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CROP PRODUCTION

Allometric equations to predict the leaf area of castor bean cultivars

João Everthon da Silva Ribeiro[1*] **Ester dos Santos Côelho**[1] **Welder de Araújo Rangel Lopes**[1] **Elania Freire da Silva**[1] **Anna Kézia Soares de Oliveira**[1] **Pablo Henrique de Almeida Oliveira**[1] **Antonio Gideilson Correia da Silva**[1] **Alexandre Maniçoba da Rosa Ferraz Jardim**[2] **Daniel Valadão Silva**[1] **Aurélio Paes Barros Júnior**[1] **Lindomar Maria da Silveira**[1]

[1]Departamento de Ciências Agronômicas e Florestais, Universidade Federal Rural do Semi-Árido (UFERSA), 59625-900, Mossoró, RN, Brasil. E-mail: j.everthon@hotmail.com. *Corresponding author.
[2]Departamento de Biodiversidade, Instituto de Biociências, Universidade Estadual Paulista (UNESP), Rio Claro, SP, Brasil.

ABSTRACT: Using non-destructive and low-cost methods to determine leaf area has gained important applications. The research objectives were (i) to propose a non-destructive method to estimate the leaf area of castor bean crops and (ii) to build equations that accurately and quickly estimate the leaf area of specie. One thousand healthy and expanded leaves of five castor bean cultivars (New Zealand Purple, Sipeal, Carmencita, Amarelo de Irecê, and IAC-80) were collected, and 200 leaves were collected from each. The maximum length, maximum width, and leaf area were calculated for each leaf. The product between length and width (LW) were calculated. We performed tests with different linear and non-linear regression models between leaf area and linear leaf dimensions of each cultivar. The models used were linear, linear without intercept, and power. The criteria for choosing the best models to estimate the leaf area of castor beans were a higher coefficient of determination, more elevated Pearson's linear correlation coefficient, lower Akaike information criterion, higher Willmott agreement index, and smallest root mean square error. The equations that presented the best criteria for estimating the leaf area of castor bean cultivars were those that used the product between length and width, compared to equations that used only one leaf dimension. The model $\hat{y} = 0.439 \times LW$ can be used to accurately and quickly estimate the castor bean leaf area through linear measurements of the leaves, using the product between length and width (LW), regardless of the cultivar chosen.

Key words: biometrics, empirical modeling, linear dimensions, *Ricinus communis* L.

Equações alométricas para predição da área foliar de cultivares de mamona

RESUMO: O uso de métodos não destrutivos e de baixo custo para determinação de área foliar tem ganhado importantes aplicações. Os objetivos da pesquisa foram (i) propor um método não destrutivo para estimar a área foliar da cultura da mamona e (ii) construir equações que estimem com precisão e rapidez a área foliar da espécie. Foram coletadas mil folhas sadias e expandidas de cinco cultivares de mamona (New Zealand Purple, Sipeal, Carmencita, Amarelo de Irecê e IAC-80), sendo coletadas 200 folhas de cada uma. O comprimento máximo, largura máxima e área foliar foram calculados para cada folha. Foi calculado o produto entre comprimento e largura (LW). Foram realizados testes com diferentes modelos de regressão linear e não linear entre área foliar e dimensões lineares das folhas de cada cultivar. Os modelos utilizados foram linear, linear sem intercepto e potência. Os critérios para escolha dos melhores modelos para estimar a área foliar da mamona foram maior coeficiente de determinação, maior coeficiente de correlação linear de Pearson, menor critério de informação de Akaike, maior índice de concordância de Willmott e menor raiz do erro quadrático médio. As equações que apresentaram melhores critérios para estimativa da área foliar das cultivares de mamona foram aquelas que utilizaram o produto entre comprimento e largura, em comparação às equações que utilizaram apenas uma dimensão foliar. O modelo $\hat{y} = 0,439 \times LW$ pode ser utilizado para estimar com precisão e rapidez a área foliar da mamona por meio de medidas lineares das folhas, utilizando o produto entre comprimento e largura (LW), independente da cultivar escolhida.

Palavras-chave: biometria, modelagem empírica, dimensões lineares, *Ricinus communis* L.

INTRODUCTION

In the last decades, stimulating the cultivation of oilseed species has been associated with increased demand for essential oils for the industry (POPESCU et al., 2019). This fact favors productivity growth and the development of oilseed production on a global scale (SOARE et al., 2014). Due to population growth, the effects of environmental conditions during growth lead to more significant pressure on the supply of these food products (ATTIA et al., 2021). In a scenario of constant climate change, the leaf is the main plant organ responsible for gas exchange and light interception (GOMES et al., 2020; JARDIM et al., 2022). Furthermore, the leaf surface directly influences photosynthetic parameters, evapotranspiration, agronomic efficiency, and yield of oilseed species (TOEBE et al., 2021). TANG et al. (2018) state that leaf dimensions determine plants' photosynthetic capacity and productive potential. For agronomic and physiological studies of oilseed species, the estimation of leaf area (LA) through mathematical models helps

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to describe the relationship between growth status and dry mass production (SALAZAR et al., 2018). Some studies prove that linear leaf measurements are viable for estimating crop leaf area (RICHTER et al., 2014; SCHWAB et al., 2014).

