Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga

ISSN 0100-316X (impresso)
ISSN 1983-2125 (online)
http://dx.doi.org/10.1590/1983-21252020v33n426rc

STRUCTURAL CHARACTERISTICS AND YIELD OF 'GIGANTE' CACTUS PEAR IN AGROECOSYTEMS IN THE SEMI-ARID REGION OF BAHIA, BRAZIL[1]

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ABSTRACT - The adaptation capacity of forage cactus (*Opuntia ficus-indica* Mill) plants to edaphoclimatic conditions and plant responses to changes in management systems contribute to increase the use of this species in agriculture and the exploration of its productive potential in semi-arid regions. The objective of this work was to evaluate the structural characteristics and cladode yield of forage cactus plants grown under different agroecosystems in the semi-arid region of Bahia, Brazil. Structural characteristics of plants and soils attributes were analyzed. The traditional information on the crop management and its correlations with cladode yield were used to identify the best yield indexes, considering the peculiarities of each agroecosystem. Plant height, cladode thickness, and number of cladodes of the forage cactus plants evaluated were less affected by the agroecosystem than by the production systems. Cladode width, length, and area were more affected by the agroecosystems. The forage cactus crop yields, expressed by the annual cladode fresh matter yield, were positively correlated with the plant structural characteristics: plant height and thickness, and cladode width and length. The cladode weight per plant and fresh matter yield per area were the yield components most affected by the management system adopted by traditional producers.

Keywords: *Opuntia ficus-indica*. Cactaceae. Yield. Production systems.

CARACTERÍSTICAS ESTRUTURAIS E RENDIMENTO DA PALMA FORRAGEIRA 'GIGANTE' EM AGROECOSSISTEMAS DO SEMIÁRIDO BAIANO

RESUMO - A capacidade de adaptação da palma forrageira às condições edafoclimáticas, associada às suas respostas às alterações no sistema de manejo, contribuem para o maior aproveitamento do seu potencial produtivo e uso na agropecuária do semiárido. Objetivou-se neste trabalho avaliar as características estruturais da planta e os rendimentos da palma forrageira (*Opuntia ficus-indica* Mill) em diferentes agroecossistemas do semiárido baiano. Para isso, foram analisadas as características estruturais das plantas e os atributos dos solos. Considerou-se o conhecimento tradicional no manejo da cultura e suas inter-relações com os níveis de rendimento, de modo a identificar os melhores índices de produtividade frente às peculiaridades de cada agroecossistema. A altura das plantas, a espessura e número de cladódios da palma forrageira 'Gigante' foram menos afetados pelos agroecossistemas, em detrimento à maior influência dos sistemas de produção. A largura, comprimento e área dos cladódios foram influenciados, em maior proporção, pelos agroecossistemas. Os rendimentos dos palmais, expressos pelas produtividades anual e de massa verde, correlacionou-se positivamente com as características estruturais da planta, como a sua altura e espessura, largura e comprimento dos cladódios. A produtividade de massa de cladódio por planta e a produtividade de massa verde por área foram os rendimentos mais influenciados pelo sistema de manejo adotado pelos produtores tradicionais.

Palavras-chave: *Opuntia ficus-indica*. Cactaceae. Produtividade. Sistemas de produção.

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[1]Received for publication in 10/19/2019; accepted in 07/21/2020.
Paper extracted from the doctoral thesis of the first author.
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INTRODUCTION

The semi-arid region of the state of Bahia, Brazil, covers 446,021 km^2, equivalent to 39.52% of the total area of the Brazilian Semi-arid region (BRASIL, 2017). The resilience of agroecosystems in this region contributed to the thriving of traditional producers, despite the adverse climate conditions and intense pressure on natural resources (RESENDE; CURI; LANI, 2002). Although resistant, forage cactus production systems are affected by dry periods (LUCENA et al., 2016). The high risk of occurrence of droughts and some technical criteria mean annual rainfall depths lower than 800 mm and aridity index lower than or equal to 0.50 - currently define the concept of semi-arid regions in Brazil (BRASIL, 2017).

Forage cactus crop systems are affected by water deficit, irregular rainfall distribution, environmental characteristics, producer profile, technological level, and social, economic, and cultural aspects (OLIVEIRA JÚNIOR et al., 2009; DONATO et al., 2014b; BARROS et al., 2016). Forage cactus plants are highly dependent on the crop environment. Their nutrient absorption capacity and vegetative development are dependent on edaphoclimatic factors, crop system, and plant genotype used (BLANCO-MACÍAS et al., 2010; DONATO et al., 2014b).

The challenge of establishing a better plant-environment-human relationship to increase the crop resilience strengthens the potential of adaptability and longevity of plants (DONATO et al., 2014a; PADILHA JÚNIOR et al., 2016; SILVA et al., 2016; DONATO et al., 2017). Information on local environments, sharing of promising experiments, and recognition of crop responses to different environments and managements contribute to improvements in yield indexes and to the sustainability of forage cactus plants in the Brazilian Semi-arid region (SILVA et al., 2012).

The specificities of agroecosystems denote the need for different management processes and adjusts for their sustainability, mitigation of environmental limitations, and exploration of their potentials, since different environments demand different managements (RESENDE et al., 2007; RESENDE; CURI; REZENDE, 2017).

Considering the importance of maintaining herds when water is scarce and the need for ensuring feed availability and improving the use of natural resources in the Brazilian Semi-arid region, the objective with this work was to evaluate the structural characteristics and cladode yield of forage cactus (*Opuntia ficus-indica* Mill cv. Gigante) plants under different agroecosystems in the semi-arid region of the state of Bahia, Brazil.

