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Macauba production estimated by regression models

Estimativas de produção de macaúba por modelos de regressão

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Abstract

Macauba has been shown to be the most promising native species for oil and biomass production. The first commercial crops have arisen mainly in Minas Gerais State, and estimates indicate a vegetable oil yield potential above 8 t ha^{-1}. In this context, research has acted strongly on technological advance for improvements in the production system and selection of superior genotypes, which requires the use of precise and less expensive methodologies. Thus, we built prediction models to estimate the weight of macauba bunches using easy-to-measure physical variables. Bunches of plants from five regions of Brazil were evaluated. The bunches were weighed, and length and diameter were measured along with four other variables. Based on the set of variables obtained, stepwise multiple regression analysis was used to build regression models for each region. The correlation between observed versus estimated data reached determination coefficients (R^2) above 0.90 in three of the models built. The main variables selected by the best models were bunch volume, bunch length/diameter ratio, and bunch square diameter.

Additional keywords: *Acrocomia aculeata*; agroenergy; oil yield; *stepwise*.

Resumo

A macaúba tem sido apontada como a mais promissora das espécies nativas para produção de óleo e biomassa. Estimativas indicam o potencial produtivo acima de 8 t ha^{-1} de óleo vegetal, e os primeiros cultivos comerciais têm surgido, principalmente, no Estado de Minas Gerais. Neste contexto, a pesquisa tem atuado fortemente para o avanço tecnológico para melhorias do sistema de produção e seleção de genótipos superiores, sendo necessário o uso de metodologias precisas e menos onerosas. Assim sendo, objetivou-se construir modelos de predição para a estimativa do peso de cachos em macaubeira, por meio de caracteres físicos de fácil mensuração. Foram realizadas avaliações em cachos de plantas originadas de cinco regiões do Brasil. Os cachos foram pesados, e foram medidos o comprimento e o diâmetro e, posteriormente, calculadas outras quatro variáveis. Com base no conjunto de variáveis obtidas, foi empregada análise de regressão múltipla, *stepwise*, para construção de modelos de regressão para cada região. A correlação entre os dados observados versus estimados alcançou coeficientes de determinação (R^2) acima de 0,90 em três dos modelos construídos. As principais variáveis selecionadas pelos melhores modelos foram volume de cacho, produto do comprimento e do diâmetro do cacho e quadrado do diâmetro do cacho.

Palavras-chave adicionais: *Acrocomia aculeata*; rendimento de óleo; *stepwise*; agroenergia.

Introduction

Soybean is currently the main raw material for biodiesel production in Brazil. However, several other oilseeds have been used and many Brazilian native species have been studied as alternative sources (Nass et al., 2007). These research efforts are mainly justified by socioenvironmental reasons in the search for options with higher yield per area, thus more suitable for family farming, with better energy balance and higher carbon fixation rate. Macauba (*Acrocomia aculeata* (Jacq.) Lodd. Ex Mart.), a native palm of the Cerrado biome, stands out as an alternative oil source and raw material for biofuels due to its yield potential and oil quality (Lopes et al., 2013; Lanes et al., 2014; César et al., 2015; Cardoso et al., 2016). This plant is considered as the most promising among Brazilian native species in the search for new alternative oilseeds (Conceição et al., 2015), which is justified by the diversity of possible and potential coproducts and the use of its residues. Macauba can be used for charcoal production (Evaristo et al., 2016), human food (Hiane et al., 2005; Hiane et al., 2006; Ramos et al., 2008), animal feed (Rufino et al., 2011; Azevedo et al., 2012; Fonseca et al., 2012), and in the production of drugs (Lescano et al., 2015) and cosmetics (Callegari, 2015).

Knowledge about this species and technological advance for its applications have increased a lot lately. Research on population assessments and field-controlled experiments has been carried out. However, designs that involve the evaluation of a large number of plants and the difficulties inherent to species peculiarities (plant height, unevenness of maturation between bunches, and large amount of thorns), besides limited financial resources, encourage the use of alternative methodologies. The solution to circumvent the difficulty of evaluating macauba fruit production may be the construction and use of biometric models that involve easily accessible and measurable morphological characteristics, based on the allometric relationship between the character and the variable of interest.

