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# Estimating the area and weight of cactus forage cladodes using linear dimensions

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**ABSTRACT.** The forage palm is one of the main forages of ruminants in semiarid regions. Measurements of leaf area are required in agronomic studies because they are one of the main parameters used to evaluate plant growth. The objective of this study was to validate and define the best models for estimating the area and weight of Giant Sweet clone (*Nopalea cochenillifera*) forage cladodes in a non-destructive way based on the linear dimensions of length, width and thickness. There were 432 randomly measured cladodes at 550 days after planting. The length, width and thickness of each cladode were measured using a digital calliper. The cladodes were weighed individually. The cladode area was calculated by the gravimetric method. The power regression model was the most efficient method to explain the cladode area as a function of the product of length by width, while the gamma model was the most efficient method to explain the weight of cladodes as a function of the product of length by width and thickness. The power model,  $\widehat{RCA} = LW^{0.982}$ , and gamma model,  $\widehat{WC} = 0.536T + 0.028LW$ , were used to determine the area and weight of *Nopalea cochenillifera* Giant Sweet clone cladodes, respectively, based on the values of linear dimensions measured independently of the order of the cladode.

**Keywords:** Giant Sweet clone; non-destructive method; modelling; *Nopalea cochenillifera*; regression.

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## Introduction

Species adapted to arid and semi-arid environments, such as forage palms (*Nopalea* spp. and *Opuntia* spp.), 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 cactus forage is a xerophilous plant with multiple uses in different countries throughout every continent; some of these uses include as forage, fruits, vegetables, raw materials for processing, biomass for energy purposes, live fences, erosion control, soil conservation, landscaping, dye production, and medicinal uses (Inglese, Barbera, & Mantia, 1995).

The cactus forage stands out as a forage alternative in semi-arid regions due to its high potential of phytomass production, high energy value, richness of non-fibrous carbohydrates, high ruminant acceptability, high digestibility coefficient, large water reserve and easy propagation (Pereira, Leite, Cavalcante, & Lucena, 2018). One of the determining factors of biomass production is the leaf area; in the cactus forage, this function of absorption and use of solar radiation in the photosynthetic process is realized by cladodes.

The cactus forage employs CAM (Crassulacean Acid Metabolism) and photosynthetic metabolism, with day closure of stomata and nocturnal carbon assimilation, thus providing a greater capacity to adapt to abiotic factors (Santos et al., 2016; Souza Filho, Ribeiro, Santos, & Macedo, 2016). The number of stomata in the cladodes is low, 10 to 30 per mm<sup>2</sup>, while the leaves of C3 plants present 300 stomata per mm<sup>2</sup>. In addition, the stomata of cactus forage can be closed for several months in water stress situations (Liguori, Inglese, Pernice, Sortino, & Inglese, 2013).

All of these anatomical and morphophysiological adaptations acquired by cactus forage 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 its high water use efficiency (Hartzell, Bartlett, & Porporato, 2018; Winter, Garcia, & Holtum, 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).

The determination of the photosynthetic area of a plant, leaf or cladode is fundamental for studying the intensity of transpiration, the leaf area ratio, the specific leaf area and the leaf area index (Schmildt, Amaral, Schmildt, & Santos, 2014). Non-destructive and indirect methods are both currently used for the estimation of leaf area (Leite, Lucena, Sá Júnior, & Cruz, 2017) based on the relationships between the measurable biometric variable and the real leaf area (Flumignan, Adami, & Faria, 2008) and allowing rapid, successive evaluations of the same plant (Toebe, Cargnelutti Filho, Loose, Heldwein, & Zanon, 2012).

The development of regression models from the linear measurements of leaves to determine leaf area has been very useful in the study of plant growth and development (Achten et al., 2010). Mathematical models are advantageous because they are fast, do not destroy plants and are easy to handle in field conditions (Leite et al., 2017).

Several studies using linear dimensions in the estimation of the cladode area of cactus forage have been established for several species of the genus *Opuntia*: *O. ficus-indica* (Cortazar & Nobel, 1991; Reis, Gazarini, Fonseca, & Ribeiro, 2016) and *O. stricta* (Lucena, Leite, Simões, Simões, & Almeida, 2018b) and have generated equations with high precision.