MATERIAL AND METHODS

Location and general characteristics of the study area

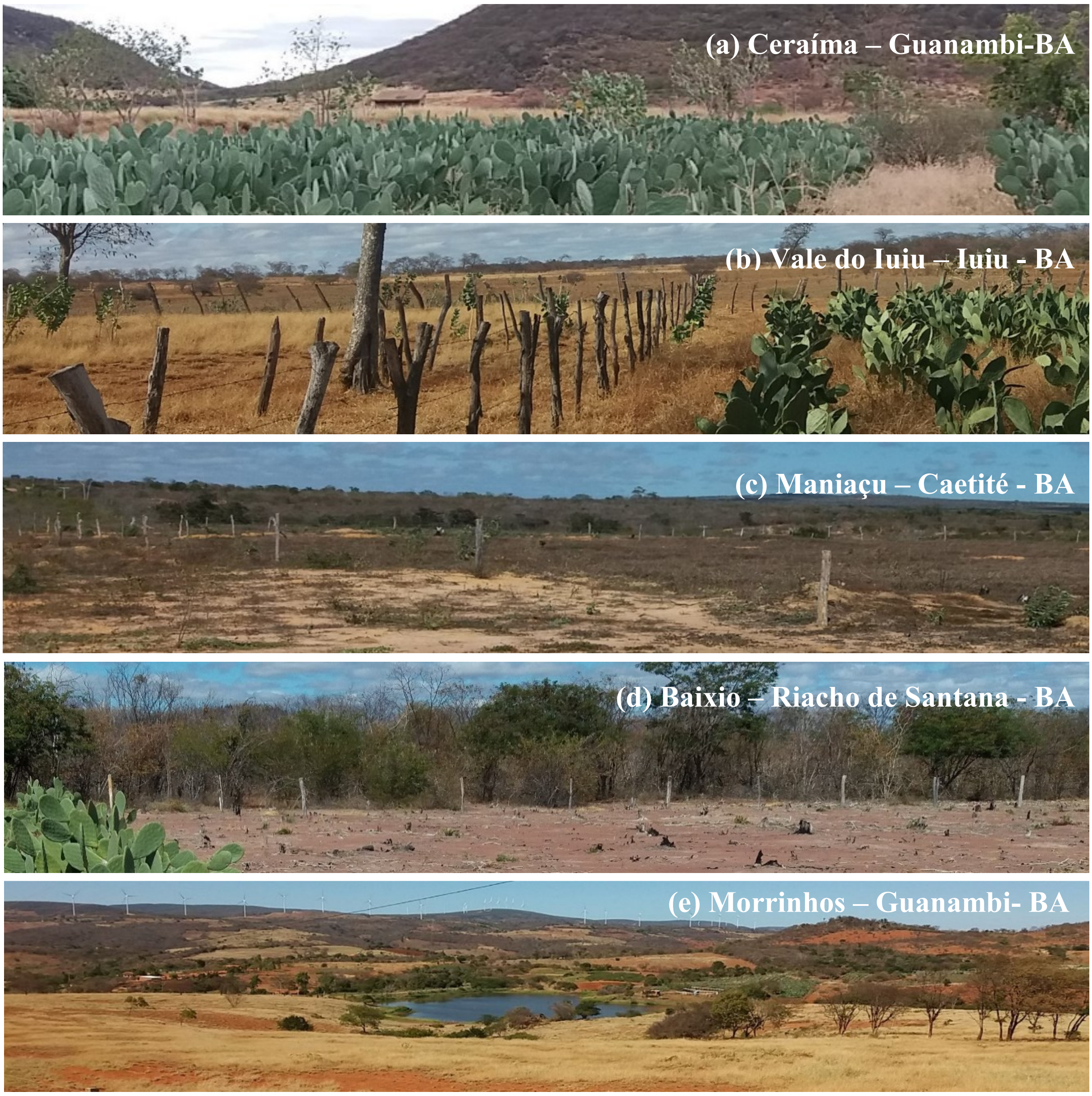
The study was conducted in different agroecosystems in the Guanambi microregion, which is under the Pediplano Sertanejo domain, in a degraded bare plain surface, at downstream of the Rio das Rãs River sub-basin. These landscapes evolved on the geology of the Guanambi Complex, which is found in the east part of the middle São Francisco River Basin, in a large plain region, whose flatness is disturbed by large smooth and sparse inselbergs. Surfaces with detritus from the Tertiary and Quaternary periods were found in small isolated flat areas of interfluves on the Santa Isabel Complex, at upstream of the Rio das Rãs River sub-basin (BRASIL, 1982).

The Rio das Rãs river sub-basin presents predominance of hypo-xerophilic Caatinga, which is a transition vegetation to Seasonal Decidual Forests (dry forests), with occurrence of Cerrado-Caatinga transition areas (ecotone) (BRASIL, 1982).

This region presents a rainy season from November to April, and the dry season has six months (May to October). The lowest water availability is found in June to August. The mean annual rainfall depth is lower than 800 mm. The predominant climate in the Guanambi microregion, according to the Köppen classification, is BSwh, which corresponds to a hot climate of Caatinga, with rainfall in the summer and a well-defined dry period; a small area in the east presents an Aw climate, tropical rainy of forests, with dry winter and rainy summer (SEI, 2014).

Identification of the agroecosystems used

Five contrasting agroecosystems were found in the Guanambi microregion, Bahia, Brazil (Figure 1 and Table 1), where traditional forage cactus producers were selected (Table 2). The proposed selection and study project were presented to traditional communities, and the five agroecosystems with history of forage cactus production were surveyed. The agroecosystems were stratified based on their differences in soil, vegetation, relief, altitude, producer profile, and production systems of forage cactus, and named according to their locations as: Irrigated District of Ceraíma, in Guanambi (14° 17'40"S, 42°42'44"W, and 542 m altitude); Iuiu Valley, in Iuiu (14°23'50'S, 43°27'07"W, and 507 m altitude); Maniaçu, in Caetité (13°48'50"S, 42° 24'32"W, and 936 m altitude); Baixio, in Riacho de Santana (13°32'08"S, 43°09'19"W, and 482 m altitude); and Morrinhos, in Guanambi (14°14'02"S, 42°37'08"W, and 843 m altitude).



Photos: Matos, 2017.

Figure 1. General view of the landscapes of the five agroecosystems where traditional forage cactus (*Opuntia ficus-indica* Mill cv. Gigante) production systems were selected.

