

ORIGINAL ARTICLE

Bambusa vulgaris leaf area estimation on short-rotation coppice

Estimativa da área foliar de Bambusa vulgaris em plantio de curta rotação

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Abstract

The use of biomass is increasing in the whole world, which makes it necessary to find new options for biomass production. In this scenario, bamboo appears as a potential species because of its fast-growing capacity. Hence this study aimed to obtain a mathematical model based on height (H), diameter at breast height (D) of the stem, leaf length (L) and width (W) and the number of stems per clump (N) to estimate the *Bambusa vulgaris* leaf area (LA) during the second year after planting. The models were obtained on a short-rotation coppice (SRC) in Botucatu, Sao Paulo, Brazil, between January 2017 and January 2018. In total, five evaluations were carried out. Before each one, a forest inventory was undertaken to select a representative clump according to the population median. From the chosen one, three culms were cut, measured, and individually defoliated. To estimate LA, 12,425 leaves L and W were measured with the assistance of a ruler; and by using a leaf area meter, the real LA was obtained. Linear and nonlinear models were tested, analyzing precision. Linear models had a higher precision when LA was correlated to L, W, H, D, and N; on the other hand, the best adjustment to the correlation between LA with C and L were the nonlinear models. Independent of the obtained model, all of them had an adjusted coefficient of determination (R^2 adjusted) higher than 67%. LA variation is between 3.7 and 6.3 cm² using these models.

Keywords: Bamboo; Regression models; Allometric relationships; Biomass; Eco-physiological index.

Resumo

O bambu é uma das espécies arbóreas que apresenta maior velocidade de desenvolvimento do mundo, apontando-o não como um substituto, mas como uma opção para produção de biomassa para energia. O objetivo deste estudo foi obter modelos matemáticos a partir do comprimento (C) e largura (L) foliar, altura (A), diâmetro a altura do peito (D) e número de colmos de cada touceira (N) a fim de estimar a área foliar (AF) de *Bambusa vulgaris*, durante o segundo ano após o plantio. Os modelos foram obtidos em um Sistema de Curta Rotação (SCR) em Botucatu, São Paulo, Brasil. Foram realizadas cinco avaliações compreendidas entre os meses de janeiro de 2017 e janeiro de 2018. Anterior a cada avaliação, inventário florestal era realizado para a seleção de touceiras representativas. Escolhida a touceira, três colmos eram cortados, as variáveis eram mensuradas e então os colmos desfolhados individualmente. Para modelar AF foram medidas 12.425 folhas do bambu e com o auxílio de régua, C e L foram obtidos e a seguir e utilizando-se medidor de área foliar, foram obtidas AF. Modelos lineares e não lineares foram testados quanto a sua precisão para estimar AF do bambu. O modelo linear múltiplo resultou em alta precisão quando foram correlacionados dados de AF com C, L, A, D, e N e modelos não lineares apresentaram um melhor ajuste para estimar AF, correlacionando C e L. Independente do modelo gerado, todos os

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coeficientes de determinação ajustados (R^2 ajustado) foram superiores a 67%. A subestimação ou superestimação da AF utilizando estes modelos varia entre 3,7, e 6,3 cm².

Palavras-chave: Bambu; Modelos de regressão; Relações alométricas; Biomassa; Índices ecofisiológicos.

INTRODUCTION

There are more than 22 million of different native bamboo forests in the world, mainly in Asia countries. In Brazil, native bamboos are also common. Around 160 species can be considered to be woody, and some species can grow up to 35 m of height (Filgueiras & Gonçalves, 2004; Guimarães Júnior et al., 2010).

Bamboos are very adaptable; they tolerate high temperatures, low levels of precipitation and fertilization, aside from having a high capacity to resprout (Azzini et al., 1989; Maoyl & Banlk, 1995). Bamboos are used from handicraft to bioenergy production through the heat from burning, although in Brazil native bamboos are primarily used for construction and handicraft. For production purposes, one of the most planted species nowadays is *Bambusa vulgaris*, a fast-growing tropical species with high biomass productivity, well adapted to northeastern Brazil. In this region, there is a pulp and paper industry that grows this species for raw material (Santi, 2015).

