Estimation of Single Leaf Area of *Acacia mangium* Willd

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Authors' contributions

This work was carried out in collaboration among all authors. Authors VSO, JKBG, IVD, NSF, KTHS, ELV and ERS designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors VSO and ERS managed the analyses of the study. Authors VSO, JSHS, GPS, HC, OS, MPC and SDA managed the literature searches. All authors read and approved the final manuscript.

Article Information

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ABSTRACT

The objective of this study was to determine the best equation for estimating the leaf area of *Acacia mangium* Willd. from the linear dimensions of the leaflets of non-destructive form. For this, 476 leaflets of plants belonging to Lajeado farm were collected in the municipality of Ecoporanga, in the north of the State of Espírito Santo, Brazil. From each leaflet was determined the length (L) along

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the main midrib, the largest width (W), the product of the multiplication between the length and the width (LW) the observed leaf area (OLA). For the modeling, we used 382 leaflets in which OLA was the dependent variable in function of L, W or LW as independent variable, being adjusted the linear models of first degree, quadratic and power. For the validation, the values of L, W and LW of 94 leaflets were replaced in the equations obtained in the modeling thus obtaining the estimated leaf area (ELA). The means of ELA and OLA were compared by Student's t test at 5% probability. . It was also determined the mean absolute error (MAE), the root mean square error (RMSE) and Willmott's index d. In order to select the best equation, the following criteria were used: : not significant of the comparison of the means of ELA and OLA, values of MAE and RMSE with closer to zero and index d closer to one. The power model equation represented by $ELA = 0.7946(LW)^{0.9727}$, is the most adequate to predict the leaf area of *Acacia mangium* Willd. quickly and non-destructively.

1. INTRODUCTION

The *Acacia mangium* Willd. is a species of the family Leguminosae and subfamily Mimosoideae. This species is widely used in reforestation and recovery programs in areas with poor or degraded soils, such as slope and mining areas, as well as the production of wood, cellulose and charcoal [1]. The *A. mangium* Willd presents its leaf structure constituted by a leaflet, that is, an expanded portion of the petiole, being dilated and flattened, resembling the limb, which in general in this case is totally absent [2]. After the growth of the plant, the petiole dilates and the composite leaves fall, making this structure responsible for the photosynthetic function of the plant [3].

The leaf area estimation helps to verify the photosynthetic surface, allows to obtain important indicators for the understanding of the plant responses to environmental factors [4]. According to Mota et al. [5], leaf area is an important indicator of the rates of CO_2 assimilation, O_2 release and transpiration, and plant vigor. This fact shows that the knowledge of the leaf area is important in the evaluation of the physiological state of a plant [6].

There are several methods for the determination of leaf area that can be performed directly (destructive method), through automatic planimeters or indirect method (non-destructive method), through portable automatic planimeters, or mathematical models, using length and width of the leaf blade. Although accurate, direct methods are expensive and laborious, while the mathematical models allow faster assessments [7].

Based on the leaf dimensions of several species and without the destruction of the sample, several studies have reported the use of mathematical models to estimate leaf area [8,9,10,11,12,13,14]. With respect to *A. mangium* Willd., A non-destructive methodology for the determination of its leaf area is of great importance, since there are no mathematical equations in the literature that allow this measurement in the specie.

Thus, the objective of this study was to determine the best equation for estimating the leaf area of *A. mangium* Willd. from the linear dimensions of the leaflets of non-destructive form.

2. MATERIALS AND METHODS

The study was carried out with leaflets of *Acacia mangium* Willd, collected from trees belonging to Lajeado farm, in the municipality of Ecoporanga, North of the State of Espírito Santo, Brazil, located at latitude 18°22'44.4" South and 40°49'22.4'' west longitude. The climate of the region according to Köppen is classified as tropical humid type AW, with dry winter and summer rains [15]. A total of 476 leaflets were collected at various stages of development of plants aged 8 to 10 years at four cardinal points and packed in plastic bags.

