Journal of Arid Environments 185 (2021) 104325

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Soil attributes and the quality and yield of 'Gigante' cactus pear in agroecosystems of the semiarid region of Bahia

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ARTICLE INFO

Keywords:
Opuntia ficus-indica
Productivity
Environement
Bromatology

ABSTRACT

Edaphoclimatic conditions determine variations in availability of water and nutrients, susceptibility to erosive processes and expression of the genetic potential of the cactus pear. Thus, management systems consistent with environmental specificities influence the expression of the plant's structural characteristics, its yield and the forage quality. Therefore, the aim of this study was to characterize the soils of traditional cactus pear production systems and to correlate it with the productivity and mineral and chemical composition of cladodes in agroecosystems in the semiarid region of Bahia. For that, five stratified agroecosystems were selected based on the distinction of the characteristics of soils, vegetation, relief, altimetry, typology of producers and production systems of cactus pear. The crop yield data were obtained based on the harvest of cladodes from all plants in each repetition, carried out between August and September 2017. Each of the three replications, in the 20 properties, had an average useful area of 14 m^2 and an average quantity of 16 plants. For the evaluation of bromatological characteristics, at the time of collection, an average of 34 samples of cladodes were collected per repetition, with approximately 40 g each. Soils with better natural fertility, that is, with higher values of sum of exchangeable bases (SB), effective cation exchange capacity (t), cation exchange capacity at pH 7.0 (T) and base saturation index (V), do not necessarily determine better structural performance of plants compared to less fertile soils, but they influence higher productivity. Other factors associated with management and climate influenced plant structure, productivity and chemical quality of cactus pear cladodes.

1. Introduction

The growing expansion of cactus pear cultivation areas is a consequence of their adaptation to the limiting environmental conditions of the Brazilian semiarid region (Oliveira Júnior et al., 2009; Lucena et al., 2016; Silva et al., 2016a; Lédo et al., 2019) and the dissemination of its cultivation is mainly done by educational, research and extension institutions, especially in years with severe drought (Silva et al., 2017). The forage palm interacts with the growing environment, and its ability to absorb nutrients and vegetative development are affected by edaphoclimatic factors, cultivation system and plant genotype (Donato et al., 2014a; Barros et al., 2016).

The contrasting edaphoclimatic conditions of agroecosystems determine variations in the availability of nutrients in the soil, susceptibility to erosive processes and capacity to store water. Thus, it is necessary to redesign different management systems, which influence the expression of the structural characteristics of the plant and its chemical composition that will affect the quality of forage and, consequently, the yield of animal production (Blanco-Macías et al., 2010; Silva et al., 2013; Donato et al., 2014b).

The characterization of agroecosystems, with a focus on soils, can contribute to the understanding of the production systems adopted by traditional producers and their strategies for using the species, as a way to shorten the path for the reorientation of viable and appropriate

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https://doi.org/10.1016/j.jaridenv.2020.104325
Received 2 July 2020; Received in revised form 28 August 2020; Accepted 22 September 2020

technologies for the production of cactus pear in the Brazilian semiarid (Resende et al., 2007; Alves et al., 2019a).

The recognition of the variability in physical and chemical attributes of soils in agroecosystems and local environmental conditions, considering the ecophysiological requirements of the crop and the plant's responses to the production system, contributes to leverage the productive potential of the species, providing greater productivity, longevity and environmental sustainability, mainly in the Brazilian semiarid region (Fialho et al., 2013; Donato et al., 2017a).

The plant-man-environment interaction, considering the influence of the environment on yields and expression of the genetic potential of the culture, given the particularities of agroecosystems, allows the formulation of specific techniques for production systems within the socio-economic and cultural conditions of producers (Nobel, 2001; Pimienta-Barrios et al., 2012), because different environments require specific management (Resende et al., 2017).

Therefore, the aim of this study was to characterize the soils of traditional cactus pear production systems and to interrelate it with plant yields and mineral and chemical composition of cladodes in five agroecosystems in the semiarid region of Bahia.

2. Material and methods

2.1. Location and general characteristics of the studied area

The study was conducted in agroecosystems in the semi-arid region of the Guanambi micro-region, an area over the domain of the pediplano in a degraded and denuded planing surface, downstream of the Rãs River hydrographic sub-basin. These features evolved over the geology of the Guanambi Complex, which has a large area of occurrence in the eastern portion of the hydrographic basin of the middle São Francisco River, in an extensive flattened region, whose monotony is broken by inselbergs of smooth and sparse shapes. Detritic covers (Tertiary/Quaternary) were found in small isolated and flat areas, in interfluves, over the Santa Isabel Complex, upstream of the Rãs River sub-basin (Brasil, 1982).

The area of the Rãs River sub-basin shows a wide domain of hypo-xerophytic Caatinga, which transitions with the Deciduous Seasonal Forest (Dry Forest), in addition to the occurrence of transition areas Cerrado-Caatinga (Ecotonous) (Brasil, 1982).

The rainy season occurs from November to April, with six months of drought (dry season) from May to October. The months of greatest water scarcity are from June to August (Table 1). The predominant climate in the micro-region of Guanambi is BSwh, according to Köppen's classification, which corresponds to the warm climate of Caatinga, with summer rains and a well-defined dry period (Sei, 2014). To a lesser extent, to the east, the Aw typology occurs, with a rainy tropical forest climate with dry winter and rainy summer (Sei, 2014).

2.2. Identification of agroecosystems and selection of traditional cactus pear production systems

Firstly, we carried out the selection and presentation of the proposal to traditional communities and the recognition of five agroecosystems with a history of cactus pear production. The five agroecosystems were stratified based on the distinction of the characteristics of soils, vegetation, relief, altimetry, typology of producers and production systems of cactus pear in the places: 1 - Irrigated District of Ceraíma, Guanambi-BA (14° 17′ 40″ S; 42° 42′ 44″ W and 542 m of altitude) - region inserted in an irrigated perimeter, a condition that allows the irrigation of some cactus fields. Most of the surveyed area has flat to smooth undulating relief, with the predominance of eutrophic Haplic Planossols and eutrophic Red-Yellow Argisols, plus the inclusions of eutrophic Tb Fluvic Neossols (Embrapa, 1977, 2013); 2 – Iuiu Valley, Iuiu-BA (14° 23′ 50″ S; 43° 27′ 07″ W and 507 m of altitude) - region with a wide range of soils of good natural fertility, representatives of eutrophic Ta Haplic Cambisols; 3. Maniaçu, Caetité-BA (13° 48′ 50″ S; 42° 24′ 32″ W and 936 m of altitude) - represents the area with the highest altitude among those studied, with smooth wavy to wavy relief. The soils have low fertility, with a wide domain of dystrophic Red-Yellow Latosols (Embrapa, 1977, 2013); 4 - Baixio, Riacho de Santana-BA (13° 32′ 08″ S; 43° 09′ 19″ W and 482 m of altitude) - presents the lowest altitude among the studied areas, flat to smooth undulating relief and soils with low fertility, with the predominance of dystrophic Red-Yellow Latosols, with inclusions of Ortic Quartzarenic Neossols. 5 - Morrinhos, Guanambi-BA (14° 14′ 02″ S; 42° 37' 08" W and 843 m of average altitude) - area with hill relief and the predominance of eutrophic and dystrophic Red-Yellow Argisols, plus the inclusion of eutrophic Haplic

Table 1
Precipitation and average monthly and annual temperature in the municipalities where the five studied agroecosystems are located in the semi-arid region of Bahia - micro-region of Guanambi - BA.