Bamboo can be used not as a substitute for *Eucalyptus* or *Pinus*, but also as a complement in such a way as to diversify the forest biomass competitiveness. Commercial bamboo plantations are still not widespread in the territory. An example is the fact there are no reports about bamboo commercial plantings only for bioenergy production. This kind of plantation is commonly designed in a Short-Rotation Coppice (SRC) that is a high-density wood plantation with less plant spacing when compared to conventional plantations (Guerra et al., 2014; Eufrede-Junior et al., 2018).

Finding high-quality bamboo information is not simple; there are mainly morphological and ecophysiological descriptions; however, trial plantations are increasing in numbers of studies in Brazil. Ecophysiological reviews are essential since they can be derived from the inputs of 3-PG (*Physiological Principles Predicting Growth*); a model that can quantify carbon, water, and energy flow on plants in general, forest or agriculture, and predicting biomass production. These models can be a tool to simulate the planting development and performance related to environmental changes or different stimulus for production (Landsberg & Sands, 2011)

Leaf area (LA) is the key-index to 3-PG such as light interception, photosynthesis efficient, respiration, transpiration, water balance and nutritional responses (Syvertsen et al., 2003; Silva et al., 2008a; Kandiannan et al., 2009).

However, LA directly data collection demands a significant number of leaf measurements that makes it into a high-cost process that requires equipment and time, besides being a destructive process. Thus it is not commercially attractive. Similarly indirect non-destructive LA data collection obtained by specialized equipment, is an expensive method as well. An accurate model for LA estimation would eliminate all the costs and time consumed being non-destructive.

These models are based on leaf dimensions such as length and width which allow the leaf area estimations by linear or nonlinear regression (Zanetti et al., 2017). Such a method has already been used in several forests or crops, such as *Populus* (Ceulemans et al., 1993), nuts (Serdar & Demirsoy, 2006) and beans (Peksen, 2007), sunflower (Rouphael et al., 2007), anthurium (Silva et al., 2008a), potato (Silva et al., 2008b), ginger (Kandiannan et al., 2009), eucalyptus (Diao et al., 2009), mango (Silva et al., 2015), broad leaved forest species (Liu et al., 2017), cassava (Zanetti et al., 2017), cocoa (Suárez Salazar et al., 2018) among other crops.

Presently no study in the literature proposes a mathematical model for bamboo LA estimation in *Bambusa vulgaris*. This study aimed to estimate the *B. vulgaris* leaf area, as the main parameter for the 3-PG model, in an SCR, over the second year after planting.

MATERIAL AND METHODS

Study area

This study was performed in a *Bambusa vulgaris* experimental plantation located at Lageado Farm, from Sao Paulo State University (UNESP), Botucatu Campus, in the central-western region of Sao Paulo State (22°50'21" S and 48°25'20" W), at 786 m above the sea level. The historical annual average rainfall is 1,428.4 mm year⁻¹, and the climate, according to Köppen classification is Cfa, humid mesothermal, with an average yearly temperature of 20.3 °C (Cunha & Martins, 2009).

During the study period, the minimum average temperature in the coldest month was 12.5 °C; while the maximum average temperature in the hottest month was 30.3 °C. The annual average temperature was 21.1 °C.

The planting was manually carried out in January 2016 in an area that, previously, had a 30 years old eucalyptus plantation mixed with grazing.

Bambusa vulgaris cuttings were provided by Taboca nursery in Tatui, Sao Paulo, Brazil. The plantation was done in a Short-Rotation Coppice (SRC) with a spacing of 3 × 2 m. From the total 48 central clumps with one border line were used to this study (Figure 1).

Line 6														
Line 5		4	x		x	x	x		x	x	x			
Line 4		x	x		x	2	x		x	3	x	x	x	
Line 3			x	x	x	x	x		x	x	x	1	x	
Line 2			x	5	x						x	x	x	
Line 1														
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14

Figure 1 – *Bambusa vulgaris* experimental area sketch located at Lageado’ Farm, UNESP, Botucatu Campus. Number one to five represents the cut clumps on each evaluation; in other words, number one is the one used in January 2017 and number five, the one used in January 2018. The “x” represents the not considered clumps in order to avoid the border effect. The simple experimental border is considered in the sketch in gray.

During the whole study the vegetative phonological stage was used; because the bamboo's life cycle is too long, and the flowering needs a long time to occur. According to Moore & Botha (2014) similar stages occur in sugar cane, such as sprouting emergency, foliar development, tillering, culm elongation, and growth.

Evaluated variables

Five evaluations were carried out quarterly, between January 2017 and January 2018, when bamboo was 12 months and 24 months old, respectively.