After the collection, in the laboratory, of each leaflet the length (L, in cm) along the main midrib and the largest width (W, in cm) were measured, both with the aid of a millimeter graduated rule (Fig. 1). The product of the multiplication between length and width (LW, in cm2) was also determined. Afterwards, all leaflets were scanned with HP Deskjet F2540[®] flatbed scanner and the images were saved in Tag Image File Format (TIFF) format with 300 dpi resolution. Then, the images were processed through ImageJ[®]

software [16], from which the observed leaf area (OLA, in cm²) of each leaflet was obtained. The values of the descriptive statistics of maximum, minimum, mean, amplitude, standard deviation (SD) and coefficient of variation (CV) for L, W, LW and OLA were determined.
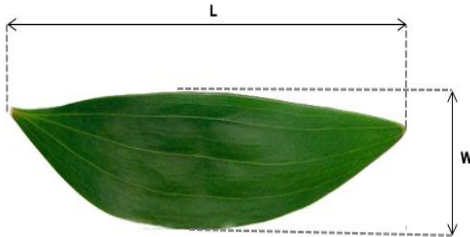
Fig. 1. Representation of the length (L) along the midrib and the maximum width (W) of leaflets of *Acacia mangium* Willd

For the modeling, we used 382 leaflets in which OLA was the dependent variable (y) as a function of L, W or LW as independent variable (x), being adjusted the linear models of first degree, quadratic and power whose representation can be seen in Table 1, totalizing nine equations in the estimation of the leaf area of *Acacia mangium* Willd.

For the validation, the L, W and LW values of 94 separate leaflets for this purpose were substituted in the equations obtained in the modeling, thus obtaining the estimated leaf area (ELA, in cm2). Using the Student t test at 5% probability, the means of ELA and OLA were compared. It was also determined the mean absolute error (MAE), the root mean square error (RMSE) and Willmott's index d [17], for all equations, by means of expressions 1, 2 and 3.

$$MAE = \frac{\sum_{i=1}^{n}|ELA-OLA|}{n} \qquad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(ELA-OLA)^2}{n}} \qquad (2)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(ELA_i-OLA_i)^2}{\sum_{i=1}^{n}(|ELA_i-\overline{OLA}|+|OLA_i-\overline{OLA}|)^2}\right] \qquad (3)$$

In that, ELA are the estimated values of leaf area by the proposed equations; OLA are the observed leaf area values; $\overline{OLA}$ is the average of the leaf area values observed; n is the number of leaflets used in validation, n = 94 in the present study.

For the selection of the equation that best estimate the leaf area of leaflets of *Acacia mangium* Willd. in function of L, W or LW, the following criteria were used: not significant of the comparison of the means of ELA and OLA, values of MAE and RMSE with closer to zero and index d closer to one. The statistical analyzes were performed with the aid of software R [18], with scripts developed for the Exp Des.pt version 1.2 package [19].

3. RESULTS AND DISCUSSION

The analysis of the descriptive statistics of the characteristics under study is present in Table 2. Note that there was high amplitude of the sample data in all the characteristics, and the values of the sample used for modeling presented values higher than the sample used for validation. This, according to Levine et al. [20] is adequate since the measures used in the validation should not extrapolate the measures used to adjust the equations.

In relation to the standard deviation (SD) and the coefficient of variation (CV) obtained, it is noted that the LW characteristic presented the highest values in both the sample used for the modeling and in the validation sample. High values of these measurements are important in studies aiming at the determination of mathematical equations of modeling of the leaf area, since it indicates the use of leaves with different sizes, corresponding to all the phenological stages of the species, suggesting that these equations can be used throughout the cycle.

In Fig. 2, it is possible to notice that there is a linear and non-linear association between L, W and LW and OLA, in this way the linear mathematical equations of first degree, quadratic

Table 1. Models of estimation of leaf area *Acacia mangium* Willd. using leaf dimensions as length (L), width (W) and the product (LW), respectively

Denomination	Representation
Linear	$ELA = \hat{\beta}_0 + \hat{\beta}_1 x$
Quadratic	$ELA = \hat{\beta}_0 + \hat{\beta}_1 x + \hat{\beta}_2 x^2$
Power	$ELA = \hat{\beta}_0 x^{\hat{\beta}_1}$

and power were adjusted for the estimation of the leaf area of *Acacia mangium* Willd. According to Toebe et al. [11], these three models are reliable, presenting high predictive efficiency and high reliability, being used with precision in the estimation of leaf area of several crops, without the necessity of the destruction of the leaves. Corroborating this assertion, several authors have tested and adjusted these models for other species, such as *Crotalaria juncea* [8], *Litchi chinensis* Sonn. [9], *Artocarpus heterophyllus* [10], *Cucurbita moschata* [11], *Pennisetumglaucum* [12] and *Plectranthus barbatus* Andrews [13].

Table 3 describes the nine models of equations generated for the estimation of the leaf area of *Acacia mangium* Willd. through the linear dimensions of the leaf surface. Note that among those models that were generated with only a linear dimension, the coefficient of determination (R^2) values were very low, less than 0.47 for the length and not greater than 0.76 for the width. For this reason, these equation models were not adequate for estimating the leaf area of *Acacia mangium* Willd. The low correlation of these characteristics (L and W) with observed leaf area (OLA) can be related due to the irregular shape that the leaflets present (Fig. 1), which may lead to erroneous estimations of leaf area when used individually.

