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Estimation of eggplant leaf area from leaf dimensions

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Abstract

This paper explores different models of non-destructive leaf area estimates for ***Solanum melongela*** L. by the measure of leaf length (C) and blade width (L). The methodology involved eggplant cultivation in the greenhouse from March to June. Plant leaves were sampled at random throughout the growing season, totalizing 186 leaves, of which 98 were used to estimate the model parameters and 88 were used for model validation. The samples covered wide spectrum of leaf dimensions, in order to minimize root mean square error (RMSE). Leaves were sampled at 71, 79, 81, 85, 92 and 99 days after transplanting. The highest possible numbers of leaf discs were obtained with a 25mm auger. Correlations were computed between the leaf area obtained by the discs method and the linear dimensions of L and C, the product of both (CL) and the square length multiplied by the width (C^2L). Regression analyses for 20 models were tested, including quadratic, exponential, linear, logarithmic and power model, of which 12 had a high coefficient of determination (R^2) value. The quadratic model ($Y = - 5.78+0.4981CL–3.263.10^{-4}CL^2$) and the power model ($Y = 0.4395CL^{1.0055}$) showed the best estimates, with R^2 of 0.964 for both, and RMSE of 33.2 and 34.4, respectively. With only one leaf dimension the quadratic model ($Y = -63.5+10.492L+0.2822L^2$; $R^2 = 0.937$; RMSE = 44.1) is an alternative, with little impact on the precision.

Key words: ***Solanum melongela*** L., leaf area index, modeling.

Estimativa da área foliar da berinjela em função das dimensões foliares

Resumo

Este trabalho explora diferentes modelos não destrutivos de estimativa da área foliar de ***Solanum melongela*** L. através de medidas do comprimento (C) e largura (L) do limbo foliar. Para tanto, um cultivo de berinjela em estufa plástica foi conduzido no período de março a junho de 2007. Amostraram-se folhas de plantas em momentos aleatórios totalizando 186 folhas, sendo 98 utilizadas na estimativa dos parâmetros dos modelos e 88 para sua validação. As amostragens abrangeram amplo espectro de dimensões foliares, visando minimizar a raiz do quadrado médio do erro (RQME). Elas foram realizadas aos 71, 79, 81, 85, 92 e 99 dias após o transplante. Posteriormente obteve-se o maior número possível de discos foliares com o auxílio de um calador de 25 mm de diâmetro. Correlações foram realizadas entre a área foliar obtida pelo método dos discos com as dimensões lineares de L e C, o produto entre elas (CL) e o quadrado do comprimento multiplicado pela largura (C^2L). Análises de regressão para 20 modelos foram obtidas, entre quadráticos, exponenciais, lineares, logarítmicos e de potência, dos quais 12 apresentaram coeficiente de determinação (R^2) elevado. O modelo quadrático ($Y = -5,78+0,4981CL-3,263.10^{-4}CL^2$) e o da potência ($Y = 0,4395CL^{1,0055}$) apresentaram melhores estimativas, com R^2 de 0,964 para ambos e RQME de 33,2 e 34,4, respectivamente. Com a medida apenas de uma dimensão foliar, o modelo quadrático ($Y = -63,5+10,492L+0,2822L^2$; $R^2 = 0,937$; RQME = 44,1) apresenta-se como alternativa, pouco afetando a precisão da estimativa.

Palavras-chave: ***Solanum melongela*** L., índice de área foliar, modelagem.

1. INTRODUCTION

Eggplant (*Solanum melongela* L.) is a vegetable of the family Solanaceae, which also includes cultivated plants like tomatoes, peppers, potatoes, gilo, physalis, jurubeba, tobacco, wolf apple, petunia, among others of lesser economic importance. According to Oliveira et al. (2011), eggplant is grown in Brazil in areas of approximately 1500 ha, with increased consumption of fruit due to the beneficial properties to human health, being an alternative to vegetable growers. For its cultivation during autumn in certain locations, plastic greenhouses are required because of low temperatures (Heldwein et al., 2009).

Leaf area index (LAI) is an important variable when assessing growth, development and yield of a crop (Taiz and Zeiger, 2013), and is related to water requirements for irrigation purposes (Busato et al., 2010). Yield is the result of the interaction of various biotic and abiotic factors, including the trapping of light energy and its conversion into chemical energy (Favarin et al., 2002), so the leaf surface is a determinant factor of the potential yield of a crop. In turn, solar radiation interception is directly dependent on LAI of plants (Favarin et al., 2002), calculated by the ratio between leaf area and horizontal ground area occupied by it.

