SEVEN publicações acadêmicas

Computer program and statistical models to estimate teak leaf area

Crossref doi
https://doi.org/10.56238/uniknowindevolp-036

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ABSTRACT
Teak has been widely used in the furniture industry. However, the characteristics of its leaves allow its use in projects for the recovery of degraded areas and the implementation of agroforestry or agrosilvopastoral systems, as its shape, size and arrangement on the tree can favor the interception of rain, which can reduce or mitigate soil erosion because of surface runoff. The objective of this research was to estimate teak leaf area with the help of the ImageJ computer program and several statistical models. Functional dependencies were elaborated based on linear, exponential, logarithmic and potential relationships, defining leaf length and width measurements as independent variables. The selection of the most appropriate models was carried out based on analytical and graphic criteria, highlighting those developed from the independent variable defined by the product of the length times the width of the sheet. The values determined by these relationships showed a high correlation with those obtained by the ImageJ program and the best performance and efficiency indices to estimate the teak leaf area, especially the logarithmic model.

Keywords: Regression analysis, residue analysis, adjustment quality.

1 INTRODUCTION

Teak *(Tectona grandis* L.f.) of the genus Tectona belongs to the Lamiaceae family, originating in the southeast of the Asian continent and occurs naturally in Peninsular India, Myanmar, Laos, Thailand, Burma and several regions located in this geographical zone (GONZALÉZ, 2013; PELISSARI et al., 2014; MIDGLEY et al., 2015; BRAGA et al., 2018; SOUZA et al., 2019; SILVA et al., 2020). This tree has opposite leaves, elliptical, leathery and rough to the touch, endowed with short or absent petioles with acute apex and base. Adult individuals have leaves, on average, with a length of 30 to 40 cm by 25 cm wide. Already, in younger individuals, up to 3 years of age, the leaves can reach twice these dimensions. In natural environments, the teak has a rectilinear trunk, with varied dimensions and shape, according to the location and conditions of growth, and can reach the diameter of 0.9 m to 2.4 m (MATRICARDI, 1989; VIEIRA et al., 2002; FIGUEIREDO and PINHO DE SÁ, 2015).

The geographical dispersion of teak plantations allows us to infer that this species has good adaptability to very varied environmental conditions. However, the type of soil, the climate, the slope of the terrain and the spacing can interfere with its development. Aiming at the production of quality wood, with dimensions for sawmill and lamination, it is necessary to meet certain climatic, edaphic and topographic requirements. In this sense, the most indicated climate is the humid tropical, with rainy summer and dry winter, the soil must be deep, permeable, with reasonable water retention capacity and good fertility, the lands must have little slope, among others (CÁCERES FLORESTAL, 2006; FIGUEIREDO and PINHO DE SÁ, 2015; SILVA et al., 2016).

Due to its rapid development and adaptability to different climatic conditions, in addition to its use for commercial purposes, teak has been widely used in the recovery of degraded areas, as well as in agroforestry systems (SAFs) and in the Crop-Livestock-Forest Integration (ICLF) or agrosilvopastoral system (MMA, 2011; SILVA et al. 2013; SOUZA et al., 2019; LIMA et al., 2022). According to SILVA et al. (2013), the use of teak in the recovery of degraded areas and in agroforestry or agrosilvopastoral systems has as main advantages, its good acceptance in the market and its high commercial value.

Several studies have considered the leaf area as an important indicator of plant productivity, because the photosynthetic process depends on the interception of light energy and its transformation into chemical energy, with the leaf being the main responsible organ. Thus, the efficiency of this process depends on the photosynthetic rate per unit leaf area and the interception of solar radiation. It should also be noted that through the photosynthetic process, plants fix carbon in the leaves, which is distributed to the remaining parts of the plant. In general, the leaf area is important for applications in evaluations of growth rates and development of plants in their interactions with the soil-atmosphere system (JENSEN, 1986; BELTRÃO, 1999; FAVARIN et al., 2002; JÁCOME, et al., 2003; MEDRANO and FLEXAS 2003; BLANCO; FOLEGATTI, 2005; FIDELES FILHO et al., 2010; TONDJO et al., 2015; BRAGA et al., 2018).

In order to estimate the leaf area of agricultural crops and evergreen trees, several allometric models were developed (FAVARIN et al., 2002; MALDANER et al., 2009; FIDELES FILHO et al., 2010; FIGUEIREDO et al., 2010; SILVA et al., 2011; MORGADO et al., 2013; ZEIST et al., 2014;