The soil chemical and physical attributes of each agroecosystem were analyzed (Table 1). Three simple soils samples of the 0-0.20 m layer were collected using a hoe in the evaluation area of each plot and replication. P, K, Na, Cu, Mn, Fe, and Zn contents were determined by Mehlich-1; Ca^{2+}, Mg^{2+}, and Al^{3+} contents were determined by the extractor KCl 1 mol L^{-1}; H+Al was determined by the extractor calcium acetate 0.5 mol L^{-1} at pH 7.0; soil organic matter was determined using the Walkley-Black factor (*SOM = organic carbon × 1.724*); remaining phosphorus was determined by the P concentration in the soil solution after shaking bulk soil for 1 hour, using a $CaCl_2$ 10 mmol L^{-1} solution containing 60 mg L^{-1} of P, at the ratio of 1:10; sulfur was extracted by monocalcium phosphate in acetic acid; boron was extracted in hot water.

Four traditional producers in representative areas of the production systems of the region were selected in each of the five agroecosystems, totaling 20 properties (Table 2). Harvesting for sampling in the production systems was carried out in August and September 2017.

Table 1. Soils physical and chemical attributes of 20 traditional production systems of forage cactus (*Opuntia ficus-indica* Mill cv. Gigante) in five agroecosystems in the Bahia semi-arid region – Guanambi microregion, state of Bahia, Brazil.

Agroecosystem crop environment	Coarse sand	Fine sand	Silt	Clay	Clay dispersed in water	pH in H_2O 1:2.5	pH in KCl 1:2.5
	g kg^{-1}						
Ceraíma	280	390	170	160	30	5.78	5.12
Iuiu	60	80	500	360	110	6.25	5.68
Maniaçu	530	220	30	220	40	4.38	3.83
Riacho de Santana	610	220	80	90	10	4.50	3.88
Morrinhos	330	150	180	340	80	4.84	4.11
Média	360	210	190	230	60	5.15	4.52
DP	30	20	20	20	10	0.22	0.21
Agroecosystem	**P**	**K**	**Na**	**Ca^{2+}**	**Mg^{2+}**	**Al^{3+}**	**H + Al**
	mg dm^{-3}			cmol$_c$ dm^{-3}			
Ceraíma	54.33	175.92	28.05	3.36	1.40	0.00	2.42
Iuiu	41.35	261.33	47.00	10.66	2.18	0.00	2.20
Maniaçu	11.59	56.17	3.94	0.83	0.35	0.45	3.44
Riacho de Santana	3.04	37.83	0.00	0.78	0.13	0.40	2.33
Morrinhos	24.15	140.83	1.54	3.04	0.91	0.18	4.57
Média	26.89	134.42	16.11	3.74	0.99	0.21	2.99
DP	24.96	106.53	12.59	1.00	0.20	0.10	0.46
Agroecosystem	**SB**	**CECe**	**CEC_{pH7}**	**BS**	**AlS**	**NaS**	**SOM**
	cmol$_c$ dm^{-3}			%			dag kg^{-1}
Ceraíma	5.33	5.33	7.75	67.89	0.00	1.40	1.62
Iuiu	13.72	13.72	15.92	85.80	0.00	1.50	2.85
Maniaçu	1.34	1.79	4.78	27.09	28.95	0.38	1.43
Riacho de Santana	1.01	1.41	3.34	30.02	29.39	0.00	0.72
Morrinhos	4.32	4.50	8.89	48.53	4.38	0.06	2.00
Média	5.14	5.35	8.14	51.87	12.54	0.67	1.720
DP	1.09	1.08	1.01	5.55	8.49	0.49	0.28
Agroecosystem	**P-Rem**	**S**	**B**	**Cu**	**Mn**	**Fe**	**Zn**
	mg L^{-1}	mg dm^{-3}					
Ceraíma	49.96	2.63	0.47	0.71	63.17	72.46	2.52
Iuiu	39.34	8.13	0.62	1.11	101.82	42.41	3.85
Maniaçu	47.00	2.01	0.68	0.83	19.78	50.45	1.66
Riacho de Santana	50.02	0.65	0.28	0.45	13.13	43.33	0.71
Morrinhos	35.67	1.93	0.81	1.47	77.09	25.06	4.71
Média	44.40	3.07	0.57	0.91	55.00	46.74	2.69
DP	2.42	4.77	0.10	0.17	14.22	14.24	1.23

SB = Sum of exchangeable bases; CECe = effective cation exchange capacity (CEC); CEC_{pH7} = CEC at pH 7.0; BS = base saturation; AlS = aluminum saturation; NaS = sodium saturation; SOM = soil organic matter; P-Rem = remaining phosphorus.

Table 2. Characterization of production systems of forage cactus (*Opuntia ficus-indica* Mill cv. Gigante) and soil textural class of five agroecosystems in the Bahia semi-arid region – Guanambi microregion, state of Bahia, Brazil.

N	Site	P	H	SP	SF	IR	Soil textural class	WC
	---------- Ceraíma – Guanambi-BA ----------							
1	Ceraíma	2013	2016	1.60x0,40	16	Y	Sandy Loam	MC and CC
2	Ceraíma	2012	2016	1.10x0.40	70	N	Sandy Loam	MC and CC
3	Ceraíma	2014	2016	0.80x0.50	90	N	Sandy Clay Loam	MC and CC
4	Ceraíma	2014	2016	1.10x0.50	--	N	Sandy Loam	MC and CC
	---------- Vale do Iuiu - Iuiu-BA ----------							
5	Agreste	2014	2016	1.50x0.40	20	N	Clay	MC and CC
6	Agreste	2016	---	2.00x0.10	15	Y	Silt Loam	MC
7	Poço de Paulo	2016	---	1.80x0.10	16	Y	Clay Loam	MC
8	Agreste	2015	---	1.80x0.10	16	Y	Silt Clay Loam	MC and CC
	---------- Maniaçu – Caetité-BA ----------							
9	Junquinho	2016	----	1.60x0.50	17	N	Sandy Clay Loam	MC
10	Cardoso	2012	2015	1.50x0.90	90	N	Sandy Loam	MC
11	Tabuleiro	2013	2016	1.30x0.90	10	N	Sandy Loam	MC
12	Barauninha	2014	2016	1.50x0.60	18	N	Sandy Clay Loam	MC
	---------- Baixio – Riacho de Santana-BA ----------							
13	Massal	2013	2015	2.50x1.50	---	N	Sandy Loam	MC
14	Várzea da Pedra	2015	---	1.00x0.90	16	N	Sand	MC and CC
15	Massal	2015	---	1.50x1.10	50	N	Loamy sand	MC
16	Massal	2012	2016	1.40x0.80	90	N	Loamy sand	MC
	---------- Morrinhos – Guanambi-BA ----------							
17	Sacoto	2005	2016	2.00x0.80	---	N	Clay Loam	MC
18	Distrito	2013	2016	1.00x0.60	---	N	Sandy Clay Loam	MC
19	Distrito	2010	2016	1.40x1.40	15	N	Sandy Clay Loam	MC
20	Distrito	2010	2016	2.80x0.80	48	N	Sandy Clay	MC and CC

N = number of the production system; P = planting; H = last harvest (NH = not yet harvested); SP = spacing (m); SF = soil fertilizer (manure bovine) applied Mg ha^{-1} in the last cycle; IR = use of irrigation (Y = yes; N = no); WC = weed control (MC = manual weeding; CC = chemical control).