Municipality	Rainfall (mm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Guanambi	114.8	74.0	93.4	26.7	7.0	1.3	0.2	0.3	5.3	41.9	146.4	155.9	667.1
Iuiu	127.0	98.0	94.0	52.0	5.0	1.0	1.0	1.0	11.0	68.0	151.0	173.0	781.0
Caetité	98.4	69.0	120.7	45.8	12.5	10.1	10.4	4.90	17.6	61.9	153.6	164.6	769.5
Riacho de Santana	142.0	108.0	106.0	60.0	5.0	1.0	1.0	1.0	9.0	68.0	160.0	174.0	837.0
	Temperature (°C)												Means
Guanambi	26.4	26.9	26.9	26.6	25.5	24.4	24.0	24.7	26.1	27.2	26.4	26.3	25.9
Iuiu	24.5	24.5	24.4	23.6	22.2	21.0	20.7	22.0	23.5	24.5	24.5	24.3	23.3
Caetité	22.9	23.5	22.9	22.5	21.5	19.9	19.6	20.4	22.3	23.5	23.1	22.9	22.1
Riacho de Santana	24.4	24.4	24.2	23.6	22.2	21.1	20.8	22.0	23.5	24.5	24.4	24.2	23.3

Source: 1. Average annual rainfall recorded in Ceraíma, Guanambi district. Codevasf Weather Station (1982–2007) and IF Baiano, *Campus* Guanambi, BA (2008 a 2019) (mm year^{-1}); 2. Time series of average temperature - considers the period of 1988–2019 in the Irrigated Perimeter of Ceraíma; Codevasf weather station from 1982 to 2007; automatic station of the IF Baiano Campus Guanambi 2008–2019; 3. The climatological data for Iuiu and Riacho de Santana come from several Brazilian and worldwide sources to estimate meteorological information in Brazil. A total of 2400 weather stations have time series of monthly temperature data over 25 years old, between 1950 and 1990 (Alvares et al., 2013); 4. Accumulated rainfall and average monthly temperature of Caetité - Brazilian climatological normals (1981–2010) (Diniz et al., 2018; Inmet, 2018).

Ta Cambisols (Embrapa, 1977, 2013).

In each agroecosystem, four families of traditional producers were selected, with production systems that represent each region, totaling 20 properties in the semi-arid region of the Guanambi micro-region (Table 2).

2.3. Characterization of the cactus pear production systems of each family

The families of the selected producers were interviewed with the aid of semi-structured questionnaires and in accordance with the legal conditions provided for in Resolution No. 466 of December 12, 2012, of the National Health Council. The interviews enabled the gathering of information related to the history of the area, production data and the management system adopted, such as planting date, fertilization, pest and disease control, weed control and time and method for harvesting (Table 2). In the field work, simple language was used, seeking to establish a horizontal and constructive dialogue with representatives of traditional cactus pear producing communities (Matos et al., 2014).

2.4. Evaluations of bromatological characteristics and yield of the plants

For the evaluation of bromatological characteristics, at the time of harvest, an average of 34 samples of cladodes were collected per repetition, with approximately 40 g each. A hole saw with a diameter of 5.8 cm and a depth of 4.0 cm was used, adapted to a battery-powered drill that, activated on the cladode, removed a circular and uniform portion of the plant tissue (Silva et al., 2013; Donato et al., 2014b). The collection of tissues from the cladodes was carried out from August to September 2017. These samples were collected within the useful area of

Table 2
Characterization of 'Gigante' cactus pear production systems and textural soil classes in agroecosystems.

P	Location	Dp	Lh	Sp. (m)	Man.	Irrig.	Textural Class	Weed control
-- Region of Ceraíma – Guanambi-BA ------------------------------------								
1	Ceraíma	2013	2016	1.60x0.40	16	Y	Sandy loam	MC / CC
2	Ceraíma	2012	2016	1.10x0.40	70	N	Sandy loam	MC / CC
3	Ceraíma	2014	2016	0.80x0.50	90	N	Sandy clay loam	MC / CC
4	Ceraíma	2014	2016	1.10x0.50	--	N	Sandy loam	MC / CC
--- Region of Vale do Iuiu - Iuiu-BA --								
5	Agreste	2014	2016	1.50x0.40	20	N	Clayey	MC / CC
6	Agreste	2016	---	2.00x0.10	15	Y	Loam silty	MC
7	Poço de Paulo	2016	---	1.80x0.10	16	Y	Clay loam	MC
8	Agreste	2015	---	1.80x0.10	16	Y	Loam clay silty	MC / CC
-- Region of 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
-------------------------------------- Region of 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	Sandy	MC / CC
15	Massal	2015	---	1.50x1.10	50	N	Loamy sand	MC
16	Massal	2012	2016	1.40x0.80	90	N	Loamy sand	MC
-------------------------------------- Region of Morrinhos – Guanambi-BA --								
17	Sacoto	2005	2016	2.00x0.80	---	N	Clayey 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 clayey	MC / CC

NOTES: P = Production system of each producer; Dp = date of planting; Lh = date of last harvest. When absent, it indicates that it has not yet been harvested; Sp. = spacing; Est. = amount of bovine manure applied to the cactus field in the last cycle (Mg ha^{-1}); Irrig. = adoption of irrigation practices: Y – irrigates, N – does not irrigate; MC = manual weed control by hoeing; CC = chemical weed control.
OBS.: Producers 1, 3 and 4 used insecticides, without technical monitoring; Producers 5 and 7 used urea and cattle manure for fertilization; Producer 7 started irrigation on July 2017; Producer 12 used ammonium sulfate and cattle manure for fertilization; In the Maniaçu region, there is a high incidence of parrots that feed on the cactus pear; Producer 17 uses urea for fertilization, every 2 years; Producers 1, 3, 9 and 12 used mineral oil to control pests and diseases. The collection of experimental samples from the production systems was carried out between August and September 2017.
Source: Authors' elaboration.

each of the three replicates of the 20 production systems (Table 2).

The green matter samples were prepared and dried in a forced ventilation oven at 60 °C for 72 h and, subsequently, taken to a Wiley mill with a 1 mm mesh sieve. At the Laboratory of Bromatology of the State University of Southwest Bahia (UESB), Campus Itapetinga, the following fractions were determined in the dry samples (Silva and Queiroz, 2009): DM - dry matter content; CP - crude protein; NDF - neutral detergent fiber.

The yield data of the cactus pear fields were obtained based on the harvest of the cladodes of all plants in each repetition, carried out between August and September 2017. Each of the three repetitions, in the 20 properties, had an average useful area of 14 m^2 and an average amount of 16 plants. The cladodes were cut at the joint with the plant. All the harvested cladodes had their masses determined in the field for the respective plots and producers and, later, the productivity was estimated. The variables analyzed in determining the yield of the cactus pear fields were: PANNUAL - annual productivity of each cactus pear field in the different properties; and DMP - dry matter productivity, calculated according to the DM content of the treatment multiplied by the FMP, fresh matter productivity.

2.5. *Statistical analysis*

A hierarchical model design was used, which considers the data dependence of each production system within agroecosystems. This design refers to the structure of factors and their levels and is used when the levels of a factor B only occur at certain levels of a factor A. In the present work (Fig. 1), factor A corresponds to environments or agroecosystems, and factor B to the production systems represented by producers and their properties (P) within a given environment.

The evaluated characteristics, chemical composition of the plants and the yield of the cactus plants were related to the chemical and physical attributes of the soils of the cactus pear production systems of each agroecosystem, thus satisfying the hierarchical condition of the design. (Ribeiro Júnior and Melo, 2008). In addition to the analysis of variance, with the hierarchical model the variance components and the total variance composition were estimated, i. e., determining how much explanation of the variation is contained in the different factors of the hierarchical levels (Dias and Barros, 2009).