Among the oilseed species of socioeconomic relevance, *Ricinus communis* L. (Euphorbiaceae), popularly known as castor bean or castor oil plant, has wide adaptability to adverse conditions and is easily propagated. *R. communis*, hereafter it will be referred to as castor bean, is a potential crop for the economy of semiarid regions since its oil is a renewable resource of great importance for the chemical and pharmaceutical industry (MUTLU & MEIER, 2010); furthermore, it has broad phenotypic plasticity for their cultivars, which allows their cultivation in different climate and soil conditions (CRUZ et al., 2021). The factor determining the productive success of castor beans is adjusting cultural practices for each region (YE et al., 2018). This adjustment can be mediated by its growth indicators, such as determining leaf area (POMPELLI et al., 2012; RIBEIRO et al., 2023a).

Methods for determining leaf area can be direct or indirect (TOEBE et al., 2021). Due to logistical factors, direct methods include expensive, time-consuming, and unfeasible processes (HERNÁNDEZ-FERNANDÉZ et al., 2021); another alternative is indirect methods, such as measuring LA through allometric models based on a correlation of linear leaf dimensions and LA (POMPELLI et al., 2012). This modeling allows measurement throughout the crop cycle and demonstrates morphological differences between cultivars of the same species (POMPELLI et al., 2019). Using mathematical models to estimate the LA of oilseed species eliminates the need for expensive meters (ADHIKARI et al., 2020). Furthermore, these models are characterized by their reliability, effectiveness, and speed (SUÁREZ et al., 2022). However, many leaves and leaflets are required for its validation, reducing the data variability between cultivars (HERNÁNDEZ-FERNANDÉZ et al., 2021).

Allometry has been an essential parameter for approaching agronomic and physiological studies, especially for plants of high economic value (SALAZAR et al., 2018). However, no studies for castor bean crops provide a regression model for estimating LA. This study will assist future research on castor bean cultivation, providing relevant information for research related to the growth, physiology, and reproduction of the species. In this way, we hypothesized that the leaf area differs among castor bean cultivars grown in the Brazilian semiarid region. Thus, the research objectives were (i) to propose a non-destructive method to estimate the leaf area of castor bean crops and (ii) to build equations that accurately and quickly estimate the leaf area of specie.

MATERIALS AND METHODS

The experiment was conducted in an experimental area at the Center for Agricultural Sciences, at the Universidade Federal Rural do Semi-Árido, RN, Brazil (5°12’25.26”S and 37°19’6.42”W). The region’s climate is classified as BSh (ALVARES et al., 2013), with dry and rainy seasons being dry and very hot. The annual precipitation is around 695 mm, and the temperature is approximately 28 °C. The soil in the region is classified as Eutrophic Red-Yellow Argisol (EMBRAPA - SOLOS, 2018). During the experiment, the average data for the air temperature was 28.2 °C, relative humidity was 70.5%, and rainfall was 34.5 mm. These average data were collected from the Automatic Meteorological Station (EMA) - LABIMC/UFERSA.

Castor bean cultivars were planted in March 2022. Useful plots consisted of cultivars sown in 10 m rows, with one seed per linear meter population and 1.50 m spacing between rows. Irrigation was carried out daily using drip tapes, with a daily water depth of 10 mm plant^{-1}. At 167 days after planting the cultivars, at the beginning of the first bunch formation, 1,000 healthy and expanded leaves were collected. Leaves were collected from five castor bean cultivars (200 leaves of each cultivar): New Zealand Purple, Sipeal, Carmencita, Amarelo de Irecê and IAC-80 (Figure 1). Sheets were selected of different sizes, thicknesses and shapes to test the model’s generality. After collection, the leaves were kept in the shade and stored in thermal

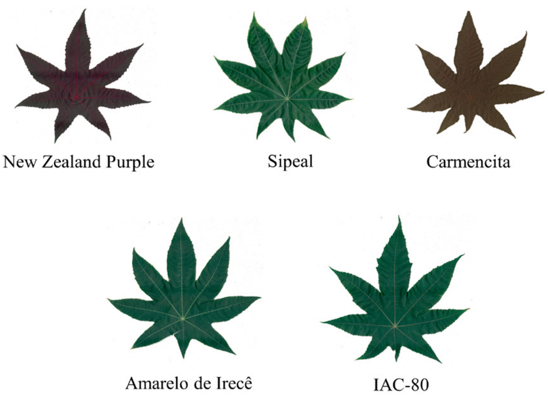

Figure 1 - Representative leaves of castor bean cultivars.

containers to avoid water loss through transpiration, maintaining turgor. The leaves were separated and scanned in a flatbed scanner (Epson, Model L380). The scanned images were processed, contrasted, and analyzed with the software ImageJ® (https://imagej.nih.gov/ij/). When scanning the images, we used a white background surface and a graduated scale as reference indicators. We used a white background surface and a graduated scale as reference indicators. For each sample (one leaf), the maximum length (L, in cm), maximum width (W, in cm), and leaf area (LA, in cm²) were calculated. Then, the product was calculated between length and width (LW, in cm²).

A unidirectional variance analysis was performed, and then the honestly significant difference (HSD) was made by the Tukey test at 5% probability to compare the leaf parameters between cultivars (e.g., L, W, LW, and LA). The degree of collinearity between the parameters was evaluated to verify whether or not there is accuracy in the estimates of regression coefficients between L and W. Therefore, the variance inflation factor (VIF) (Equation 1) (MARQUARIDT, 1970) and the tolerance value (T) (Equation 2) (GILL, 1986) were calculated. If the VIF is greater than 10 and the T is less than 0.1, it indicates that L and W have multicollinearity and may affect the estimation of the leaf area. One of these two parameters must be disregarded to fit regression models to estimate leaf area (GILL, 1986).

$$VIF = \frac{1}{1-r^2} \tag{1}$$

$$T = \frac{1}{VIF} \tag{2}$$

where r is the correlation coefficient between L and W.

