Cladode area and weight of *Nopalea cochenillifera* clones as a function of morphometric characteristics

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ABSTRACT

The study aims estimate the cladode area and weight of Little Sweet and Giant Sweet clone based on its linear dimensions by method non-destructively. The experiment was realized in randomized blocks with five replicates using Little and Giant Sweet clones of *Nopalea cochenillifera*. To determine the length, width, thickness, area and weight of cladodes were used a random sample of 1018 cladodes. Cladode area and weight were estimated through of the cladode morphometric characteristics using regression models. Power model was most adequate to explain cladode area of clones and regardless *N. cochenillifera* clones. Power model was most adequate to explain cladodes weight of Little Sweet clone and regardless *N. cochenillifera* clones, while that gamma model was most adequate to explain cladode weight of Giant Sweet clone. Cladode area and weight of *N. cochenillifera* can be explain as a function of morphometric characteristics with larger explanation power.

Keywords: estimation; linear dimension; modelling.

INTRODUCTION

Forage cacti of *Nopalea cochenillifera* (L.) Salm-Dyck genus can contribute to increasing the biomass yields of agricultural areas by improving the efficiency at which local natural resources are used (Diniz *et al*., 2017). The forage cactus stands out as a forage alternative in hot climate regions due to its high potential of phytomass production, energy value, large water reserve and easy propagation (Pereira *et al*., 2018; Freire *et al*., 2018). Cladodes are responsible by photosynthetic process in forage cactus, this process is of fundamental importance for biomass production (Lucena *et al*., 2019a).

The forage cactus uses photosynthetic metabolism kind CAM (Crassulacean Acid Metabolism), thus providing a greater capacity to adapt to abiotic factors (Freire *et al*., 2018; Santos *et al*., 2016). All of these anatomical and morphophysiological adaptations acquired by forage cactus contribute to the high agroecological success of the crop, allowing adaptation to environmental

conditions with high atmospheric evaporative demand and reduced soil water contents due to greater efficiency in water absorption and use (Hartzell *et al*., 2018; Winter *et al*., 2011). The yield of this crop is influenced mainly by light interception, which in turn is determined by morphological characteristics such as the cladode area (Pinheiro *et al*., 2014).
Determination of the plant photosynthetic area, leaf or cladode is a fundamental tool in study of ecophysiology (Schmildt *et al*., 2014). Non-destructive and indirect methods are both currently used for the estimation of cladode area (Lucena *et al*., 2019b) based on the relationships between the measurable biometric variable and the real cladode area and allowing rapid, successive evaluations of the same cladode (Lucena *et al*., 2018a).
The used of regression models using morphometric characteristics of leaves to estimate leaf area is very useful in the plant growth and development (Achten *et al*., 2010). These models are advantageous because they are fast, do not destroy plants and are easy to handle in field conditions (Leite *et al*., 2017).

Recently, studies using linear dimensions in the estimation of the cladode area of forage cactus have been established for species of the *N. cochenillifera* Giant Sweet clone (Lucena *et al*., 2019a, 2019b) and Little Sweet clone (Silva *et al*., 2014) have generated equations with high precision. Although there is information about the agronomic characteristics of *N. cochenillifera,* studies have rarely been reported in the literature for this species, with estimative cladode areas (Silva *et al*., 2014; Lucena *et al*., 2019a and 2019b) and weights (Cunha *et al*., 2012), using the linear dimensions as an explanatory variable, however none of these studies estimated the area and weight of cladodes for the genus *N. cochenillifera* regardless of clone.
Given the above, the objective was estimate the area and weight of cladode *N. cochenillifera* Little Sweet and Giant Sweet clone and independent of the clone based on its linear dimensions (length, width and thickness) by method non-destructively.

MATERIAL AND METHODS

Study area

This research was conducted from March 2016, to July 2019, in the forage farming sector (GEFOR) of the Federal Rural University of Pernambuco (UFRPE), Brazil (07° 57’ 01” S and 38° 17’ 53” E) at an altitude of 523 m.a.s.l. The climate condition is BSwh’ according to Köppen. The average annual rainfall is 632.2 mm, the average annual air temperature is 26 ºC, and the average air relative humidity is 60% (Leite *et al*., 2017).