Although there is information about the agronomic characteristics of the species *N. cochenillifera*, studies have rarely been reported in the literature for clones of this species, with estimated cladode areas (Silva et al., 2014) and weights, using the linear dimensions as an explanatory variable. The objective of this study was subsequently to validate and define the best models for non-destructively estimating the areas and weights of the cactus forage cladode (*Nopalea cochenillifera* (L.) Salm-Dyck) Giant Sweet clone based on its linear dimensions of length, width and thickness.

## Material and methods

This research was conducted from March 15, 2016, to October 12, 2018, in the forage farming sector (GEFOR) of the Federal Rural University of Pernambuco (UFRPE), Academic Unit of Serra Talhada (UAST), which was located in the following geographic coordinates (07°57'01" S e 38°17'53" E) at an elevation of 523 metres. According to Koppen, the climate condition is a BSwh' with a rainy season during the summer, starting in November and ending in April. The average annual rainfall is 632.2 mm, the average annual air temperature is 26°C, and the average air relative humidity is 60% (Leite et al., 2017).

The soil used in the experiment was collected at a depth of 0-20 cm and classified as Typical Haplic Cambisol Ta Eutrophic, as described by EMBRAPA (2013). The soil sample was analysed by the soil fertility laboratory of the Empresa Pernambucana de Pesquisa Agropecuária (IPA) and was characterized by the following chemical attributes: pH (water) = 6.80; P (extractor Mehlich I) = 40 mg dm<sup>-3</sup>; K<sup>+</sup> = 0.45; Ca<sup>2+</sup> = 5.50; Mg<sup>2+</sup> = 1.60; and Al<sup>3+</sup> = 0.0 cmol<sub>c</sub> dm<sup>-3</sup>. The cleaning and preparation of the study area were performed manually in March 2016. Soon after, the cladodes of forage palms were planted. Organic fertilization was performed using 40 t ha<sup>-1</sup> 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.

A uniformity trial was conducted using a cactus forage clone, Giant Sweet (*Nopalea cochenillifera* (L.) Salm-Dyck). The experimental unit was an area of 22.4 m<sup>2</sup> (5.6 x 4.0 m), which consisted of five rows and 40 columns of cacti spaced in rows 1.40 apart (228,570.7 plants ha<sup>-1</sup>). The rows and columns of the border were excluded. Cultural dealings were made where necessary. Two weeds were identified upon their emergence. The area was maintained in dry conditions throughout the crop cycle. Evaluations were performed 550 days after planting (DAP).

To determine the cladode areas, a randomized collection of 432 cladodes (162- primary; 127-secondary, and 143- tertiary), free of damage, diseases or pests, was conducted according to methodologies established in the literature (Schmildt et al., 2014; Leite et al., 2017, Lucena, Leite, Cruz, & Sá Jr., 2018a). The cladodes were numbered from 1 to 432 and then measured using a digital calliper; the length (L) (cm), width (W) (cm) and thickness (T) (mm) of each cladode were also recorded. The regions of greatest width and length of each cladode were used to measure the two characteristics. The length and width were multiplied, determining the product in cm<sup>2</sup>. The cladodes were weighed on a precision balance, and their values were recorded in grams (g).

Each cladode was spread over a millimetre graph paper, and the outline of the cladode was drawn following the methodology described by Leite et al. (2017). Using scissors, the area of the millimetre graph paper covered by the outline was cut and weighed on an electronic balance. From the same paper, a square

of 10 cm x 10 cm was cut, equivalent to 100 cm<sup>2</sup>, weighing 0.630 g. Thus, it was possible to calculate the proportional cladode area.

To determine the most fit model to predict the real cladode area (RCA) as a function of the product between L and W (LW), regression studies were performed using linear, gamma and power models (Lucena et al., 2018b; Leite et al., 2017; Leite, Lucena, Cruz, Sá Jr., & Simões, 2019) (Table 1). The best fit model was used to predict the weight of the cladodes as a function of thickness (T) and product between L and W (LW), and regression studies were performed using linear, gamma and power models (Table 1). The linear and power models with normal distributions assumed that the response of the dependent variable was in the range of  $-\infty$  to  $\infty$ , and the gamma models with gamma distributions assumed that the response of the dependent variable was in the range of 0 to  $\infty$  (Lucena et al., 2018b; Leite et al., 2017; Leite et al., 2019), (Table 1).