Before each evaluation, a forest inventory measured the culms’ total height, base diameter, and number of stems per clump. A clump was selected that represented the culms average number and the diametrical breast height class frequency per clumps in the trial population. The clumps around the chosen one were excluded from the next evaluation to avoid the study of favored plants by an opened clearing as shown on Figure 1.

Right before harvesting the chosen clump, the culms number (N) and selected three culms were selected, according to diameter (Table 1) and physical characteristics (Figure 2), which were defined as young, intermediate, and old.

After characterization, the total height (H, cm), from the base to the tip of the culm, and diameter at breast height (D, mm) were measured. Culms were defoliated one by one, the leaves were mixed so as to obtain leaves from the lower, middle, and upper thirds of the crown.

Immediately after the leaves were collected the total fresh matter of each culm type (young, intermediated, and old) was determined. After this, a quarter of the leaves were put

in different plastic bags and refrigerated at 4°C, so as to maintain the vigor until measurements.

Table 1 – Culm diameter at breast height (D).

Culm	D (mm)
Old	3 – 10
Intermediated	15 – 25
Young	30 – 40

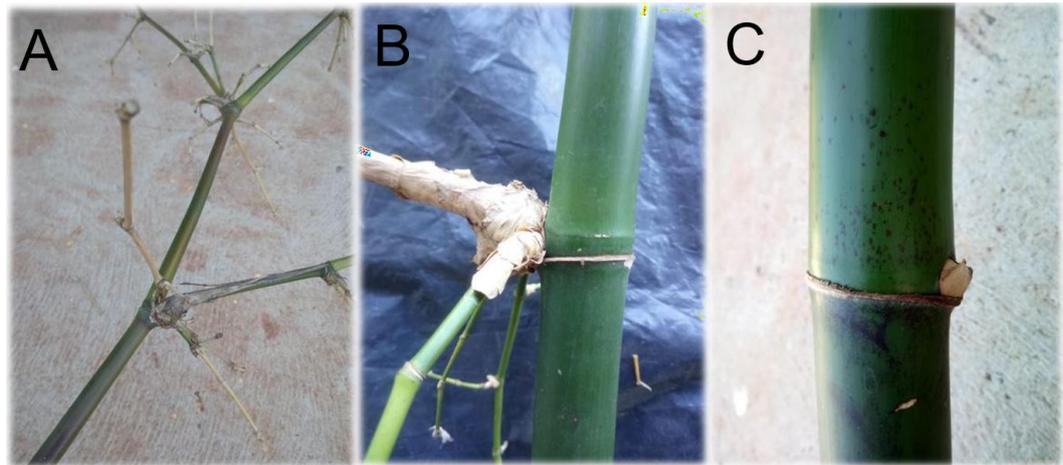


Figure 2 – Physical characteristics of *Bambusa vulgaris* culms as color, sprouts or not in the node, and number of lateral branches to classification as old (A), intermediated (B), and young (C).

In the laboratory, bamboo leaves were rehydrated to reverse the dehydration that quickly occurs in bamboo leaves. All the leaves were numbered to guarantee the traceability and with a ruler the length (L, cm) and width (W, cm) were measured. The leaf area (LA) of each leaf was obtained by a leaf area meter (LAI-3100 model, LI-COR Biosciences Inc., Lincoln, NE, USA). During the evaluation year 12,425 leaves of *Bambusa vulgaris* were singly measured.

Model adjustment to LA estimate

The variables L, W, H, D, and N, were analysed for regression analysis at 5% of significance with the Minitab 16 software to define the best fit. The variable LA was considered dependent, while the variables above were deemed to be independent or predictors.

The coefficient of determination (R²), adjusted coefficient of determination (R² adjusted), and standard error (S) were analyzed. Besides, the Mallow’s Cp (Equation 1) was performed. The number of predictor variables were close to the Cp value; the model had a higher precision and lower variable than the regression coefficient estimate. Therefore, the better models were the ones with higher R²; R² adjusted; lower S; and Mallow’s Cp.

$$Cp = \frac{SQR}{QMR} - (n - 2p) \tag{1}$$

Where: SQR is the sum of the squares of the residual error; QMR is the mean square residual error; n is the observation number; and p is the number of predictor variables; which in this study were five (L, W, H, D, and N) and two (L and W).

