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BASIC AREAS - Article

Models for leaf area estimation in dwarf pigeon pea by leaf dimensions

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ABSTRACT: This study aims to determine the most suitable model to estimate the leaf area of dwarf pigeon pea in function of the leaf central leaflet dimension. Six samplings of 200 leaves were performed in the first experiment, at 36, 42, 50, 56, 64, and 72 days after emergence (DAE). In the second experiment, seven samplings of 200 leaves were performed at 29, 36, 43, 49, 57, 65, and 70 DAE, totaling 2600 leaves. The length (L) and width (W) of the central leaflet were measured in all leaves composed by left, central, and right leaflets, the product of length times width (LW) was calculated, and the leaf area (Y – sum of left, central, and right leaflet areas) was determined by digital images. Linear, power, quadratic, and cubic models of Y as function of L, W, and LW were built using data from the second experiment. Leaves from the first experiment were used to validate the models. In dwarf pigeon pea, the linear ($\hat{Y} = -0.4088 + 1.6669x$, $R^2 = 0.9790$) is preferable, but power ($\hat{Y} = 1.6097x^{1.0065}$, $R^2 = 0.9766$), quadratic ($\hat{Y} = -0.3625 + 1.663x + 0.00007x2$, $R^2 = 0.9790$), and cubic ($\hat{Y} = 0.7216 + 1.522x + 0.005x^2 - 5E{-}05x^3$, $R^2 = 0.9791$) models in function of LW are also suitable to estimate the leaf area obtained by digital images. The power model ($\hat{Y} = 5.2508x^{1.7868}$, $R^2 = 0.95$) based on the central leaflet width is less laborious because requires only one variable, but it presents accuracy reduction.

Key words: *Cajanus cajan* (L.) Millsp, modeling, non-destructive method.

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INTRODUCTION

The dwarf pigeon pea (*Cajanus cajan* (L.) Millsp) is a native species from the African continent, belonging to the Fabaceae family. In Brazil, it can be cultivated from the north to the south region due to its rusticity and proper adaptation to the tropical and subtropical climate. It is used for animal feed as green forage, hay or silage; for grain production intended for human and animal consumption, or as a soil cover crop. In study developed by Pereira et al. (2012), the authors reported a yield of 21.25 $t \cdot ha^{-1}$ of fresh matter and 8.7 $t \cdot ha^{-1}$ of dry matter. In a research performed by Cavalcante et al. (2012), seeking to study the accumulation of nutrients in the dry matter and the nutrient extraction of soil cover crops, the dwarf pigeon pea presented nitrogen accumulation in the dry matter of the aerial part of 26.5 $g \cdot kg^{-1}$ and extraction of 107.2 $kg \cdot ha^{-1}$, demonstrating the potential of biological nitrogen fixation when used as a cover crop for green manure.

Crop traits such as leaf area are important in plant growth studies (Moraes et al. 2013), since it presents a positive correlation with the solar radiation interception rate, the photosynthetic rate, and the dry matter produced by the plant (Porras et al. 1997). The implementation of appropriate crop management practices, such as the selection of plant density at sowing time, fertilization times, pesticides application, and performing cuts are related to the crop leaf area at certain times of its cycle (Silva et al. 2011).

The determination of leaf area can be performed by means of different methods, which can be direct, when the measurement is performed directly on the leaves, or indirect, when the leaf area is estimated by equations that correlate a measured variable with the actual leaf area, or even using measuring instruments such as leaf area integrators and ceptometer (Keane et al. 2005). However, the use of such equipment can often make the procedure more costly and laborious, since it is expensive and requires constant calibration.

Direct and indirect methods can be either destructive or non-destructive. Leaf removal from the plants is necessary in destructive methods, requiring larger experiments. The leaf removal makes it impossible to follow the development of the leaves during the crop development cycle. In addition, leaf removal reduces the photosynthetic area of the plant and, as a consequence, may decrease photosynthetic rate and plant development (Chabot and Hicks 1982). Meanwhile, in non-destructive methods, the measurement of traits is performed directly in the plant, without the necessity of collecting the leaves, causing minor disturbances to the plant. Among the non-destructive methods, models that use foliar dimensions and digital images stand out because of the high precision, simplicity presented, and low cost (Flumignan et al. 2008).