Experimental conditions

Soils characteristics

The soil used in the experiment was collected at a depth of 0-20 cm and classified as Typical Haplic Cambisol Ta Eutrophic. The soil sample was analysed by the soil fertility laboratory of the Instituto Agronômico de Pernambuco (IPA) and was characterized by: pH (water)= 6.80; P (extractor Mehlich I)= 40 mg dm^{-3}; K^{+}=0.45; Ca^{2+}=5.50; Mg^{2+}=1.60; and Al^{3+}=0.0 $cmol_c$ dm^{-3}.
The cleaning and preparation of the study area were performed manually in March 2016, after two cleanings were performed annually. Posteriorly, the cladodes of forage cactus were planted. Organic fertilization was performed using 40 t ha^{-1} of bovine manure. The row spacing was 1.4 m, and the planting was performed using the card of deck system. In this system, a

groove is made, and the cladodes are planted in a single file where one plant overlaps the other.

Experimental design

The design used was randomized blocks with five replicates using the forage cactus clones Little and Giant Sweet of *N. cochenillifera* (Fig. 1). The experimental unit was an area of 126.0 m^2 (12.6 m × 10.0 m), which consisted of 10 rows and 40 columns of cacti spaced in rows 1.40 apart (1285710 plants ha^{-1}). The rows and columns of the border were excluded. The area was maintained in dry conditions throughout the crop cycle. Evaluations were performed 1200 days after planting (DAP).

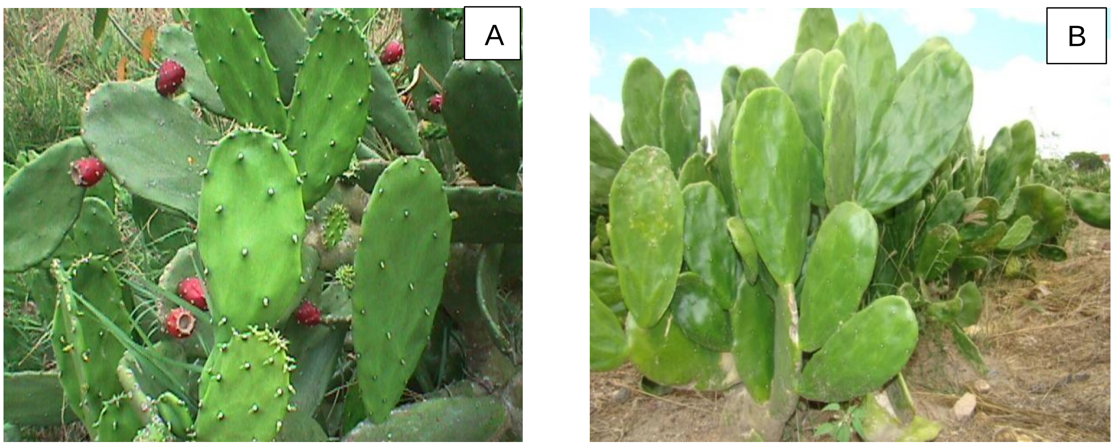

Figure 1. Clones of *Nopalea cochenillifera,* Little Sweet (A) and Giant Sweet (B).

Statistical analysis

Sample a randomized of 1018 healthy cladodes (190-primary; 186-secondary and 205- tertiary of Little Sweet clone) and (167-primary; 127-secondary and 143-tertiary of Giant Sweet clone), was collected to determine the cladode morphometric characteristics [length (cm), width (cm), thickness (mm), area (cm^2) and weight (g)], according to methodologies established in the literature (Lucena *et al*., 2019a, 2019b, 2018a). Each cladode was numbered and their recorded morphometric characteristics (length (L), width (W) and thickness (T)), using a digital calliper. The regions of greatest width and length of each cladode were used to measure the two characteristics. The cladodes were weighed on a precision balance. The real cladode area (RCA) was estimate following the methodology described by Lucena *et al*. (2019a).

