949	0.0549	0.4364
	TV	0.1759	0.0744	0.0354	0.3323

DBH = diameter at 1.3 m above ground level (cm); TH = total height (m); TVb = total volume with bark (m^3) and TV = total volume without bark (m^3)

Statistical analysis

To evaluate the effect of planting density on the bark volume of teak trees, the trunk was divided into three parts. The first one consisted of the trunk up to DBH. The second was from the base to 3.3 m in height, which is equivalent to the log of highest commercial value for teak and finally the total bark volume of the tree was evaluated.

The percentages of bark in relation to the volume in each portion of the trunk were submitted to the Shapiro-Wilk normality test and subsequent analysis of variance. If a significant difference was detected, the averages were compared by the Tukey test. Regression analysis was also used to determine the relationship between DBH and volume with and without bark, as well as the bark volume of the trees.

To estimate the tree bark thickness at each spacing, a fifth-degree polynomial model (Model 1) was used, as it is a very flexible function for this type of modeling (Vendruscolo et al., 2019). The dependent variable used was bark thickness (BT, in cm), while the independent variable was the relative height (h), ranging from 0 to 1.

$$BT_{ij} = \beta_0 + \beta_1 h_{ij} + \beta_2 h_{ij}^2 + \beta_3 h_{ij}^3 + \beta_4 h_{ij}^4 + \beta_5 h_{ij}^5 + \varepsilon_{ij} \quad (1)$$

Where: BT_{ij} = bark thickness of the i-th tree at the j-th position of the trunk (cm); β_{is} = parameters to be estimated by regression; h_{ij} = relative height of the j-th position in the i-th tree, and $\mathcal{E}_i$ = random error.

The regression parameters of the model were obtained using the least squares method. The accuracy of the estimates was evaluated according to the significance of regression coefficients (β), coefficient of determination (R^2), relative standard error (SE%), and graphical analysis of percent residuals.

To evaluate the effect of planting spacing on the bark thickness of teak trees, the equations between treatments were compared using the model identity test proposed by Graybill (1976). The procedure determines whether the parameter of the equation differs among themselves. It applies the F-test to the statistic given by the ratio between the mean square of the difference of the complete model and the reduced model, and the mean square of the complete model. Each spacing in question was fitted in an equation for comparison purposes in order to obtain the complete model, according to procedures described by Vendruscolo et al. (2019a).

The statistical analyzes were performed in the R programming language (R Core Team, 2017), at a significance level of 5%.

Results

The database presented a normal distribution pattern, indicated by the normality tests. The analysis of variance indicated significant differences in bark content among the trunk (Table 2).

Table 2. Test of averages for the percentage of bark in different portions of the trunk of *Tectona grandis* at different tree spacing.

Spacing	Percentage of bark		
	Up to 1.3 m	Up to 3.3 m	Total
3 × 2 m	36.90 a	38.83 ab	29.86 a
4 × 2 m	36.62 a	38.09 ab	29.34 a
5 × 2 m	39.66 a	40.28 a	29.91 a
6 × 2 m	31.79 a	32.52 b	26.44 b
cv %	7.68	6.65	4.61
W (*p-value*)	0.9723	0.7101	0.9675

cv = coefficient of variation; W = Shapiro-Wilk normality test; Means followed by the same letter in a column do not differ by Tukey test ($p > 0.05$).

The trees grown more densely (3 m × 2 m, 4 m × 2 m and 5 m × 2 m) differed statistically from the more open spacing (6 m × 2 m), and they presented the highest percentage of bark volume for trunk and total trunk.

The sections of tree trunk showed that the highest proportion of bark is found in trunk up to 3.3 m from the ground and can represent 40% of the trunk volume. When the percentage of bark in the total trunk was evaluated, bark percentage reduced to around 30%.

The regression analyses performed to model the volumes with and without bark and the bark volumes by spacing are presented in Figure 2. The equations explained more than 92% (R^2) of the variation in volume with and without bark as a function of the DBH of the trees, whereas for the bark volume the accuracy of the estimates decreased for the larger spacings (4 m × 2 m, 5 m × 2, m and 6 m × 2 m), with R^2 ranging from 80% to 90%.

The estimated coefficients and accuracy indicators (R^2 and SE%) obtained from the model equations to predict bark thickness along the tree trunk are presented in Table 3. Due to the non-significance of the variable associated with the "β_5" parameter of the polynomial model, it was not used in the modeling process.