Tests were performed with different linear and nonlinear regression models between the leaf area (LA) (dependent variable) and the linear dimensions of the leaf (L, W, LW, LL, and WW) (independent variables) of each cultivar. Then the test was performed with the grouped data (all cultivars). Twenty-five models were selected, which presented satisfactory criteria to estimate the leaf area of the castor bean. Logarithmic and polynomial models from second to fifth order were excluded. The models used were linear ($\hat{y} = \beta_0 + \beta_1 x$), linear without intercept ($\hat{y} = \beta_1 x$), and power ($\hat{y} = \beta_0 + x^{\beta 1}$). $\hat{y}$ corresponds to the estimated value of leaf area (LA) as a function of x which corresponds to the linear dimensions of the leaf (L, W, and LW). The following hypotheses were tested: H_0: $\beta_0 = 0$ versus H_a: $\beta_0 \neq 0$ and H_0: $\beta_1 = 0$ versus H_a: $\beta_1 \neq 1$ from Student's t-test at 5% probability, where β_0 and β_1 are regression coefficients. β_0 corresponds to the intercept coefficient, and β_1 is the angular or slope coefficient of the line.

The criteria for choosing the best models to estimate castor bean leaf area were the highest coefficient of determination (R²) (Eq. 3), Pearson's linear correlation coefficient (r) (Eq. 4) and Willmott's concordance index (*d*) (Eq. 5) (WILLMOTT, 1981), and minor Akaike Information Criterion (AIC) (AKAIKE, 1974), and Root Mean Square Error (RMSE) (Eq. 7) (JANSSEN & HEUBERGER, 1995).

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y'_i)^2} \tag{3}$$

$$r = \frac{\sum_{i=1}^{n} (y_i - \overline{y})(x_i - \overline{x})}{\sqrt{\sum_{i=1}^{n} (y_i - \overline{y})^2 \sum_{i=1}^{n} (x_i - \overline{x})^2}} \tag{4}$$

$$d = 1 - \frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{\sum_{i=1}^{n} (|\hat{y}'_i| + |y'_i|)^2} \tag{5}$$

$$AIC = -2 \ln L(x \setminus \hat{\theta}) + 2(N) \tag{6}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \tag{7}$$

where $\hat{y}_i$: estimated values of leaf area; y_i: estimated values of leaf area; $\overline{y}_i$: average of observed values; $\hat{y}'_i = \hat{y}i - \overline{y}; y'_i = y_i - \overline{y}$; $L(x \setminus \hat{\theta})$: maximum likelihood function in the model; *N*: number of the independent parameters in the model; *n*: observation numbers; x_i and y_i: i-th observations of the variables y and x; $\overline{y}$ and $\overline{x}$: averages of the variables y and x.

Descriptive statistics of the data were calculated for each leaf parameter. Data normality was verified by the Shapiro-Wilk test (SHAPIRO & WILK, 1965). Principal component analysis (PCA) was performed to verify the association between cultivar morphology and between leaf dimensions (L, W, LW, and LA), seeking to reduce the dimensionality of the database. A 10-fold cross-validation was used to avoid overfitting and test the predictive ability of models fitted on unevaluated leaves. The leaf area observed and estimated was compared to each other by the Student's t-test for paired samples ($P < 0.01$). Statistical data analyses were performed with the software R® v.4.1.2 (R CORE TEAM, 2022), with the help of the packages 'caret' (KUHN et al., 2020) and 'hydroGOF' (ZAMBRANO-BIGIARINI, 2020).

RESULTS AND DISCUSSION

This study proposes a nondestructive method to estimate the leaf area of castor bean cultivars, seeking a single model that accurately estimates the leaf area of five cultivars. Therefore, we observed that the cultivars showed little intraspecific difference in leaf morphology, evidencing the possibility of indicating a single model to estimate the leaf area of castor bean culture. The high number of samples with leaves of different shapes and sizes used in this study (n = 1,000 leaves) provided a high variation of the data for constructing models that value the leaf area of the castor bean (Figure 2). The leaves of castor bean cultivars presented length ranges (L) between 11.5 to 41.5 cm (New Zealand Purple), 2.6 to 37.6 cm (Sipeal), 2.3 to 44.6 cm (Carmencita), 3.8 to 40.1 cm (Amarelo de Irecê), and 6.1 to 40.0 cm (IAC-80) (Figure 2a). The width ranges (W) of the leaves were from 14.1 to 39.7 cm (New Zealand Purple), 2.6 to 36.9 cm (Sipeal), 3.8 to 47.0 cm (Carmencita), 3.3 to 41.1 cm (Amarelo de Irecê), 6.0 to 42.3 cm (IAC-80) (Figure 2b). In addition, the product between length and width (LW) of the leaves varied between 162.4 and 1591.8 cm^2 (New Zealand Purple), 7.1 and 1075.6 cm^2 (Sipeal), 14.1 and 20 25.1 cm^2 (Carmencita), 12.8 and 1606.3 cm^2 Amarelo de Irecê), and 36.8 and 1555.0 cm^2 (IAC-80) (Figure 2c). The leaf area averaged 284.5±115.5 cm^2, 264.8±119.1 cm^2, 240.0±191.3 cm^2, 240.5±160.4 cm^2, and 340.7±141.4 cm^2 for New Zealand Purple, Sipeal, Carmencita, Amarelo de Irecê, and IAC-80, respectively (Figure 2d). In this study, the lowest coefficients of variation were recorded for length ($20.5\% \leq L \leq 39.8\%$) and leaf width ($19.5\% \leq W \leq 42.2\%$), and the highest data variability was observed for the product between length and width ($39.9 \leq LW \leq 80.0$), and real leaf area ($38.4 \leq LA \leq 79.1$) (Figure 2).