The areas and producers presented some specificities: the Maniaçu region has high incidence of parrots that feed on forage cactus seeds; producers 1, 3, and 4 used insecticides without technical monitoring; producers 5 and 7 used urea and bovine manure for soil fertilization; producer 7 started irrigation in July 2017; producer 12 used ammonium sulfate and bovine manure for soil fertilization; producer 17 used urea for soil fertilization every 2 years; producers 1, 3, 9, and 12 used mineral oil for pest and disease control.

Characterization of forage cactus production systems of each producer

Selected producers were interviewed through semi-structured questionnaires, according to legal conditions (Resolution no. 466 of December 12, 2012 of the Brazilian National Health Council). This survey showed information of the history of the area, production data, and management system used, such as: planting time; soil fertilization; pest, disease, and weed control; and harvest time and method (Table 2).

The forage cactus produced in the region is used, mainly, as feed for bovine and ovine herds. Traditional crop systems incorporate experiences shared between generations of producers, combined with technical information provided by education, research, and extension institutions, non-governmental organizations of technical assistance, and class representation entities (unions). These crop systems present low use of external inputs, but demand agroecological and technical practices, which are developed by researches considering specificities of the sites to improve the maintenance, resilience, and sustainability of the activity in the semi-arid region.

The field survey was carried out using simple language to establish a horizontal and constructive dialogue with representants of the traditional communities (MATOS et al., 2014).

Evaluation of plant structural characteristics and yield

The structural characteristics of four randomized plants in each of the three replications (12 plants) of each of the 20 properties were evaluated, totaling 240 plants (GUIMARÃES et al., 2019). These characteristics consisted of: cladode thickness (CT), determined in the middle part of all cladodes; cladode width (CW), measured in the highest widest part of the cladode; cladode length (CL), measured in the longest part of the cladode; total number of cladodes (TNC) per plant; plant height (PH), distance from the top of the highest cladode and the soil; cladode area (CA) [$CA\ (cm^2) = CC \times LC \times 0.693)$; 0.693 is the correction factor due to the elliptical form of the cladode (PINTO et al., 2002)]; total cladode area (TCA); cladode area index (CAI), which is the TCA of both sides of the cladodes divided by the area used by the plant (AUP) (m^2 of cladode per m^2 of soil).

The forage cactus crop yields were based on the cladode harvest of all plants in August and September 2017. Each plot presented a mean evaluation area of 14 m^2 and 16 plants. The cladodes were cut at their insertion point in the plant. The weight of all cladodes harvested were determined in the field for the plots and producers, and used to determine the cladode yield. The variables analyzed to determine the yield of the forage cactus crops were: annual cladode yield of each forage cactus crop in the different properties (ACY); annual cladode yield per plant (AYP); fresh matter yield annual or biannual, depending on the time of the last harvest (FMY); dry matter yield (DMY), calculated by multiplying the dry matter content of the treatment by its FMY.

Considering the dependency of the data of each production system within the agroecosystems, the hierarchical model was used. This design includes the structure of the factors and their levels; it is used when the levels of a factor B only occur in determined levels of a factor A. The factor A in the present work (Figure 2) is the regions or agroecosystems, and the factor B is the production systems represented by the producers and their properties within a same region. The characteristics evaluated (structural and yield) for forage cactus plants (*Opuntia ficus-indica* Mill cv. Gigante) in the agroecosystems represent a specific production system, thus satisfying the hierarchical condition (RIBEIRO JÚNIOR; MELO, 2008). In addition to the analysis of variance, the hierarchical model also estimates the variance of components and investigates the composition of the total variance, i.e., determines the explanation of the variance by the different factors of hierarchical levels (DIAS; BARROS, 2009).

The statistical analysis of the data was carried out in the SAEG 9.0 (System of Analyses Statistical) program of the Federal University of Viçosa, MG, Brazil, using the nested ANOVA/Hierarchical Model procedure (RIBEIRO JÚNIOR; MELO, 2008). When the variances were significantly different from zero, indicating the existence of at least one difference between agroecosystems and between production systems within each agroecosystem, the Tukey's test ($p \leq 0.05$) was applied to compare the means of the variables evaluated.

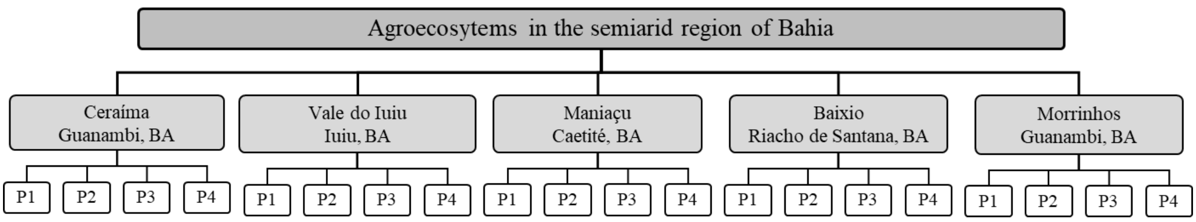


Figure 2. Arrangement of the hierarchical experimental design.