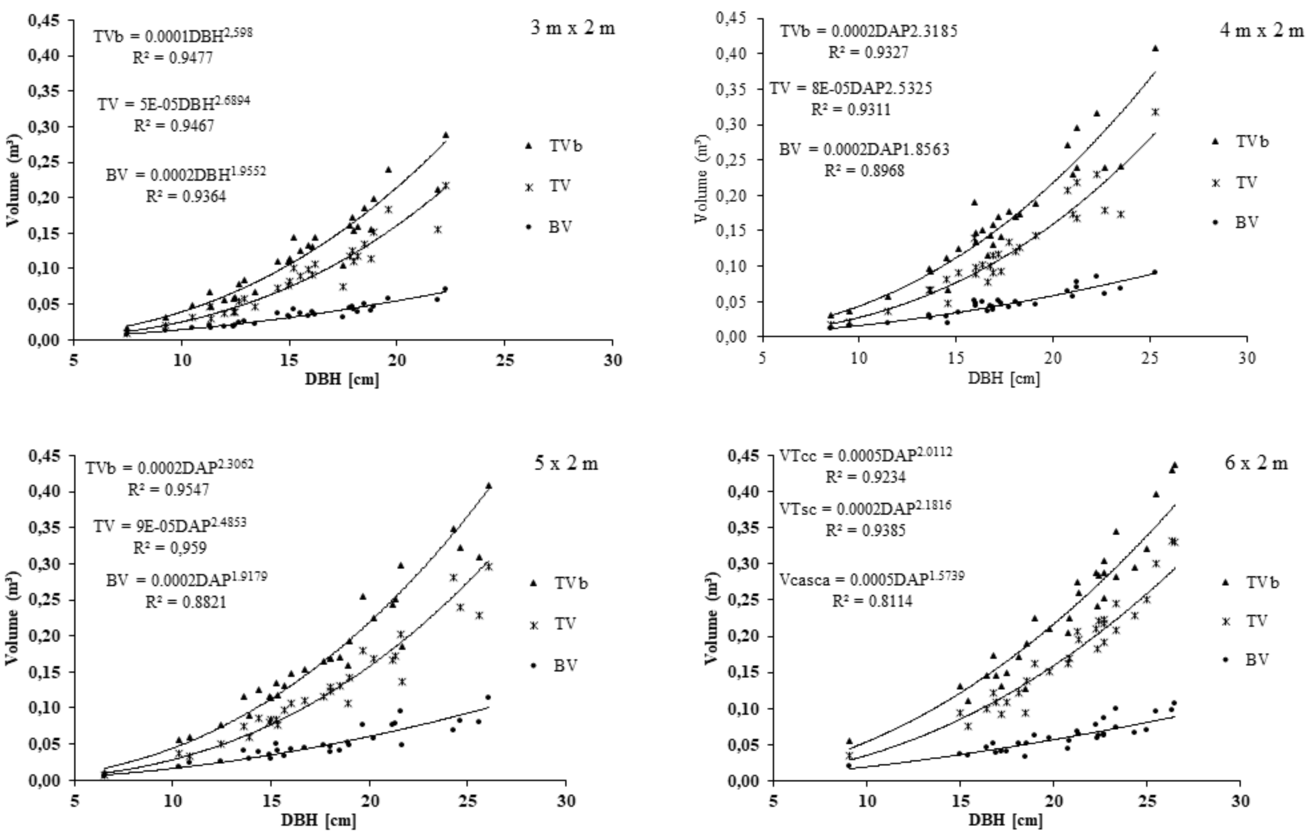

Figure 2. Relation between diameter at 1.3 m above ground level (DBH) and: total volume with bark (TVb), total volume without bark (TV), and bark volume (BV) of *Tectona grandis* trees.

Table 3. Coefficients and accuracy statistics for the bark thickness equations of *Tectona grandis*.

Spacing (m)	β_0	β_1	β_2	β_3	β_4	R^2	SE%
3 × 2	1.22911*	-1.97023*	5.38194*	-8.79692*	4.87932*	0.646	16.72
4 × 2	1.40206*	-2.71510*	7.38650*	-10.70732*	5.19226*	0.668	17.72
5 × 2	1.61583*	-4.81501*	16.67748*	-25.96611*	13.35660*	0.617	22.03
6 ×2	1.50025*	-3.31357*	11.34086*	-18.71157*	9.93477*	0.690	11.97

* = significant at the 5 % level R^2 = determination coefficient; SE% = standard error percentage.

The functional relationship [$BTf(h_{rel})$] explained between 61% and 69% (R^2) of the variation in bark thickness along the trunk, and the mean error was moderate (11.97%) to high (> 22%). Thus, it was possible to observe trends in residual errors (Figure 3). In general, the residuals were homogeneously distributed. There was a trend of increasing residual variance in the portion comprising 40-80% of the trunk height.

