



Bragantia

ISSN: 0006-8705

editor@iac.sp.gov.br

Instituto Agronômico de Campinas

Brasil

Unigarro-Muñoz, Carlos Andrés; Hernández-Arredondo, Juan David; Montoya-Restrepo, Esther Cecilia; Medina-Rivera, Ruben Darío; Ibarra-Ruales, Lizardo Norbey; Carmona-González, Claudia Yoana; Flórez-Ramos, Claudia Patricia

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Bragantia, vol. 74, núm. 4, octubre-diciembre, 2015, pp. 412-416

Instituto Agronômico de Campinas

Campinas, Brasil

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Estimation of leaf area in coffee leaves (*Coffea arabica* L.) of the Castillo[®] variety

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Received: Jan. 21, 2015; Accepted: May 25, 2015

Abstract

Allometric models based on measurements of single leaf dimensions or a combination there are useful tools for determining individual leaf area (LA) because they are non-destructive, precise, simple and economical methods. The present study was carried out at the Central Station Naranjal of Cenicafe, located in the Department of Caldas (Colombia), four models were defined using the variables length (L) and/or width (W) to estimate LA in coffee leaves of the Castillo[®] variety (*Coffea arabica* L.). Estimation of regression coefficients was performed using information recorded from 6,441 leaves (group 1), and their validation was performed using records from another 992 leaves (group 2). Leaves were collected from all strata of the canopy and ranged from 0.76 to 140 cm² in LA. In addition to exhibiting coefficients of variation differing from zero based on t-tests at 1%, the evaluated models possess coefficients of determination between 0.93 and 0.99. Four expressions have developed and adjusted to estimate leaf area in individual leaves, based on the measurement of simple variables and non-destructive.

Key words: modeling, length, width.

1. INTRODUCTION

Coffee is cultivated in 56 countries located in tropical and subtropical regions of the world (ICO, 2013). Coffee agro-ecosystems support millions of farmers through the income they generate and the environmental services they offer (Castro-Tanzi et al., 2014). Coffee is one of the main crops grown in countries such as Brazil, Mexico, Colombia, Ethiopia and Kenya (Hein & Gatzweiler, 2006). In Colombia, the area dedicated to coffee farms was approximately 949,000 hectares in 2014, with coffee rust-resistant varieties being grown on 64% of the land (FNC, 2014). Among such varieties, the Castillo[®] variety is noteworthy, as are its regional components developed by the Colombian National Coffee Research Center (CENICAFÉ, based on its initials in Spanish) (Alvarado et al., 2005, 2009; Cortina et al., 2012).

Several studies have shown that leaf area (LA) plays a determinant role in light interception and, as a consequence, in processes such as vegetative growth, development rates, photosynthetic efficiency, evapotranspiration, the use of nutrients and water, and even the response to fertilizers (Blanco & Folegatti, 2005; Goudriaan & Van

Laar, 1994; Herbert, 2004; Williams & Martinson, 2003). The productivity potential of the plant is determined by the leaf area available for carbon assimilation during its life cycle (Arcila & Chaves, 1995). For this reason, quantifying LA is fundamental to assessing plant primary productivity (Pandey & Singh, 2011) and as a functional component of crop modeling (Lizaso et al., 2003). In this context, the simple, economical and precise estimation of LA has been a subject that is widely discussed by scientists (Pandey & Singh, 2011).

Methodologies aimed at quantifying LA may or may not be destructive (Ilkkae et al., 2011). In the first case, cutting the leaf is necessary, and measuring is performed using traditional methods such as copying on graph paper, photographing, or using a planimeter (Falovo et al., 2008). However, the greatest limitation of such methodology is the impossibility of taking successive measurements through time on the same leaf. Additionally, the resulting defoliation may alter other experimental measurements (Falovo et al., 2008). In certain cases, when the number of leaves to be assessed is high, quantification of LA is costly

in time and resources (Antunes et al., 2008). Non-destructive methods, such as the use of a portable scanning planimeter, can be fast and precise (Daughtry, 1990) but are only feasible on small plants with few leaves (Nyakwende et al., 1997). Alternatively, analysis of images using software is also fast and precise (Bignami & Rossini, 1996) but may be limited by not being user-friendly.