In the case of variances significantly different from zero, which indicated the existence of at least one difference between agroecosystems and between production systems within each agroecosystem, the Tukey test ($p \leq 0.05$) was applied to compare the means of the evaluated variables.

3. Results

Agroecosystems show greater influence on the maintenance of physical and chemical characteristics of soils, even in the face of human intervention through the management system. However, this explanation does not apply to all elements, such as P (18.62%), K (18.45%), Na (35.82%), S (11.00%) and Fe (16.79%), which did not represent the largest composition of variance in the agroecosystem (Table 3).

The contents of Ca^{2+} in the soil registered significant and positive correlations with the contents of Mg^{2+} in the soil and with those of Ca^{2+} in plant tissues, both with a strong magnitude. The contents of Mg^{2+} in the soil, on the other hand, showed higher significant, positive and strong correlations with Ca^{2+} (0.76) and Na (0.71) in the tissues. On the other hand, with the contents of Mg^{2+} (0.65) and P (0.52) in the cactus pear tissues, the correlations were moderate (Table 6).

Soils with better potential for natural fertility, with higher contents of sum of exchangeable bases (SB), effective cation exchange capacity (t), cation exchange capacity at pH 7.0 (T) and base saturation index (V), do not necessarily determine better structural performance of plants compared to those cultivated in less fertile soils (Table 7). Other factors associated with management and climate influence the plant structure, yield and chemical quality of the cactus pear cladodes.

The contents of B in the soil registered the greatest correlations, significant and positive, with the contents of Cu (0.62) and Zn (0.59) in soils and with the contents of Cu (0.45) in plant tissues, all with moderate magnitude, besides correlation with the neutral detergent fiber (NDF) composition (0.30) (Table 8). Despite presenting a low correlation, this is the highest magnitude of association recorded for the NDF contents, which also includes its correlation with crude protein (CP) (0.30) and Cu contents in the soil (0.32). These results corroborate with the dynamics of B, as it is related to other elements and establish itself in the processes of extraction and export of nutrients by plants and can affect forage quality.

The contents of Cu in the soil showed the highest correlations, significant and positive, with the contents of Mn (0.45) and Zn (0.66) of the soil and with the contents of Cu in plant tissues (0.51), establishing a moderate magnitude for all. The correlations between the contents of Mn in the soil and those of Zn in the soil (0.66) with the contents of S in the tissues of the cactus pear (0.42) were significant, positive and of moderate magnitude (Table 8). The correlations between S and micronutrient contents in soils and plant tissues were not significant ($p > 0.05$), with the exception of the association with Mn of plant tissues of moderate magnitude (0.41).

4. Discussion

4.1. *Analysis of variances of physical and chemical attributes of soils in agroecosystems*

The variables of the physical and chemical attributes of the soils, studied in the production systems of 'Gigante' cactus pear, were significant, with the exceptions of aluminum (Al^{3+}), aluminum saturation index (m) and boron (B) referring to the systems (producer) within each agroecosystem (environment) (Table 3). Based on the compositions of the total variance, explanations of the variation in physical attributes are concentrated in agroecosystems with an average of 80.23%, to the detriment of the effect of production systems (16.60%) and plants (3.17%) (Table 3). The chemical attributes showed an average variation of 58.07% in agroecosystems, 25.60% in production systems and 16.33% in plants. These results demonstrate the greater influence of environments in maintaining the physical and chemical characteristics of soils, even in the face of human intervention through a management system (Curi and Kämpf, 2015), with emphasis on physical attributes, as

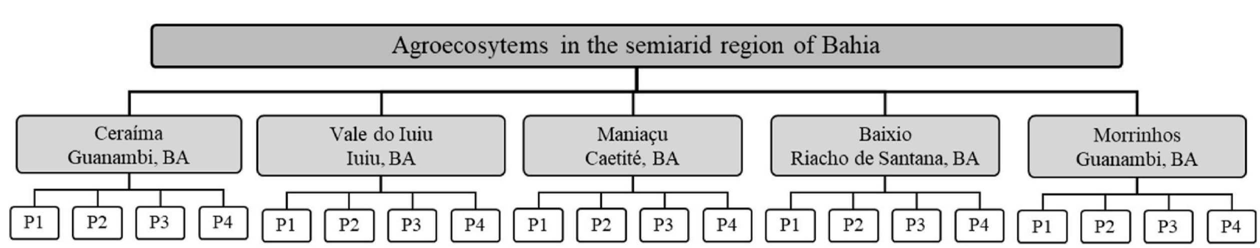

Fig. 1. Scheme of the experiment in hierarchical design.
Source: Authors' elaboration.

Table 3
Analysis of variance of physical and chemical attributes of soils in 20 traditional production systems of the 'Gigante' cactus pear distributed in five agroecosystems in the semi-arid region of Bahia - Guanambi micro-region-BA.

Variable	Sources of variation							
	Agroecossystem			Producer/Agroecossystem			Plant/Producer	
	(DF = 4; F_{tab} = 2,61)			(DF = 15; F_{tab} = 1,92)			(DF = 40)	
	MS	%	F_{calc}	MS	%	F_{calc}	MS	%
CS	0.57*	90.72	499.32	0.01*	7.05	10.50	0.00	2.23
FS	0.16*	89.44	375.84	0.00*	7.64	8.84	0.00	2.92
SIL	0.41*	90.79	1788.67	0.01*	8.59	42.29	0.00	0.62
CL	0.16*	67.55	119.26	0.02*	29.51	13.73	0.00	2.94
CDW	0.02*	62.65	119.26	0.00*	30.23	13.73	0.00	7.13
pH_{H2O}	8.20*	83.37	167.51	0.30*	10.43	6.05	0.05	6.20
pH_{KCl}	8.24*	81.40	187.00	0.36*	13.13	8.22	0.04	5.46
P	5317.55*	18.62	8.53	2181.22*	37.00	3.50	623.11	44.39
K	99968.00*	18.45	8.81	41688.84*	38.43	3.67	11348.10	43.12
Na	5149.78*	35.82	32.49	1374.22*	46.13	8.67	158.52	18.05
Ca^{2+}	197.25*	73.20	199.00	14.72*	22.02	14.80	0.99	4.78
Mg^{2+}	8.25*	79.67	201.77	0.42*	15.34	10.22	0.04	4.99
Al^{3+}	0.54*	80.04	58.47	0.01^{ns}	3.09	1.55	0.01	16.87
H + Al	12.22*	56.39	58.33	1.63*	30.23	7.77	0.21	13.38
SB	317.47*	81.16	265.74	15.16*	14.99	12.69	1.19	3.85
t	297.00*	80.23	255.93	15.04*	15.80	12.96	1.16	3.96
T	286.58*	76.31	283.31	18.76*	20.23	18.55	1.01	3.46
V	7531.82*	90.92	244.11	123.21*	4.53	3.99	30.85	4.54
m	2803.31*	71.12	38.87	127.38^{ns}	5.88	1.77	72.12	23.00
ISNa	6.35*	24.21	26.31	2.52*	57.49	10.43	0.24	18.29
MOS	7.34*	56.57	92.86	1.05*	34.90	13.27	0.08	8.53
P-Rem	513.18*	67.77	87.69	44.06*	22.08	7.53	5.85	10.15
S	102.11*	0.11	4.50	101.48*	53.57	4.47	22.71	46.32
B	0.51*	74.75	46.17	0.02^{ns}	5.06	1.75	0.01	20.20
Cu	1.83*	51.55	62.57	0.30*	36.61	10.28	0.03	11.83
Mn	17218.70*	76.20	85.18	872.28*	12.49	4.31	202.15	11.31
Fe	3526.98*	16.79	17.38	1770.43*	59.94	8.73	202.89	23.27
Zn	31.29*	40.94	20.63	6.06*	29.51	4.00	1.52	29.54