The Mallow’s Cp analysis was performed twice in this study, first counting all the five variables, L, W, H, D, and N; and later only the two variables L and W, in such a way as to verify and to compare the best adjustment to each evaluation.

RESULTS AND DISCUSSIONS

Leaf area showed a high variation in all evaluations, first probably due to the mix of all crown leaves from the lower, medium, and superior third (Figure 3). Secondly, despite different seasons of the years, plants stayed in the vegetative development stage. Hence, minimum and maximum LA, as well as variables (L, W, H, D, and N), maintained a similar standard.

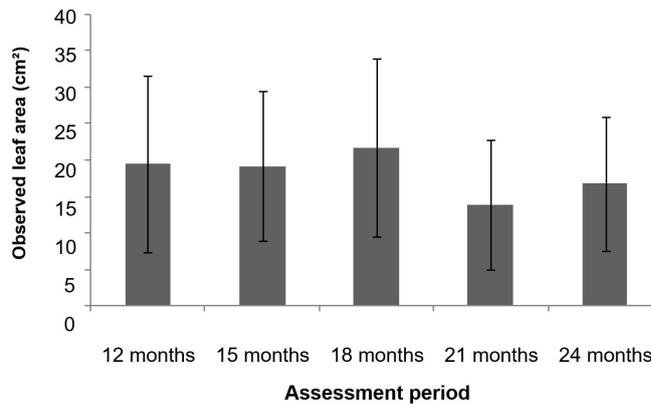


Figure 3 – Leaf area (LA) variation of each leaf during the studied period between January 2017 (12 months old) and January 2018 (24 months old).

Similar results were obtained by Zanetti et al. (2017) and Silva et al. (2015) with cassava and mango, respectively, in which, as in this study, the authors mixed leaves to obtain LA; which can be the cause of the observed results.

The length (L) of the leaves varies around 30 cm on average, whereas the variation of width (W) was approximately 3 cm. The values of the number of culms (N) by clumps were similar between the evaluations: ten culm at 12 months; eight culms at 15 months; also eight culms at 18 months; 12 culms at 21 months; and nine culms at 24 months (Table 2). According to Maoyl & Bank (1995), sympodial bamboo species planted at a 4 × 5 m or 5 × 5 m spacing, can have 6 to 9 culms per clump one or two years after planting, which is supported in this study, as their used spacing was 3 × 2 m, giving more space to some clumps havin then a larger culm number.

The results showed relatively low standard deviations, showing that, in spite of the difference in the variable values, the data did not disperse much from the average. To the dependent variable, LA, the average standard deviation was also low, close to the averages (Table 2).

In general, the relationship between the estimated LA and the studied variables is strong, taking into account the adjusted R², standard error (S), and Mallow's Cp values. This is in agreement with other agricultural studies, such as hazelnut, Persian nut, sunflower and kiwi (Keramatlou et al., 2015).

The best adjustment to all variables analysis (L, W, H, D, and N) was the multiple linear model. This model had an adjusted R² in a range between 62.30 and 86.00 ($p \leq 0.05$); considered to be high to adjustment in the LA estimate.

Equations were generated for each evaluation, called "individual equations," and to all the assessments together, which we called "groups equation", both with all variables (L, W, H, D, and N). The individual equations which had better adjustment contained the variables L, W, H, and D; whereas, for groups equation, the best model contains the variables L, W, D, and N. L and W were evaluated to identify the best fit, in this case, non-linear multiple was the best model. These equations shown similar adjusted R² to the models above, varying between 67.68 and 86.20 (Table 3). According to Archontoulis & Miguez (2015), non-linear models are more appropriate for crops and soils, since they better represent all their processes.

Table 2 – Minimum (Min) and maximum (Max) values, standard deviation (SD), leaf area (LA), length (L), width (W), height (H), diameter at breast height (D), and number of culms (N) average obtained from *Bambusa vulgaris* clumps in five different evaluations in a period of one year after planting.