RESULTS AND DISCUSSION

According to the correlation analysis, the yields of the forage cactus crops, expressed by the annual and fresh matter yields of forage cactus plants, present significant, positive, and high-magnitude correlations with plant height and cladode thickness, width, and length (Table 3). The higher planting density (Table 5) used in the Iuiu and Ceraíma agroecosystems, combined with the higher soil fertility in these environments (Table 1) and use of irrigation (Table 2), resulted in the highest forage cactus yield (Tables 4 and 5).

The plant height (PH) and cladode thickness (CT) of the forage cactus crops were similar between agroecosystems and between production systems within each agroecosystem ($p \leq 0.05$) (Tables 4 and 5); 57.61% and 69.89% of the total variance for PH and CT, respectively, were explained by the production systems (Table 4).

The plants presented mean height of 1.03 m with coefficient of variation (CV) of 12.38%, and mean cladode thickness of 1.50 cm with CV of 18.59%. These are low variabilities according to the classification of Pimentel-Gomes and Garcia (2002).

Table 3. Correlation between structural characteristics and forage cactus (*Opuntia ficus-indica* Mill cv. Gigante) yield of 20 traditional production systems in five agroecosystems in the Bahia semi-arid region – Guanambi microregion, state of Bahia, Brazil.

	PD	PH	TNC	CT	CW	CL	AUP	FMY	DMY
PH	0.1255^{ns}	1							
TNC	-0.4400^{*}	0.4225^{**}	1						
CT	0.2989^{*}	-0.0749^{ns}	-0.0073^{ns}	1					
CW	0.1643^{ns}	0.2021^{ns}	-0.2561^{*}	0.4009^{**}	1				
CL	-0.1201^{ns}	0.3605^{**}	0.1646^{ns}	0.2181^{*}	0.7992^{**}	1			
AUP	-0.6626^{**}	-0.2638^{*}	0.3160^{**}	-0.0162^{ns}	-0.2604^{*}	-0.1377^{ns}	1		
FMY	0.2899^{*}	0.6419^{**}	0.2847^{*}	0.4736^{**}	0.4019^{**}	0.3912^{**}	-0.3814^{**}	1	
DMY	0.1407^{ns}	0.7433^{**}	0.4173^{**}	0.0709^{ns}	0.3585^{**}	0.4984^{**}	-0.4201^{**}	0.8107^{**}	1
ACY	0.2789^{*}	0.6076^{**}	0.2949^{*}	0.4428^{**}	0.4194^{**}	0.4919^{**}	-0.4305^{**}	0.8816^{**}	0.7519^{**}

PD = plant density (plant ha^{-1}); PH = plant height; TNC = total number of cladodes per plant; CT = cladode thickness; CW = cladode width; CL = cladode length; AUP = area used by the plant (AUP); FMY = fresh matter yield; DMY = dry matter yield; ACY = annual cladode yield; ns = not significant; ** = significant at 1%, and * = significant at 5%.

Table 4. Analysis of variance for structural characteristics and yield of forage cactus plants (*Opuntia ficus-indica* Mill cv. Gigante) of 20 traditional production systems in five agroecosystems in the Bahia semi-arid region – Guanambi microregion, state of Bahia, Brazil.

	Source of variation							
	Agroecosystem (DF = 4; F-Tab = 2.61)			Producer / Agroecosystem (DF = 15; F-Tab = 1.92)			Plant / Producer (DF = 40)	
	MSq	EV%	F-Cal	MSq	EV%	F-Tab	MSq	EV%
PH	0.19*	12.59	11.87	0.11*	57.61	6.80	0.02	29.80
TNC	234.18*	5.15	9.61	183.69*	65.01	7.53	24.38	29.84
CT	1.16*	8.19	15.05	0.82*	69.89	10.57	0.08	21.92
CW	29.19*	49.90	25.48	4.02*	22.83	3.51	1.15	27.26
CL	76.98*	53.36	21.18	7.84*	12.98	2.16	3.63	33.66
AUP	6.63*	41.87	43.61	1.48*	43.29	9.75	0.15	14.84
CA	37236.57*	52.38	22.97	4253.61*	16.73	2.62	1620.88	30.89
TCA	1.50*	17.50	13.60	0.71*	53.17	6.44	0.11	29.34
CAI	25.48*	43.32	39.32	5.30*	39.99	8.19	0.65	16.69
CMW	258724.20*	21.01	9.12	96101.30*	35.01	3.39	28365.42	43.98
C/Mg	15983810.00*	38.80	17.2	3188035.00*	27.41	3.43	928596.60	33.79
ACY	22681.53*	36.90	27.57	5639.21*	41.72	6.85	822.69	21.38
AYP	182.07*	7.58	10.20	128.27*	62.25	7.19	17.84	30.17
PD	845552400.00*	60.91	281.18	111715500.00*	36.09	37.15	3007105.00	3.00
FMY	26156.68*	21.87	25.90	11273.06*	60.32	11.16	1009.85	17.81
DMY	119.25*	37.61	29.14	29.18*	41.89	7.13	4.09	20.50

DF = degrees of freedom; MSq = mean square; F-Cal = F calculated; F-Tab = F tabulated; EV% = percentage of explained variation or variation explanation in the hierarchical levels; Agroecosystem = environment of the forage cactus crop; Producer / Agroecosystem = production systems within the crop environment; Planta / Producer = plant genotype within the production systems; PH = plant height; TNC = total number of cladodes per plant; CT = cladode thickness; CW = cladode width; CL = cladode length; AUP = area used by the plant (AUP); CA = cladode area; TCA = total cladode area; CAI = cladode area index; CMW = cladode mean weight; C/Mg = estimated number of cladodes per Mg; ACY = annual cladode yield; AYP = annual cladode yield per plant; PD = plant density (plant ha^{-1}); FMY = fresh matter yield; DMY = dry matter yield; * = significant at 5%.

Cladode length (CL) and cladode width (CW) presented significant variations between agroecosystems, probably due to responses to environmental differences (Table 1), as shown by the composition of the total variance (Tables 4 and 5). These results corroborate those of Barros et al. (2016); however, Mondragón-Jacobo and Pérez-Gonzáles (2001) reported that cladode size is determined by genotype and, at a lesser extent, by plant spatial arrangement and soil fertility. The use of a single cultivar and vegetative propagation in the same microregion, did not exclude the occurrence of differences in clones or even somaclonal variation, which may have been summed to environmental differences and increased genetic variability of the *Opuntia ficus-indica* Mill cv. Gigante used in the production systems.