There are several studies based on biometric models or allometric relationships that make use of multiple regression equations, which through morphological characters estimate yield, product or coproduct biomass, or yield components. Examples are found in other palm species such as pupunha (Vega et al., 2004) and carnauba (Silva et al., 2015), and in traditional perennial fruit such as banana (Zucoloto et al., 2013) and mango (Castro Neto & Reinhardt, 2003; Morais et al., 2004).

The concept of allometry applies in studies where there is a scale relationship between the different morphological components of a given organism (Klingenberg & Nijhout, 2016; Mirth et al., 2016), in which characteristics of the relative dimensions of parts of an organism are correlated with the characteristics of shape and total size (Moraes, 2015). Tabachnick and Fidell (1996) define multiple regression as a statistical method that allows the evaluation of the relationship of a dependent variable with several independent variables. The equation generated by multiple regression represents an additive model to explain and predict the variable of interest from several predictor variables (Abbad & Torres, 2002). Based on these principles, we built biometric models for different macauba populations to estimate bunch weight.

Materials and methods

Plant populations from five regions (Montes Claros; Alto Paranaíba; Lavras region, Minas Gerais State; Formosa region, Goiás State; and Distrito Federal) were evaluated (Table 1). Mature macauba bunches were evaluated *in situ*. The bunches were harvested, and the following field variables were observed with the help of a measuring tape and a suspended digital scale: bunch length (BL), bunch diameter (BD), and bunch weight (BW). The following variables were also calculated: bunch volume ($BV = \pi*(BD/2)^2*BL$), bunch length-diameter ratio ($BLD = BL*BD$), square bunch length ($SBL = BL^2$), and square bunch diameter ($SBD = BD^2$).

Table 1 - Origin of Macauba populations, sampling locations for bunches evaluation and number of bunches observed.

Federative unit	Region	Collection municipalities	Number of bunches
State of Minas Gerais	1 - Montes Claros	Mirabela	10
	2 - Alto Paranaíba	São Gotardo	5
		Carmo do Paranaíba	15
		Córrego Danta	8
	3 - Lavras	Ingaí	5
Federal district	4 - Distrito Federal	Núcleo Rural Buriti Vermelho	11
State of Goiás	5 - Formosa	Formosa	9

Exploratory analysis made it possible to verify the existence of possible outliers through standardized residuals greater than +2 or less than -2. Analysis of variance was used to evaluate the multiple linear regression model by the least squares method. The t-test evaluated the statistical significance of the regression coefficients estimated in each model at a significance level of 5%. The quantile-quantile (QQ) plot was used to assess the assumption of normality in the models. The fit quality of the model was evaluated by the coefficient of determination (R^2). The multicollinearity assumption was also verified when in the presence of a high correlation between explanatory variables, that is, between two or more independent variables included in the model, a problem which may impact the estimation of model parameters. Therefore, multicollinearity was assessed by Pearson's linear correlation coefficient and variance inflation factor (VIF). With these procedures, the four regression assumptions (linearity, error independence, error normality, and equality of variance) were evaluated (Santana et al., 2015).

The stepwise procedure was used to identify the potential variables for the multiple linear regression model. This procedure is based on the construction of models by adding or removing variables, using variables correlated with the response variable. For the entry and permanence of potential variables in the model, the significance level of 5% was adopted as the criterion to estimate the variable of interest (dependent variable). The multiple linear regression equation is given by:

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_k x_{ik} + \varepsilon_i \ (i = 1, \ldots, n)$$

wherein:

n is the number of individuals;

y_i is the observation of the dependent variable for the ith individual;

$X_i = (x_{i1}, x_{i2}, . . ., x_{ik})$ is a vector of observations of the independent variables for the ith individual;
$\beta = (\beta_0, \beta_1, \beta_2, . . ., \beta_k)$ is a vector of regression coefficients (parameters);
ε_i is a random error component.

The Statistical Package for Social Sciences (SPSS) version 19.0 for Windows (SPSS Inc., Chicago, IL) was used to perform multiple linear regression analysis and correlations.

Results and discussion

Table 2 shows the descriptive statistics for all variables observed in the five regions studied. Dispersion parameters (SD and CV) show the heterogeneity of variables within each population, which denotes variability and contributes to representativeness in correlation and predictive model construction studies. Regarding the asymmetry coefficient of the distribution of variables, it can be stated that BL, BV, BLD, and SBL presented symmetrical behavior in all Regions/Populations, i.e., the mean, median, and mode values for each variable were statistically similar. For the characters BD and SBD, this same pattern was only observed in the regions of Lavras, Alto Paranaíba, and Formosa. Bunch weight (BW) also showed symmetrical behavior in the regions of Federal District, Alto Paranaíba, and Formosa.