To determine the best adjustment model to predict the real cladode area (RCA) using product between L and W (LW) with explanatory variable, regression studies were performed using linear, gamma and power models (Lucena *et al*., 2018a, 2019a) (Table 1). To predict the weight of the cladodes as a function of thickness (T) and product between L and W (LW) were used the linear, gamma and power models (Table 1). The linear and power models with normal distributions assumed that response variable assumes values in the range of $-\infty$ to ∞, and gamma models with gamma distributions assuming that response variable presente values between 0 to ∞ (Lucena *et al*., 2018 and 2019a; Leite *et al*., 2017 and 2019) (Table 1).

Table 1. Regression models of the real cladode area (RCA) and weight of the cladode (WC) using product of length by width (LW) and thickness (T) with explanatory variables.

Models	Equation	
	Real cladode area	Weight of cladode
Linear	$RCA_i = \beta_1 LW_i + \varepsilon_i$	$WC_i = \beta_1 T_i + \beta_2 LW_i + \varepsilon_i$
Power	$RCA_i = \beta_0 LW_i^{\beta_1} \varepsilon_i$	$WC_i = \beta_0 T_i^{\beta_1} LW_i^{\beta_2} \varepsilon_i$
Gamma	$RCA_i = \beta_0 + \beta_1 LW_i + \varepsilon_i$	$WC_i = \beta_0 + \beta_1 T_i + \beta_2 LW_i + \varepsilon_i$

where, RCA_i is the real cladode area of the i-th forage cactus; WC_i is the weight of the cladode of the i-th forage cactus; LW_i is product of the length and width of the i-th cladode; T_i is the thickness of the i-th cladode; and ε_i is the i-th error interrelated with the cladode area or weight. ε_i exhibited a normal distribution of mean 0 and variance constant $\sigma^2 > 0$ for the linear and power models, and gamma distributions of parameters α and β for the gamma models. The β_0, β_1 and β_2 are parameters associated to the model.

The Coefficient of determination (R^2), Akaike's Information Criterion (AIC) defined by Akaike (1974), Sum of Square of Residuals (SSR) and the Willmott index (d) defined by Willmott (1981) were used to adequacy of models (Table 2).

Table 2. Criteria of adequacy of the model.

Criteria	
R^2	$1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y}_i)^2}$
SSR	$\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$
AIC	n ln (SSR/n)+ 2(p)
d	$1 - \frac{\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2}{\sum_{i=1}^{n}(\lvert\hat{Y}_i - \bar{Y}\rvert + \lvert Y_i - \bar{Y}\rvert)^2}$

where n and p are the number of cladode, and the number of parameters; $\hat{Y}_i$ is the values of the i-th cladode area or weight after model adjustment; and $\bar{Y}$ is the mean value of the cladode area (Y_i) or the weight cladode (Y_i) of the forage cactus.

To evaluate the correlations between the morphometric variables (real cladode area, product between the length and width, thickness, and cladode weight), the Pearson correlation coefficient was used (Lucena *et al*., 2018b), described by:

$$r = \frac{\sum_{i=1}^{n}(Y_i - \bar{Y})(X_i - \bar{X})}{\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}} \quad (1)$$

where Y_i and X_i are the i-th observations of variables, while $\bar{Y}$ and $\bar{X}$ are the means of the variables Y and X, respectively.

RESULTS AND DISCUSSION

Evaluating the morphometric characteristics of the Little Sweet clone a high positive correlation was observed between RCA and LW (*r*=0.97), RCA and WC (*r*=0.82), and LW and WC (*r*=0.84) (Fig. 2a). Real cladode area of clone Giant Sweet showed a high correlation between product of length by width (*r*=0.97) and between weight cladode (*r*=0.82), product of length by width presented correlation with weight cladode (*r*=0.81) (Fig. 2b). Regardless of the clone evaluated the real cladode area presented a high correlation with the product of length by width (*r*=0.98) and weight cladodes (*r*=0.83) (Fig. 2c). Product of length by width positively correlated with cladode weight.