The harvest cycle interval showed differences, with plants that were not harvested since the planting and others that had completed one or two years after the last harvest, when all plants were harvested to collect the data for the present work (Table 2). The Morrinhos and Ceraíma agroecosystems had higher cladode yield per plant (24 to 28). Increasing planting density decreases the number of cladodes per plant and contributes to increases in forage cactus yield up to its biological potential.

The Maniaçu agroecosystem showed the greatest cladode widths and longest cladode lengths, with similar cladode lengths to those found in Ceraíma (Table 5). These results were found in Maniaçu, despite the soil low natural fertility when compared to the other regions (Table 1). Maniaçu has a mean altitude of 936 m, which is the highest altitude among the studied regions (Ceraíma = 542 m, Iuiu = 507 m, Riacho de Santana = 482 m, and Morrinhos = 843 m); this condition results in nights with milder temperatures, which is proper to the crop physiological demands, favoring the capture of CO_2 (SANTOS et al, 2013). However, based on the percentage of composition of the total variance, TNC was the variable most affected by the management systems used by the producers (Table 4).

Padilha Júnior et al. (2016) evaluated forage cactus in the Ceraíma region (Guanambi, BA, Brazil) and found that cladode width is not affected by soil fertilization; however, Barros et al. (2016) found this effect. In the present work, the differences in cladode width were more significant between agroecosystems (49.90%) than between production systems, which include the effect of soil fertilization (Tables 4 and 5).

The first cladode harvest in most traditional forage cactus crops is done at two years after planting (SILVA; SAMPAIO, 2015). However, harvest intervals in soils with high natural fertility (Tables 1 and 2) can be shorter than a year, depending on the forage demand (DONATO et al., 2014b; DONATO et al., 2017). The cladodes were harvested at one year after the last harvest, except for the producer eight in Iuiu, producer 10 in Maniaçu, and producers 13, 14, and 15 in Riacho de Santana, who harvested the cladodes after two years. Farias, Santos and Dubeux Junior (2005) reported that the biannual harvests provide greater longevity to forage cactus crops; however, is the demand and need to compensate for local edaphoclimatic limitations that define this period.

The number of residual cladodes, left in the plant by producers at harvest, varies. The producers in Iuiu harvested all cladodes, leaving only the main cladode, as the producers nine and 12 of Maniaçu and the producer 14 of Riacho de Santana. In the other agroecosystems, two to three cladodes were preserved to promote a more vigorous regrowth and provide greater longevity to forage cactus crops (Table 2). This practice assists in the maintenance of larger photosynthetic area and reserves in the plant (DONATO et al., 2014a).

The difference in number of cladodes between producers in Morrinhos was not significant (Table 5). This indicates a high similarity of the techniques used in these production systems. Dubeux Junior et al. (2006) evaluated four locations in the semi-arid region of the state of Pernambuco, Brazil, with the forage cactus clone IPA-20 and found higher number of cladodes in the lowest planting densities, constituting an inverse relation due to the larger soil surface explored.

The Ceraíma and Iuiu agroecosystems showed homogeneity in cladode width and length (Table 5). Maniaçu, Riacho de Santana, and Morrinhos presented only two levels of AUP, thus showing less variability in the spacings used by producers in each region, except Riacho de Santana, which presented three spacings adopted by producers (Table 5).

AUP presented significant positive correlation with TNC, but with low magnitude; and TNC presented negative significant correlation with plant density (Table 3). This denotes that the availability of a larger area per plant favors the emission of cladodes.

Among the production systems evaluated, a producer in Ceraíma and other three in Iuiu used irrigation for their forage cactus crops (Table 2), but without technical monitoring of the water depths applied and watering shift used. Despite the use of irrigation, the cladode thickness did not differ (Table 4). However, application of water, even at low quantities, is a viable option to ensure more satisfactory productions under the adverse conditions of the Brazilian Semi-arid region (LIMA et al., 2015).

Table 5. Structural characteristics of forage cactus (*Opuntia ficus-indica* Mill cv. Gigante) crops grown in 20 traditional production systems in five agroecosystems in the Bahia semi-arid region – Guanambi microregion, state of Bahia, Brazil.

		TNC	CW	CL	AUP	CA	TCA	CAI
		(un)	------ (cm) ------		(m^2)	------- (cm^2) -------		(m^2 m^{-2})
Agroecosystem								
Ceraíma		24.00ab	15.74b	32.15a	0.58c	351.64a	1.71a	3.11a
Iuiu		18.00c	14.70bc	27.62bc	0.33c	281.90b	1.01bc	3.92a
Maniaçu		19.00bc	17.10a	31.72a	1.08b	377.30a	1.39ab	1.24b
Riacho de Santana		18.00c	13.33d	26.34c	2.00a	244.43b	0.86c	0.50b
Morrinhos		28.00a	13.60cd	29.00b	1.85a	276.44b	1.52a	1.13b
Mean		21.00	14.90	29.36	1.17	306.34	1.30	1.98
Standard deviation		4.94	1.07	1.91	0.39	40.26	0.33	0.81
CV (%)		23.12	7.19	6.49	33.40	13.14	25.57	40.63
Production systems (producers/agroecosystems)								
	1	30a	16.20	33.44	0.64	375.45	2.26a	3.53ab
Ceraíma	2	26ab	15.54	31.73	0.63	343.25	1.72ab	2.83ab
	3	23ab	16.37	31.39	0.43	356.93	1.66ab	4.09a
	4	18b	14.85	32.03	0.61	330.92	1.18b	2.00b
	5	30a	13.70	28.61	0.77	271.51	1.63a	2.30b
Iuiu	6	4c	15.94	27.47	0.20	304.25	0.21b	1.10b
	7	18b	14.53	27.44	0.19	276.57	0.96a	5.26a
	8	22ab	14.61	26.94	0.18	275.25	1.23a	7.02a
	9	10b	16.66ab	29.27b	0.83	338.04b	0.66b	0.84
Maniaçu	10	26a	16.83ab	31.74ab	1.37	372.13ab	1.92a	1.41
	11	28a	16.00b	31.74ab	1.20	352.16b	1.99a	1.68
	12	11b	18.89a	34.14a	0.93	446.85a	0.97b	1.05
	13	28a	12.92ab	26.73ab	3.76a	239.56	1.32a	0.34
Riacho de Santana	14	11b	12.60b	23.92b	0.89c	208.90	0.46b	0.53
	15	13b	14.97a	28.57a	1.58bc	296.77	0.80ab	0.52
	16	18ab	12.83ab	26.13ab	1.76b	232.46	0.82ab	0.61
	17	27	14.11a	29.87ab	2.47a	292.69ab	1.53	0.69
Morrinhos	18	28	11.56b	26.87b	0.53b	215.69b	1.17	2.25
	19	24	15.41a	31.40a	2.09a	339.57a	1.69	0.86
	20	32	13.33ab	27.86ab	2.32a	257.79ab	1.67	0.73