There are direct and indirect methods for the correct determination of leaf area (LA), which are destructive and nondestructive, respectively, and the most used is the direct method (Peksen, 2007). However, the use of these methods does not allow monitoring the evolution of LA during the development of the crop. Moreover, they are difficult and in many cases destroy a large portion of the sample (Grecco et al., 2011).

Precise LAI measurements are required to observe changes in this variable due to other factors during cultivation, such as the water deficit or excess (Taiz and Zeiger, 2013). One of the most widely used methods for non-destructive leaf area estimation is the measurement of length and width of leaves and use of this data in mathematical equations that usually reach high accuracy (Blanco and Follegati, 2005). The use of a simple and precise equation can eliminated the need for the destruction of plants, and for costly and complex leaf area integrators.

Leaf area determination from linear leaf dimensions, such as maximum length and/or width, has been performed for melon (Nascimento et al., 2002), snap bean (Queiroga et al., 2003), cucumber (Nied et al., 2001), sunflower (Rouphael et al., 2007), radish (Cargnelutti Filho et al., 2012) among others, but it is possible to obtain simpler models with only one dimension of the leaf blade (Blanco and Folegatti, 2005; Maldaner et al., 2009a; Nascimento et al., 2002; Queiroga et al., 2003). Maldaner et al. (2009b) developed a model to estimate eggplant LAI only by counting the number of leaves, but scientific studies require a higher accuracy.

Considering the leaf area as an important measure for evaluating plant growth, this study sought to generate models for estimating eggplant leaf area from indirect and non-destructive measurements of length and width of the leaf blade.

2. MATERIAL AND METHODS

The experiment was conducted from March to June 2007 in a plastic greenhouse with 240 m^2area, in the experimental area of the Department of Plant Science, Federal University of Santa Maria (29°43’23”S, 53°43’15”W and 95 m). According to Köppen, the climate of the region is Cfa, humid subtropical with hot summers (Moreno, 1961). The soil was classified as Paleudalf (EMBRAPA, 2006).

The greenhouse used is north-south oriented, with quonset design with sidewalls, maximum height of 3.50 m in the center and 2.00 m on the sides, covered with low density polyethylene film (LDPE) with 150 μm thickness. The sides were fixed with a height of 1 m above ground level with upper movable curtains. The curtains and the doors for ventilation were opened up around 07:30 am, and closed up at 5 pm, at dusk. When frost was forecasted, the green house was closed at 2 pm, while on days with strong northern wind, the green house remained closed.

After preparation and fertilization according to soil analysis, 1 m spaced ridges with about 0.10 m height and 0.30 m wide were built and covered with black plastic mulching. Seeds were sown in trays on February 12th, 2007, and seedlings were placed in a greenhouse until the date of transplantation. Transplantation of seedlings of eggplant (cv. Napoli) occurred on March 18th, 2007, when they had two expanded leaves, being grown in the 0.50 m spacing between plants in the row. Plants were conducted with two rods and supported with raffia. We also carried out a complete thinning of emerging branches in the leaf axils. The control of pests and diseases was performed whenever necessary. Irrigation in 10 rows of plants was performed by the morning through drippers, with 1.5 L h^{-1}. They were installed below the mulching and housed in small grooves in the center of the ridges to avoid water draining to the edges. The decision to irrigate or not and the amount of water to be provided on the day were defined based on the matric potential of the soil water measured with a porous cup tensiometer and mercury manometer under conditions of atmospheric water demand at the time of irrigation and plant size (Dalsasso et al., 1997).

Leaf samples were taken on six dates throughout the crop cycle, with the first collection at 71 days after transplanting (DAT), followed by samplings at 79, 81, 85, 92 and 99 DAT. With this sampling methodology, leaves of a diverse spectrum of sizes and areas were obtained, enabling the development of a more accurate model. In each leaf, we measured length (L) along the central rib, considering the distance from the leaf apex to the leaf base and the greatest width (L) perpendicular to the central rib.

A 25 mm diameter-auger was used to obtain the largest possible amount of leaf blade discs, including the ribs. The sampled discs and the rest of the blade were placed in paper bags and taken to a forced circulation oven at 65 °C for drying to constant weight. The dry mass was determined with the aid of an electronic balance with a resolution of 1 mg and accurate of 5 mg.