The wide variability of the data observed for the product between length and width (LW) and leaf area (LA) is of great relevance for studies with the estimation

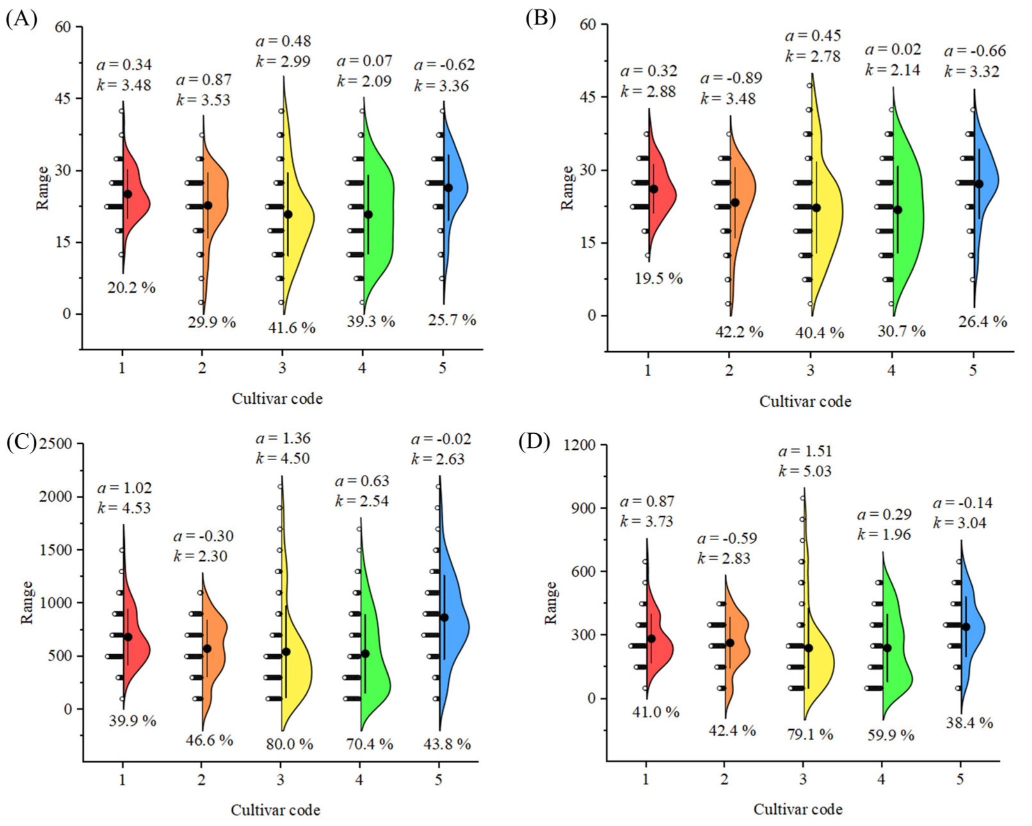

Figure 2 - Descriptive analysis of length (a), width (b), the product between length and width (c), and leaf area (d) of castor bean cultivars. Each violin's upper and lower extremities represent quartiles 1/4 and 3/4; the horizontal line of each box refers to the median. The distribution of upper and lower points to violins represents the data set's extreme values (maximum and minimum). The symbols (·) within the violins represent the averages of the cultivars. The numbers below the points refer to the coefficients of variation. The data above the topics refer to asymmetry (*a*) and kurtosis (*k*) coefficients. Cultivars code: 1: New Zealand Purple; 2: Sipeal; 3: Carmencita; 4: Amarelo de Irecê; 5: IAC-80.

of leaf area using allometric models (RIBEIRO et al., 2020a; FANOURAKIS et al., 2021). This high sample amplitude provides greater representativeness of the regression models and high precision of the constructed equations, which can be used to estimate the leaf area of leaves of different sizes and morphotypes during the plant life cycle. Although, castor bean cultivars were cultivated in only one experimental area, the number of leaves collected (1,000) was adequate for constructing allometric equations that determine the leaf area as a function of linear leaf dimensions. ANTUNES et al. (2008) and POMPELLI et al. (2012) confirmed that a small number of samples (< 200 leaves/leaflets) for allometric modeling could generate biased and unreliable equations to estimate the leaf area of plant species.

The values of kurtosis coefficients (*k*) of leaf parameters (L, W, LW, and LA) showed different distributions of data for each cultivar, with mesokurtic curves (*k* = 3.26), platykurtic (*k* > 3.26) and leptokurtic (*k* < 3.26) (Figure 2). In addition, we observed the linear and nonlinear association patterns between L, W, LW, and LA in the data sampled to be used in constructing regression models to estimate the leaf area of the castor bean (Figure 3). Linear patterns were observed between LW and LA, and not linear between L and LA, and W and LA, thus confirming the need to test different models to adjust and validate leaf dimensions data (TOEBE et al., 2021).