Kurtosis evaluates the data distribution dispersion degree (Table 2). Data with Leptokurtic distribution are more concentrated around the mean. In the Mesokurtic case, the data follow the behavior of a normal distribution. Finally, in the case of Platykurtic distribution, the values are more dispersed in relation to the average. According to the results of the kurtosis coefficient, variables BL, BD, BV, BLD, BSL, and BSD predominantly showed Platykurtic distribution (with greater data dispersion) regarding the Regions/Populations studied. Thus, BW was the only variable that showed Leptokurtic distribution (with the smallest dispersion) as dominant in the Regions analyzed.

Table 2 – Descriptive statistics of variables related to physical characteristics of bunch in Macauba, referring to the five regions studied.

Region	Statistical parameters	BW	BL	BD	BV	BLD	BSL	BSD
Montes Claros	Mean	17.35	66.50	37.50	76674.50	2530.00	4527.50	1427.50
	SD	8.34	10.81	4.86	28967.31	680.67	1367.15	356.58
	CV	48.1%	16.3%	13.0%	37.8%	26.9%	30.2%	25.0%
	SE	2.64	3.42	1.54	9160.27	215.25	432.33	112.76
	As	1.19	-0.28	-1.54	-0.84	-0.75	-0.08	-1.45
	Kurt	0.25	0.32	0.24	0.42	0.38	0.34	0.25
Lavras	Mean	18.22	36.00	36.00	42058.07	1360.00	1360.00	1360.00
	SD	10.71	8.94	8.94	27991.83	643.14	643.14	643.14
	CV	58.8%	24.8%	24.8%	66.6%	47.3%	47.3%	47.3%
	SE	4.79	4.00	4.00	12518.33	287.62	287.62	287.62
	As	1.74	0.34	0.34	0.90	0.63	0.63	0.63
	Kurt	0.39	0.42	0.42	0.45	0.44	0.44	0.44
Alto Paranaíba	Mean	13.77	61.54	30.68	50616.11	1947.50	3951.39	983.11
	SD	7.08	13.07	6.59	32917.98	804.61	1738.95	435.42
	CV	51.4%	21.2%	21.5%	65.0%	41.3%	44.0%	44.3%
	SE	1.34	2.47	1.25	6220.91	152.06	328.63	82.29
	As	0.12	0.35	0.31	0.86	0.64	0.61	0.57
	Kurt	0.26	0.23	0.33	0.19	0.19	0.20	0.31
Federal District	Mean	38.17	77.64	42.09	129760.13	3493.73	6475.82	1903.36
	SD	14.37	22.21	12.04	83586.82	1727.55	3369.77	917.34
	CV	37.6%	28.6%	28.6%	64.4%	49.4%	52.0%	48.2%
	SE	4.33	6.70	3.63	25202.38	520.88	1016.02	276.59
	As	-0.97	0.36	-1.47	-0.21	-0.18	0.76	-1.31
	Kurt	0.29	0.33	0.31	0.38	0.36	0.35	0.33
Formosa	Mean	19.10	54.44	29.33	37975.75	1608.89	3011.11	875.11
	SD	5.86	7.26	4.06	13575.14	373.49	789.10	240.29
	CV	30.7%	13.3%	13.8%	35.7%	23.2%	26.2%	27.5%
	SE	1.95	2.42	1.35	4525.05	124.50	263.03	80.10
	As	0.51	-0.23	-0.49	0.58	0.87	-0.05	-0.31
	Kurt	0.24	0.31	0.25	0.21	0.29	0.32	0.23

SD: Standard deviation; CV: Coefficient of variation; SE: Standard error; As: 2nd Coefficient of asymmetry to Pearson = (Symmetric: -1 < As < 1 ; Positive asymmetry: As > 1; Negative asymmetry: As < -1); Kurt: Kurtosis coefficient = (Leptocurtic: Kurt < 0.263; Mesocurtic: Kurt = 0.263; Platicurtic: Kurt > 0.263); BW: bunch weight (kg); BL: bunch length (cm); BD: bunch diameter (cm); BV: bunch volume (cm^3); BLD = BL*BD; BSL = BL^2; BSD = BD^2.