Note: DF = degrees of freedom; F_{tab} = tabulated F; F_{calc} = calculated F; MS = mean square; % = percentage of the total variance composition, which determines how much of the variation explanation is contained in the different hierarchical levels; agroecossystem = cactus pear growing environment; Producer/Agroecossystem = cactus pear production system of each traditional producer within their respective agroecosystems; Plant/Producer = variance contained in the residue, which in this case refers to the effects attributed to the plants of each producer; CS = coarse sand; FS = fine sand; SIL = silt; CL = clay; CDW = clay dispersed in water; pH_{H2O} = pH in water (1:2.5 ratio); pH_{KCl} = pH in KCl (1:2.5 ratio); P = phosphorus; K = potassium; Na = sodium; P, K and Na - Mehlich-1 extractant; Ca^{2+} = calcium; Mg^{2+} = magnesium; Al^{3+} = aluminum; Ca^{2+}, Mg^{2+} e Al^{3+} - KCl extractant – 1 mol L^{-1}; H + Al = hidrogen plus aluminum - calcium acetate extractant 0.5 mol L^{-1} – pH 7.0; SB = sum of exchangeable bases; t = effective cationic exchange capacity; T = cationic exchange capacity at pH 7.0; V = base saturation index; m = aluminum saturation index; ISNa = sodium saturation index; SOM = soil organic matter – SOM = organic carbon x 1.724 - Walkley-Black; P-Rem = remaining phosphorus, concentration of P in the equilibrium solution after stirring the air-dried fine earth (ADFE) for 1 h with 10 mmol L^{-1} $CaCl_2$ solution, containing 60 mg L^{-1} of P, in a 1/10 ratio; S = sulfur - monocalcium phosphate extractant in acetic acid; B = boron (hot water extractant); Cu = copper; Mn = manganese; Fe = iron; Zn = zinc; Cu, Mn, Fe and Zn –Mehlich-1 extractant; ^{ns} = non significant; * = significance level of 5%.
Source: Authors' elaboration.

they are unlikely to change with handling, especially the texture.

It is worth mentioning that the composition of variance of chemical attributes was not concentrated in agroecosystems for all variables, which demonstrates the possibility of the effects of anthropic actions on production systems, mainly in the application of bovine manure and the adoption of irrigation, in addition to the effects of the error in the sample composition. In these cases, the variables with their respective percentages with less explanation for agroecosystems were represented by P (18.62%), K (18.45%), Na (35.82%), S (11%) and Fe (16.79%) (Table 3).

4.2. Physical attributes and soil pH of agroecosystems and production systems

The Ceraíma and Iuiu soils had the highest average pH ($p \leq 0.05$), ranging from 5.78 to 6.25 for pH in H_2O and from 5.12 to 5.68 for pH in KCl 1 mol L^{-1}, respectively, while the other regions maintained their statistically similar values at the second level (Table 4). The average values of pH in H_2O (5.15) were higher than those in KCl 1 mol L^{-1} (4.52), indicating the domain of negative charges in the exchange complex (Pavan and Miyazawa, 1997).

Considering the interpretations of the results of soil analysis proposed by CFSEMG (1999), the agronomic classification for acidity of Ceraíma soils is considered good and that of Iuiu is high. In the other regions, the pH in H_2O was considered from low to very low (CFSEMG, 1999). In crop-specific studies, Donato et al. (2017c) recommend that the soil pH sufficient for the 'Gigante' cactus pear ranges from 5.6 to 6.3, based on experiments developed in the semi-arid region of the micro-region of Guanambi.

In the granulometric composition of the soils of the studied agroecosystems, there were significant differences for the coarse sand fraction, with the highest value in Riacho de Santana, Maniaçu, Morrinhos and Ceraíma, unlike Iuiu, which concentrated the soils with finer granulometry (Table 4). Despite being cultivated in soils with a texture that varies from sandy to clayey, the cactus pear is more suitable for clay-sandy soils (Lopes et al., 2012; Donato et al., 2017d).

The low productivity of the cactus pear in the Brazilian semiarid is the result of the mistaken understanding that it is a crop that is tolerant of environmental limitations and that does not demand land with better agricultural aptitude. For this reason, many cactus pear fields are planted in marginal areas, with compacted and stony soils, with low availability of nutrients and eventual occurrence of salinity, and are also conducted without the agronomic practices necessary for the productive potential of the crop (Silva et al., 2016a; Donato et al., 2017a, 2017d). Thus, the cactus pear presents responses to the specificities of the

Table 4
Physical attributes and soil pH of 20 traditional 'Gigante' cactus pear production systems in five agroecosystems in Bahia's semiarid - Guanambi microregion - BA.

Agroecossystem	P	CS	FS	SIL	CLA	CDW	pH_{H2O}	pH_{KCl}
		(g kg^{-1})						
Agroecossystem								
Ceraíma		280ab	390	170	160	30	5.78a	5.12a
Iuiu		60b	80	500	360	110	6.25a	5.68a
Maniaçu		530a	220	30	220	40	4.38b	3.83b
Riacho de Santana		610a	220	80	90	10	4.50b	3.88b
Morrinhos		330ab	150	180	340	80	4.84b	4.11b
Means		360	210	190	230	60	5.15	4.52
DP		30	20	20	20	10	0.22	0.21
CV (%)		9.36	9.70	7.88	9.60	23.23	4.30	4.64
Agroecossystem	P	Production system (producer / agroecossystem)						
Ceraíma	1	270	430	170	120	20	5.73	5.32
	2	360	390	110	140	30	5.76	4.95
	3	220	340	240	200	50	6.09	5.47
	4	250	390	170	180	20	5.55	4.73
Iuiu	5	30	30	370	570	190	6.36	5.48ab
	6	40	100	610	250	60	6.30	5.91ab
	7	90	120	490	300	80	5.48	4.85b
	8	70	60	550	310	110	6.88	6.46a
Maniaçu	9	450	260	40	250	50	4.72	3.93
	10	570	200	40	190	40	4.15	3.67
	11	610	200	10	180	20	4.30	3.82
	12	490	220	40	260	40	4.33	3.89
Riacho de Santana	13	580	220	50	150	20	4.34	3.88
	14	700	200	40	60	10	4.58	3.92
	15	510	280	140	70	10	4.63	3.89
	16	650	180	80	90	20	4.46	3.83
Morrinhos	17	260	150	220	380	100	4.93	4.13
	18	340	170	170	320	70	5.01	4.22
	19	390	160	160	290	60	4.85	4.10
	20	330	130	160	380	100	4.57	3.99

Note: Agroecossystem = cactus pear growing environment; Producer/agroecossystem = each production system in its respective cultivation environment; P = cactus pear production system for each traditional producer; Collection = the soils were sampled from the collection, with a hoe, of three simple samples in the useful area of each repetition of the fields with cactus pear; Layer = 0–0.20 m; CS = coarse sand; FS = fine sand; SIL = silt; CLA = clay; CDW = clay dispersed in water; pH_{H2O} = pH in water (ratio 1: 2.5); pH_{KCl} = pH in KCl (ratio 1: 2.5). Averages followed by the same letter in the column for each environment do not differ by the Tukey test ($P \leq 0.05$). The absence of letters in the column indicates that the variable was not significant for that environment ($P \leq 0.05$).
Source: Authors' elaboration.

environments and management and, when considering them, there is the optimization of yields and the possibility of greater environmental and cultivation sustainability (Oliveira Júnior et al., 2009; Silva et al., 2012; Donato et al., 2014b; Barros et al., 2016).