The use of leaf area models based on the measurement of leaf size in the field is a simple and fast method that can be used to evaluate a large number of leaves. In this method there is no need of acquisition and use of expensive equipment and, especially, the leaf destruction (Peksen 2007; Demirsoy 2009; Rouphael et al. 2010).

Models relating linear measures (leaf length, leaf width, or the product of length times width) with the leaf area determined by means of digital images were developed for crops, such as forage turnip (Cargnelutti Filho et al. 2012a), sunn hemp (Cardozo et al. 2011) and jack bean (Toebe et al. 2012a). Leaf area models have also been developed for the pigeon pea, no definition of cultivar (Fakir et al. 2013) and pigeon pea, cultivar BRS Mandarim (Cargnelutti Filho et al. 2015a). However, the extrapolation of these models to other cultivars causes doubt about the possibility of estimating the leaf area with accuracy, making it necessary to develop the models for the other cultivars. There are no reports in the literature regarding models of leaf area estimation for the dwarf pigeon pea, which is smaller height than pigeon pea. We assumed that is possible to determine models to estimate the leaf area of dwarf pigeon pea as a function of the dimensions of the central leaflet of the leaf. Thus, the objective of this study was to determine the most suitable model to estimate the leaf area of dwarf pigeon pea in function of the leaf central leaflet dimension.

MATERIAL AND METHODS

Two experiments (uniformity trials, without treatments) with dwarf pigeon pea (*Cajanus cajan* (L.) Millsp), cultivar Iapar 43 (Aratã) were carried out in an experimental area of 1,080 m² (30 m × 36 m) located at lat 29°42'S, long 53°49'W, and 95 m of altitude during the agricultural year of 2015/2016. According to Köppen climate classification, the climate is Cfa, humid subtropical, with hot summers and no dry season (Heldwein et al. 2009). The soil is classified as d as "Argissolo Vermelho Distrófico arênico" Paleudalf (Santos et al. 2013).

The experimental area was prepared with a light harrowing and the base fertilizer composed of 25 kg·ha^{-1} of N, 100 kg·ha^{-1} of P_2O_5, and 100 kg·ha^{-1} of K_2O was incorporated. Sowing procedures in the first and second experiment were performed respectively on November 25, 2015 and December 9, 2015. Sowing was performed in rows with spacing between rows of 0.5 m, occupying an area of 540 m^2 in each experiment. The emergence in the first experiment occurred on December 8, 2015 and in the second experiment on December 15, 2015.

A total of 200 leaves were collected weekly in each experiment. For this, plants were randomly selected in the experimental area and in these plants the leaves were collected from the lower, middle, and upper thirds of plants. The samplings were performed during the growth period until the beginning of the crop flowering. Only complete and expanded leaves were collected, being considered expanded leaves the ones in which leaflets of the trifolium superior to the collected leaf no longer touched. In the first experiment, six samplings (36, 42, 50, 56, 64, and 72 DAE) were performed, totaling 1200 leaves. In the second experiment, seven samplings (29, 36, 43, 49, 57, 65 and 70 DAE) were performed, totaling 1400 leaves.

In each leaf composed by three leaflets (left, central, and right), the traits length (L) and maximum width perpendicular to the midrib (W) of the central leaflet (Figure 1) were measured using a millimeter ruler. The product of length times width (LW) of the central leaflet was calculated and then the leaves were photographed with a digital camera.

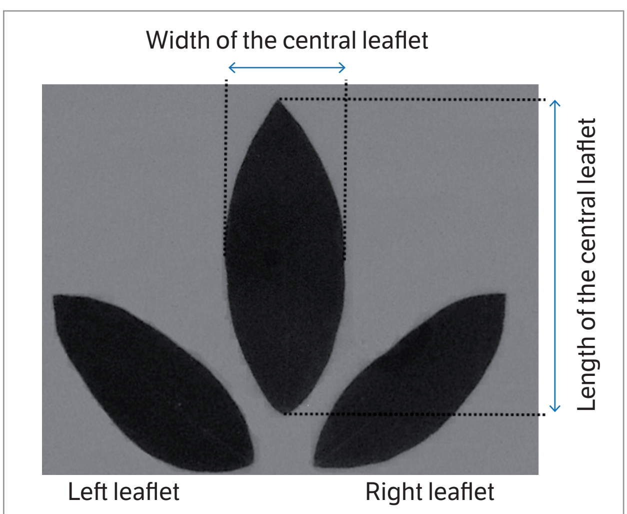

Figure 1. Graphical representation of the three leaflets (left, central, and right) of one dwarf pigeon pea (*Cajanus cajan* (L.) Millsp) leaf with the respective measurements of length (L) and width (W) of the central leaflet.