Agroecosystem = environment of the forage cactus crop; Producer / Agroecosystem = production systems within the crop environment; TNC = total number of cladodes per plant; CW = cladode width; CL = cladode length; AUP = area used by the plant; CA = cladode area; TCA = total cladode area; CAI = cladode area index. Cladodes were harvested at one year after the last harvest, except for producers 8, 10, 13, 14, and 15, who harvested cladodes after two years. Means followed by the same letter in the columns for each agroecosystem are not different by the Tukey's test ($p \leq 0.05$). Absence of letters in the columns of a variable indicates not significant differences.

The Iuiu and Ceraíma agroecosystems had higher cladode area index (CAI): 3.92 and 3.11 m^2 cladode m^{-2} soil, respectively (Table 5). According to Nobel (2001), CAI of 4 to 5 indicates that the area of both cladode faces is four- to five-fold higher than the area used by the plant, and that they reached a morphology favorable to a high solar radiation capture and maximum yield. Contrastingly, when the CAI surpasses these indexes, forage cactus crop yield decreases (NOBEL, 2001). The CAI found in the present work were between 0.50 to 3.92, with coefficient of variation of 40.63% (Table 5), denoting very high variability (PIMENTEL-GOMES; GARCIA, 2002). The spatial arrangement of plants affects the CAI, even when maintaining the plant density (DONATO et al., 2014a).

The soils of the agroecosystems had low water and nutrient retention capacity (Table 1), and the producers did not use irrigation (Table 2); thus, the mean number of cladodes needed to reach 1 Mg in forage cactus crops in Riacho de Santana was 4,714 (Table 6). The other agroecosystems presented similarity ($p \leq 0.05$) in cladode weight, between 466 and 642 g, higher than the 245 g of the cladodes of Riacho de Santana (Table 6).

Table 6. Mean yield of forage cactus plants (*Opuntia ficus-indica* Mill cv. Gigante) grown in 20 systems of production traditional in five agroecosystems in the Bahia semi-arid region – Guanambi microregion, state of Bahia, Brazil.

		ACY Mg ha^{-1}	AYP kg plant^{-1}	PD plant ha^{-1}	CMW g	C/Mg cladode Mg^{-1}	FMY Mg ha^{-1}	DMY Mg ha^{-1}
Agroecosystem								
Ceraíma		131.74a	9.25ab	14.617b	468.88a	2696.31b	131.74a	11.46a
Iuiu		101.75ab	5.54b	26.603a	549.85a	2121.87b	129.73a	9.89a
Maniaçu		88.58b	13.85a	9.317c	642.37a	1708.29b	117.60a	9.77a
Riacho de Santana		15.12c	5.03b	6.657d	245.85b	4713.96a	24.66c	3.79b
Morrinhos		68.43b	12.09a	6.621d	466.07a	2752.61b	68.43b	6.10b
Média		81.12	9.15	12.763	474.60	2798.61	94.43	8.20
DP		28.68	4.22	1734.10	168.42	963.64	31.78	2.02
CV (%)		35.36	46.16	13.59	35.49	34.43	33.65	24.66
Production system (producer/agroecosystem)								
Ceraíma	1	202.64a	14.40a	14.067ab	645.99	2319.23	202.64a	11.99ab
	2	75.76b	7.65ab	10.692b	411.17	2674.54	75.76b	10.32ab
	3	182.53a	11.04ab	16.863a	533.26	2071.89	182.53a	14.31a
	4	66.03b	3.91b	16.846a	285.10	3719.60	66.03b	9.21b
Iuiu	5	65.80b	5.49	12.126d	319.14b	3164.86	65.80b	12.63a
	6	55.86b	1.31	42.222a	781.67a	1388.33	55.86b	3.04b
	7	173.39a	7.18	24.113c	618.18ab	1639.90	173.39a	11.19a
	8	111.93ab	8.19	27.949b	480.40ab	2294.39	223.86a	12.68a
Maniaçu	9	51.54b	4.55b	11.238	530.42b	1988.85	51.54b	5.39b
	10	116.05a	30.07a	7.743	904.40a	1150.63	232.09a	14.78a
	11	106.69ab	12.05b	9.004	472.28b	2127.01	106.69b	11.92a
	12	80.05ab	8.72b	9.284	662.38ab	1566.67	80.05b	7.00b
Riacho de Santana	13	14.78	11.20a	2.571b	360.81	2835.67b	29.56	3.38
	14	8.52	1.92b	9.308a	201.47	5857.80a	17.03	2.60
	15	14.85	3.94ab	7.542a	252.85	4212.06ab	29.70	5.23
	16	22.33	3.05ab	7.208a	168.26	5950.33a	22.33	3.96
Morrinhos	17	44.08	8.50b	5.261b	329.35b	3142.58ab	44.08	6.20
	18	71.56	5.82b	12.067a	228.26b	4459.66a	71.56	7.56
	19	102.00	20.20a	5.010b	737.77a	1650.29b	102.00	6.70
	20	56.08	13.82ab	4.144b	568.90ab	1757.92b	56.08	3.97

Agroecosystem = environment of the forage cactus crop; Producer / Agroecosystem = production systems within the crop environment; ACY = annual cladode yield in each production system; AYP = annual cladode yield per plant; PD = plant density (plant ha^{-1}); CMW = cladode mean weight; C/Mg = number of cladodes per Mg; FMY = fresh matter yield; DMY = dry matter yield. Cladodes were harvested at one year after the last harvest, except for producers 8, 10, 13, 14, and 15, who harvested cladodes after two years. Means followed by the same letter in the columns for each agroecosystem are not different by the Tukey's test ($p \leq 0.05$). Absence of letters in the columns of a variable indicates not significant differences.