The estimated coefficient (β_0) that indicated the intercept of the curve on the y-axis increased as spacing did from 3 m × 2 m to 5 m × 2 m, which indicates that bark thickness tends to increase as tree spacing increases. The model identity test was conducted to verify these differences, with the first test comparing data among the four spacings, which was significant. Thus, further tests evaluated pairwise differences between spacings (Table 4).

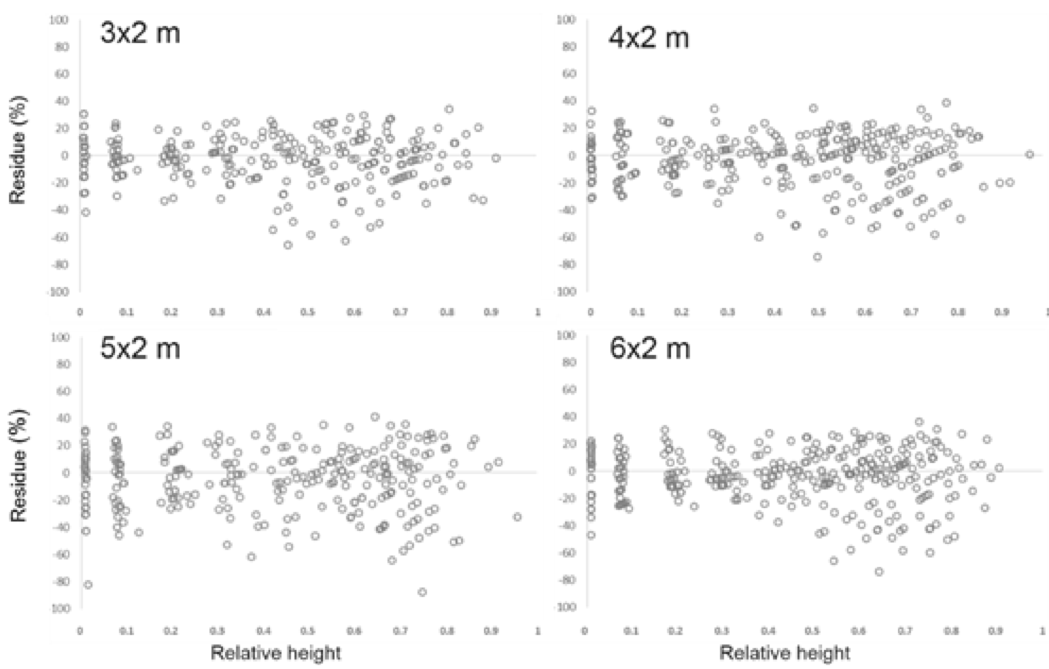

Figure 3. Distribution of residuals of the polynomial model used to estimate bark thickness of *Tectona grandis.*

Table 4. Results of model identity tests between different planting spacings.

Condition	Significant: P-value ≤ 0.05		
Treatments (Spacing)	3 m × 2 m	4 m × 2 m	5 m × 2 m
4 m × 2 m	p < 0.001		
5 m× 2 m	p < 0.001	p < 0.001	
6 m × 2 m	p < 0.001	p < 0.001	0.16234[NS]

NS = not significant

All pairs of treatments were significantly different in the identity tests, except for between the 5 m × 2 m and 6 m × 2 m spacing (Table IV). Therefore, bark thickness along the trunks at the two largest spacings did not differ from each other and can be modeled by a single equation.

The curves (Figure 4) show that increased spacing increases average bark thickness. Considering the densities of 3 m × 2 m and 4 m × 2 m, the thickness difference was approximately 12%, indicated by the intercept value (β_0). When 3 m × 2 m was compared with the combined curve for 5 m × 2 m and 6 m × 2 m spacings, bark thickness difference was 21%, on average.

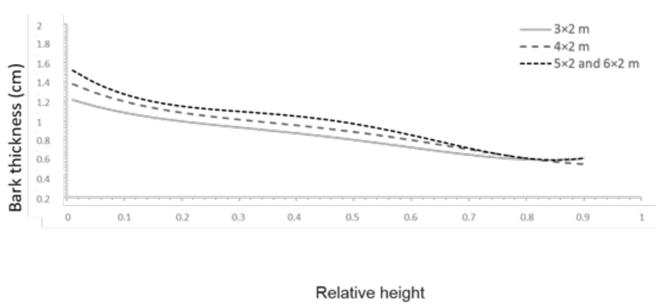

Figure 4. *Tectona grandis* bark thinning curves at different tree spacing.

Discussion

Studies on the bark content and thickness of forest species are important, since in some cases the bark volume may represent a significant part of the trunk volume (Li & Weiskittel, 2011). Therefore, precise estimates of this variable are very useful for biometric diagnostics, especially when the bark can become a potentially profitable byproduct for the forestry sector (Marshall et al., 2006; Stängle et al., 2015).