Variables		Development stages				
		jan/17	apr/17	jul/17	oct/17	jan/18
LA (cm ²)	Min	1.00	1.00	1.31	0.72	1.34
	Max	78.32	73.95	74.33	61.36	78.80
	SD	12.21	10.31	12.27	8.88	9.22
	Average	19.55	19.21	21.80	14.00	16.80
L (cm)	Min	1.00	1.10	1.40	1.60	0.80
	Max	27.00	24.70	27.00	26.0	30.60
	SD	4.01	3.96	4.57	4.31	4.31
	Average	12.61	13.14	14.11	13.34	14.64
W (cm)	Min	0.20	0.40	0.50	0.30	0.50
	Max	4.00	4.00	3.90	2.80	4.10
	SD	0.68	0.57	0.58	0.43	0.49
	Average	1.82	1.85	1.85	1.41	1.65
H (cm)	Min	133.00	246.00	380.00	339.00	342.00
	Max	323.00	650.00	550.00	524.00	608.00
	SD	78.68	177.61	61.62	80.08	75.26
	Average	233.48	496.51	458.21	438.59	534.84
D (mm)	Min	10.00	7.92	24.00	19.00	17.18
	Max	19.10	40.63	35.00	34	34.20
	SD	4.36	15.00	4.01	6.74	5.81
	Average	13.25	29.23	28.96	26.77	29.26
N total		10	8	8	12	9

Authors such as Liu et al. (2017), Meng et al. (2015), Pompelli et al. (2012), and Ceulemans et al. (1993) studied, respectively, broadleaf species, *Jatropha curcas*, and *Populus* spp. leaf area and all had the same conclusion: that L and W variables are the best option to generate linear or nonlinear models to predict LA; not only because of precision but also because of the convenience of data obtained. In this study, *Bambusa vulgaris* LA in an SCR was estimated by five variables (L, W, H, D, or N) in multiple linear models; or by two (L and W), in a multiple nonlinear models.

Table 3 – A – Linear multiple models to leaf area (LA) estimation of length (L) and width (W) of the leaves, height (H), and diameter at breast height (D) of culms and number of culms (N) of the clump. B – Non-linear multiple models to estimate LA by L and W. Both in a *Bambusa vulgaris* SCR.

A	L, W, H, D and N	R ² adjust	S	Mallow'sCp
12 months	LA = -13.2377 + 1.71385L + 5.28378W + 0.0626757H - 0.992284D	73.1	6.3	5.0
15 months	LA = -28.71 + 1.8787L + 4.269W + 0.0737H - 0.7310D	74.1	5.2	5.0
18 months	LA = -13.219 + 1.32941L + 10.707W - 0.192469H + 2.92447D	83.0	5.1	4.0

Table 3 – Continued...

A				
Evaluation*	L, W, H, D and N	R²adjust	S	Mallow'sCp
21 months	LA = -13.502 + 1.0159L + 9.644W + 0.07237H - 1.1741D	79.7	4.0	5.0
24 months	LA = -14.625 + 0.8184L + 11.400W + 0.00513H - 0.0703D	81.1	4.0	5.0
Grouped	LA = -5.843 + 1.2182L + 8.3682W - 0.4652N - 0.10219D	71.2	5.9	6.0
B				
Evaluation*	L and W	R²adjust	S	Mallow'sCp
12 months	LA = 0.157819 - 1.29853L + 10.7681W + 0.0934558L ² - 0.812763W ² + 0.128505L×W	77.9	5.7	6,0
15 months	LA = 0.170464 - 0.678287L + 6.22317W + 0.054381L ² - 0.403179W ² + 0.300376L×W	80.3	4.67581	6,0
18 months	LA = 1.99913 + 0.377772L - 3.3131W - 0.025211L ² - 0.0576323W ² + 1.01839L×W	86.2	4.6	5.7
21 months	LA = 4.78361 - 0.668112L - 0.287123W + 0.00586836L ² - 2.32811L ² + 1.13035L×W	67.7	5.0	2.7
24 months	LA = 1.5729 - 0.0693413L - 0.0559163W - 0.00422665L ² + 0.412814W ² + 0.636845L×W	83.8	3.7	2.8
Grouped	LA = -1.61698 - 0.554914L + 7.61045W + 0.0344957L ² - 0.631455W ² + 0.382555W×W	77.6	5.19815	6,0

* 5% of significance, average n of 2.485 leaves by evaluation

CONCLUSION

Bambusa vulgaris leaf area can be estimated by simple non-destructive methods such as multiple linear or nonlinear regression analysis.

From all involved models, multiple linear models were the most precise to estimate LA when correlated with all the studied variables in this study. However, nonlinear models were the best adjustment when LA is associated only with L and W.

Among the proposed models, the equations using the variables length (L) and width (W) are the most recommended because the data is easy to obtain; however it is up to the reader to choose the model which fits best.

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