**Table 1.** Regression models to explain the real cladode area (RCA) and weight of the cladode (WC) in relation to the explanatory variables, the product of length by width (LW) and thickness (T).

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 cactus forage;  $WC_i$  is the weight of the cladode of the  $i$ -th cactus forage;  $LW_i$  is the product between the length and width of the  $i$ -th cladode;  $T_i$  is the thickness of the  $i$ -th cladode; and  $\varepsilon_i$  is the  $i$ -th error interrelated with the cladode area or weight.  $\varepsilon_i$  exhibited a normal distribution of mean 0 and variance constant  $\sigma^2 > 0$  in the distributions of parameters  $\alpha$  and  $\beta$  for the linear, power and gamma models. The  $\beta_0$ ,  $\beta_1$  and  $\beta_2$  are parameters related to the model.

The following criteria were used to evaluate the models: 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).

The coefficient of model determination is expressed by:

$$R^2 = 1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2}$$

The Akaike information criteria (AIC), as defined by Akaike (1974), is given by:

$$AIC = -2 \ln L(x|\hat{\theta}) + 2(p)$$

The sum of square of the residuals (SSR) is the square sum of the difference between the values observed and predicted by the models, where the lowest value contributes to the choice of the best equation. SSR for this study is defined by the following expression:

$$SSR = \sum_{i=1}^n (Y_i - \hat{Y}_i)^2$$

The d index defined by Willmott (1981) is given by:

$$d = 1 - \frac{\sum_{i=1}^n (\hat{Y}_i - Y_i)^2}{\sum_{i=1}^n (|\hat{Y}_i - \bar{Y}| + |Y_i - \bar{Y}|)^2}$$

where:  $L(x|\hat{\theta})$  is the maximum likelihood function, defined as the production of density function, and  $p$  is the number of model 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 cactus forage.

To evaluate the correlations between the variables, the Pearson correlation coefficient was used (Lucena et al., 2018a), which was denoted by:

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

where:  $Y_i$  and  $X_i$  are the  $i$ -th observations of the variables  $Y$  and  $X$ , while  $\bar{Y}$  and  $\bar{X}$  are the means of the variables  $Y$  and  $X$ , respectively. T-tests were used to assess the significance of the correlation between the variables.

## Results and discussion

Table 2 shows a high variation in Giant Sweet clone cladode size, independent of the cladode order. The mean cladode length ranged from  $25.53 \pm 6.33$  cm in secondary cladodes to  $17.30 \pm 4.81$  cm in tertiary cladodes. Similar variations occurred for the cladode width, especially in the secondary cladodes ( $12.06 \pm 2.95$  cm) and in the detriment of tertiary cladodes ( $8.53 \pm 2.06$  cm). The thickness of the cladodes ranged from 2.50 mm (tertiary) to 33.40 mm (primary). The mean real cladode area ranged from  $300.23 \pm 133.71$  cm<sup>2</sup> in secondary cladodes to  $140.15 \pm 68.83$  cm<sup>2</sup> in tertiary cladodes. Heavier cladodes were primary ( $288.70 \pm 108.87$  g), and the lighter cladodes were tertiary ( $61.29 \pm 30.40$  g). The cladode weights showed a high dispersion, with secondary cladodes weighing 1.05 g and primary cladode weighing 965.00 g. This high variation in the size of the cladodes likely occurred because some cladodes were in expansion, while others were fully expanded, which is a peculiar growth characteristic of this cactus.

**Table 2.** Descriptive measures of the real cladode area (RCA), length (C), width (W), product of length and width (LW), weight (W) and thickness (T) of *Nopalea cochenillifera*, Giant Sweet clone.