For the photographic record, the leaves were placed on paper sheets marked with known dimensions in order to be a measurement reference during the image processing. The 2600 images were processed with the help of ImageJ software in order to determine the leaf area (Y – obtained by the sum of left, central, and right leaflet areas) by the method of digital images.

The evaluations were considered independent because they were performed on distinct leaves from different plants. Thereby, it was possible to generate models of leaf area estimation for dwarf pigeon pea as a function of leaf dimensions, which can be used independently of the crop development stage.

From the data of length and width of the leaves central leaflet, the product of length times the width, and the leaf area determined by digital images of the 2600 leaves, the statistics minimum, mean, maximum, standard deviation, and coefficient of variation were calculated. With the data from the 1400 leaves from the second experiment, the leaf area (Y) determined by digital images was modeled as a function of L, W, and LW using the following models: linear ($Y = a + bx$), power ($Y = ax^b$), quadratic ($Y = a + bx + cx^2$), and cubic ($Y = a + bx + cx^2 + dx^3$), totaling twelve models (four models × three independent variables).

The validation of the estimation models was performed based on data from the 1200 leaves from the first experiment. A linear regression ($\hat{Y}_i = a + bY_i$) of the leaf area estimated by the model (dependent variable) was adjusted for each model as a function of the observed leaf area (independent variable). Then, the Pearson linear correlation coefficient (r) and the coefficient of determination (R^2) among $\hat{Y}_i$ and Y_i were calculated. For each model, the mean absolute error (MAE), the root of mean square error (RMSE), and Willmott's index d (Willmott 1981) were calculated by means of equations:

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n}|\hat{Y}i - Yi|}{n} \tag{1}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\hat{Y}i - Yi)^2}{n}} \tag{2}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(\hat{Y}i - Yi)^2}{\sum_{i=1}^{n}(|\hat{Y}i - \bar{Y}| + |Yi - \bar{Y}|)^2}\right] \tag{3}$$

where $\hat{Y}_i$ are estimated values of leaf area, Y_i are observed values of leaf area by means of the method of digital images,

$\bar{Y}$ is the mean of observed values, and n is the number of leaves, being n = 1200 in the first experiment and n = 1400 in the second experiment.

The models developed for pigeon pea, no definition of cultivar (Fakir et al. 2013) and pigeon pea, cultivar BRS Mandarim (Cargnelutti Filho et al. 2015a) were tested with data from the first and second experiments in order to verify if they can be used for the dwarf pigeon pea (*Cajanus cajan* (L.) Millsp), cultivar Iapar 43 (Aratã).

As a criteria for selecting the best models of leaf area estimation of dwarf pigeon pea as a function of the central leaflet dimensions, we chose models with linear coefficient, mean absolute error, and square root of mean square error closer to zero and angular coefficient, Pearson linear correlation coefficient, coefficient of determination, and Willmott's index d closer to one. All statistical analyzes were performed using Microsoft Office Excel® software.

RESULTS AND DISCUSSION

In the 1400 leaves of dwarf pigeon pea utilized in the construction of the models, the mean, maximum, and minimum values of length (L) and width (W) of the leaves central leaflet were similar among the samplings (Table 1). The mean length was 7.46 cm (2.20 cm $\leq$ L $\leq$ 13.40 cm), the mean width was 2.95 cm (0.80 cm $\leq$ W $\leq$ 6.10 cm), and the leaf area (Y) obtained by the sum of the left, central, and right leaflet areas of each leaf presented a mean of 38.26 cm^2 (3.28 $cm^2 \leq Y \leq$ 130.12 cm^2).

Regarding the variability, the L and W traits had lower coefficients of variation (CV), respectively, 22.26% and 26.96%, when compared to LW (CV = 48.25%) and Y (CV = 49.28%). Similar results were obtained in the crops of velvet bean (Cargnelutti Filho et al. 2012b), forage turnip (Cargnelutti Filho et al. 2012a), and pigeon pea (Cargnelutti Filho et al. 2015a).

This wide variability is important for the study and it can be explained by the collection of leaves at different crop cycle stages, the trait measurements being carried out on leaves of different sizes and ages, and the large number of leaves evaluated throughout the experiment. Thus, it is possible to infer that the generated models can be used to estimate the leaf area of dwarf pigeon pea, regardless of the development stage in which the crop is found.