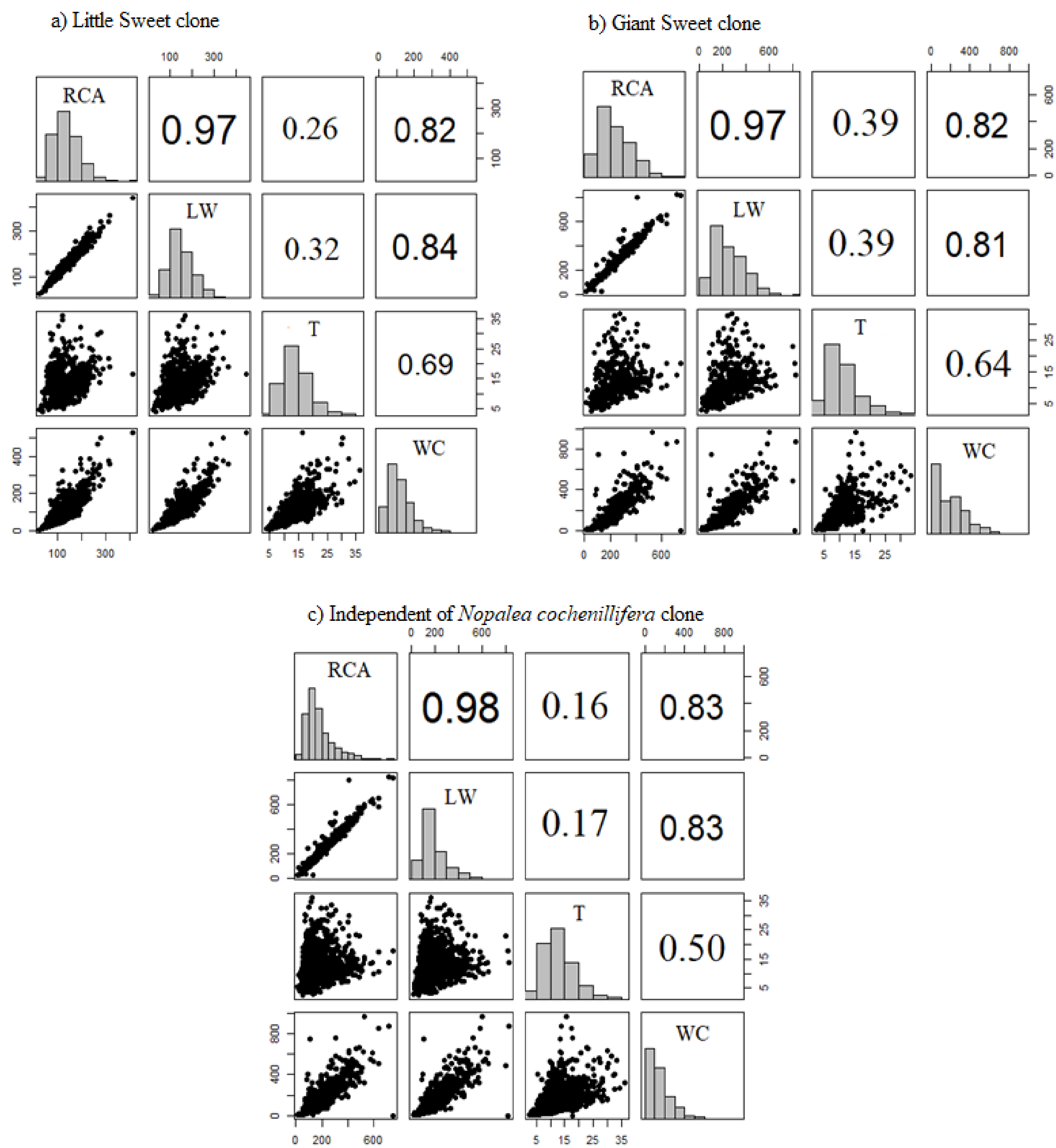

Figure 2. Correlation between morphometrics measurements of *Nopalea cochenillifera*, Little Sweet clone (a), Giant Sweet clone (b) and independent of clone (c).