The average values of clay dispersed in water (CDW) between the different regions studied were similar (Table 4). With the exception of pH in KCl in the region of Iuiu, the averages of each fraction of the granulometric composition in the CDW and pH between the soils of the production systems of each region did not differ, a fact that demonstrates homogeneity in the attributes within each agroecosystem (p ≤

Table 5
Content of macronutrients, sodium, exchangeable acidity (Al^{3+}) and potential acidity (H + Al) of the soils of 20 traditional production systems of 'Gigante' cactus pear in five agroecosystems in the semiarid of Bahia - Guanambi microregion - BA.

Agroecossystem		P	K	Na	Ca^{2+}	Mg^{2+}	Al^{3+}	H + Al
		--------- (mg dm^{-3}) ------			--------------- ($cmol_c$ dm^{-3}) ------------			
---------- Agroecossystem ----------								
Ceraíma		54.33a	175.92ab	28.05b	3.36b	1.40b	0.00	2.42c
Iuiu		41.35ab	261.33a	47.00a	10.66a	2.18a	0.00	2.20c
Maniaçu		11.59c	56.17bc	3.94c	0.83c	0.35cd	0.45	3.44b
Riacho de Santana		3.04c	37.83c	0.00c	0.78c	0.13d	0.40	2.33c
Morrinhos		24.15bc	140.83abc	1.54c	3.04b	0.91bc	0.18	4.57a
Means		26.89	134.42	16.11	3.74	0.99	0.21	2.99
SD		24.96	106.53	12.59	1.00	0.20	0.10	0.46
CV (%)		92.82	79.25	78.17	26.67	20.36	46.77	15.30
Agroecossystem	Pr	------------ Production system (producer / agroecossystem) --------------						
Ceraíma	1	47.30ab	74.67b	35.50b	3.42	1.42ab	0.00	1.90b
	2	96.83a	103.33b	0.97c	2.40	0.84b	0.00	2.30ab
	3	43.93ab	411.00a	74.77a	3.82	2.41a	0.00	2.20b
	4	29.27b	114.67b	0.97c	3.81	0.92b	0.00	3.27a
Iuiu	5	21.00b	172.00b	6.97c	17.81a	1.95	0.00	3.03a
	6	26.13b	196.67b	60.13ab	7.48b	1.92	0.00	1.67b
	7	6.67b	112.00b	81.40a	7.79b	2.19	0.00	3.33a
	8	111.60a	564.67a	39.50b	9.57b	2.68	0.00	0.77b
Maniaçu	9	4.80	70.00	13.47	0.73	0.36	0.43	3.10b
	10	11.77	28.00	0.10	0.62	0.27	0.49	2.83b
	11	9.83	28.00	0.00	0.55	0.14	0.56	3.57ab
	12	19.97	98.67	2.20	1.42	0.60	0.31	4.27a
Riacho de Santana	13	2.30	26.67	0.00	0.89	0.11	0.52	2.77a
	14	3.03	42.00	0.00	0.61	0.15	0.31	1.73b
	15	1.63	54.00	0.00	0.85	0.14	0.40	2.47ab
	16	5.20	28.67	0.00	0.77	0.13	0.37	2.37ab
Morrinhos	17	5.07	118.67	6.07	3.18	1.08	0.18	5.17a
	18	54.77	190.67	0.00	3.82	0.77	0.09	4.83a
	19	22.60	125.33	0.00	2.67	0.90	0.21	3.80b
	20	14.17	128.67	0.10	2.50	0.89	0.25	4.47ab

Note: Collection = the soils were sampled from the collection, with a hoe, of three simple samples in the useful area of each repetition of palms; Layer = 0–0.20 m; agroecosystem = cactus pear cultivation environment; Producer/agroecosystem = each production system in its respective cultivation environment; Pr = production system of cactus pear from each traditional producer; P = phosphorus; K = potassium; Na = sodium; P, K and Na - Mehlich-1 extractant; Ca^{2+} = calcium; Mg^{2+} = magnesium; Al^{3+} = aluminum (exchangeable acidity); Ca^{2+}, Mg^{2+} and Al^{3+} - KCl extractant - 1 mol L^{-1}; H + Al = hydrogen plus aluminum (total or potential acidity) - calcium acetate 0.5 mol L-1 - pH 7.0 extractant. Means followed by the same letter in the column for each environment do not differ by the Tukey test ($p \leq 0.05$). The absence of letters in the column indicates that the variable was not significant for that environment ($p \leq 0.05$).
Source: Authors' elaboration.

0.05) (Table 3).

The high silt/clay ratio indicates a low degree of pedogenetic evolution of soils in the cactus pear production systems in Iuiu (Embrapa, 2013), unlike the other regions (Table 4). The high value of the silt/clay ratio, 1.38, indicates a high potential for crusting (Resende et al., 2007), which can be more pronounced in crops irrigated with sprinkler and pivot systems. The predominance of fine sand over the coarsest fraction in the soils of Ceraíma and the expressive composition in clays in Iuiu

Table 6
Correlation between the contents of macronutrients in soil and plant tissues with the productivity of dry matter (DMP), neutral detergent fiber (NDF) and crude protein (CP) of the 'Gigante' cactus pear from 20 traditional production systems distributed in five agroecosystems in the semiarid region of Bahia - microregion of Guanambi-BA.

Variable	P	K	Na	Ca^{2+}	Mg^{2+}	CMP	CMK	CMNa	CMCa	CMMg	PMS	PB
K	0.66**	1.00										
Na	0.12^{ns}	0.35**	1.00									
Ca^{2+}	0.21^{ns}	0.37**	0.37**	1.00								
Mg^{2+}	0.39**	0.62**	0.75**	0.75**	1.00							
CMP	0.76**	0.51**	0.36**	0.22*	0.52**	1.00						
CMK	0.46**	0.30**	0.35**	0.12^{ns}	0.38**	0.55**	1.00					
CMNa	0.04^{ns}	0.21^{ns}	0.72**	0.63**	0.71**	0.18^{ns}	0.23*	1.00				
CMCa	0.17^{ns}	0.35**	0.62**	0.87**	0.76**	0.22*	0.19^{ns}	0.81**	1.00			
CMMg	0.22*	0.25*	0.69**	0.23*	0.65**	0.43**	0.44**	0.50**	0.41**	1.00		
DMP	0.37**	0.33**	0.29*	0.32**	0.44**	0.57**	0.19^{ns}	0.27*	0.25*	0.30**	1.00	
CP	-0.12^{ns}	-0.05^{ns}	0.12^{ns}	-0.17^{ns}	-0.06^{ns}	0.24*	0.03^{ns}	-0.06^{ns}	-0.10^{ns}	-0.11^{ns}	0.21^{ns}	1.00
NDF	-0.03^{ns}	-0.07^{ns}	−0.24*	0.03^{ns}	-0.11^{ns}	0.12^{ns}	0.11^{ns}	-0.16^{ns}	-0.13^{ns}	-0.13^{ns}	0.27*	0.30**

Note: P = phosphorus content in the soil; K = potassium content in the soil; Na = sodium content in the soil; Ca^{2+} = calcium content in the soil; Mg^{2+} = magnesium content in the soil; CMP = phosphorus content in plant tissue; CMK = potassium content in plant tissue; CMNa = sodium content in plant tissue; CMCa = calcium content in plant tissue; CMMg = magnesium content in plant tissue; DMP = dry matter productivity; CP = crude protein; NDF = neutral detergent fiber. ns = not significant; significance level: ** = 1% and * = 5%.
Source: Authors' elaboration.

contributes to the greater capacity to maintain moisture during the rainy season, especially when considering the conditions of precipitation in the semiarid (Table 4). On the other hand, the predominance of the sand fraction in the soils of Riacho de Santana and Maniaçu suggests low water and nutrient retention capacity and higher albedo, which requires adjustments in plant management to obtain higher productivity.