Variables	Min.	Mean	Standard deviation	Max.
Primary cladode				
RCA (cm <sup>2</sup> )	78.94	271.49	106.69	714.08
L (cm)	12.40	25.51	5.80	42.50
W (cm)	5.50	11.49	2.73	24.00
LW (cm <sup>2</sup> )	91.84	303.37	128.39	828.75
W (g)	65.00	288.70	108.87	965.00
T (mm)	5.30	15.70	5.87	33.40
Secondary cladode				
RCA (cm <sup>2</sup> )	59.86	300.23	133.71	745.60
L (cm)	11.00	25.53	6.33	45.40
W (cm)	5.00	12.06	2.95	20.00
LW (cm <sup>2</sup> )	59.00	323.10	142.84	820.00
W (g)	1.05	253.08	106.39	850.00
T (mm)	4.20	11.18	3.31	25.50
Tertiary cladode				
RCA (cm <sup>2</sup> )	17.14	140.15	68.83	396.95
L (cm)	4.50	17.30	4.81	33.20
W (cm)	3.40	8.53	2.06	16.90
LW (cm <sup>2</sup> )	20.06	155.22	76.92	445.56
W (g)	5.00	61.29	30.40	290.00
T (mm)	2.50	6.57	2.16	15.20

Similar results were obtained by Silva et al. (2010) relating the morphological and productive characteristics of 50 clones of cactus forage, which were first cut at 720 DAP; a mean cladode length of 21.97 cm was observed. Gomes, Queiroz, Pereira, Costa, and Oliveira (2016) verified the cladode length of *Nopalea cochenillifera* Giant Sweet clones, fertilized with bovine manure, as 12.35 cm at 210 DAP. Gomes et al. (2016) found a mean cladode length of 12.56 cm, width of 5.87 cm and thickness of 7.81 mm. Reis et al. (2016) verified the cladode measurements of *Opuntia ficus-indica*, with a mean length of 38.61 cm, a width of 18.70 cm, a thickness of 18.6 mm, an area of 586.71 cm<sup>2</sup> and a weight of 893.93 g independent of the cladode order.

There was a positive correlation between the RCA and LW ( $r = 0.95$ ;  $p < 0.0001$ ) of the primary cladodes, between RCA and W ( $r = 0.77$ ;  $p < 0.0001$ ) and between W and LW ( $r = 0.76$ ;  $p < 0.0001$ ) (Table 3). For secondary cladodes, RCA was positively correlated with LW ( $r = 0.99$ ;  $p < 0.0001$ ) and weight ( $r = 0.75$ ;  $p < 0.0001$ ), and W was positively correlated with LW ( $r = 0.73$ ;  $p < 0.0001$ ). There was a positive correlation between RCA and LW ( $r = 0.96$ ;  $p < 0.0001$ ) of the tertiary cladodes, between RCA and W ( $r = 0.91$ ;  $p < 0.0001$ ), W and LW ( $r = 0.87$ ;  $p < 0.0001$ ), and W and T ( $r = 0.67$ ;  $p = 0.035$ ). Cunha et al. (2012) observed a small positive correlation of cladode weight with length ( $r = 0.59$ ), width ( $r = 0.61$ ), thickness

( $r = 0.73$ ) and area ( $r = 0.65$ ) in Sweet cacti clone. Lucena et al. (2018b) observed that, independent of the cladode order, the area of Elephant-Mexican clone (*O. stricta*) presented a positive correlation ( $r$ ) with the product of length by width with a magnitude of 0.90. Guimarães, Donato, Azevedo, Aspiázú, and Silva Jr. (2018) also verified a positive correlation of weight with the cladode area of 0.86 in *O. ficus-indica*.

**Table 3.** Correlation between real cladode area (RCA), product of length and width (LW), weight (W) and thickness (T) of *Nopalea cochenillifera*, Giant Sweet clone.