Our results showed that the variance inflation factor (VIF) varied between 0.01 and 0.40 (< 10), while the tolerance (T) values varied between 2.47 and 57.72 (> 0.10). The preliminary analysis to calibrate the models showed that the collinearity between L and W was considered negligible, indicating that these parameters can be used in regression models to estimate the leaf area of the castor bean (GILL, 1986; FANOURAKIS et al., 2021). The regression models obtained to estimate the leaf area of castor bean cultivars showed coefficients of determination ranging from 0.8310 to 0.9973 (New Zealand Purple), 0.8308 and 0.9915 (Sipeal), 0.8403 and 0.9923 (Carmencita), 0.8217 and 0.9838 (Amarelo de Irecê), 0.8178 and 0.9968 (IAC-80) (Table 1). Also, the accuracy criteria for choosing the best models indicated that model #10 is not recommended to estimate the leaf area of any castor bean cultivar because it recorded the lowest coefficients of determination - R^2 (0.8479), linear correlation coefficients - *r* (0.8901), and Willmott agreement index - *d* (0.9402), and higher Akaike information criteria - AIC (7593.33) and root mean square error - RMSE (53.32) (Table 1).

The equations that presented the best criteria for estimating the leaf area of castor bean

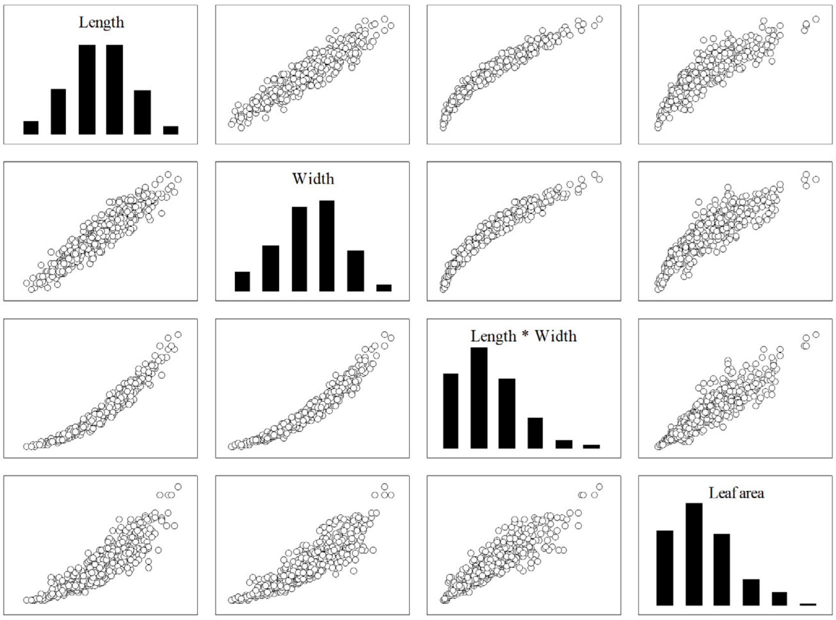

Figure 3 - Histograms (diagonal) and scatter plots between length (L), width (W), the product between length and width (LW), and leaf area (LA) of 1000 leaves (grouped data) were used to generate models to estimate the leaf area of castor bean.

Table 1 - Models, regression coefficients (β_0 and β_1), coefficient of determination (R^2), Pearson's linear correlation coefficient (r), Akaike information criterion (AIC), Willmott agreement index (*d*), root mean square error (RMSE), and equations for estimating leaf area of castor bean cultivars as a function of linear leaf dimension.