All leaf models of dwarf pigeon pea leaf area as a function of leaf dimensions presented a high coefficient of determination ($R^2 \geq 0.90$), indicating that they can be used satisfactorily (Table 2). The power models presented the best fit with $R^2 \geq 0.95$, followed by cubic models with $R^2 \geq 0.94$, and quadratic models with $R^2 \geq 0.93$. Researches performed by Toebe et al. (2012a) and Cargnelutti Filho et al. (2015b), respectively with jack bean and canola, observed better adjustments for power models.

The leaf area of dwarf pigeon pea is estimated more accurately by models that take into account the product of length times width of the central leaflet ($R^2 = 0.98$), followed by models using the width ($R^2 \geq 0.93$). Similar results were obtained by Antunes et al. (2008), Tsialtas et al. (2008), Mazzini et al. (2010), and Padrón et al. (2016), when studying respectively coffee, grapevine, citrus, and bell pepper with models presenting high R^2 by using the product of the leaves length times width. This can be explained due to shape differences in each leaflet, which may vary from more lanceolate to more oval. Thereby, the models that take into consideration only the length or width do not describe the behavior of the leaf area as properly as the models that use the product of the two traits multiplication.

In the validation of the models based on the 1200 leaves collected in the first experiment, the linear, power, quadratic, and cubic models in function of LW product were also the ones that best fit the established criteria: linear coefficient closer to zero, angular coefficient closer to one, Pearson linear correlation coefficient and coefficient of determination closer to one, besides the lower absolute mean error, and square root of mean square error and Willmott's index d closer to one (Table 3). Thus, it is indicated that the models of dwarf pigeon pea leaf area estimation in function of the product of the central leaflet length times the width should be preferentially used when the higher accuracy is the objective in relation to the other models that are based only on length or width of the central leaflet, as confirmed by Schwab et al. (2014) and Schmildt et al. (2015). However, the power model based on the width of the central leaflet can be used, with a small reduction of accuracy, but being less laborious, since only one measured variable is required.

The generation of models for leaf area estimation based on leaf dimensions was performed for other crops of the Fabaceae family. In snap bean, Toebe et al. (2012b) verified high coefficients of determination for quadratic ($R^2 = 0.9901$) and power models ($R^2 = 0.9883$) as a function →

Table 1. Minimum, mean, maximum, standard deviation, and coefficient of variation (CV) of the traits length, width, product of length times width of the central leaflet, and leaf area determined by digital images of dwarf pigeon pea (*Cajanus cajan* (L.) Millsp) leaves in seven samplings and in general (all samplings). These data obtained in the second experiment were used to construct the models.

Statistics	Days after emergence							
	29	36	43	49	57	65	70	General
	L – Length of the central leaflet, in cm							
Minimum	2.20	3.50	3.50	4.20	3.00	4.30	4.00	2.20
Mean	6.41	6.52	7.34	8.37	7.59	7.94	8.05	7.46
Maximum	8.90	8.80	9.40	11.90	11.70	12.40	13.40	13.40
Standard deviation	1.26	1.08	1.20	1.63	1.84	1.59	1.78	1.66
CV(%)	19.61	16.57	16.42	19.49	24.24	19.99	22.15	22.26
Number of leaves	200	200	200	200	200	200	200	1,400
Statistics	W – Width of the central leaflet, in cm							
Minimum	0.80	1.30	1.20	1.20	1.30	1.60	1.20	0.80
Mean	2.35	2.58	2.75	3.16	3.00	3.40	3.38	2.95
Maximum	3.40	3.70	3.90	4.50	5.40	6.00	6.10	6.10
Standard deviation	0.48	0.52	0.56	0.69	0.86	0.82	0.91	0.80
CV(%)	20.40	20.29	20.50	21.72	28.76	24.04	27.18	26.96
Number of leaves	200	200	200	200	200	200	200	1,400
Statistics	LW – Length times width of the central leaflet, in cm²							
Minimum	1.98	4.55	4.20	5.59	3.90	7.04	4.80	1.98
Mean	15.60	17.33	20.83	27.49	24.23	28.18	28.73	23.20
Maximum	29.04	31.82	35.88	53.55	63.18	74.40	80.40	80.40
Standard deviation	5.58	5.85	6.86	10.16	12.32	12.25	13.78	11.19
CV(%)	35.77	33.73	32.93	36.97	50.84	43.46	47.96	48.25
Number of leaves	200	200	200	200	200	200	200	1,400
Statistics	Y – Leaf area (sum of leaf area of the left, central, and right leaflets) determined by digital images, in cm²							
Minimum	3.28	7.55	7.32	8.38	5.80	11.13	8.08	3.28
Mean	25.43	28.81	35.60	45.48	40.44	45.75	46.33	38.26
Maximum	45.51	52.23	57.65	83.21	113.96	123.29	130.12	130.12
Standard deviation	8.87	9.74	11.57	17.34	21.43	21.12	23.35	18.86
CV(%)	34.89	33.82	32.50	38.13	52.99	46.16	50.40	49.28
Number of leaves	200	200	200	200	200	200	200	1,400