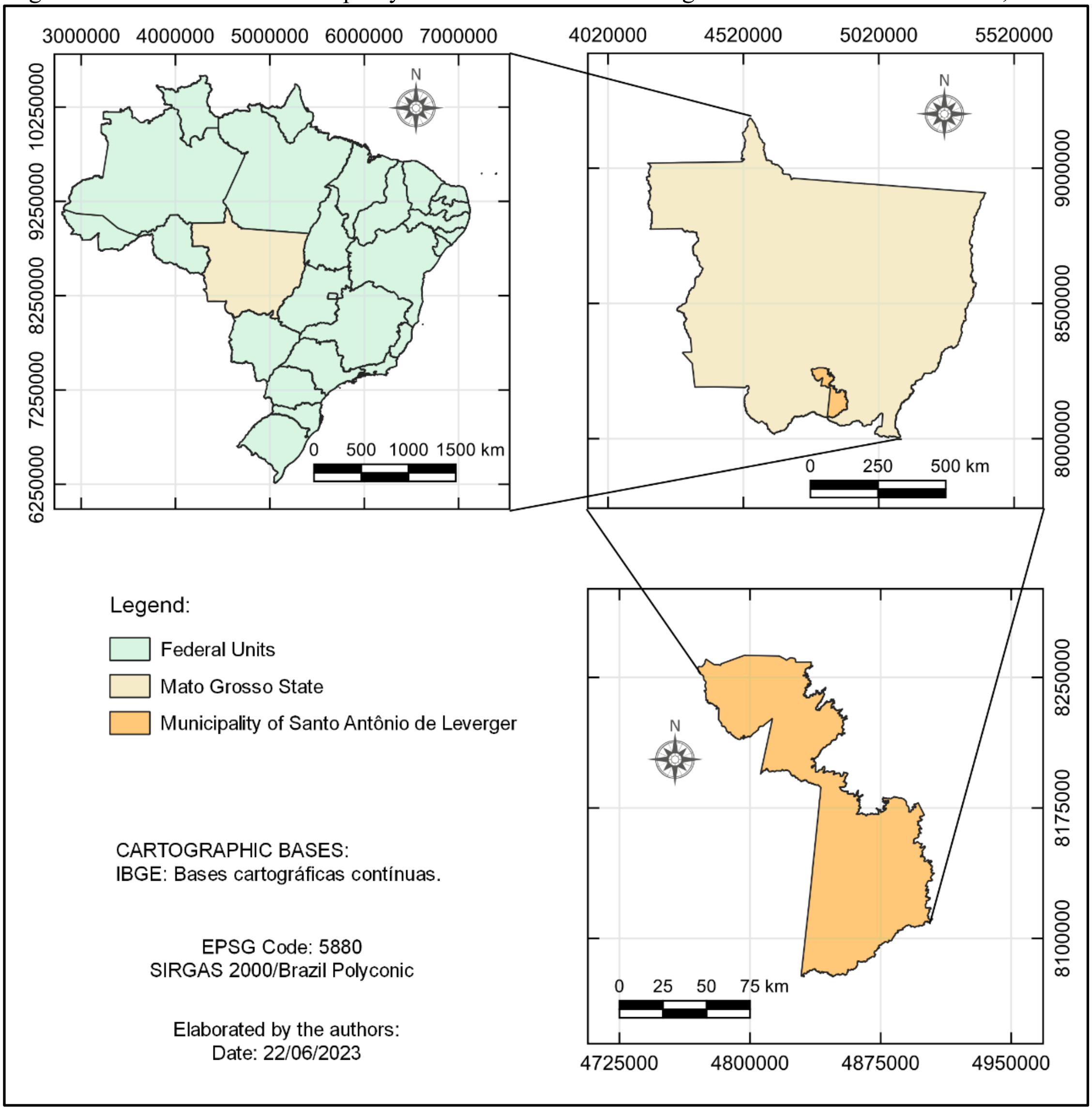
MATOS et al., 2015; BRAGA et al., 2018; FONSECA et al., 2020; NASCIMENTO and FREIRE, 2020; PEREIRA et al., 2020; SILVA et al. 2020; ALMEIDA JÚNIOR et al., 2021; BORGES et al., 2021). However, from these studies it is inferred that the coefficients and the type of model depend on the climatic conditions of the place, soil class and variety of the crop. Braga et al. (2018) and Silva et al. (2020) obtained specific allometric models to estimate leaf area in teak. However, the models and their coefficients, as well as the accuracy were different. These discrepancies may be associated with the climate of the region, the type of soil and probably the measurement method used.

According to the bibliography consulted, this research is based on the hypothesis that the leaf area of teak has essential importance for several purposes, among them the evaluation of its potential for use in agroforestry or agrosilvopastoral systems and in the recovery of degraded areas. Thus, its determination can serve as a subsidy to establish the necessary criteria in relation to crop, livestock and forest integration projects (ICLF), as well as for the recovery of degraded areas. The problem presented motivated the accomplishment of this study, which aimed to estimate the leaf area of teak by means of a computer program and statistical models.

2 MATERIAL AND METHODS

In the period from April to June 2023, 160 teak leaves (*Tectona grandis* L.f.) were collected from the trees of an equine plantation aged 12 years, located at the Experimental Farm of the Federal University of Mato Grosso. This geographical zone is located in the municipality of Santo Antônio de Leverger, state of Mato Grosso, Brazil (Figure 1). In this territory the Aw or tropical savanna climate predominates, which is characterized by presenting two seasons in the year, hot and dry (PEEL et al., 2007; ALVARES et al., 2013). The average annual temperature and total annual rainfall vary around 26 °C and 1260 mm, respectively, with an altitude of 140 m (INMET, 2023). The soil of the region was classified as Quartzarenic Neosoil Ortic eutric, A moderate, cerrado phase, flat relief (EMBRAPA, 2006; CHIG et al., 2008; MATOS et al., 2020; ALMEIDA JÚNIOR et al., 2021).