4.3. *Content of macronutrients, sodium, exchangeable acidity and potential acidity in soils of agroecosystems and production systems*

The contents of P were higher in Ceraíma and Iuiu soils, with 54.33 and 41.35 mg dm^{-3}, respectively, a value considered very good in both agroecosystems (Table 5) (CFSEMG, 1999; Novais and Smith, 1999). Iuiu benefits from the influence of the source material on the characteristics of the soils, presenting a greater supply of nutrients. Ceraíma, being an irrigated perimeter region, has a history of fertilizer application in its areas; furthermore, in the studied area, there is the inclusion of eutrophic Fluvic Neosol (Santos et al., 2016) formed by addition caused by the floods of the Carnaíba de Dentro River.

The critical level (CL) of a nutrient is defined as its concentration in the tissue or soil referring to the threshold of maximum crop production, in order to reach 90% of its productivity or growth (Novais et al., 2007; Donato et al., 2017c).

Donato et al. (2017c) applied the critical level technique by the criterion of reduced normal distribution (NCRIz) (Maia et al., 2001) to generate patterns and critical levels of interpretation of nutrients in the soil (Alves et al., 2019a, b) and in vegetable tissues of cactus pear in the semi-arid region of the Guanambi microregion. According to Donato et al. (2017c), the NCRIz of P in the soil is 21.7 mg dm^{-3}, twice the value determined by Dubeux Júnior et al. (2010), 11 mg dm^{-3}. It is worth mentioning that the critical level varies according to the method of analysis, the species and age of the culture, the level of P adsorption, the clay content and the ability of the extractor correction factor to estimate the P-Rem in a manner consistent with the reality (Novais et al., 2007; Donato et al., 2017c).

Agroecosystems with soils of coarser granulometry, represented by Riacho de Santana and Maniaçu, had the lowest nutrient content in the soils (Table 5). The magnitude of the productivity of the cactus pear depends on the availability of nutrients and its ability to extract them from the soil, so that the production system adopted can favor these conditions to reach potential productivity (Galizzi et al., 2004).

The soils of Iuiu, Ceraíma and Morrinhos had the highest K contents, ranging from 140.83 to 261.33 mg dm^{-3} (Table 5), which correspond to the middle to very high (very good) classes (Donato et al., 2017c). In Ceraíma and Iuiu, there were two differences in the contents of P and K between the soils of the production systems within these regions; in the others, there were no significant differences. As the nutrients most extracted by the cactus pear, K and Ca require adequate monitoring of their contents in soils and plants, so that they can be returned to the soil and made available to the plants properly. (Silva et al., 2016b; Donato et al., 2017d).

The soils of Iuiu had the highest average contents of Ca^{2+} and Mg^{2+}, which is justified by their limestone origin, unlike Riacho de Santana and Morrinhos, which showed the lowest contents of these nutrients (Table 4). The contents of Mg^{2+} were very low for Riacho de Santana (0.13 $cmol_c$ dm-3) and Maniaçu (0.35 $cmol_c$ dm^{-3}), medium for Ceraíma (1.4. $cmol_c$ dm^{-3}) and very good for Iuiu (2.18 $cmol_c$ dm^{-3}) (Table 5) (Donato et al., 2017d). The differences in Mg^{2+} contents between the soils of the properties in Iuiu, Maniaçu, Riacho de Santana and Morrinhos were not significant; only in Ceraíma there was a differentiation. For Ca^{2+}, there was a significant difference only between the production systems of Iuiu (Table 5).

According to Marschner (2012), the contents of Ca^{2+} required for full root growth are higher at low pH. Soil contents of 2.0–3.0 $cmol_c$ dm^{-3} of Ca^{2+} and 1.0–1.6 $cmol_c$ dm^{-3} of Mg^{2+} are considered average for the 'Gigante' cactus pear (Donato et al., 2017c).

The average contents of Ca^{2+} in the soils in Maniaçu and Riacho de Santana were considered very low; in Ceraíma and Morrinhos, good; and very good in Iuiu (Donato et al., 2017c). By the CFSEMG method (1999), the classification for good values of Ca^{2+} contents occur in the range of 2.41–4.0 $cmol_c$ dm^{-3}. These values show the high demand of cactus pear for Ca^{2+} and Mg^{2+} and, consequently, a high need to extract these elements from the soil (Silva et al., 2016a; Donato et al., 2017c).

The highest average in Na contents was found in soils in Iuiu (47.00 mg dm^{-3}), followed by Ceraíma (28.05 mg dm^{-3}); these are the only regions where the producers irrigated the plants. Soil salinization (Table 5) is explained by irrigation, since the water collected comes from tubular wells with the presence of Na. In the other regions, Na contents ranged from 0.00 to 3.94 mg dm^{-3} (Table 5). Only in Ceraíma and Iuiu, significant variations ($p \leq 0.05$) were observed in the Na content among the soils of the production systems in their respective agroecosystems. Silva et al. (2016c) estimated quantities extracted/exported of Na in dry matter in the order of 32.3 g Mg^{-1}. Marschner (2012) reports that Na is an important element for crassulaceae acid metabolism (CAM) plants, so it is considered essential for these.

The *Opuntia ficus-indica* species is sensitive to soil salinity, as are most cacti. Growth inhibition often shows a linear effect with Na content. Contents of 150 mg dm^{-3} of Na can cause a 50% inhibition of the

Table 7
Cation exchange complex, aluminum and sodium saturation indexes and organic matter content in the soils of 20 traditional 'Gigante' cactus pear production systems distributed in five different agroecossystems in the semiarid of Bahia – microregion of Guanambi – BA.

Agroecossystem	P	SB	t	T	V	m	NaSI	SOM
		------------ ($cmol_c\ dm^{-3}$)		------------	------------ (%)		---------------	($dag\ kg^{-1}$)
---------- Agroecossystem ----------								
Ceraíma		5,33b	5.33b	7.75b	67.89b	0.00b	1.40a	1.62bc
Iuiu		13.72a	13.72a	15.92a	85.80a	0.00b	1.50a	2.85a
Maniaçu		1.34c	1.79c	4.78c	27.09d	28.95a	0.38b	1.43bc
Riacho de Santana		1.01c	1.41c	3.34d	30.02d	29.39a	0.00b	0.72c
Morrinhos		4.32b	4.50b	8.89b	48.53c	4.38b	0.06b	2.00ab
Means		5.14	5.35	8.14	51.87	12.54	0.67	1.720
SD		1.09	1.08	1.01	5.55	8.49	0.49	0.28
CV (%)		21.24	20.13	12.36	10.71	67.70	73.71	16.32
Agroecossystem	P	------------- Production system (producer / agroecossystem) ---------------						
Ceraíma	1	5.19b	5.19b	7.09bc	73.06a	0.00	2.13b	1.59
	2	3.51b	3.51b	5.81c	60.16b	0.00	0.08c	1.24
	3	7.60a	7.60a	9.80a	77.63a	0.00	3.32a	1.51
	4	5.03b	5.03b	8.30ab	60.70b	0.00	0.06c	2.13
Iuiu	5	20.23a	20.23a	23.26a	86.46ab	0.00	0.13c	4.30a
	6	10.17c	10.17c	11.83c	85.76ab	0.00	2.20ab	3.02ab
	7	10.62c	10.62c	13.95bc	76.16b	0.00	2.52a	2.44ab
	8	13.87b	13.87b	14.63b	94.80a	0.00	1.14bc	1.64b
Maniaçu	9	1.33	1.76	4.43ab	30.03a	24.93bc	1.32a	1.33
	10	0.97	1.46	3.80b	25.60ab	34.20ab	0.01b	1.11
	11	0.77	1.33	4.34b	17.43b	45.03a	0.00b	1.46
	12	2.29	2.60	6.56a	35.30a	11.63c	0.16b	1.82
Riacho de Santana	13	1.06	1.58	3.83	27.73	33.43	0.00	0.80
	14	0.87	1.17	2.60	32.20	29.06	0.00	0.44
	15	1.13	1.53	3.60	31.16	26.90	0.00	0.93
	16	0.98	1.35	3.34	28.96	28.16	0.00	0.71
Morrinhos	17	4.59	4.77	9.75ab	46.76	4.13	0.25	2.53
	18	5.08	5.17	9.91a	51.30	1.86	0.00	2.18
	19	3.90	4.11	7.70b	50.63	5.30	0.00	1.42
	20	3.72	3.96	8.18ab	45.43	6.20	0.01	1.86