of the central leaflet width and concluded that they are adequate for the estimation of leaf area with precision, besides requiring the measurement of only one variable (W) in the field. In sunn hemp, Cardozo et al. (2011) concluded that the linear model based on the product of the leaf length times width was the one that presented the least error in the estimates. In the crops of jack bean (Toebe et al. 2012a), velvet bean (Cargnelutti Filho et al. 2012b), and pigeon pea (Cargnelutti Filho et al. 2015a), the best adjustments were obtained as a function of LW, using the linear, power, and quadratic models. Meantime, the authors recommend the power model as a function of only W for jack bean and velvet bean, since it requires only one measurement.

Testing the models of pigeon pea leaf area estimation (Fakir et al. 2013; Cargnelutti Filho et al. 2015a) was verified that they can be used to estimate the leaf area of pigeon pea. However, the accuracy indicators were lower →

when compared to the models developed for dwarf pigeon pea (Table 4). Therefore, it is recommended to use the leaf area models developed specifically for dwarf pigeon pea.

For the estimation of leaf area of dwarf pigeon pea, the use of linear ($\hat{Y} = -0.4088 + 1.6669x$, $R^2 = 0.98$), power ($\hat{Y} = 1.6097x^{1.0065}$, $R^2 = 0.98$), quadratic ($\hat{Y} = -0.3625 + 1.663x + 0.00007x^2$, $R^2 = 0.98$), and cubic ($\hat{Y} = 0.7216 + 1.522x + 0.005x^2 - 5E\text{–}05x^3$, $R^2 = 0.98$) →

Table 2. Models for determining the leaf area obtained by digital images (Y), using length (L), width (W), and product of length times width (LW) of the central leaflet as independent variables (x) and coefficient of determination (R^2) of each model. Models generated based on 1400 leaves of dwarf pigeon pea (*Cajanus cajan* (L.) Millsp) collected in the second experiment.

Model	Independent variable	Equation	Coefficient of determination (R^2)
Linear	L	$\hat{Y} = -39.432 + 10.374x$	0.90
Linear	W	$\hat{Y} = -28.7 + 22.735x$	0.93
Linear	LW	$\hat{Y} = -0.4088 + 1.6669x$	0.98
Power	L	$\hat{Y} = 0.4873x^{2.136}$	0.95
Power	W	$\hat{Y} = 5.2508x^{1.7868}$	0.95
Power	LW	$\hat{Y} = 1.6097x^{1.0065}$	0.98
Quadratic	L	$\hat{Y} = 5.4814 - 2.2952x + 0.8511x^2$	0.93
Quadratic	W	$\hat{Y} = -5.2517 + 6.6295x + 2.5751x^2$	0.95
Quadratic	LW	$\hat{Y} = -0.3625 + 1.663x + 0.00007x^2$	0.98
Cubic	L	$\hat{Y} = -4.0605 + 1.9274x + 0.2598x^2 + 0.0264x^3$	0.94
Cubic	W	$\hat{Y} = -1.2008 + 2.3662x + 3.9608x^2 - 0.14x^3$	0.95
Cubic	LW	$\hat{Y} = 0.7216 + 1.522x + 0.005x^2 - 5E\text{–}05x^3$	0.98

Table 3. Minimum, mean, maximum, and coefficient of variation (CV) for the traits length (L, in cm), width (W, in cm), product of length times width (LW, in cm²) of central leaflet and leaf area determined by digital images (Y, in cm²) of dwarf pigeon pea (*Cajanus cajan* (L.) Millsp) leaves. Validation of the models based on the indicators: linear (a), angular (b), Pearson linear correlation coefficient (r), and coefficient of determination (R^2), mean absolute error (MAE), root of mean square error (RMSE), and Willmott's index d (Willmott 1981) calculated on the basis of the estimated and observed leaf areas in the leaves collected from the two experiments.