High and positive correlations were found for practically all variables for all populations (105 possible associations), except for BL x BD, BL x SBD, BD x SBL, and SBL x SBD for plants in the Formosa region (Table 3). The variable of interest bunch weight (BW) showed a significant, high, and positive correlation with the other variables for all populations. High degrees of associations were found in the regions of Lavras and Distrito Federal, where the highest correlations were observed for BW x BV ($R^2 = 0.971$) and BW x BLD ($R^2 = 0.974$), respectively (Table 3).

Table 3 - Pearson correlation estimates between the variables observed in Macauba bunches for the five regions evaluated.

Correlated variables	Montes Claros	Lavras	Alto Paranaíba	Federal District	Formosa
BW x BL	0.798*	0.942*	0.797*	0.967*	0.608*
BW x BD	0.745*	0.942*	0.667*	0.961*	0.956*
BW x BV	0.841*	0.971*	0.737*	0.957*	0.952*
BW x BLD	0.839*	0.959*	0.778*	0.974*	0.914*
BW x BSL	0.830*	0.959*	0.782*	0.950*	0.604*
BW x BSD	0.764*	0.959*	0.665*	0.962*	0.958*
BL x BD	0.767*	1.000*	0.718*	0.930*	0.456^{ns}
BL x BV	0.908*	0.991*	0.854*	0.974*	0.717*
BL x BLD	0.952*	0.997*	0.922*	0.989*	0.841*
BL x BSL	0.996*	0.997*	0.995*	0.994*	0.999*
BL x BSD	0.777*	0.997*	0.720*	0.942*	0.456^{ns}
BD x BV	0.956*	0.991*	0.941*	0.949*	0.936*
BD x BLD	0.924*	0.997*	0.919*	0.961*	0.859*
BD x BSL	0.798*	0.997*	0.721*	0.899*	0.455^{ns}
BD x BSD	0.998*	0.997*	0.993*	0.991*	0.998*
BV x BLD	0.992*	0.998*	0.987*	0.995*	0.979*
BV x BSL	0.930*	0.998*	0.871*	0.974*	0.722*
BV x BSD	0.965*	0.998*	0.961*	0.978*	0.942*
BLD x BSL	0.967*	1.000*	0.930*	0.983*	0.844*
BLD x BSD	0.932*	1.000*	0.928*	0.978*	0.862*
BSL x BSD	0.809*	1.000*	0.729*	0.923*	0.460^{ns}

*: Significant to Pearson correlation ($p < 0.05$); BW: bunch weight (kg); BL: bunch length (cm); BD: bunch diameter (cm); BV: bunch volume (cm^3); BLD = BL*BD; BSL = BL^2; BSD = BD^2.

The variables selected using the stepwise method to construct the five models (BV, BL, BLD, and BSD) (Table 4) were the most correlated with the variable of interest within each region (Table 3). The stepwise method usually selects more than one variable for model building, generating a multiple regression model. However, due to the multicollinearity between the variables, evidenced by the high correlation between them, models with only one variable were generated.

Table 4 - Regression models and respective determination coefficients (R^2) for bunch weight estimation (BW), as a function of selected predictor variables, obtained for the five regions evaluated.

Region	Model (Y = BW)	R^2
Montes Claros - MG	-1.232+0.000242(BV)	0.71**
Lavras - MG	2.602+0.000371(BV)	0.94**
Alto Paranaíba - MG	-12.799+0.432(BL)	0.64**
Federal District	9.882+0.008(BLD)	0.95**
Formosa - GO	-1.35+0.023(BSD)	0.92**

**: Significant to F Test ($p < 0.01$); BV: bunch volume (cm^3); BL: bunch length (cm); BLD = BL*BD; BSD = BD^2.

After stepwise, the models built for the Lavras, Distrito Federal, and Formosa regions explain over 90% of the total variance in the prediction of bunch weight, while the models for the Montes Claros and Alto Paranaíba regions explain 71 and 64%, respectively (Table 4). The observed versus estimated BW graphs present the data dispersion in relation to the equation line, showing that the points are closer to the line in models where the coefficient of determination has a higher value (Figure 1,Table 4).