Figure 1. Location of the municipality of Santo Antônio de Leverger in the state of Mato Grosso, Brazil.



The collected leaves showed no physical damage or signs of attack caused by diseases or pests, that is, photosynthetically active. The leaves were placed next to a ruler graduated in millimeters and on a table covered with a white paper background, separated by approximately 5 cm, in order to highlight their outline. Then, the leaves and the ruler were photographed with a 50 Megapixel camera and a resolution of 8165x6124 pixels. Subsequently, the length, width and leaf area of each leaf were determined digitally, using the respective photos and the open-source program ImageJ, Version 1.51k for Java (RASBAND, 2017).

The length was determined along the midrib, distance between the base of the leaf at the point of insertion of the petiole to its apex, while the width was obtained in the median part of the leaf. Based on leaf length and width measurements, several statistical models have been developed to estimate teak leaf area, as suggested by Borges et al. (2021), described below:

$$AF = a \cdot C + b \quad \text{(Linear)}$$

$$AF = a \cdot e^{b \cdot C} \quad \text{(Exponential)}$$

$$AF = a \cdot \ln(C) + b \quad \text{(Logarithmic)}$$

$$AF = a \cdot C^{b} \quad \text{(Potential)}$$

$$AF = a \cdot L + b \quad \text{(Linear)}$$

$$AF = a \cdot e^{b \cdot L} \quad \text{(Exponential)}$$

$$AF = a \cdot \ln(L) + b \quad \text{(Logarithmic)}$$

$$AF = a \cdot L^{b} \quad \text{(Potential)}$$

$$AF = a \cdot (C \cdot L) + b \quad \text{(Linear)}$$

$$AF = a \cdot e^{b \cdot C \cdot L} \quad \text{(Exponential)}$$

$$AF = a \cdot \ln(C \cdot L) + b \quad \text{(Logarithmic)}$$

$$AF = a \cdot (C \cdot L)^{b} \quad \text{(Potential)}$$

where:

AF = Leaf area (cm2);

C = Leaf length (cm);

L = Leaf width (cm);

a, b = Fit coefficients of the models (dimensionless).

The procedures to determine the adjustment coefficients were performed with the function's "lm" and "nls", available in the R Program (R CORE TEAM, 2020). In addition, multiple features of this program were used to evaluate the models analytically and graphically. The values of the leaf area estimated with the aid of the aforementioned models were compared with those obtained through the ImageJ program. Therefore, the coefficient of determination (R^2), the mean absolute error (EAM), the root of the mean square error (RMSE) and the mean percentage of absolute error (MAPE) were calculated. Based on these indices, the models with the best results were selected, aiming to reduce the number of mathematical relationships. Subsequently, an analysis of the normality of the residues from these comparisons was performed, applying the Kolmogorov-Smirnov, Lilliefors and Shapiro-Wilk tests. Finally, the adjustment between the observed and estimated values was verified, according to the student's t-test.

Based on the product of the correlation coefficients and Willmott's coefficients, the performance index was determined. The efficiency of the models was corroborated by the Nash-Sutcliffe coefficient (NASH & SUTCLIFFE, 1970). Soon after, the graphical analysis of the residues was performed. In this sense, the histogram of the residuals, the quantile-quantile diagram with the reference line (QQ-Normal), the graph with the values of the residues as a function of the dependent variable and the distribution of the observed values were elaborated, according to the estimated ones and in relation to the bisection of the first quadrant. These procedures were performed with the R Program (R CORE TEAM, 2020).

3 RESULTS AND DISCUSSION

Table 1 presents the functional dependencies of the models obtained, as well as the significance of the corresponding coefficients and the indices used to evaluate the adjustment. According to this Table, the models with the independent variable formed by the product between the length and width showed the best indicatives, that is, the highest coefficients of determination and the lowest metrics of errors.

Table 1. Expression of the models, significance of the coefficients and indices used to evaluate the adjustment.

Model expression	**Significance of coefficients**		**Coefficients of determination**		**Error metrics**		
	the	**b**	**R^2 (-)**	**R_{adj}^2 (-)**	**MAE (cm^2)**	**RMSE (cm^2)**	**MAP (%)**
AF = 22.237·C – 354.933	***	***	0,6351	0,6320	45,01	53,36	13,10
$AF = 50.160434 \cdot e0.060764^{\cdot C}$	***	***	0,6122	0,6090	45,92	55,04	13,63
AF = 703.88·ln C – 2079.26	***	***	0,6430	0,6400	44,50	52,78	12,86
AF = 0.3820·C1.9709	ns	***	0,6248	0,6216	45,54	54,13	13,40
AF = 27.1527·L – 164.5893	***	***	0,8640	0,8629	23,81	32,58	6,21
$AF = 73.952696 \cdot e0.080479^{\cdot L}$	***	***	0,8652	0,8641	24,42	32,44	6,75
AF = 483.32·ln L – 1064.66	***	***	0,8492	0,8479	26,44	34,31	7,17
AF = 4.00192·L1.51613	***	***	0,8667	0,8656	23,15	32,25	6,00
AF = 0.59188·C·L – 11.69524	***	***	0,9059	0,9051	20,60	27,10	5,40
AF = 119,80·e0,001708 · C·L	***	***	0,9051	0,9043	22,35	27,22	6,46
AF = 330,00·ln (C·L) – 1756,34	***	***	0,8812	0,8802	23,23	30,44	6,11
$AF = 0.42838 \cdot (C \cdot L)^{1.04496}$	***	***	0,9064	0,9056	20,61	27,04	5,42

According to the Kolmogorov-Smirnov test, the residues corresponding to the models based on the length of the leaf and the product of both leaf dimensions showed normality. However, the residues from the models obtained did not show normality, according to the Shapiro-Wilk and Lilliefors tests (Table 2). However, the null hypothesis of the residual means equals to zero was satisfied by applying the t-test (Student), as indicated in Table 2.