Equation code	Models	Coefficients		R²	r	AIC	*d*	RMSE	Equations
		β_0	β_1						
New Zealand Purple									
#1	Linear	-265.45	21.87	0.9292	0.9642	1341.2	0.9814	30.53	$\hat{y} = -265.45 + 21.87 \times L$
#2	Linear	-294.2	22.10	0.9224	0.9607	1353.8	0.9796	31.96	$\hat{y} = -294.2 + 22.10 \times W$
#3	Linear	-11.36	0.434	0.9823	0.9911	1149.5	0.9955	15.24	$\hat{y} = -11.36 + 0.434 \times LW$
#4	Linear (0.0)	---	0.419	0.9973	0.9690	1157.1	0.9950	15.78	$\hat{y} = 0.419 \times LW$
#5	Power	0.528	1.939	0.9481	0.9737	1299.2	0.9737	26.22	$\hat{y} = 0.528 \times L^{1.939}$
#6	Power	0.310	2.076	0.9421	0.9706	1314.4	0.9849	27.70	$\hat{y} = 0.310 \times W^{1.939}$
#7	Power	0.316	1.042	0.9827	0.9913	1147.4	0.9956	15.13	$\hat{y} = 0.316 \times LW^{1.042}$
Sipeal									
#1	Linear	-98.79	15.96	0.8317	0.9126	1362.9	0.9529	48.50	$\hat{y} = -98.79 + 15.96 \times L$
#2	Linear	-94.00	15.35	0.8566	0.9261	1342.4	0.9603	44.77	$\hat{y} = -94.00 + 15.35 \times W$
#3	Linear	15.63	0.434	0.9523	0.9760	1201.5	0.9877	25.81	$\hat{y} = 15.63 + 0.434 \times LW$
#4	Linear (0.0)	---	0.457	0.9915	0.9760	1207.6	0.9886	26.64	$\hat{y} = 0.457 \times LW$
#5	Power	2.313	1.506	0.8367	0.9147	1360.4	0.9530	48.02	$\hat{y} = 2.313 \times L^{1.506}$
#6	Power	2.211	1.507	0.8649	0.9300	1336.1	0.9618	43.67	$\hat{y} = 2.211 \times W^{1.507}$
#7	Power	0.818	0.911	0.9537	0.9766	1198.5	0.9880	25.52	$\hat{y} = 0.818 \times LW^{0.911}$
Carmencita									
#1	Linear	-193.91	20.75	0.8983	0.9439	1763.5	0.9704	62.98	$\hat{y} = -193.91 + 20.75 \times L$
#2	Linear	-189.82	19.27	0.8946	0.9461	1757.1	0.9716	61.72	$\hat{y} = -189.82 + 19\ 27 \times W$
#3	Linear	2.914	0.436	0.9802	0.9901	1491.6	0.9950	26.81	$\hat{y} = 2.914 + 0.436 \times LW$
#4	Linear (0.0)	---	0.439	0.9923	0.7722	1554.6	0.8743	83.38	$\hat{y} = 0.439 \times LW$
#5	Power	0.543	1.952	0.9490	0.9742	1643.5	0.9868	43.08	$\hat{y} = 0.543 \times L^{1.952}$
#6	Power	0.428	1.983	0.9591	0.9793	1609.8	0.9895	38.72	$\hat{y} = 0.428 \times W^{1.983}$
#7	Power	0.427	1.004	0.9804	0.9901	1493.5	0.9950	26.80	$\hat{y} = 0.427 \times LW^{1.004}$
Amarelo de Irecê									
#1	Linear	-151.6	18.78	0.9266	0.9628	1623.5	0.9807	43.18	$\hat{y} = -151.6 + 18.78 \times L$
#2	Linear	-132.14	17.04	0.8985	0.9482	1674.1	0.9727	50.79	$\hat{y} = -132.14 + 17.04 \times W$
#3	Linear	18.262	0.423	0.9515	0.9756	1558.9	0.9875	35.10	$\hat{y} = 18.262 + 0.423 \times LW$
#4	Linear (0.0)	---	0.446	0.9838	0.9756	1570.2	0.9871	36.64	$\hat{y} = 0.446 \times LW$
#5	Power	1.187	1.720	0.9346	0.9667	1608.0	0.9822	41.08	$\hat{y} = 1.187 \times L^{1.720}$
#6	Power	1.293	1.667	0.9113	0.9546	1654.7	0.9757	47.73	$\hat{y} = 1.293 \times W^{1.667}$
#7	Power	0.998	0.881	0.9575	0.9785	1540.9	0.9887	33.13	$\hat{y} = 0.998 \times LW^{0.881}$
IAC-80									
#1	Linear	-179.95	19.68	0.8976	0.9478	1290.9	0.9726	44.89	$\hat{y} = -179.95 + 19.68 \times L$
#2	Linear	-161.08	18.43	0.8812	0.9392	1309.1	0.9677	48.35	$\hat{y} = -161.08 + 18.43 \times W$
#3	Linear	21.088	0.419	0.9815	0.9907	1080.6	0.9953	19.10	$\hat{y} = 21.08 + 0.419 \times LW$
#4	Linear (0.0)	---	0.442	0.9968	0.9907	1100.6	0.9947	20.88	$\hat{y} = 0.442 \times LW$
#5	Power	1.326	1.683	0.9114	0.9546	1274.1	0.9762	41.93	$\hat{y} = 1.326 \times L^{1.686}$
#6	Power	1.543	1.623	0.8943	0.9456	1295.8	0.9712	45.79	$\hat{y} = 1.543 \times W^{1.623}$
#7	Power	0.728	0.927	0.9817	0.9908	1080.2	0.9953	19.06	$\hat{y} = 0.728 \times LW^{0.927}$
Pooled data									
#1	Linear	-168.14	19.06	0.8893	0.9431	7537.5	0.9699	51.30	$\hat{y} = -168.14 + 19.06 \times L$
#2	Linear	-161.08	17.98	0.8833	0.9399	7574.4	0.9681	52.66	$\hat{y} = -161.08 + 17.98 \times W$
#3	Linear	10.101	0.427	0.9681	0.9839	6684.8	0.9918	28.01	$\hat{y} = 10.101 + 0.427 \times LW$
#4	Linear (0.0)	---	0.439	0.9919	0.9839	6663.3	0.9918	27.55	$\hat{y} = 0.439 \times LW$
#5	Power	0.818	1.823	0.9222	0.9603	7290.3	0.9794	43.03	$\hat{y} = 0.818 \times L^{1.823}$
#6	Power	0.780	1.814	0.9191	0.9587	7318.1	0.9785	43.89	$\hat{y} = 0.780 \times W^{1.814}$
#7	Power	0.570	0.961	0.9780	0.9839	6664.5	0.9918	27.57	$\hat{y} = 0.570 \times LW^{0.961}$

cultivars were those that used the product between length and width, compared with equations that used only one leaf dimension (RIBEIRO et al., 2018, 2019, 2023a; SUÁREZ et al., 2022; AMORIM et al., 2024). Thus, seeking greater practicality in the analyses, the leaf area can be estimated using only one leaf dimension. However, using these equations with only one dimension can cause less precision with the minor fitting of the regression models. To estimate the leaf area of each cultivar individually, equations #4 and #7, constructed from the linear models without intercept and power, using the product between length and width (LW), are the most indicated to estimate the leaf area with greater precision (> 95%) (Table 1). Other models, such as #3, can also be used to individually estimate the leaf area of cultivars with an accuracy greater than 90% (Table 1).