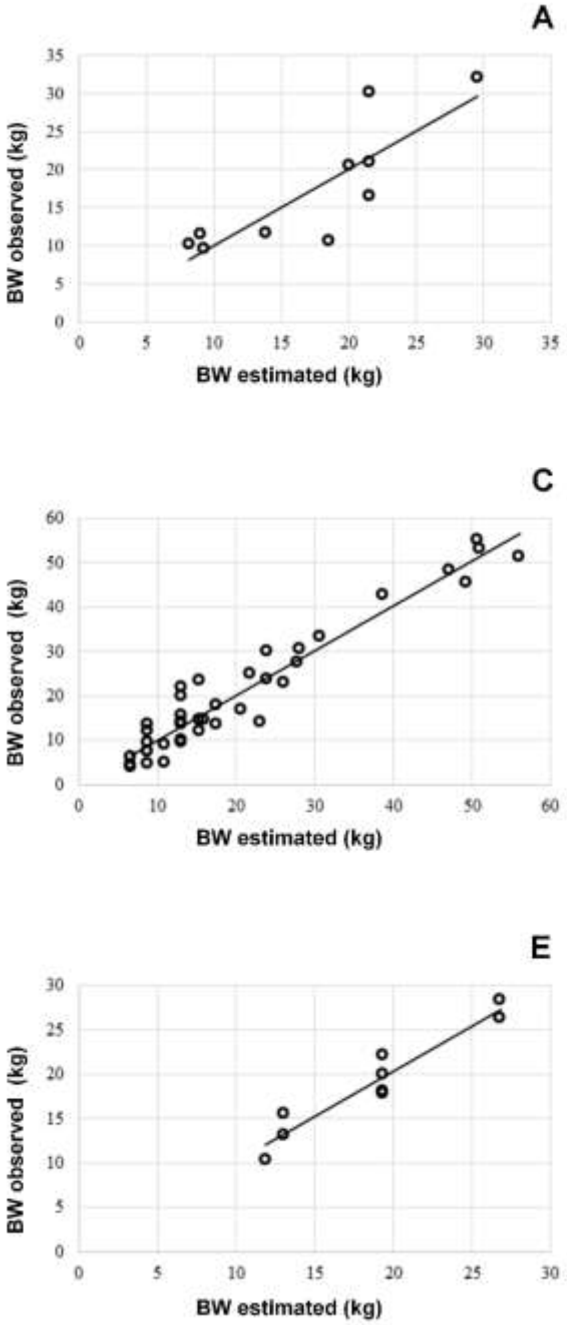

Figure 1 - Scatter plot of bunch weight (BW) values observed versus estimated by constructed models corresponding to each region: (A) Montes Claros, (B) Lavras, (C) Alto Paranaíba, (D) Federal District, and (E) Formosa.

There are no prediction models for characters related to macauba production or yield. There are studies of performance prediction of macauba fruit biomass using Artificial Neural Networks (Castro et al., 2017). In turn, there are some reports analyzing the correlation between physical characters of bunches and fruits, yield components and oil content (Ciconini et al., 2013; Conceição et al., 2015), and correlations between morphological and physiological variables of vegetative development (Domiciano et al., 2015).

Ciconini et al. (2013) did not find significant correlations between bunch length and the variables bunch weight and number of fruits, and bunch diameter was not considered in the estimates. In *Astrocaryum aculeatum* G. Meyer, Tucumã, another potential oil source native from the Amazon region, some authors found a positive correlation between bunch weight and bunch length, in addition to a high correlation between bunch weight and bunch diameter (Nascimento et al., 2007). Domingos Neto & Ferreira (2014) also found high correlations between bunch weight and bunch diameter when studying with Jarina palm tree (*Phytlephas macrocarpa* Ruiz & Pavon), showing that diameter is an important component to be tested in models for yield prediction in palm trees in general. Notwithstanding, the models built proved to be suitable for the purposes of the research. Using these models will reduce costs and time, and make plant evaluations less laborious, whether in natural populations or in experimental areas.

Conclusions

The variables bunch volume, bunch length, bunch length/diameter ratio, and square bunch diameter were effective for constructing the putative models for plants of all studied populations. The models may serve the final purpose of their use in evaluations of natural populations of the respective regions. However, prior validation of these models is necessary to verify their respective effectiveness.

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