Table 2. Probability and significance values corresponding to the tests applied to each model.

Model expression	**Normality tests**			**Hypothesis test (Student)**
	Ko mo gor ov- Sm	**Sha pir o- Wi k**	**Lil efo rs**	
AF = 22.237·C – 354.933	0,295760 (ns)	0,003570 (**)	0,020280 (*)	0,9999 (ns)
$AF = 50.160434 \cdot e0.060764^{\cdot C}$	0,107391 (ns)	0,000844 (***)	0,001068 (**)	0,9518 (ns)
AF = 703.88·ln C – 2079.26	0,149853 (ns)	0,003858 (**)	0,002851 (**)	0,9999 (ns)
AF = 0.3820·C1.9709	0,231726 (ns)	0,001507 (**)	0,010100 (*)	0,9578 (ns)
AF = 27.1527·L – 164.5893	0,001346 (**)	0,00005 (***)	0,00002 (***)	0,9999 (ns)
$AF = 73.952696 \cdot e0.080479^{\cdot L}$	0,001022 (**)	0,00002 (***)	0,00001 (***)	0,9684 (ns)
AF = 483.32·ln L – 1064.66	0,000016 (***)	0,00003 (***)	0,00001 (***)	0,9999 (ns)
AF = 4.00192·L1.51613	0,000113 (***)	0,00001 (***)	0,00000 (***)	0,9894 (ns)
AF = 0.59188·C·L – 11.69524	0,050227 (ns)	0,00059 (***)	0,00011 (***)	0,9999 (ns)
AF = 119,80·e0,001708 · C·L	0,063065 (ns)	0,00034 (***)	0,00001 (***)	0,9392 (ns)
AF = 330,00·ln (C·L) – 1756,34	0,070845 (ns)	0,00055 (***)	0,00031 (***)	0,9999 (ns)

$AF = 0.42838 \cdot (C \cdot L)^{1.04496}$	0,083649 (ns)	0,00074 (***)	0,00051 (***)	0,9564 (ns)

The models developed, considering the product of length times the width of the leaf as an independent variable, showed the best performance, given by the higher correlation coefficients, Willmott index and consequently its multiplication. Moreover, these models presented the highest efficiency, evaluated by means of the Nash Sutcliffe index (Table 3). In this Table it is observed that the lowest values of the performance and efficiency indices corresponded to the models elaborated from the leaf length. Thus, it is confirmed that leaf length should not be the recommended variable in the estimation of leaf area of teak.

Table 3. Results on the performance and efficiency of the models.

Model expression	**Performance and efficiency indices**			
	Performance			**Efficiency**
	Correlation (r)	**Willmott (W)**	**Product (r · W)**	**Nash Sutcliffe**
AF = 22.237·C – 354.933	0,7970	0,6598	0,5259	0,6351
AF = 50.160434·e0.060764 · C	0,7825	0,6530	0,5109	0,6119
AF = 703.88·ln C – 2079.26	0,8019	0,6637	0,5322	0,6430
AF = 0.3820·C1.9709	0,7904	0,6558	0,5184	0,6245
AF = 27.1527·L – 164.5893	0,9295	0,8200	0,7622	0,8640
AF = 73.952696·e0.080479 ·L	0,9302	0,8154	0,7585	0,8652
AF = 483.32·ln L – 1064.66	0,9215	0,8002	0,7374	0,8492
AF = 4.00192·L1.51613	0,9310	0,8251	0,7681	0,8667
AF = 0.59188·C·L – 11.69524	0,9518	0,8443	0,8036	0,9059
AF = 119,80·e0,001708 · C·L	0,9514	0,8311	0,7907	0,9050
AF = 330,00·ln (C·L) – 1756,34	0,9387	0,8244	0,7739	0,8812
$AF = 0.42838 \cdot (C \cdot L)^{1.04496}$	0,9520	0,8442	0,8037	0,9063

According to the results of the analytical procedures, it can be stated that the models developed, using the product of both dimensions of the leaf as an independent variable, showed adequate performance, precision and efficiency to estimate the leaf area of the teak. The value of the performance index for these models exceeded the lower limit recommended by Camargo and Sentelhas (1997) of 0.7. still, the efficiency index was higher than the minimum recommended by Nash and Sutcliffe (1970). Therefore, taking as reference the performance and efficiency criteria applied to the models obtained in this research, the four with the best indexes for the graphical analysis were selected.