In the principal component analysis (PCA), the first two axes corresponded to 43.89 and 93.90 (axis 1) and 21.91 and 3.73% (axis 2) of total inertia, with a total concentration of 65.80 and 97.63% about data variability (Figure 4A and 4B). There was grouping among the cultivars, indicating that they have similar phylogenetic characteristics (Figure 4A and Figure 4C). Thus, this analysis showed that leaf morphotypes of castor bean cultivars showed slight variation among themselves, with low morphological variation (Figure 4C).

In addition to the equations proposed to estimate the leaf area of cultivars individually, it was possible through criteria and results obtained to create a generalized equation to estimate the leaf area of the castor bean, regardless of the cultivar, being the linear model without intercept $\hat{y} = 0.439 \times LW$

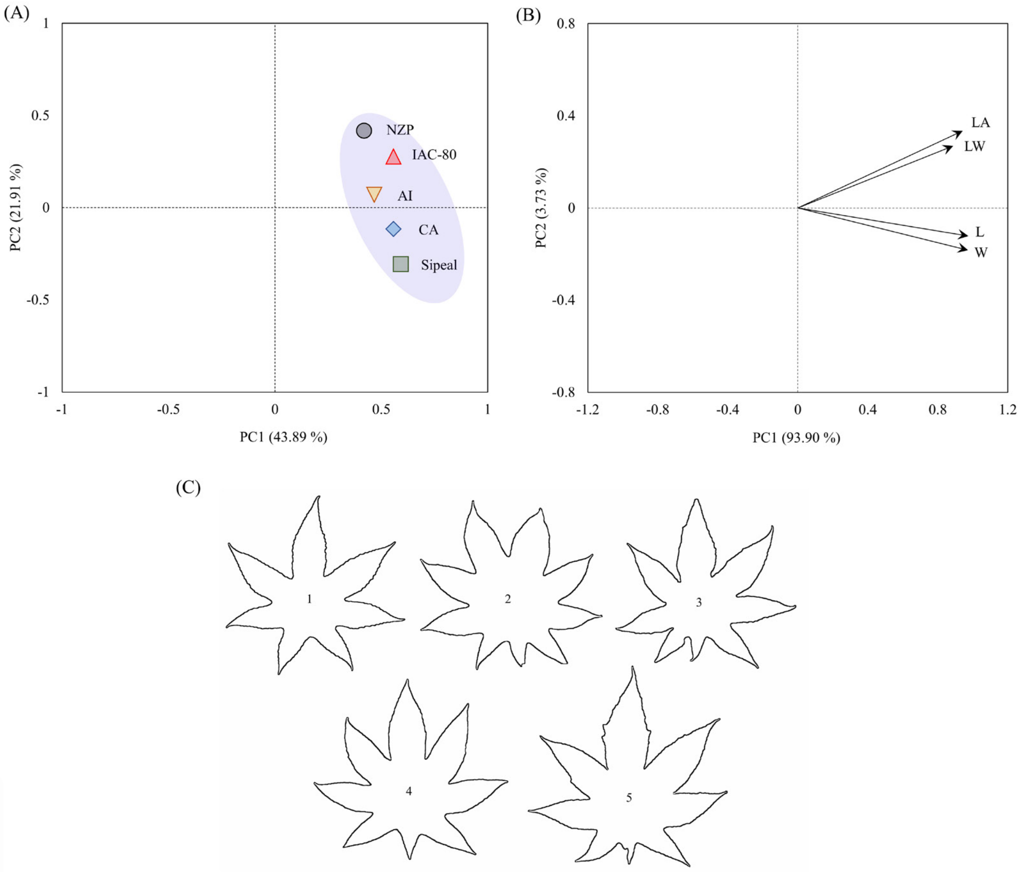

Figure 4 - Principal component analysis (PCA) of leaf parameters of five castor bean cultivars. The large circle represents the grouping formed by the Euclidean distance of similarity. (b) Loading plot between length, width, the product between length and width, and leaf area of castor bean cultivars. (c) Design of leaf morphotypes of castor bean cultivars: (1) New Zealand Purple (NZP); (2) Sipeal; (3) Carmencita (CA); (4) Amarelo de Irecê (AI); and (5) IAC-80.

using the product between length and width (LW), the most indicated to estimate the leaf area (accuracy greater than 99%), independent of the cultivar (Table 1). Other researchers also indicated this model to estimate the leaf area of other species, such as *Erythrina velutina* Willd. (RIBEIRO et al., 2022), *Ceiba glaziovii* (Kuntze) K.Schum. (RIBEIRO et al., 2020b), *Crotalaria juncea* L. (CARVALHO et al., 2017), *Tectona grandis* L. f. (BRAGA et al., 2018), *Erythroxylum simonis* Plowman (RIBEIRO et al., 2018), and *Cassia fistula* L. (RIBEIRO et al., 2023b), due to the greater precision and speed in the determination of the leaf area.