Cunha *et al*. (2012) observed in *N. cochenillifera* Little Sweet clone positive correlation of cladode weight with length, width, thickness and area less than 0.74, while Silva *et al*. (2014) verified high correlation (*r*=0.985) between cladode area and LW with this same clone. Similar results were report by Lucena *et al*. (2019) observed in *N. cochenillifera*, Giant Sweet clone a high positive correlation of real cladode area with LW (*r*=0.97). Independent of cladode order a positive correlation between RCA and product of length by width has reported by Lucena *et al*. (2018) in *Opuntia stricta* (*r*= 0.90). In *O. ficus-indica* Reis *et al*. (2016) verified correlation between RCA and LW (*r*=0.95), Guimarães *et al*. (2018) verified correlation between cladode area and their morphometric characteristics smaller than 0.65, while Cortazar and Nobel (1992) and Flores *et al*. (1996) verified high correlation (*r*=0.99 and 0.914) between weight and cladode area, respectively.

This proves the existence of a linear association between the fresh mass of cladodes and the other variables. This is important in conducting non-destructive studies to monitor the development of forage cactus. In this scenario, it may also be possible to develop equations to obtain estimates of cactus mass production under field conditions when in the absence of balance.

The power model presented the better performance to estimate the real cladode area of the Little Sweet clone (larger R^2= 99.98%, smaller SSR= 79972.75 and AIC=1131.4) using the product of length and width with explanatory variable (Table 3).

Table 3. Fitted models and criteria of model evaluation of the real cladode area (RCA) of *Nopalea cochenillifera* Little and Giant Sweet clone considering the product of length and width (LW) as the explanatory variable.

Models	Equation of real cladode area	Criteria of adequacy of the model			
		R^2	SSR	AIC	d
		Little Sweet clone			
Linear	$\widehat{RCA}$=0.891LW	99.33	80784.54	4526.7	0.987
Power	$\widehat{RCA}=LW^{0.977}$	99.98	79972.75	1131.4	0.987
Gamma	$\widehat{RCA}$=0.899LW	94.68	81611.97	4498.2	0.987
		Giant Sweet clone			
Linear	$\widehat{RCA}$=0.901LW	98.85	357257.60	4174.80	0.987
Power	$\widehat{RCA}=LW^{0.982}$	99.91	349576.60	360.38	0.987
Gamma	$\widehat{RCA}$=0.926LW	94.45	380413.70	4416.17	0.986
		Independent clone			
Linear	$\widehat{RCA}$=0.898LW	95.97	439038.7	9068.91	0.990
Power	$\widehat{RCA}=LW^{0.98}$	99.94	437165.6	1329.28	0.990
Gamma	$\widehat{RCA}$=0.91LW	95.90	446803.6	9162.2	0.990

R^2 (determination coefficient); SSR (sum squared of residuals); AIC (Akaike information criteria); d (Willmott index).

Evaluating the real cladode area of Giant Sweet clone the best fit criteria of the models were attributed to the power model, the same presented higher explanatory power (R^2=99.91%) and smaller sums of residual squares (SSR=349576.60) and Akaike information criteria (AIC=360.38) (Table 3).

Regardless of the *N. cochenillifera* clone evaluated the best relationship between real cladode area and product of length by width was explained by the power model, which presented the best results of R^2 (99.94%), SSR (437165.6), AIC (1329.28) and similar Willmott index (0.99) (Table 3). For the Sweet and Giant sweet clones, and regardless of *N. cochenillifera* clone the worst fit criteria of the model, and consequently the worst estimates of the real cladode area were attributed to gamma model (Table 3).

To explain the real cladode area of Little Sweet clone as a function of the product of length by width Silva et al. (2014) used linear model with explanatory power of 96.96%, while Lucena *et al*. (2019a) used power model with explanatory power of 99.91%. The product of length by width is a reliable measure to explain the cladode area with high precision power as reported in the findings of Lucena *et al*. (2018a) in *Opuntia Stricta* R^2= 99.66% and Reis *et al*. (2016) in *O. fícus-indica* R^2=91%.

Weight of the cladodes of the Little Sweet clone can be explained using the thickness and product of the length and width with most accurate by power model. Power model presented greater power of explanation (R^2=93.72%) and larger Willmott index (d=0.977), and smaller SSR (290572.1) and AIC (471.28) that linear and gamma models (Table 4).

Table 4. Fitted models and criteria of model evaluation of weight cladode (WC) of *Nopalea cochenillifera* Little and Giant Sweet clone considering the thickness (T) and the product of length by width (LW) with explanatory variables.