Initially, residue histograms were elaborated, as illustrated in Figure 2. Note that the probability of the residuals was very close to the normal curve for all models. However, the logarithmic equation, having as independent variable the product of length by leaf width presented the best distribution of residues in relation to the zero value. On the other hand, the expressions corresponding to the exponential and potential models, as a function of the aforementioned variables, showed the greatest oscillations around the zero value (Figure 2).

Figure 2. Histograms of the probability density corresponding to the standardized residues for the four models with satisfactory results in the analytical tests.

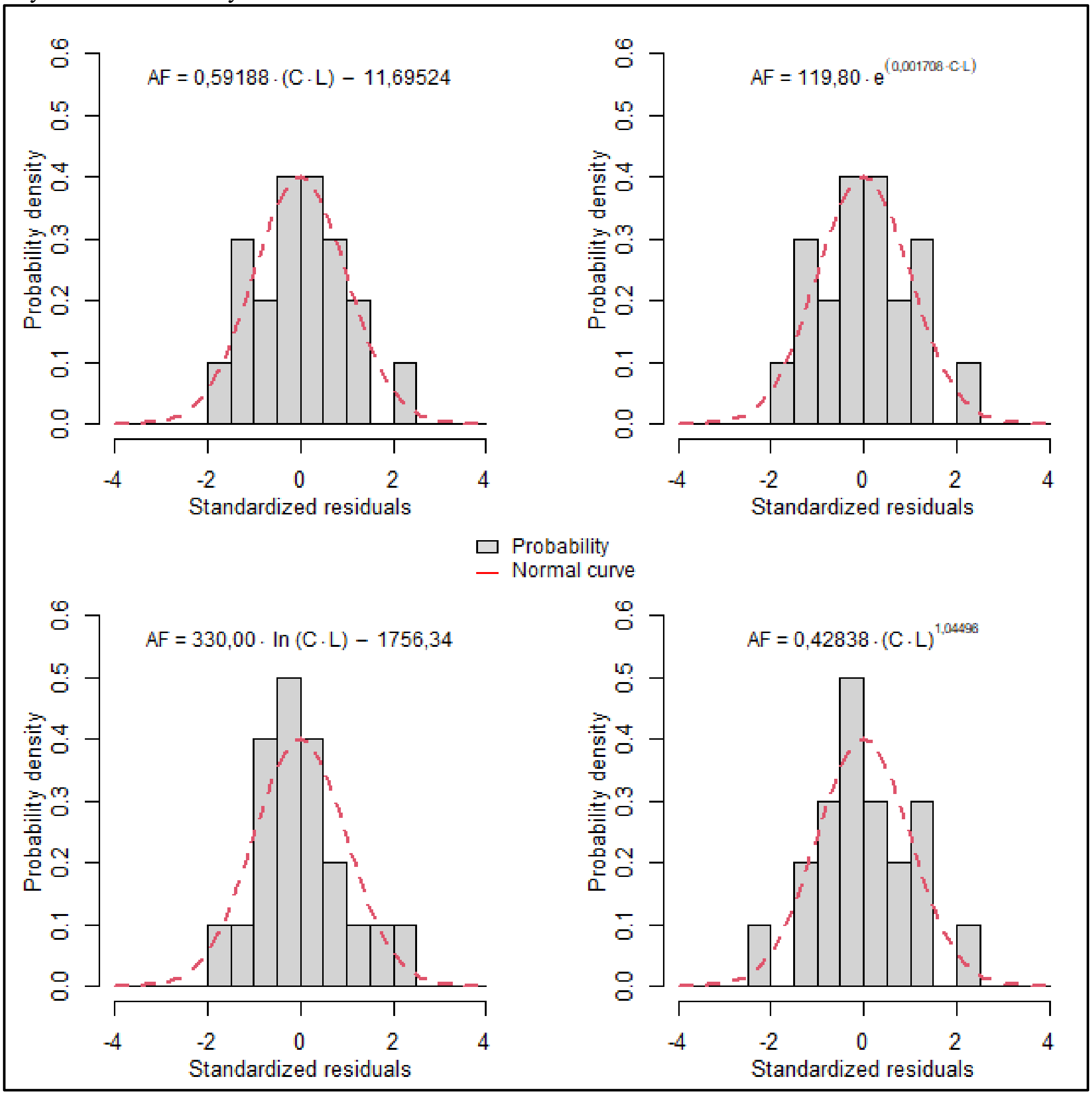
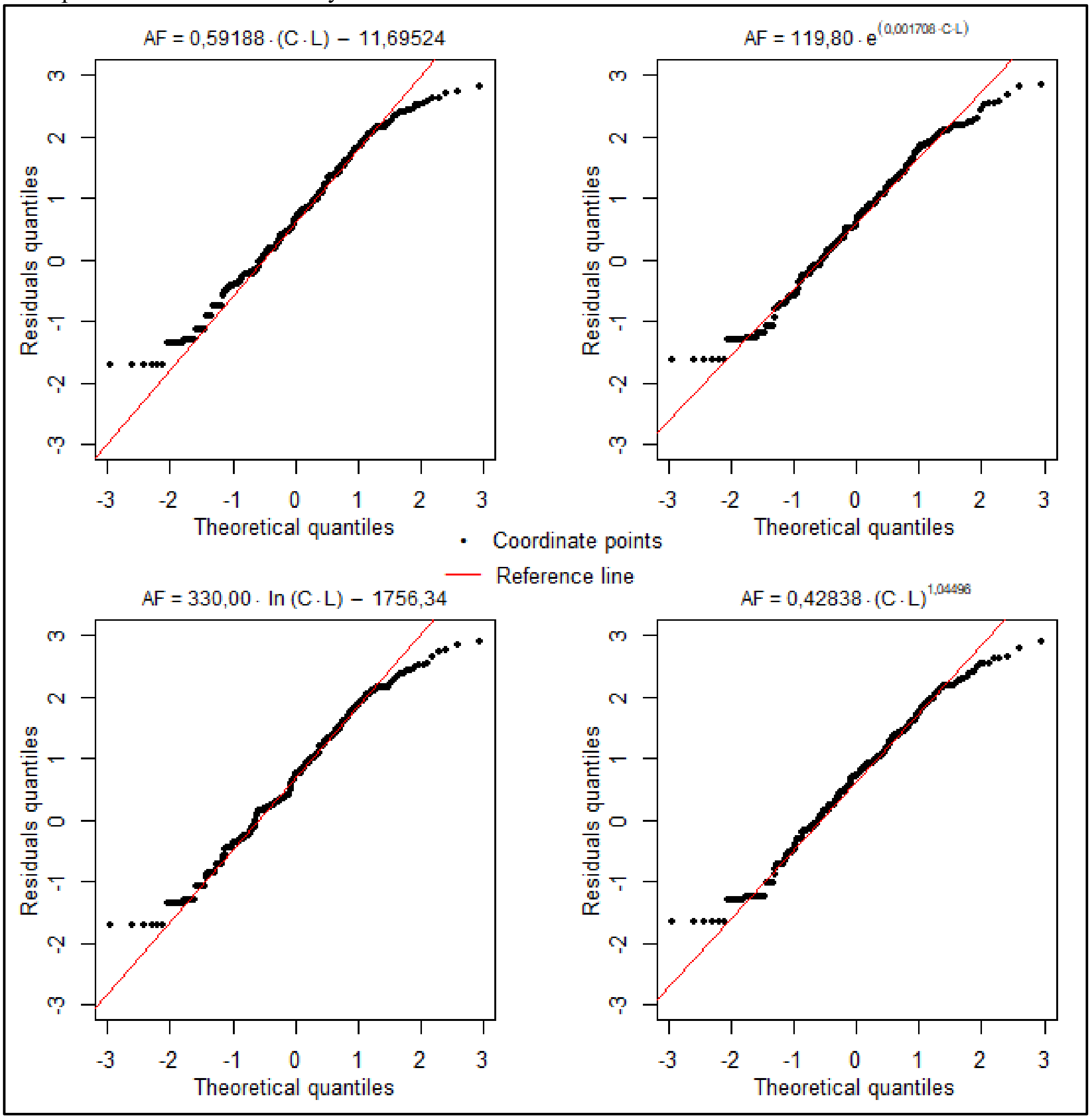