Primary cladode				
	RCA	LW	W	T
RCA	1.00	---	---	---
LW	0.95*	1.00	---	---
W	0.77*	0.76*	1.00	---
T	0.01 <sup>ns</sup>	-0.004 <sup>ns</sup>	0.39*	1.00
Secondary cladode				
	RCA	LW	W	T
RCA	1.00	---	---	---
LW	0.99*	1.00	---	---
W	0.75*	0.73*	1.00	---
T	0.34 <sup>ns</sup>	0.34 <sup>ns</sup>	0.49*	1.00
Tertiary cladode				
	RCA	LW	W	T
RCA	1.00	---	---	---
LW	0.96*	1.00	---	---
W	0.91*	0.87*	1.00	---
T	0.46*	0.45*	0.67*	1.00

\*significant by t-test ( $p < 0.005$ ); <sup>ns</sup>non-significant by t-test ( $p > 0.05$ ).

Evaluating the relationship between the RCA and LW of the primary cladodes verified that the linear regression model presented an explanatory power ( $R^2$ ) of 98.55%, while the power model had an  $R^2$  of 99.97%, and the gamma model had an explanatory power of 99.52% (Table 4). The linear regression model showed a sum of squared residuals (SSR) of 199,676.40, while the power model showed an SSR of 194,707.10, and gamma model showed an SSR of 192,109.10. The linear model presented an Akaike information criterion (AIC) of 1,616.67, with 295.15 in the power model and 1,485.50 in the gamma model. All the models presented a Willmott index ( $d$ ) of 0.974 (Table 4). The models that presented the best results for the primary cladodes were the power model followed by the gamma model.

**Table 4.** Estimates of parameters and criteria of model adequacy of the real cladode area (RCA) of *Nopalea cochenillifera* taking into account 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	$d$
Primary cladode					
Linear	$\widehat{RCA} = 0.88LW$	98.55	199,676.40	1,616.67	0.974
Power	$\widehat{RCA} = LW^{0.981}$	99.97	194,707.10	295.15	0.974
Gamma	$\widehat{RCA} = 0.907LW$	99.52	192,109.10	1,485.50	0.974
Secondary cladode					
Linear	$\widehat{RCA} = 0.928LW$	99.53	64,427.09	1,155.51	0.993
Power	$\widehat{RCA} = LW^{0.987}$	99.98	64,372.63	315.07	0.993
Gamma	$\widehat{RCA} = 0.931LW$	97.14	64,550.56	1,097.90	0.993
Tertiary cladode					
Linear	$\widehat{RCA} = 0.894LW$	98.46	53,635.13	1,257.39	0.980
Power	$\widehat{RCA} = LW^{0.979}$	99.76	53,164.52	291.57	0.980
Gamma	$\widehat{RCA} = 0.945L$	98.36	64,828.02	1,440.60	0.977
Independent cladode order					
Linear	$\widehat{RCA} = 0.901LW$	98.85	357,257.60	4,174.80	0.987
Power	$\widehat{RCA} = LW^{0.982}$	99.91	349,576.60	360.38	0.987
Gamma	$\widehat{RCA} = 0.926LW$	94.45	380,413.70	4,416.17	0.986