The model proposed to estimate the leaf area of the castor bean had a high adjustment of the data about the straight obtained ($R^2 = 0.99$), in which the residual variance was homogeneous, with normal distribution and low dispersion of the data (Figure 5). The leaf area estimated using the recommended model had a strong positive correlation with the observed leaf area (real leaf area measured by digital images), with a coefficient of determination of 0.9681 and a correlation coefficient of 0.9782, indicating a significant relationship between these parameters (Figure 6A). No significant differences existed between the values of the estimated leaf area and the leaf area observed (Figure 6B).

Therefore, the model $\hat{y} = 0.439 \times LW$ can be used to accurately and quickly estimate the leaf area of the castor bean using linear dimensions of the leaves, using the product between length and width, regardless of the cultivar chosen. The indicated equation can estimate the leaf area of castor bean cultivars at different stages of crop growth throughout the cycle. Thus, the data of this research will be of great importance for researchers who seek to evaluate the growth and physiology of this species under different environmental conditions and planting conditions, making it possible to determine the leaf area of this species using a non-destructive method.

CONCLUSION

The leaf area of castor bean cultivars can be estimated by a nondestructive method from allometric models using linear leaf dimensions. Regardless of the cultivar, the leaf area of the castor

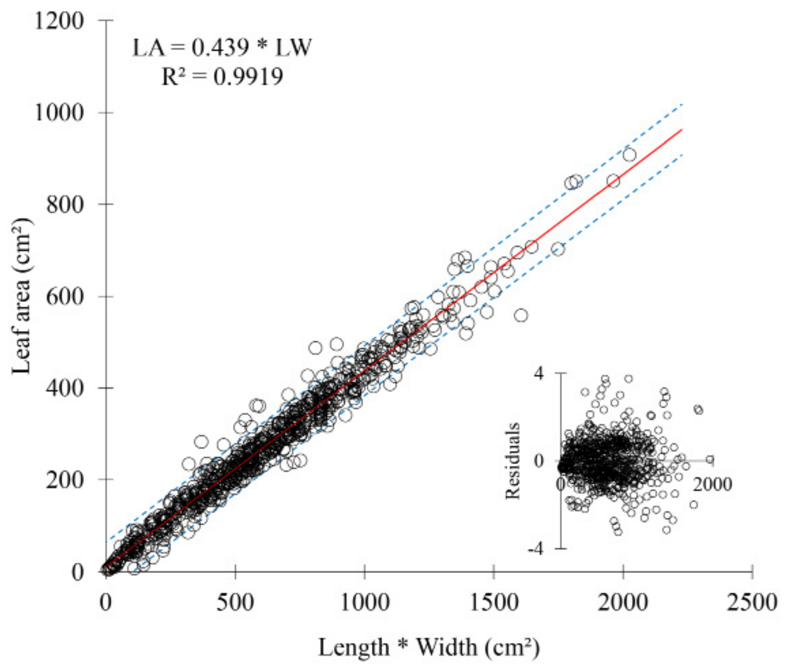

Figure 5 - Relationship between leaf area observed and product between length and width (LW) of castor bean leaves (grouped data), from the model LA = 0.439 × LW. The insertion presents the analysis of the residues' dispersion pattern. LW: product between length and width; LA: leaf area.

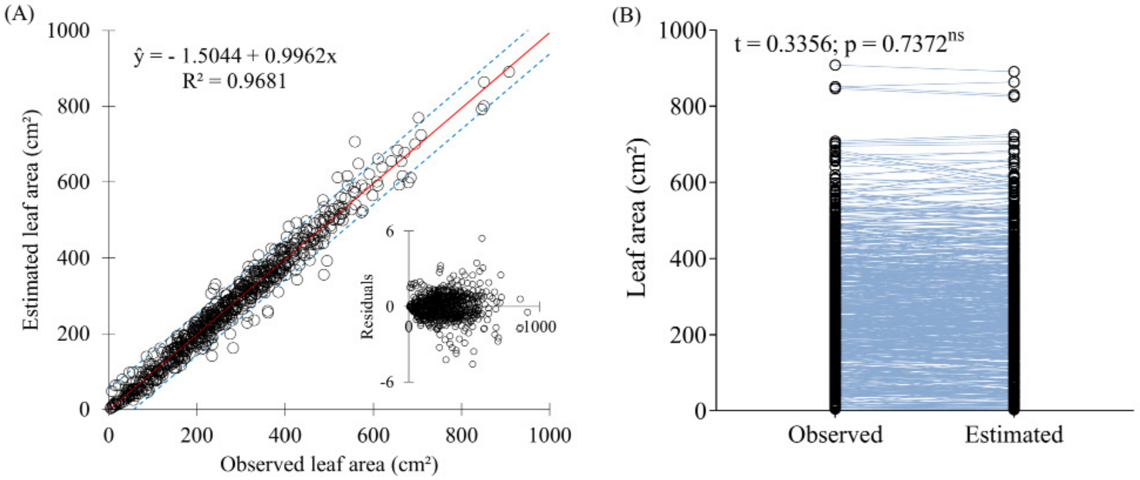

Figure 6 - Relationship between leaf area observed and estimated by the model as a function of the product between length and width (a). The insertion presents the analysis of the residues' dispersion pattern. Leaf areas observed and estimated (b) compared to each other by student's t-test ($P < 0.01$).

bean can be estimated with the linear model without intercept ŷ = 0.439 × LW using the product between the length and width of the leaves. Using this model will allow successive and accurate measurements of the leaf area of castor bean, being possible to perform measurements on the same leaves or plants during the crop cycle.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript.

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