Figure 3 shows the normal probability diagram (Q-Q Normal) of the standardized residuals with the reference line. In this Figure, it is noted that most of the coordinate points formed by the values of the theoretical quantiles and the residues were very close to the reference line and some points moved away only at the ends, from the standardized values -2 and 2. These characteristics indicate that the residues presented normal distribution, graphically verifying this property, which gives greater reliability to the estimation of leaf area values by the four models represented.

Figure 3. Normal probability plots corresponding to the standardized residuals with the reference line for the four models with the best performance and efficiency.



The validity of the assumption of independence can be qualified by means of the scatterplot of the residues according to the order of the actual leaf area values observed. For this purpose, the standardized residue graph was implemented, as a function of the leaf area values, estimated by the four models (Figure 4). In this Figure, two horizontal lines were included passing through the values corresponding to the standardized residues -2 and 2 of the vertical axis, in order to facilitate the identification of the number of points with the largest deviations from the observed data.

Figure 4. Dispersion of standardized residues, as a function of the dependent variable, corresponding to the four models with the best performance and efficiency.

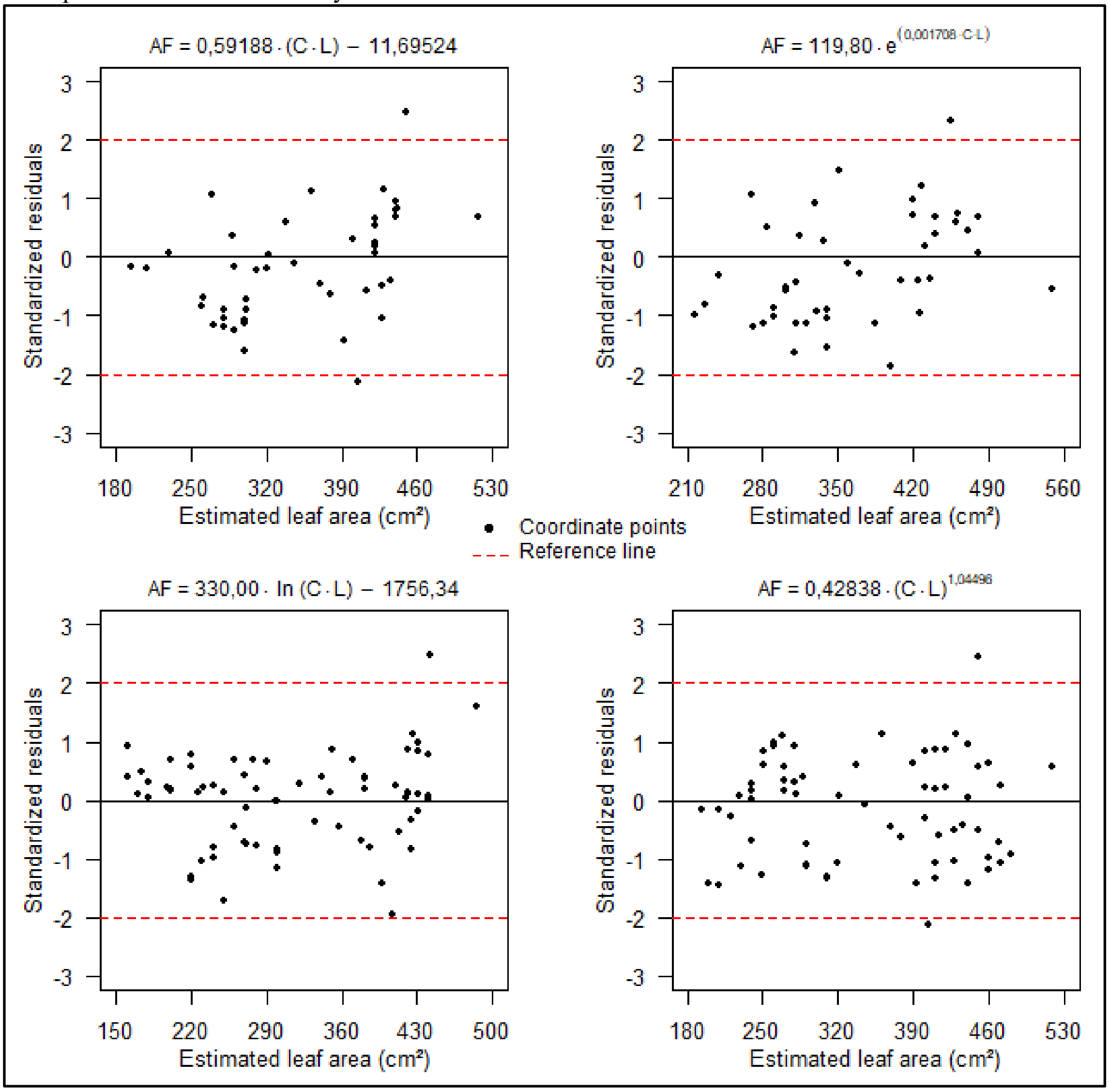
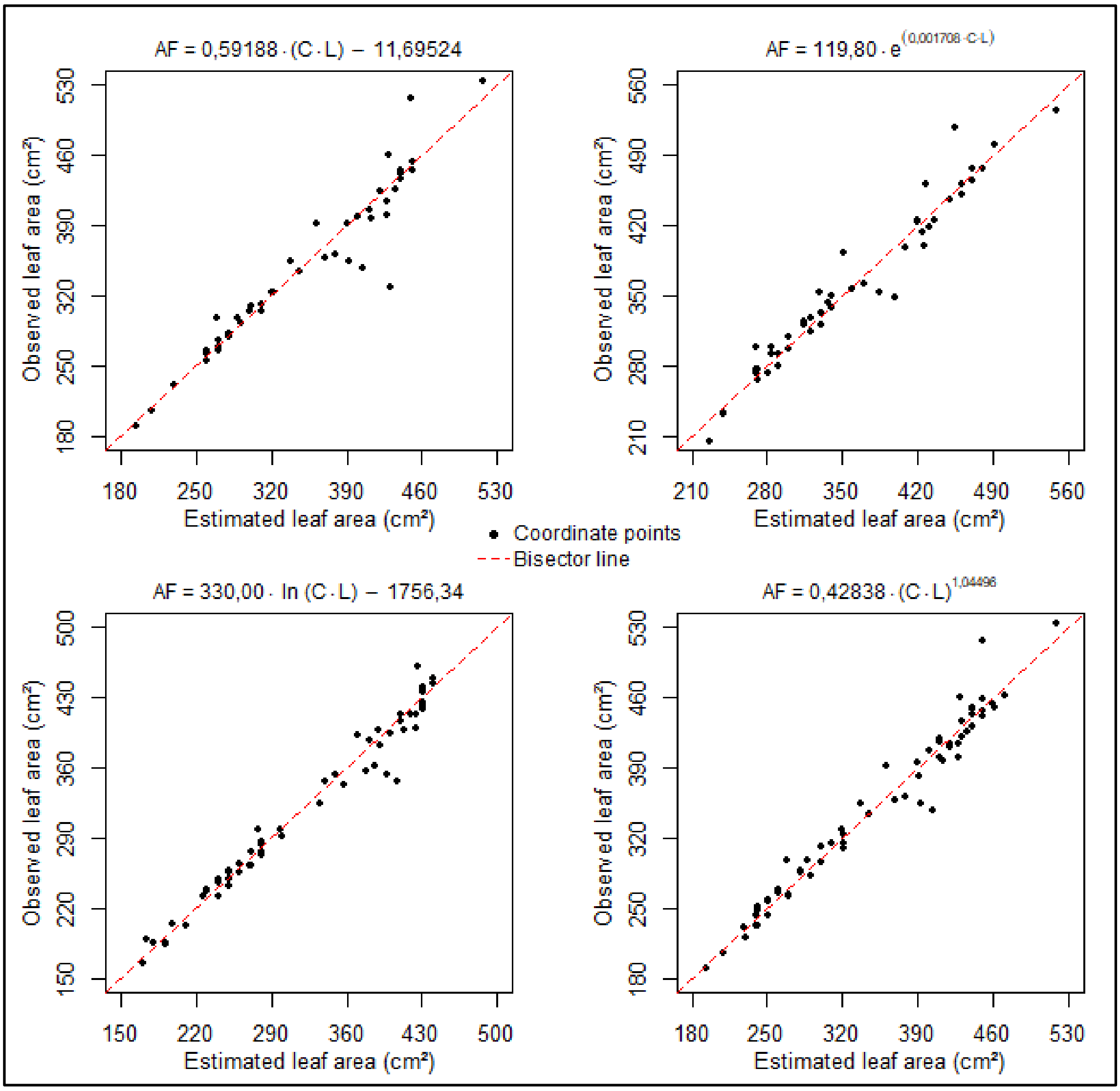