The total area of each blade (LA), in cm^2, was determined from the relationship between the discs dry mass (DDM), the total area of the discs (TAD) and total leaf dry mass (TDM), that is, $LA = \frac{TDM.TAD}{DDM}$. Thus, regression analyses were run between the linear dimensions (C and L), the product of these (CL), and the square of the length multiplied by the width (C^2L) with leaf area, selecting the models that presented high coefficient of determination (R^2>0.90).

The coefficients of the equations were tested for statistical significance of p>0.05.

In the six evaluations, we obtained a total of 186 leaves for the estimation of parameters and validation of models, 98 samples were used for parameter estimation, while 88 samples were used for the validation. These samples were randomly picked, from each collection. Quadratic, exponential, linear, logarithmic and power models were obtained. To evaluate the performance of the models in the test, we used the root mean square error (RMSE) and mean absolute error (MAE). RMSE was calculated according Janssen and Heuberger (1995) (Equation 1) and MAE, according to Equation 2.

$$RMSE=\sqrt{\frac{\sum_{i=1}^{n}\left(\hat{Y}_i-Y_i\right)^2}{n}} \quad (1)$$

$$MAE=\frac{\sum_{i=1}^{n}\left|\hat{Y}_i-Y_i\right|}{n} \quad (2)$$

Where $\hat{Y}_i$ is the estimated value, Y_i is the observed value and n is the number of observations.

The final model was selected on the basis of the combination of the highest R^2 and RMSE and MAE closer to zero, aiming the selection by criteria with higher relationship and smaller error between the observed and estimated values.

3. RESULTS AND DISCUSSION

It was obtained 20 models of eggplant leaf area estimation through quadratic, exponential, linear, logarithmic and power models, of which 12 resulted in a high coefficient of determination (R^2> 0.90) (Figure 1), and were excluded the models derived from logarithmic and exponential equations due to the low R^2 (< 0.90) and high RMSE (> 90).

Regressions relating the actual leaf area of eggplant with equations obtained from linear measurements (C, L, C^2L and CL) of leaves showed a correlation for these variables. The equations obtained allow a satisfactory estimation of leaf area of eggplant through the quadratic, linear and power equations, as illustrated in figure 1. The result of the best models and their respective numbers of presentation is listed in table 1.The models from the power, quadratic and linear equations resulted in satisfactory values of R^2 and RMSE. Maldaner et al. (2009a) estimated the leaf area in sunflower and also obtained the best results with these equations, demonstrating their usefulness for this purpose. Among the 12 models, the RMSE ranged from 33.2 cm^2 to 77.8 cm^2, and MAE from 23.79 to 68.59 (Table 1).

Leaf area of eggplant was better estimated by the models which used measures of length and width, as found by Pinto et al. (2007) for the cultivation of maniçoba, the models that presented the lowest values of RMSE and MAE were obtained by the product (CL) between these measurements. These findings corroborate the results of Monteiro et al. (2005) and Busato et al. (2010) for leaf area estimation in cotton and potato, respectively. This result differs from that found for sunflower (Maldaner et al., 2009a), melon (Nascimento et al., 2002) and jack bean (Toebe et al., 2012), in which only the measurement of the leaf blade width, or the central leaflet in the case of jack bean, was enough to get the best models for estimating leaf area of these crops.

The smaller the RMSE and MAE, the lower the error of the model, so it is more suitable for use, since the equation for its calculation compares the estimated data with the actual data. For field measurements, the use of only one leaf dimension facilitates the work because it results in approximately half the time required for its completion. The values of RMSE and MAE for the quadratic model (6), using the leaf width, result in values of 44.1 cm^2 and 31.76 cm^2, respectively (Table 1). From these results, it appears that this simplification is able to estimate the leaf area in eggplant, and although resulting in lower precision, it can be considered, given the reduced time required for measurements, and smaller error due to the fatigue of operators. The best results were obtained with the quadratic (1) and power (2) models, using the product of width and length, with RMSE of 33.2 cm^2 and 34.4 cm^2, respectively, and R^2 equal to 0.964 for both (Table 1).

Leaf shape and its variation during plant growth is crucial for the development of highly accurate estimation models (Queiroga et al., 2003). As an example, Monteiro et al. (2005) found three different models, one for each leaf size, but the authors indicated no need for using these different models due to small improvement achieved. Thus, single equations are usually calibrated to different sizes and ages of leaves with great accuracy, such as sunflower (Maldaner et al., 2009a). In this sense, figure 2a-b shows that the two best estimation models (1 and 2) result in excellent fit with the growth of leaf area, slightly deviating from the trend line in larger sized leaves, while maintaining the accuracy of the estimate. In figure 2c, there is also the good fit of equation 6, using only the width of the leaf.