On the other hand, the equations based on LW presented the highest values R^2, surpassing 0.97, which according to Pompelli et al. [14] shows good accuracy of the models if the selection criterion were only the high values of R^2. However, in order to choose the best adjusted equation, it should not only be based on the values of R^2 because there may be underestimation of the leaf area leading to imprecise measurements using the equations used.

When we analyzed the comparison of the means of OLA and ELA by the student t test ($p < 0.05$), we observed that for all the models generated from a single linear dimension (L or W), there were significant results, attesting that the predictive leaf area by the models is different from the actual leaf area of the plants, or this

Table 2. Descriptive statistics with value minimum, maximum, mean, amplitude, standard deviation (SD) and coefficient of variation (CV) of the variables: length (L); width (W); product of the length and width (LW) and observed leaf area (OLA) of leaflets of *Acacia mangium* Willd

Variable	Unit	Minimum	Maximum	Mean	Amplitude	SD	CV (%)
382 leaflets were used for modeling							
L	cm	10.00	23.40	15.85	13.40	2.44	15.44
W	cm	2.80	7.70	4.71	4.90	0.97	20.62
LW	cm^2	33.00	150.80	75.34	117.80	21.53	28.58
OLA	cm^2	22.34	99.85	53.12	77.51	15.02	28.27
94 leaflets for validation							
L	cm	10.90	22.70	16.83	11.80	2.01	11.95
W	cm	2.70	5.70	3.88	3.00	0.64	16.63
LW	cm^2	36.71	122.58	66.06	85.87	16.86	25.52
OLA	cm^2	26.53	88.04	47.05	61.51	12.15	25.82

Table 3. Equation with linear adjustment of first degree, quadratic and power and its respective coefficient of determination (R^2) using the observed leaf area (OLA) as dependent variable, in function of length (L), width (W), product of length with width (LW) of leaflets of *Acacia mangium* Willd

Model	Equation	R^2
Linear	$ELA = -13.0938 + 4.1774\,(L)$	0.4636
Linear	$ELA = -10.3455 + 13.4676(W)$	0.7588
Linear	$ELA = 1.25971 + 0.68837(LW)$	0.9741
Quadratic	$ELA = -34.77086 + 6.88965(L) - 0.08286(L)^2$	0.4654
Quadratic	$ELA = -14.6376 + 15.3323(W) - 0.1942(W)^2$	0.7590
Quadratic	$ELA = -2.3619848 + 0.7868752(LW) - 0.0006189(LW)^2$	0.9747
Power	$ELA = 1.7832\,(L)^{1.2273}$	0.4564
Power	$ELA = 8.3418(W)^{1.1913}$	0.7559
Power	$ELA = 0.7946(LW)^{0.9727}$	0.9741
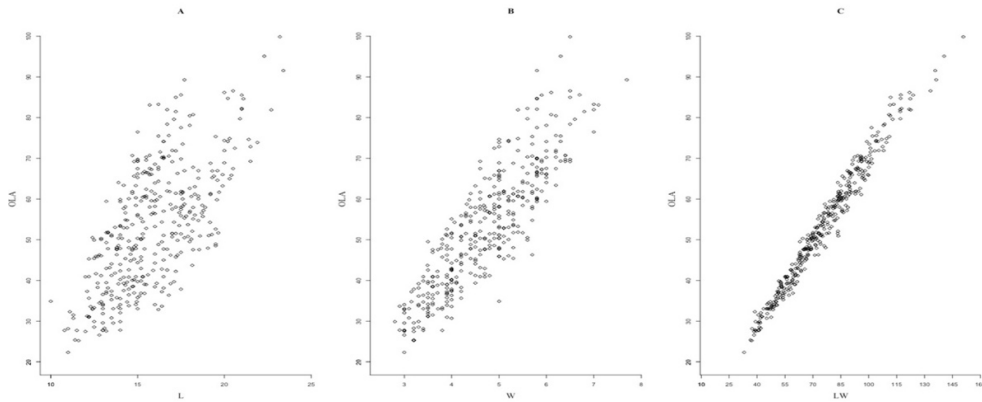
Fig. 2. Scatter plot of the actual leaf area in relation to length (L) (A), width (W) (B) and product of length with width (LW) (C)

reason, these equations were not efficient in the estimation of the leaf area of *Acacia mangium* Willd (Table 4). Therefore, models based on only one linear dimension, be it length or width, should not be used, so these equations have been eliminated.