Figure 4 shows that most of the residues are located near the horizontal line with a value of 0, concentrating mainly in the range of -2 to 2 and a few points outside this range for the four models developed. This Figure also shows the absence of positive and negative residue sequences, as well as no patterns of alternation of signals, that is, the residues are randomly distributed along the horizontal line of value 0. These characteristics confirm the independence of the residues, which corroborates the high efficiency of the models to estimate with adequate precision the leaf area of the teak, as a function of the product of the leaf length times its width, which was defined as an independent variable.

The dispersion of the leaf area values observed, as a function of those estimated by the four models, as well as the bisect line, are shown in Figure 5. Based on this Figure, it is observed that the coordinated points are randomly distributed along the bisection, evidencing a high correlation between the values observed and those estimated by the models. In addition, the highest concentration of coordinated points and the smallest distances in relation to the bisection corresponded to the logarithmic model, especially in the interval between the values of estimated leaf area from 150 to 365 cm². However, the largest deviations were determined between 370 and 410 cm² of leaf area for all models (Figure 5).

Figure 5. Dispersion of the observed leaf area values, as a function of those estimated by the four models, as well as the bisect line.



Although the logarithmic model proved to be more appropriate in leaf area estimates, the other three functional dependencies could be a viable alternative, without significant errors. These expressions revealed high precision, especially in the intermediate interval of the independent variable, where most of the observations were. However, the aforementioned mathematical relationships overestimated or underestimated the leaf area values for the extremes of the independent variable (Figure 5).

The mathematical functions that represented the models of the present work were different from those obtained by Braga et al. (2018) and Silva et al. (2020) to estimate the leaf area of teak. These authors defined the linear model without intercept with the product of length times the width of the sheet as an independent variable. However, the aforementioned authors did not test the logarithmic and exponential functions, which could have presented a better fit to the data due to their flexibility. It should also be emphasized that both in this study and in the one carried out by these authors, the best results were obtained for the independent variable formed by the product of the two dimensions of the leaf, that is, the length times the width of the leaves.

The elaboration of statistical models to estimate leaf area in evergreen trees were performed by Favarin et al. (2002), Coelho Filho et al. (2005) and Borges et al. (2021), respectively, with coffee, acid lime and mango tree. In these studies, it is possible to verify the feasibility of using digital mays to estimate the leaf area in large trees. Other researches revealed the possibility of determining the leaf area by digital means for herbaceous plants with high precision and efficiency, in these cases we highlight the works developed by Fideles Filho et al. (2010) in cotton, Cardozo et al. (2009) evaluating two sugarcane weed vines, Busato et al. (2010) studying potato and Bosco et al. (2012) verifying apple trees. The first authors proposed a potential model, while the remaining three obtained the best results for a linear expression.

The performance and efficiency indices for the statistical models elaborated in this research were similar to those proposed by Guimarães et al. (2019), estimating the leaf area of several cassava genotypes. These authors found the best results with linear and potential relationships, as a function of length and the product of length times the width of the leaf, being defined as independent variables. Still, the linear model to determine the leaf area, from the product between the length and width of the leaf of current grass, was considered by Sá Júnior et al. (2016) as satisfactory. On the other hand, Maller et al. (2013) obtained the best results when calculating the leaf area by means of a linear model, as a function of the width of the Italian zucchini leaf. According to these discrepancies, it is deduced the need to develop specific equations to estimate the leaf area of each crop, in order to define which dimension provides the greatest reliability.

4 CONCLUSIONS

The statistical models elaborated were satisfactory to estimate the leaf area of the teak, as a function of the leaf dimensions, with adequate precision and reliability. The values determined by the models showed a high correlation with those obtained by the computer program ImageJ. The independent variable defined by the product between the length and width of the sheet provided the best performance and efficiency indices for the logarithmic model.

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