RMSE of the best models (1 and 2) is considered low. Aquino et al. (2011) and Maldaner et al. (2009a) estimated leaf area in sunflower, and the best results demonstrated RMSE of 39 cm^2 and 27.5 cm^2, respectively. Therefore, in models 1 and 2, the RMSE was lower than these values, making them suitable for estimating leaf area in eggplant, once on a leaf with area of 300 cm^2, with more frequent occurrence, the average error is around only 10%. Besides that, in figure 2, leaves with area up to 200 cm^2 are on the 1:1 line, with excellent estimation of leaf area, and error close to zero. Compared with the study of Toebe et al. (2012), MAE (models 1 and 2) is lower than that estimated for the

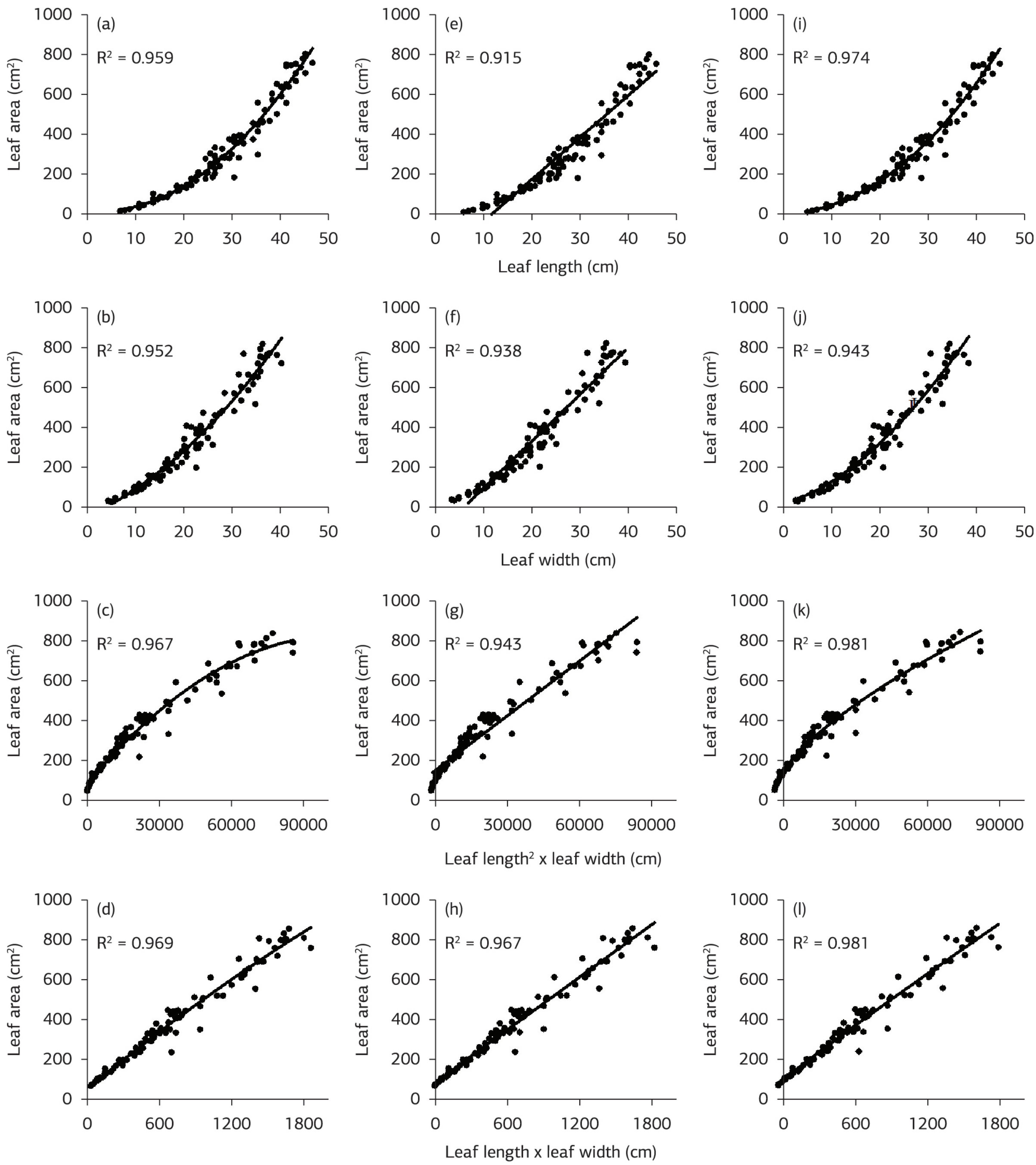

Figure 1. Regressions of eggplant leaf area and linear measurements using the quadratic (A, B, C and D), linear (E, F, G and H) and power (I, J, K and L) models.

jack bean crop (25.29 cm^2), considering that the leaves of this species have a morphology more easily estimated by mathematical models, compared with the eggplant leaves.