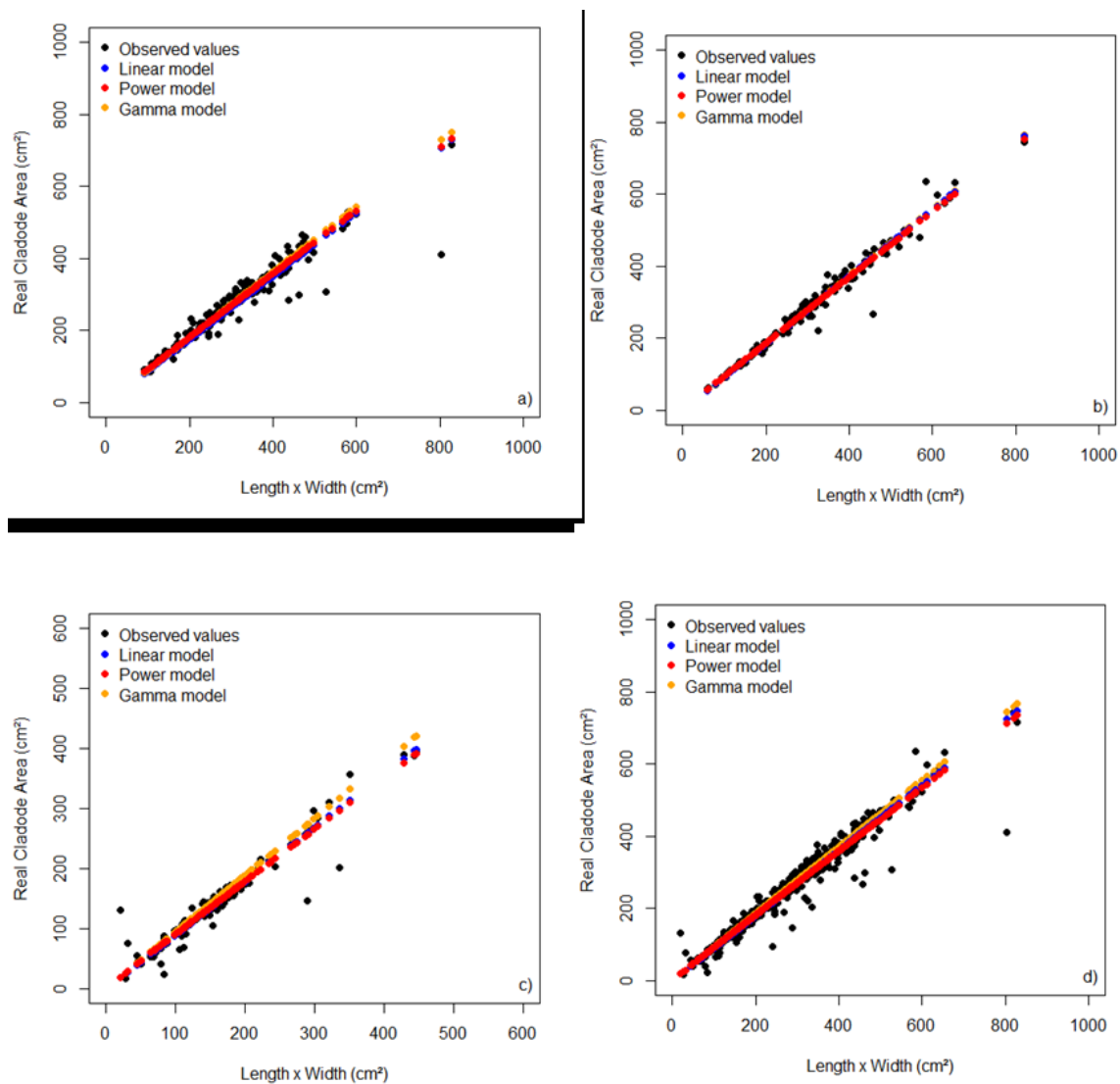
$R^2$  (determination coefficient); SSR (sum squared of residuals); AIC (Akaike information criteria);  $d$  (Willmott index).

In evaluating the relationship between RCA and LW in the secondary cladodes, the power model presented the best results for the coefficient of model determination (99.98%), sum squared of residuals

(64,372.63), Akaike information criteria (315.07) and Willmott index (0.993) compared with the linear and gamma models whose explanatory powers were 99.53% and 97.14%, SSR (64,427.09 and 64,550.56), AIC (1,155.51 and 1,097.90) and Willmott index (0.993 and 0.993), respectively (Table 4). For the tertiary cladodes, the power model presented the best results for  $R^2$  (99.76%), SQR (53,164.52), AIC (291.57) and Willmott index (0.98) compared with the linear and gamma models (Table 4). Independent of the cladode order evaluated, the highest performance was for the power model, which presented the highest power of explanation ( $R^2 = 99.91\%$ ) and lowest SSR (349,576.60), AIC (360.38) and Willmott index (0.987) compared to the linear and gamma models (Table 4).

Similar results were reported in *Opuntia stricita* (Lucena et al., 2018b), *Opuntia ficus-indica* (Reis et al., 2016) and *Nopalea cochenillifera* (Silva et al., 2014) when the authors verified the relation of the cladode areas as a function of the products of length and width using a linear regression model that presented explanatory powers of 96.77, 91, and 96.96%, respectively.

Figure 1 shows the relation of observed values of the real cladode area and the values estimated by models of both according with and independent of the cladode order. Note that for all orders and independent of the cladode order, the values estimated by the models are very close to the observed values, indicating good model adequacies.