In this context, estimation of LA based on one or more leaf dimensions (length and width) is an economical, quick, reliable, non-destructive method that can be applied *in situ* (Beerling & Fry, 1990; Fallovo et al., 2008; Lu et al., 2004; Serdar & Demirsoy, 2006; Sousa et al., 2005; Williams & Martinson, 2003) and is presently applicable (Galindo & Clavijo, 2007). However, the precision of LA estimation does not take into account external factors such as leaf morphology (length/width ratio), which can vary among genotypes (Stoppani et al., 2003). Nevertheless, Antunes et al. (2008) did not find significant differences in leaf shape when evaluating eight coffee genotypes. Other factors, such as violating the assumptions of statistical models, require modification of such conclusions (Chatterjee & Hadi, 2006). Several allometric models have been proposed to estimate LA in coffee (Antunes et al., 2008; Awantramani & Gopalakrishna, 1965; Barros et al., 1973; Rey & Alvarez, 1991; Valencia, 1973). In 1973, Valencia established an algorithm based on measuring the length of the midrib for the Caturra variety.

Taking into account the above discussion and considering the new coffee varieties produced at Cenicafé, the present study aims to find statistical models for estimating coffee LA in the Castillo® variety based on its dimensions.

2. METHODS

A total of 6,441 coffee leaves from the Castillo® variety (*Coffea arabica* L.) were collected from five three year-old trees (group 1) that were grown at the Central Station Naranjal of Cenicafé, located in the City of Chinchiná, Department of Caldas, Country of Colombia (04° 59'N and 75° 39'W), at an altitude of 1,381 m, during April 2014. At this Central Station, 992 leaves from the same variety were collected in June 2014 (group 2). For each leaf, we measured the length (L), width (W), LA, and different widths along the leaf, which were used to calculate the mean width. The length from the apex to the point where the leaf joins the petiole and W from the right to the left edge at the widest point were also measured. These measurements, as well as those for LA, were performed with specialized LI-3100C Area Meter equipment for surface quantification (LI-COR, Lincoln, Nebraska). The sampling unit was the leaf in both cases, i.e., when determining the models using information from group 1 and for their validation using information from group 2.

The values of the relation L/W gathered in three classes ($L/W \leq 2$; $2 < L/W \leq 3$; $L/W \geq 3$) and were evaluated by variance analysis. The differences among classes were resolved by Duncan test at 5% of significance.

For determination of the model, LA or observed leaf area (OLA) was the dependent variable, and L, W and $L \times W$ (LW) were taken in each case as independent variables. Fits involving non-linear data were linearized (Chatterjee & Hadi, 2006; Sit & Poulin-Costello, 1994) to estimate the coefficients via ordinary least squares. The criteria for evaluating expressions describing LA included regression coefficients significantly different from zero based on a t-test at 1% and determination coefficients greater than 90%.

Once the expressions were determined, they were applied with the values of the independent variable for group 2, and the mean absolute relative difference (relative error) from the LA recorded for this group was estimated, determining the 75th and 99th percentiles, for the relative error. The relationship between the observed value of LA (dependent variable) and the estimated value (independent variable) was obtained using a simple linear regression model to verify that the regression coefficient was statistically equal to one using a t-test at 1%. This procedure led to the conclusion that the obtained expressions do not overestimate or underestimate LA. All the statistical analyses were performed using the software SAS version 9.3 (SAS Institute, 2010).

3. RESULTS AND DISCUSSION

In general, the collected leaves were elliptical and between 0.76 and 140 cm² in LA. Differences in leaf shape were classified according to L/W in three classes according to observations made by Antunes et al. (2008). In general terms, when the value of equatorial diameter of a leaf is half or more than half of the polar diameter, the ratio is equal to or less than two. When the polar diameter exceeds the equatorial diameter more than once, the ratio will be greater than two. Table 1 shows that the average values of the L/W ratio and LA are significantly different between classes, according to the Duncan test at 5%. Based on a L/W ratio between 2 and 3, 82.7% of the evaluated leaves were classified. Therefore, leaves with a value of L twice the value of W represented the most common shape of coffee leaves of the Castillo® variety. Leaves tending toward a circular shape (Class $L/W \leq 2$) or that were very elongated (Class $L/W \geq 3$) represented only 5.5 and 11.8% of the sample, respectively (Table 1). Antunes et al. (2008) found lower proportions in the sampled leaves, with 4.7% falling into the $L/W \leq 2$ class and 4.7% into the $L/W \geq 3$ class, possibly due to the mixture of Arabica and Robusta as well as Timor hybrid coffee varieties sampled.

The behavior of the OLA as a function of the length (L) or width (W) of the leaf indicated a non-linear association.