Models	Equation of weight cladode	Criteria of adequacy of the model			
		R^2	SSR	AIC	d
	Little Sweet clone				
Linear	$\widehat{WC}$=-93.4+5.05T+0.968LW	85.50	475124.1	5561.87	0.960
Power	$\widehat{WC}=0.057(T^{0.806}\ LW^{1.099})$	93.72	290572.1	471.28	0.977
Gamma	$\widehat{WC}$=-33.19+4.46T+0.58LW	85.23	516491.7	5343.4	0.900
	Giant Sweet clone				
Linear	$\widehat{WC}$=5.77T+0.603LW	87.56	3679152	5195.87	0.879
Power	$\widehat{WC}=T^{0.888}\ LW^{0.533}$	98.86	4537108	698.83	0.847
Gamma	$\widehat{WC}$=0.536T+0.028LW	99.04	3505923	4751.90	0.939
	Independent clone				
Linear	$\widehat{WC}$=-120.89+8.49T-0.856LW	92.02	2980555	11022.66	0.949
Power	$\widehat{WC}=0.056(T^{0.867}\ LW^{1.069})$	96.83	2964388	467.68	0.951
Gamma	$\widehat{WC}$=2.507T+0.551LW	83.65	5774752	10829.00	0.844

R^2 (determination coefficient); SSR (sum squared of residuals); AIC (Akaike information criteria); d (Willmott index).

Cladodes weight of the of Giant Sweet clone was explained using the thickness and product of the length and width of the cladodes with greater accuracy by the gamma model. Gamma model presented greater power of explanation (99.04%) and larger Willmott index (0.939), and smaller SSR (3505923) and AIC (698.83) when compared to the linear and power models (Table 4).

Regardless of the *N. cochenillifera* clone evaluated the best estimates for cladode weight when associated with morphometric measurements (thickness and product between length and width of cladodes) were represented by the power model followed by the linear and gamma models (Table 4). Power model presented greater power of explanation (R^2=96.83%) and larger Willmott index (d=0.951), and values smaller of SSR (2964388) and AIC (467.68). Gamma model presented worst adequacy criteria.

Cunha *et al*. (2012) estimated the cladodes weight of Little Sweet using the morphometric characteristics (length, width, and thickness) with explanatory power 92.25%. Cladodes weight *O. ficus-indica* can be explained by the area of cladodes with explanatory power 99% (Cortazár and Nobel, 1992) and 88.17% (Flores *et al*., 1996).

CONCLUSIONS

Cladode area of *N. cochenillifera* can be estimated by the power model $\widehat{RCA}=LW^{0.98}$, while weight can be explained by the power model $\widehat{WC}=0.056(T^{0.867}\ LW^{1.069})$.

The morphometric characteristics can be used to explain the cladode area and weight of clones and regardless of *N. cochenillifera* clone with high reliability.

The cladode weight of *N. cochenillifera* can be measured under field conditions when in the absence of balance.

ETHICS STATEMENT

"Not applicable"

CONSENT FOR PUBLICATION

"Not applicable"

AVAILABILITY OF SUPPORTING DATA

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

"The authors declare that they have no competing interests"

FUNDING

"Not applicable"

AUTHOR CONTRIBUTIONS

Conceptualization, Mauricio Luiz de Mello Vieira Leite; methodology, Mauricio Luiz de Mello Vieira Leite and Leandro Ricardo Rodrigues de Lucena; software, Leandro Ricardo Rodrigues de Lucena; validation, Antônio Dennys Melo de Oliveira; investigation, Antônio Dennys Melo de Oliveira, Álefe Chagas de Lima Costa, Fredson Luan Queiroz dos Anjos, Igor Masterson de Farias; resources, Mauricio Luiz de Mello Vieira Leite; data curation, Mauricio Luiz de Mello Vieira Leite; writing-original draft preparation, Vicente José Laamon Pinto Simões and Mirna Clarissa Rodrigues de Almeida; writing-review and editing, Mauricio Luiz de Mello Vieira Leite; visualization, Leandro Ricardo Rodrigues de Lucena; supervision, Mirna Clarissa Rodrigues de Almeida; project administration, Mirna Clarissa Rodrigues de Almeida; funding acquisition, Mauricio Luiz de Mello Vieira Leite.

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