**Figure 1.** Relation of the real cladode area and the product of length by width of primary (a), secondary (b), and tertiary (c) cladodes and independent of the cladode order (d) and their respective model fittings.

In the evaluation of the weights of the primary cladodes as a function of the thickness and the product of length by width, it was verified in Table 5 that the gamma model presented the best results

with an R<sup>2</sup> of 99.90%, an SSR of 1,301,280, an AIC of 1,879.40 and a Willmott index of 0.892, while the linear model presented the lowest values of R<sup>2</sup> (91.30%), SSR (15,514,515), AIC (1,950.80) and Willmott index (0.854). The power model presented a higher power of explanation of 99.74% and a smaller AIC (157.55), as well as an SSR of 1,566,153 and a Willmott index of 0.854. Checking the adequacy criteria of the models, the gamma model is the most adequate model to explain the relationship between the weight of primary cladodes as a function of thickness and the product of length by width. Based on the four criteria evaluated, the gamma model presents better results compared to the linear and power models.

**Table 5.** Estimates of parameters and adequacy criteria of the models of weight cladode (WC) of *Nopalea cochenillifera* taking into account the thickness (T) and the product of length by width (LW) as explanatory variables.

Models	Equation of weight cladode	criteria of adequacy of the model			
		R <sup>2</sup>	SSQ	AIC	d
Primary cladode					
Linear	$\widehat{WC} = 5.08T + 0.73LW$	91.30	1,551,415	1,950.80	0.854
Power	$\widehat{WC} = T^{0.476}LW^{0.754}$	99.74	1,566,153	157.55	0.854
Gamma	$\widehat{WC} = -108.62 + 10.06T + 0.77LW$	99.90	1,301,280	1,879.40	0.892
Secondary cladode					
Linear	$\widehat{WC} = 5.98T + 0.60LW$	89.40	1,148,626	1,533.37	0.836
Power	$\widehat{WC} = T^{0.436}LW^{0.756}$	98.51	1,238,354	259.70	0.821
Gamma	$\widehat{WC} = 5.55 + 0.246T + 0.022LW$	98.65	1,218,674	1,531.40	0.852
Tertiary cladode					
Linear	$\widehat{WC} = -65.28 + 8.32T + 0.463LW$	85.11	53,730.86	1,261.65	0.958
Power	$\widehat{WC} = T^{0.594}LW^{0.567}$	99.06	150,987.60	134.93	0.979
Gamma	$\widehat{WC} = 0.458T + 0.028LW$	99.38	39,943.54	1,088.62	0.984
Independent cladode order					
Linear	$\widehat{WC} = 5.77T + 0.603LW$	87.56	3,679,152	5,195.87	0.879
Power	$\widehat{WC} = T^{0.888}LW^{0.533}$	98.86	4,537,108	698.83	0.847
Gamma	$\widehat{WC} = 0.536T + 0.028LW$	99.04	3,505,923	4,751.90	0.939