Statistics	First Experiment (n = 1200 leaves)				Second Experiment (n = 1400 leaves)			
	L	W	LW	Y	L	W	LW	Y
Minimum	2.80	1.00	2.80	38.56	2.20	0.80	1.98	3.28
Mean	7.64	29.62	23.73	38.29	7.46	2.95	23.20	38.26
Maximum	11.80	48.00	54.24	88.48	13.40	6.10	80.40	130.12
CV(%)	21.61	24.10	42.15	42.21	22.26	26.96	48.25	49.28
Model	**First Experiment (n = 1200 leaves)**							
	x	**a**	**b**	**r**	**R^2**	**MAE**	**RMSE**	**d**
Linear	L	3.52	0.91	0.95	0.91	3.89	4.90	0.98
Linear	W	3.48	0.91	0.95	0.91	3.80	4.88	0.98
Linear	LW	1.81	0.95	0.98	0.95	2.83	3.51	0.99
Power	L	2.47	0.93	0.96	0.92	3.48	4.61	0.98
Power	W	2.48	0.93	0.96	0.92	3.66	4.63	0.98
Power	LW	1.50	0.96	0.98	0.95	2.84	3.51	0.99
Quadratic	L	3.07	0.92	0.96	0.92	3.51	4.57	0.98
Quadratic	W	3.12	0.92	0.96	0.92	3.63	4.61	0.98
Quadratic	LW	1.76	0.95	0.98	0.95	2.82	3.49	0.99
Cubic	L	3.02	0.92	0.96	0.92	3.48	4.54	0.98
Cubic	W	3.11	0.92	0.96	0.92	3.61	4.61	0.98
Cubic	LW	1.41	0.97	0.98	0.95	2.82	3.50	0.99

....continue

Table 3. Continuation...

Model	Second Experiment (n = 1400 leaves)							
	x	a	b	r	R^2	MAE	RMSE	d
Linear	L	4.72	0.87	0.95	0.90	4.12	5.91	0.97
Linear	W	2.63	0.93	0.97	0.93	3.73	4.94	0.98
Linear	LW	0.80	0.98	0.99	0.98	1.90	2.73	0.99
Power	L	3.20	0.90	0.97	0.93	3.38	4.81	0.98
Power	W	1.47	0.96	0.97	0.95	3.17	4.29	0.99
Power	LW	0.95	0.97	0.99	0.98	1.91	2.74	0.99
Quadratic	L	2.81	0.92	0.97	0.94	3.36	4.75	0.98
Quadratic	W	1.97	0.95	0.97	0.95	3.17	4.28	0.99
Quadratic	LW	0.80	0.98	0.99	0.98	1.90	2.73	0.99
Cubic	L	2.71	0.92	0.97	0.94	3.36	4.74	0.98
Cubic	W	1.97	0.95	0.97	0.95	3.16	4.27	0.99
Cubic	LW	0.89	0.98	0.99	0.98	1.89	2.73	0.99

models are recommended, where x is the LW. Considering the proper fit and its easier application, the linear model it is recommended in order to estimate the dwarf pigeon pea leaf area, where Y is the leaf area and x is the product of length times the width of the central leaflet. However, the power model ($\hat{Y} = 5.2508x^{1.7868}$, $R^2 = 0.95$) based on the width of the central leaflet can be used, with a small reduction of accuracy, but being less laborious, since only one measured variable is required. With the use of this model of leaf area estimation, the destruction of the leaves is avoided and it is possible to follow their development throughout the crop cycle.

CONCLUSION

For the dwarf pigeon pea (*Cajanus cajan* (L.) Millsp), the linear, power, quadratic, and cubic models are indicated for estimation of leaf area (Y) based on the product of length times the width of the central leaflet (x). The linear model ($\hat{Y} = -0.4088 + 1.6669x$, $R^2 = 0.9790$) is preferable to be used due to its simplicity. The power model ($\hat{Y} = 5.2508x^{1.7868}$, $R^2 = 0.95$) based on the width of the central leaflet can be used with a small accuracy reduction, but being less laborious because it requires only one variable.

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