Meanwhile, the product of L and W (LW) was linear in coffee of the Castillo® variety (Figure 1). Authors such as Valencia (1973) and Antunes et al. (2008) arrived at a similar conclusion when examining the dispersion patterns in coffee leaves of Arabica (Yellow Bourbom, Catuai, Mundo Novo and Tipica), Robusta (Conilon and CC 3580) and Timor hybrid varieties.

Once the behaviors shown in figure 1 were identified, a descriptive model was determined. For the figures 1a and 1b, the model corresponds to $Y = \beta_0 X^{\beta_1}$. For the figure 1c, it corresponds to a linear model, $Y = \beta_0 + \beta_1 X$. The estimated values of the coefficients are shown in table 2. In this table, the lineal model in equation 4 did not consider the intercept because it was statistically similar to zero based on a t-test at 1%.

The fourth equation involves the estimation of mean width (Z) as a function of maximum width, so that the independent variable for estimating leaf area (ELA) is the product of length by the estimated mean width ($L \times Z$).

For all expressions, the regression coefficient was significantly different from zero based on a t-test at 1%, with coefficients of determination between 0.93 and 0.99 being obtained. Authors like Antunes et al. (2008), Arcila & Chaves (1995), Awantramani & Gopalakrishna (1965), Barros et al. (1973) and Rey & Alvarez (1991) also have reported R^2 similar in predictive of LA non-destructive for coffee leaves in function of the L and/or W.

With respect to the intercept, in all expressions, except for the fourth (Table 2), it was significantly different from zero

Table 1. Mean and standard error for the variables length/width (L/W) ratio and observed leaf area (OLA) in coffee of the Castillo® variety, according to the established classes

Classes	No. leaves	L/W Relationship			Observed leaf area (cm)		
		Mean		Standard error	Mean		Standard error
$L/W \leq 2$	355	1.7	C	0.013	26.7	B	1.18
$2 < L/W \leq 3$	5348	2.5	B	0.003	32.6	A	0.25
$L/W \geq 3$	763	3.4	A	0.020	13.4	C	0.40

Different letters indicate differences between means according to Duncan's test at 5%.

Table 2. Estimation of the intercept and regression coefficients with their respective standard error and coefficient of determination (R^2) for each of the expressions related to the evaluated models to estimate leaf area (ELA) in individual leaves of the Castillo® coffee variety

Model	Intercept			Regression coefficient			R^2	Equation
	β_0	SE	Pr > t	β_1	SE	Pr > t		
$Y = \beta_0 X^{\beta_1}$	0.19494	1.01685	<0.0001	2.06621	0.00714	<0.0001	0.93	$ELA = 0.19494 \times (L)^{2.06621}$ [1]
$Y = \beta_0 X^{\beta_1}$	1.68938	1.00725	<0.0001	1.87577	0.00496	<0.0001	0.96	$ELA = 1.68938 \times (W)^{1.87577}$ [2]
$Y = \beta_0 + \beta_1 X$	-0.95201	0.06691	<0.0001	0.59632	0.00111	<0.0001	0.98	$ELA = -0.95201 + 0.59632 \times (L \times W)$ [3]
$Y = X\beta_1$	-	-	-	0.99927	0.00097	<0.0001	0.99	$ELA = 0.99927 \times (L \times (-0.14757 + 0.60986 \times W))$ [4]

SE: Standard error.