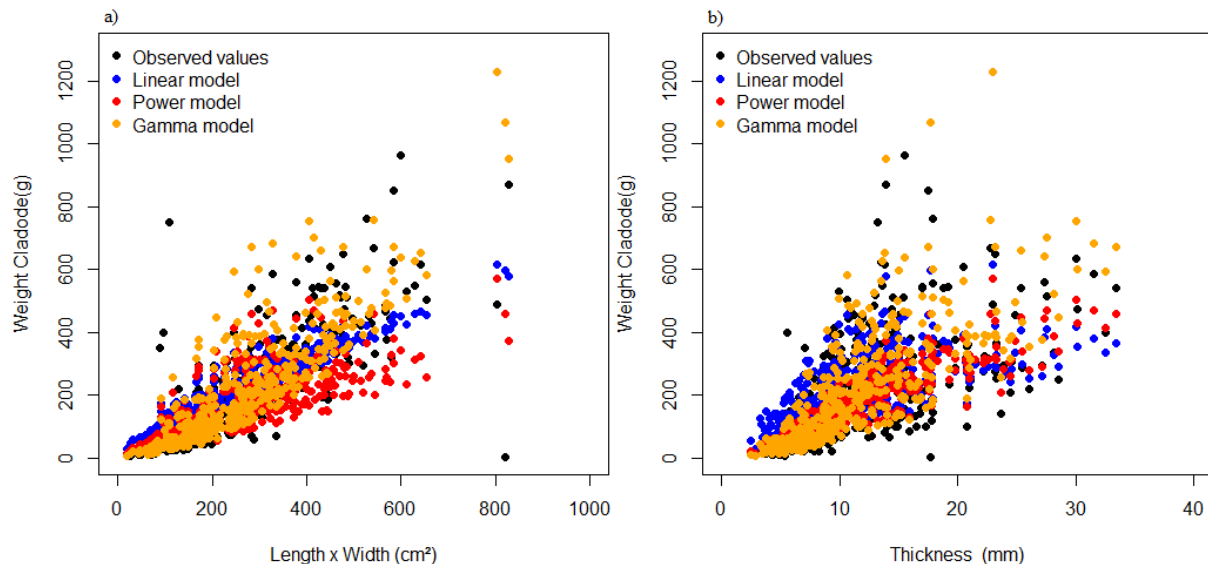
R<sup>2</sup> (determination coefficient); SSR (sum squared of residuals); AIC (Akaike information criteria); d (Willmott index).

In the evaluation of the relationship between the weight, thickness and the product of length by width of the secondary cladodes, the gamma model presented the highest coefficient of determination of the model (98.65%), a sum squared of residuals of 1,218,674, Akaike information criteria of 1,531.40 and a larger Willmott index (0.852); the linear model presented a smaller R<sup>2</sup> (89.40%) and SSR (1,148,626), an AIC of 1,533.37 and a Willmott index of 0.836, while the power model presented a higher power of explanation (98.51%), an SSR of 1,238,354, and a smaller AIC (259.70) and Willmott index (0.821) (Table 5). Checking the adequacy criteria of the model, the gamma model was most adequate to explain the relationship between the weight of secondary cladodes as a function of thickness and the product of length by width; compared with the other models, it presented better results in three of the four analysed criteria.

For the tertiary cladodes, the gamma model showed the best performance for R<sup>2</sup> (99.38%), SSR (39,943.54) and Willmott index (0.984) compared to the linear and power models (Table 5). Independent of the cladode order evaluated, the gamma model was also the most adequate to explain the weight of cladodes because it presented the highest R<sup>2</sup> (99.04%) and Willmott index (0.939) and a smaller SSR (3,505,923) compared to the linear and power models (Table 5). Reis et al. (2016) found that the weight of cladodes of *Opuntia ficus-indica* can be estimated by a linear regression model with a precision of 91%. The linear regression model was used to explain the weight of cucumber leaves (Cho, Oh, Oh, & Son, 2007) and cacao leaves (Salazar, Melgarejo, Bautista, Rienzo, & Casanoves, 2018); taking into account the product of length and width as the explanatory variable, these models presented explanatory powers of 93.3% and 97%, respectively.

Figure 2 shows the relation of the observed values of weight cladodes and the values estimated by the models independent of the cladode order as a function of the explanatory variables of cladode length by width and thickness. Note that independent of the cladode order, the values estimated by the models are very close to the observed values, indicating good model adequacies.





**Figure 2.** Relation of weight cladodes observed and adjusted by models independent of cladode order as a function of the explanatory variables product of length by width (a) and thickness (b).

## Conclusion

The product of cladode length and width is an appropriate parameter for use as an independent variable in the prediction of the cladode area of the *Nopalea cochenillifera* Giant Sweet clone by regression models.

The power ( $\widehat{RAC} = LW^{0.982}$ ) and gamma ( $\widehat{WC} = 0.536T + 0.028LW$ ) models, can be used to determine the cladode area and weight of *Nopalea cochenillifera* Giant Sweet clone.

The adoption of the power and gamma models makes it possible to non-destructively estimate the area and weight of cladodes of cactus forage Giant Sweet clone with high precision, speed and low cost, requiring only measurement of the cladode length, width and thickness.

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