Note: Collection = the soils were were sampled collecting, with a hoe, three samples in the useful area of each repetition in the cactus pear fields; layer = 0–0.20 m; agroecossystem = cactus pear cultivation environment; producer/agroecossystem = each production system in its respective cultivation environment; P = cactus pear production system of each traditional producer; SB = sum of exchangeable bases; t = effective cation exchange capacity; T = cation exchange capacity at pH 7,0; V = base saturation index; m = aluminum saturation index; NaSI = sodium saturation index; SOM = soil organic matter – SOM = organic carbon x 1.724 – Walkley-Black. Means followed by the same letter in the column for each environment do not differ by the Tukey test ($p \leq 0.05$). The absence of letters in the column indicates that the variable was not significant ($p \leq 0.05$).
Source: Authors' elaboration.

accumulation of biomass of the 'Gigante' cactus pear (Nobel, 2001).

The variations in the contents of P, K, Na, Ca^{2+} and Mg^{2+} in the soils of each production system that make up the regions of Maniaçu, Riacho de Santana and Morrinhos were not significant ($p \leq 0.05$), which demonstrates homogeneity of the attributes within each region (Table 4). The cultivation of cactus pear requires nutrient contents in the following decreasing order: K, Ca^{2+}, N and Mg^{2+} (Donato et al., 2017b).

Based on CFSEMG (1999), the critical level in the soil for K, Ca and Mg is 70 mg dm^{-3}, 2.4 $cmol_c\ dm^{-3}$ and 0.90 $cmol_c\ dm^{-3}$, respectively. The NCRIz of these nutrients for the cactus pear are 101.4 mg dm^{-3}, 2.2

Table 8
Contents of remaining P, S and micronutrients in the soils of 20 traditional 'Gigante' cactus pear production systems distributed in five different agroecossystems in the semiarid of Bahia – microregion of Guanambi – BA.

Agroecossystem	P	P-Rem	S	B	Cu	Mn	Fe	Zn
		($mg\ L^{-1}$)	($mg\ dm^{-3}$)					
Agroecossystem								
Ceraíma		49.96a	2.63ab	0.47ab	0.71bc	63.17b	72.46a	2.52bc
Iuiu		39.34c	8.13a	0.62ab	1.11ab	101.82a	42.41b	3.85ab
Maniaçu		47.00b	2.01b	0.68a	0.83bc	19.78c	50.45b	1.66cd
Riacho de Santana		50.02a	0.65b	0.28b	0.45c	13.13c	43.33b	0.71d
Morrinhos		35.67d	1.93b	0.81a	1.47a	77.09b	25.06c	4.71a
Means		44.40	3.07	0.57	0.91	55.00	46.74	2.69
SD		2.42	4.77	0.10	0.17	14.22	14.24	1.23
CV (%)		5.45	155.30	18.34	18.71	25.85	30.47	45.81
Agroecossystem	P	Production system (producer / agroecossystem)						
Ceraíma	1	51.17	3.97	0.39	0.94	51.47b	83.57b	3.47
	2	52.63	1.63	0.40	0.60	59.83b	21.50c	3.41
	3	48.33	1.30	0.55	0.71	48.80b	62.40b	1.28
	4	47.70	3.63	0.54	0.58	92.57a	122.37a	1.90
Iuiu	5	29.60b	0.00b	0.61	1.26	136.93a	21.27b	4.13ab
	6	45.47a	4.13b	0.55	1.12	90.30b	43.70ab	2.98b
	7	40.80a	26.57a	0.61	0.84	76.57b	55.27a	2.51b
	8	41.50a	1.80b	0.69	1.22	103.47b	49.40ab	5.77a
Maniaçu	9	45.00	0.00	0.63	0.68	20.67	39.17b	1.36
	10	49.93	2.60	0.69	1.27	15.50	48.27ab	1.77
	11	48.03	0.00	0.63	0.65	8.47	73.63a	1.04
	12	45.03	5.43	0.78	0.73	34.50	40.73b	2.47
Riacho de Santana	13	46.50b	1.30	0.37	0.41	8.97	18.57b	0.35
	14	54.70a	1.30	0.15	0.49	20.83	46.43ab	0.87
	15	49.30b	0.00	0.23	0.46	13.47	77.53a	1.04
	16	49.57ab	0.00	0.35	0.45	9.27	30.80b	0.57
Morrinhos	17	32.73	5.10	0.79	0.96	82.77ab	24.20	2.74b
	18	36.40	0.00	0.91	1.89	82.77ab	28.13	8.37a
	19	37.33	2.60	0.81	2.06	54.80b	32.63	4.24b
	20	36.20	0.00	0.74	0.96	88.03a	15.27	3.50b

Note: Collection = the soils were were sampled collecting, with a hoe, three samples in the useful area of each repetition in the cactus pear fields; layer = 0–0.20 m; agroecossystem = cactus pear cultivation environment; producer/agroecossystem = each production system in its respective cultivation environment; P = cactus pear production system of each traditional producer; P-Rem = remaining phosphorus, concentration of P in the equilibrium solution after agitation for 1 h the air-dried fine soil (ADFS) with a solution of $CaCl_2$ 10 mmol L-1, containing 60 mg L^{-1} of P, in a 1/10 ratio; S = sulfur – extractant monocalcium phosphate in acetic acid; B = boron (extractant hot water); Cu = copper; Mn = manganese; Fe = iron; Zn = zinc; Cu, Mn, Fe e Zn – extractant Mehlich-1. Means followed by the same letter in the column for each environment do not differ by the Tukey test ($p \leq 0.05$). The absence of letters in the column indicates that the variable was not significant ($p \leq 0.05$).
Source: Authors' elaboration.

$cmol_c\ dm^{-3}$ and 1.0 $cmol_c\ dm^{-3}$, respectively. The NCRIz for K (Donato et al., 2017c) with a higher value than the indicated for generic conditions, i.e., without considering species, by CFSEMG (1999), is compatible with the high contents of K extraction/export by 'Gigante' cactus pear (Silva et al., 2016; Donato et al., 2017c).

The variations in the contents of aluminum (Al^{3+}) between the soils of the agroecosystems were not significant ($p \leq 0.05$). It is worth mentioning that the analysis did not find the presence of Al^{3+} in the soils of the Ceraíma and Iuiu agroecosystems, while Morrinhos presented very low exchangeable acidity (0.0–0.20 $cmol_c\ dm^{-3}$) and Riacho de Santana and Maniaçu showed low values (0.21–0.50 $cmol_c\ dm^{-3}$), according to the CFSEMG (1999) (Table 5). The differences in Al^{3+} contents between the production systems within each agroecosystem were not significant ($p \leq 0.05$).