On the other hand, the leaf area estimated by the models based on combined length and width (LW) values was similar to the actual leaf area. Although the LW based linear of first degree, quadratic and power models showed good accuracy in the prediction of the leaf area of *Acacia mangium* Willd., With identical values of 0.9952 of the index d for all three models, the power model better met the criteria of MAE and RMSE with values closer to zero indicating more precision for this model.

Thus, it is evident that the equations generated with LW presented better performance when compared to the equations based on only one dimension of the leaflet. Although the combined measures of L and W require more time to determine the leaf area of a species, this combination is the most used, due to the high precision of the generated models, reducing the error in the forecast [21]. Corroborating with this statement, in fact, the models involving the combination of linear measurements are notoriously reported as those that present better fit for several plant species as already observed for *Crotalaria juncea* [8], *Litchi chinensis Sonn*.[9], *Artocarpusheterophyllus* [10], and *Plectranthus barbatus* Andrews [13].

Therefore, we indicate the power model equation represented by $ELA = 0.7946(LW)^{0.9727}$ as the best model to estimate of the leaf area of *Acacia mangium*Willd. because it better meets the statistical criteria established in this study

Table 4. Observed Leaf Area (OLA) and estimated leaf area (ELA) of linear equations of first degree, quadratic and power for the independent variables length (L), width (W) and product of length and width (LW), besides the value of p, mean absolute error (MAE), root mean square error (RMSE) and Willmott d index of leaflets of *Acacia mangium* Willd. used for validation

Model	Variable	OLA	ELA	p* value	MAE	RMSE	d
Linear	L	47.0511	57.2021	<0.05	10.9157	12.2060	0.7201
Linear	W		41.9274	<0.05	5.9906	7.6759	0.8676
Linear	LW		46.7367	0.8562	1.2802	1.6454	0.9952
Quadratic	L		57.3705	<0.05	11.1342	12.4501	0.7079
Quadratic	W		41.8672	<0.05	6.0118	7.6599	0.87074
Quadratic	LW		46.7474	0.8622	1.3243	1.6590	0.9952
Power	L		57.1159	<0.05	10.8261	12.1207	0.7217
Power	W		42.0982	<0.05	5.9365	7.6756	0.8627
Power	LW		46.7806	0.8762	1.2794	1.6448	0.9952

*Note. *p values higher than 0.05 indicate that the observed leaf area (OLA) and the estimated leaf area (ELA) do not differ by Student t-test*
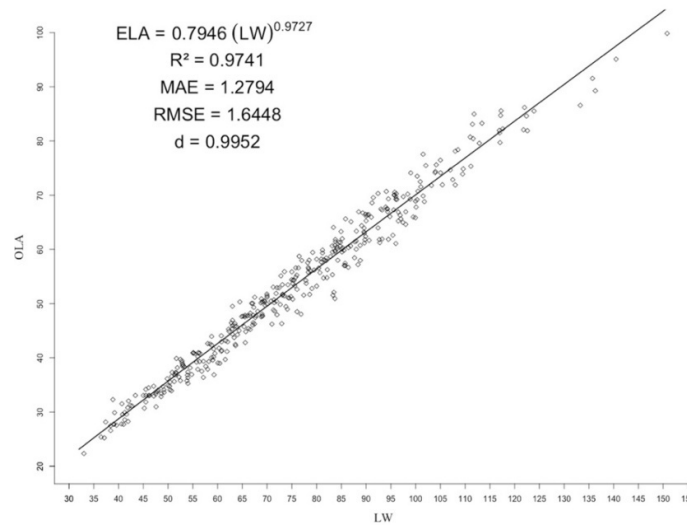
Fig. 3. Equation of power model, determination coefficient (R^2), the mean absolute error (MAE), the root mean square error (RMSE) and index d, using the foliar area observed (OLA) as dependent variable, in function of the product of the length and width (LW) of leaflets of *Acacia mangium* Willd

(Fig. 3). Developing such models required destructive sampling. However, once successfully fitted, the models can be used to non-destructively predict leaf area with only the aid of a simple equipment as a ruler.

4. CONCLUSION

The equation models generated with only a linear measure of the leaflet (L or W) were not adequate for the estimation of the leaf area of *Acacia mangium* Willd. for failing to meet the statistical parameters established in this study.

The power model equation represented by $ELA = 0.7946(LW)^{0.9727}$, where LW is the multiplication of length and width measurements, is the most adequate to predict the leaf area of *Acacia mangium* Willd. quickly and non-destructively without the need for specific equipment.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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