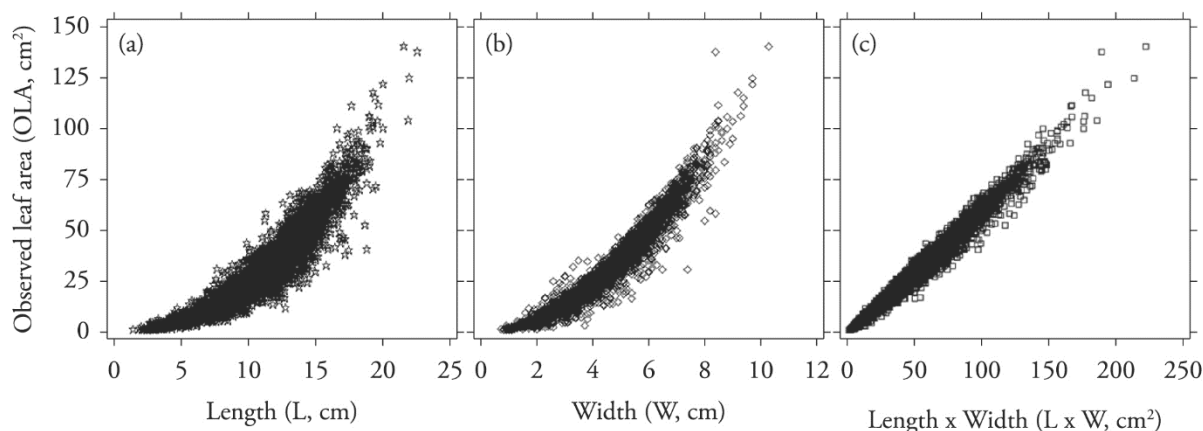


Figure 1. Behavior of the observed leaf area (OLA) as a function of: (a) length (L), (b) width (W) and (c) length*width (LW) in coffee leaves of the Castillo® variety.

Table 3. Absolute relative error and regression coefficients between the observed (OLA) and estimated leaf area (ELA) values for Castillo® variety coffee according to the evaluated expressions

	Equation	Absolute relative error (%)			β_1	SE	R ²
		Mean	75th percentile	99th percentile			
a	$ELA=0.563983 \times (L)^{2.02501}$	124.5	141.0	219.6	0.45**	0.0017	0.98
[1]	$ELA=0.19494 \times (L)^{2.06621}$	15.8	21.0	46.7	1.13**	0.0088	0.95
[2]	$ELA=1.68938 \times (W)^{1.87577}$	10.2	13.6	59.4	1.10**	0.0073	0.96
[3]	$ELA=-0.95201 + 0.59632 \times (L \times W)$	9.2	10.5	50.2	1.07**	0.0018	1.00
[4]	$ELA=0.99927 \times (L \times (-0.14757 + 0.60986 \times W))$	5.3	7.1	22.6	1.05**	0.0035	0.99

^a Equation developed by Valencia (1973); ** Coefficients significantly different from one according to a t-test at 1%; SE: Standard error.

according to a t-test at 1%. Therefore, the fourth equation is shown only in terms of the regression coefficient.

The ELA values estimated with equation 4 showed an absolute relative error of 5.3% on average, so that there was a 75% probability that such errors were less than 7.1% and a probability of 99% that they were less than 22.6%; this was the equation with the least error (Table 3). Validation of the expressions for estimating leaf area indicated overestimation with equation of Valencia (1973) and underestimation with all of the others. The regression coefficient (β_1) in equation 4, estimated as 1.05, indicated that the observed OLA was 0.05 cm² greater than what was estimated (ELA). For example, if leaf area is estimated to be 3.5 cm², the observed leaf area would be 3.675 cm² (Table 3). Field or greenhouse measurements of leaf L and W are relatively easy to perform and offer the possibility of repetition through time because of their non-destructive nature, which is a requirement of some studies on growth and development. However, if the study requires monitoring of a large number of leaves, one-dimensional models may be an acceptable option for simplifying the measurement process, although the error will be greater in relation to the real value. In this sense, it must be considered that measuring L is easier than measuring W because the latter measurement requires the consideration of an imaginary line perpendicular to the equatorial diameter of the leaf, which is not clearly defined given the irregularity of the leaf surface (Antunes et al., 2008). A practical action to measure the W is to bend mildly the leaf joining the apex with the petiole of the leaf, which it would permit to measure its width in more appropriate way.

4. CONCLUSION

In conclusion, four expressions have developed and adjusted to estimate leaf area in individual leaves of Castillo® variety coffee, based on the measurement of simple variables and non-destructive. The developed expression based on the product of L by W ($L \times W$) ($ELA=0.99927 \times (L \times (-0.14757 + 0.60986 \times W))$) showed to be the most appropriate when estimating the foliar area, with regard to the developed expressions with a single measurement of the leaf (length: L or width: W).

Leaf length and width explain leaf area in individual leaves, accounting for 93% and 99% of the observed variation.

ACKNOWLEDGEMENTS

This research was funded by the National Federation of Coffee Growers of Colombia and the National Coffee Research Center (Cenicafé). The authors thank Claudia Valencia, Marcela Mora and Mario Franco, technical personnel of Cenicafé, for their valuable collaboration. Thanks also go to tenured professor Dr. Enrique Martínez and to Sara Isabel Bedoya, a student in Agricultural Engineering, appointed to the Universidad Nacional de Colombia – Medellín Campus.

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