The forage cactus crops within the Ceraíma, Iuiu, and Maniaçu agroecosystem presented no significant difference for number of cladodes per Mg. This denotes a low structural variability of cladode produced between forage cactus crops within these agroecosystems (Table 6).

The productive potential of forage cactus crops of the Ceraíma and Iuiu agroecosystems showed high annual yield: 131.73 and 101.74 Mg ha^{-1} year^{-1}, respectively (Table 6). The overall coefficient of variation of annual yield for the agroecosystems studied was 35.36%, denoting very high variability (PIMENTEL-GOMES; GARCIA, 2002).

These yields denote the productive potential of forage cactus crops based on the cultural practices adopted in the agroecosystems and local edaphoclimatic conditions (Table 4), despite the higher soil fertility in the Ceraíma and Iuiu agroecosystems (Table 1). The producer is the main factor in this process, because of its interest, capacity to thrive, traditional knowledge, and technical information, which affect the adoption of agricultural practices (RESENDE; CURI; LANI, 2002).

Irrigation for forage cactus crops in the irrigated perimeter of Ceraíma and in the Valley of Iuiu (Table 2) has contributed to increase their yield (FONSECA et al., 2019) to values higher than those found for agroecosystems with low fertility soils and water deficit, such as Riacho de Santana (Table 1). Forage cactus crops in Riacho de Santana had the lowest yield, with a mean of 15 Mg ha^{-1} year^{-1} (Table 6). The low yield per plant (5.54 kg) of forage cactus crops in Iuiu was similar to that found in Riacho de Santana (5.03 kg), despite the higher soil natural fertility in Iuiu (Table 1).

The low yield per plant was compensated by the denser production system in Iuiu (26,603 plants ha^{-1}), different than Riacho de Santana and Morrinhos, which had 6,657 and 6,621 plants ha^{-1}, respectively (Table 6). Increases in plants population increase the yield forage cactus plants up to their biological potential, considering the use of adequate cultural practices (DONATO et al., 2014a; SILVA et al., 2016). Plant density presented positive significant correlation with cladode fresh matter yield and thickness, but with low magnitude (Table 3).

Forage cactus crops in Iuiu presented significant differences in plant density ($p \leq 0.05$); whereas those in Maniaçu were uniform in all production systems (Table 6). This denotes the effect of specificities in the adopted management systems on each agroecosystem, as in Iuiu, which showed high effect of practices used in other states of Brazil, mainly Pernambuco, where harvest managements preserve only the main cladode in the plant. This practice allows for the harvest of two to three more cladodes per plant in the first harvest; however, the plant end up with less reserves for the next cycles (Table 2).

The maintenance of secondary cladodes increases the number of cladodes per plant and the forage yield, since the plant will have more reserves for the emission and maintenance of new cladodes (LIMA et al., 2015). This is very important due to the environmental conditions, mainly rainfall distribution after harvest (BLANCO-MACÍAS et al., 2010; BARROS et al., 2016).

The fresh matter yield (FMY) of the agroecosystems varied from 68.43 to 131.74 Mg ha^{-1}, with overall mean of 94.43 Mg ha^{-1} (Table 6). Plant density varied from 6,621 to 26,603 plants ha^{-1}. The DMY was higher in Ceraíma (11.46 Mg ha^{-1} $year^{-1}$), Iuiu (9.89 Mg ha^{-1} $year^{-1}$), and Maniaçu (9.77 Mg ha^{-1} $year^{-1}$); Morrinhos had 6.10 Mg ha^{-1} $year^{-1}$ and Riacho de Santana had 3.79 Mg ha^{-1} $year^{-1}$, presenting forage cactus crops with lower DMY (Table 6).

The yield of traditional crops is dependent on the site conditions, soil, climate, management, and genotype used, which are interrelated. The yield of forage cactus plants is affected by the following factors: occurrence of mild temperatures caused by high altitudes, which occur in sites with native forage cactus plants (SANTOS et al., 2013); soil nutrient availability because of natural fertility or addition of fertilizers, which involves edaphic conditions and anthropogenic actions of management; use of irrigation; and changes in plant population.

The high fresh matter yield found in Iuiu and Ceraíma due to the high soil fertility, high plant population, and use of irrigation confirms the results of studies developed in Ceraíma which found relative percentual increases in fresh matter yield for different managements - 135.18% for soil chemical fertilization with N-P-K (SILVA et al., 2016); 73.90% for the first production cycle (DONATO et al., 2014a) and 180.00% for the second production cycle (BARROS et al., 2016) because of the use of bovine manure for soil fertilization; 104.20% for the first cycle, 153.32% for the second cycle, and 175.96% for the third cycle due to soil organo-mineral fertilization (LÉDO et al., 2019); 55.57% due to increase in population of plants from 22,857 to 69,112 plants ha^{-1} (FONSECA et al., 2020); and 92.18% for the first production cycle, and 156.43% for the second production cycle because of the use of irrigation with saline water (FONSECA et al., 2019).

CONCLUSIONS

The plant structure and cladode yield of forage cactus plants are affected by the correlations between the crop agroecosystem (environment) and agricultural production system adopted by the producer (management techniques) and by the plant characteristics (genotype).

The plant structure variables most affected by the agroecosystems evaluated were cladode length and width. The variables most affected by the production systems adopted by the producers were: cladode weight per plant, fresh matter yield, total cladode area, and number of cladodes per plant.

Despite being more affected by the production system, plant height and cladode thickness of the forage cactus crops studied were similar. Cladode weight was the variable most affected by the effect of plant genotype.

ACKNOWLEDGEMENTS

The authors thank the State University of Montes Claros (Unimontes); the Brazilian Institute for Colonization and Agrarian Reform (INCRA); the Bahia Federal Institute – Guanambi *campus*; the Federal University of Viçosa (UFV); the Rural Worker Unions of Guanambi and Caetité for their contribution to this research project. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001

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