4. CONCLUSION

The models for leaf area estimation in eggplant allowed to obtain the leaf area of plants using indirect and non-destructive measurements of leaf blade. Models using the product between the linear measurements of length and width (CL) of the leaf blade satisfactorily estimate the leaf area in eggplant. The use of this input variable in the quadratic (Y = -5.78 +0.4981CL-0.00003263CL^2) and power (0.4395CL$^{1.0055}$) models results in better estimates of leaf area. For a better operating performance, it can be used the quadratic model of width (Y = -63.5+10.492L0.2822L^2).

Table 1. Regression models for leaf area estimation (cm^2) in eggplant and their respective coefficients of determination (R^2) of the generation of the model, linear coefficient (a), slope (b), coefficient of determination (R^2) of the test of the model, root mean square error (RMSE), mean absolute error (MAE) according to width (L), length (C), their product (CL) and length squared, multiplied by the width (C^2L)

	Model	R^2	---- Modeltest ----				
			a	b	R^2	RMSE	MAE
1	$-5.78+0.4981CL-0.00003263CL^2$	0.968	4.62	0.9645	0.964	33.2	23.79
2	$0.4395CL^{1.0055}$	0.981	15.55	0.9341	0.964	34.4	23.36
3	$0.3379C^2L^{0.6878}$	0.981	14.81	0.9122	0.965	37.2	26.28
4	$10.997+0.4401CL$	0.967	24.74	0.9727	0.965	37.0	26.24
5	$47.4+0.0142C^2L-0.0000000664C^2L^2$	0.966	0.843	0.9607	0.949	40.4	29.54
6	$-63.5+10.492L0.2822L^2$	0.951	3.69	1.0215	0.937	44.1	31.76
7	$0.9531L^{1.8488}$	0.970	22.58	0.9740	0.932	47.7	33.01
8	$-187.2+23.429L$	0.938	13.53	0.9618	0.914	50.7	39.49
9	$94.6+0.0092C^2L$	0.943	7.45	0.9456	0.925	48.5	36.46
10	$0.2014C^{2.1609}$	0.974	17.12	0.8511	0.943	56.9	41.38
11	$17.2-2.6283C+0.4196C^2$	0.959	13.42	0.8586	0.942	57.2	41.91
12	$-270.1+20.969C$	0.915	21.19	0.8151	0.882	77.8	68.59

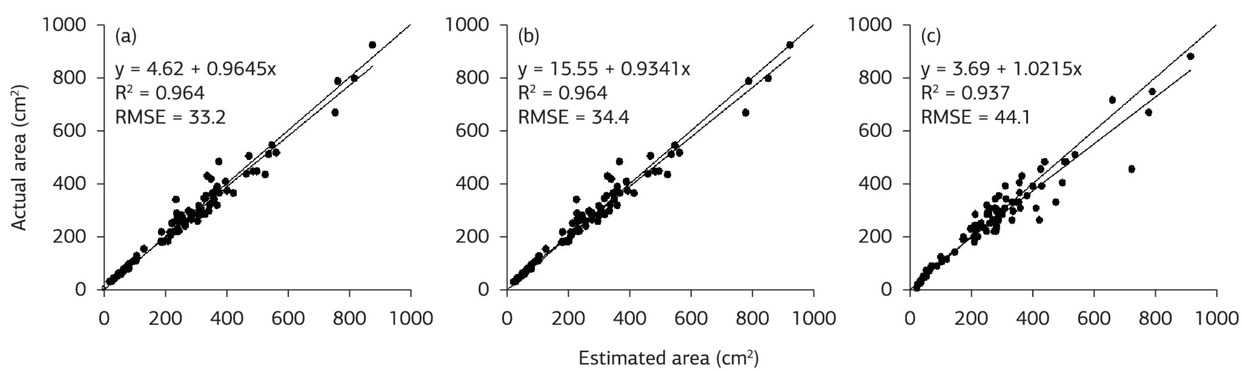

Figure 2. Testing quadratic (A) and power (B) models using as input variable the product of the linear measurements of length and width of eggplant leaves and quadratic (C) model using the linear measurement of width.

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