The data analyzed showed a reduction of bark percentage in the highest portions of the trees. This tendency was expected as at higher altitudes the bark is thinner because it is younger. In the region closest to the base, the proportion is higher due to the existence of external dead bark, which is a barrier that the plant maintains to defend itself from adversities that may affect the vital stem tissues (Marshall et al., 2006; Pausas, 2015). Vendruscolo et al. (2019b) observed that the thickness of the bark in teak trees decreases notoriously from the tree base to the treetop. The findings of Laasasenaho et al. (2005) for the species *Picea abies* were similar.

The highest bark content was observed under denser planting regimes (3 m × 2 m, 4 m × 2 m and 5 m × 2 m) (Table 2). This occurs because in teak plantations with smaller spacing and no thinning, tree growth is strongly impaired, with smaller diameter trees predominating (Pelissari et al., 2013; Silva et al., 2016). Vendruscolo et al. (2019b) reported a negative correlation when modeling the percentage of teak bark as a function of tree diameter. This suggests that in trees of smaller diameter the bark content increases compared to larger trees, due to volumetric growth occurring exponentially, corroborating the findings of Figueiredo et al. (2005).

The percentage of bark in relation to the volume of the trees was high (30% to 40%) due to green bark (active phloem). Studies on the percentage of bark in teak trees show that the species presents high percentage values, ranging from 10% to 30% depending on tree diameters (Cordero & Kanninen, 2003; Leite et al., 2011). Additionally, studies have reported that measurements with bark meters generally tend to overestimate bark thickness (Althen, 1964; Stängle et al., 2015), and that bias depends heavily on the operator's experience, requiring practice in advance of use (Gray, 1956).

The general trend observed in the regression analysis for tree volumes with and without bark followed an expected biological pattern, that is, as diameter at 1.3 m above ground level (DBH) increases, an exponential increase in volume occurs. Modeling of the bark volume presented a more linear relationship with the tree DBH values. This tendency was similar to that observed by Cordero & Kanninen (2003) for teak with ages between 5 and 47 years at different densities across different regions of Costa Rica.

The polynomial function used to describe bark thickness along the tree trunk through the functional relationship $EC = f(h_{rel})$ had a moderate coefficient of determination (R^2) and potentially high errors (varying

11% and 22%). Tewari & Mariswamy (2013) pointed out that modeling of bark thickness usually results in models with a low degree of explanation between the independent and dependent variables and it may be a consequence, according to Stängle et al. (2017), of geospatial variation, site productivity, and individual tree growth rates, or even the ontogenic characteristics of some species. Moreover, research by Stängle et al. (2015) on *P. abies* revealed that variation in bark thickness can occur even at different sampling points at the same relative sampling height.

The equation to estimate bark thickness presented difficulties in capturing the variation of the data in the portions between 40% and 80% of the total height of the trunk. This is associated with a part of the trunk with a higher incidence of live branches and dead branches due to no stands being subjected to thinning, which generates greater variation in bark thickness. This tendency was similar to that observed by Vendruscolo et al. (2019b) when modeling the thickness of teak bark with ages varying between 6 and 33 years. They found that the highest errors were between 60% and 80% of the total height of the trees.

The modeling of the bark profile along the trunk using a polynomial function showed that bark thickness decreases from the base to the top. Vendruscolo et al. (2019b) described the same tendency for teak trees with different ages across multiple regions in Mato Grosso state, Brazil. In the larger spacing, due to the development of the trees, the bark was also thicker (Figure 4). This is attributed to the positive correlation between tree diameter and bark thickness, corroborating several studies (Cordero & Kanninen, 2003; Marshall et al., 2006; Li & Weiskittel, 2011; Stängle et al., 2015).

The use of the polynomial function was shown to be efficient in modeling teak bark thickness. The suitability of this type of function for modeling bark thickness was also reported by Laasasenaho et al. (2005), that emphasized the consistency of taper functions for estimating bark thickness as a function of relative height for *P. abies* trees. According to the authors, the relativization of height allows the effective standardization of trees that commonly present varied heights.

The bark thickness curves decreased significantly from the base of trees to their tops (Figure 4) and were similar to tree trunk thinning, which is the diameter decrease along the trunk as height increases (Campos & Leite, 2013).

Conclusions

The percentage of bark in teak trees is higher with denser spacing (3 m × 2 m, 4 m × 2 m and 5 m × 2 m) due to the predominance of trees with smaller diameters. The percentage of bark decreases from the base to the top of teak trees, with an average volume of green bark reaching 24% to 30% of the total volume. Spacing significantly influenced tree bark thickness, and the general tendency was that increased spacing promotes a higher average tree bark thickness.

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