However, the soils in Morrinhos showed the highest contents of H + Al, 4.57 $cmol_c\ dm^{-3}$, a value considered as average potential acidity (CFSEMG, 1999). The lowest contents of H + Al occurred in the agroecosystems of Iuiu, Riacho de Santana and Ceraíma, varying from 2.20 to 2.42 $cmol_c\ dm^{-3}$, which represents low potential acidity by the CFSEMG method (1999) and high to very high based on Donato et al. (2017c). Within agroecosystems, the potential acidity in the soils of the production systems showed only two levels of differentiation (Table 5).

Based on the correlation analysis of the variables (Table 6), the contents of P in the soil showed the highest significant and positive correlations with the contents of K in the soil (0.66) and with those of P (0.76) and K (0.46) in the cactus pear cladode tissues. The K in the soil showed better correlations, significant and positive, with the contents of Mg^{2+} in the soil (0.62) and with those of P in the plant tissues (0.51), both with moderate magnitude values. This demonstrates the ability of cactus pear to extract these nutrients from the soil.

The contents of Na in the soil showed a higher significant and positive correlation with the contents of Mg^{2+} in the soil, with a strong magnitude, and, in the plant tissues, the intensity of the association with Na was strong, while with the contents of Ca^{2+} and Mg^{2+} it was moderate. The correlations between these elements are associated with the practice of irrigation in the places that presented the highest Na content, in addition to the quality of the water used, originating from tubular wells that probably contain Ca^{2+} and Mg^{2+} (Table 6). Ca^{2+} in the soil showed a significant, positive and strong correlation with Mg^{2+} in the soil and with Ca^{2+} in plant tissues. The Mg^{2+} in the soil showed greater significant and positive correlations, in the cactus pear tissues, with the contents of Ca^{2+} and Na, of strong magnitude, and for the contents of Mg^{2+} and P, the association was moderate (Table 6).

Significant and positive correlations were found between the contents of P in plant tissues and K (0.55) and with Mg^{2+} (0.43) in plant tissues, with moderate magnitude. The contents of K correlated significantly and positively with Mg^{2+} (0.44), both in plant tissues and with moderate magnitude. The Na of plant tissues showed a significant, positive and strong correlation with Ca^{2+} in the plant (0.81), just as the latter showed a moderate and positive correlation with Mg^{2+} in plant tissues (0.41) (Table 6). As the Na contents were more expressive in the irrigated production systems, this greater correlation between Ca and Na may be associated with the quality of the water used in the irrigation of the cactus pear fields.

Dry matter productivity (DMP) showed a significant, positive and moderate correlation with P in plant tissues (0.57). In the soil, its highest significant and positive correlations were with P, K, Na, Ca2+ and Mg^{2+}, all of moderate magnitude (Table 6). Donato et al. (2017c) highlighted the correlation of Ca^{2+} with DMP, corroborating the need to understand the nutrient extraction/export processes to favor the development of the cactus pear according to the specificities of each cultivation environment.

The significant and positive correlation of macronutrient contents in cactus pear cladodes with the macronutrient content in soils which received fertilizers allowed to establish sufficiency ranges to evaluate the nutritional status of the crop by Alves et al. (2019a). These correlations between nutrient contents in plant tissues and in soil were established for K with P and K, Mg^{2+} with P and Ca^{2+}, and P with Mg^{2+}. The negative correlations occurred with K and Ca^{2+} (Galizzi et al., 2004; Alves et al., 2019a). In the present work, the magnitudes of the correlations were lower because most of the traditional producers do not use mineral fertilizers in cactus pear cultivation, only for N, with the use of ammonium sulfate only by one producer in Maniaçu and urea by one in Morrinhos.

4.4. Cationic exchange complex, base saturation index, aluminum and sodium and organic matter content in the soils of agroecossystems and production systems

Iuiu showed the soils with the best natural fertility potential, reaching the higher values of sum of exchangeable bases (SB), effective cation exchange capacity (t), cation exchange capacity at pH 7,0 (T) and base saturation index (V) (Table 7). In a decreasing order of natural fertility, after the Iuiu region, follows a step formed by by Ceraíma and Morrinhos. In the end, with low fertility potential, Riacho de Santana and Manialu appear together, also with the higher values of aluminum saturation index (m).

According to Donato et al. (2017c), the SB of Iuiu (13.72 $cmol_c\ dm^{-3}$) can be classified as very high dry matter production for cactus pear, while Ceraíma (5.33 $cmol_c\ dm^{-3}$) and Morrinhos (4.32 $cmol_c\ dm^{-3}$) fit in high and sufficent classifications, respectively. For the CFSEMG (1999), the class comprising the SB between 3.61 and 6.00 $cmol_c\ dm^{-3}$ is considered as good. The variations in the values of SB and t were significant between the soils of the producers in the Maniaçu, Riacho de Santana and Morrinhos regions (Table 7).

The performance of the crops, regarding the soils, varies as for the tolerance of the plant species to active acidity, exchangeable acidity and aluminum saturation, demand for nutrients and base saturation levels, as well as aeration (CFSEMG, 1999). The 'Gigante' cactus pear shows higher productivity in soils in which the pH ranges from medium to weak acidity (Donato et al., 2017c), by the chemical classification, and good to very high in the agronomical classification (CFSEMG, 1999). Nevertheless, the interpretation classes for soil chemical attributes show only interpretation references, which hardly contemplate the specific interactions between soil, genotypes, edaphoclimatic conditions, production system and socioeconomical and cultural aspects of the producer (Donato et al., 2017c).

Base saturation (V) in Morrinhos (48.53%), Riacho de Santana (30.02%) and Maniaçu (27.09) was considered very low according to the criteria of Donato et al. (2017c). According to the CFSEMG (1999), V was low in Maniaçu and Riacho de Santana, average in Morrinhos, good in Ceraíma (67.89%) and very good in Iuiu (85.80%) (Table 6). The class of V considered as average was from 61.1% to 78.5% and the NCRIz, 67.4% (Donato et al., 2017d). The higher sodium saturation indexes (NaSI) were found in Iuiu and Morrinhos, which are the regions that employ irrigation (Table 7).

The soils with finer granulometry, represented by Iuiu and Morrinhos, showed the highest contents of soil organic matter (SOM), with 2.85 and 2.00 dag kg^{-1}, respectively; both can be classified as average (CFSEMG, 1999) (Table 7). According to the CFSEMG (1999), in Morrinhos it is good, in Iuiu it is very good and in Riacho de Santana, with 0.72 dag kg^{-1}, it is low. Among the production systems, there was a significant difference for SOM content only in Iuiu.

The application of manure to the soil contributes to a decrease in P adsorption, favors the increase in available S and N, and also causes a higher mobility of N and P in their soluble organic forms (Novais et al., 2007). Additionally, it contributes for enhancing physical characteristics of soils and, consequently, favors nutrient availability for the plants (Donato et al., 2017c).

In an experiment carried out in Gauanambi, in the semiarid region of Bahia, Donato et al. (2017c) showed the equivalence of applying manure in nutrient availability, in a way that the dose of 71.8 Mg ha^{-1} $year^{-1}$ of manure, applied when planting and repeated during the rainy season, resulted in an input equivalent to 310-640-180 kg ha^{-1} of $N–P_2O_5–K_2O$ per application.

4.5. Contents of remaining P, S and micronutrients in the soils of agroecosystems and 'Gigante' cactus pear production systems

The remaining phosphorus (P-rem) reflects an indirect measure of the maximum adsorption capacity of P in soils and, because of that, it is used in the interpretation of available P in the soil (CFSEMG, 1999). The highest contents of P-rem occurred in Riacho de Santana and Ceraíma, while the lowest occurred in Iuiu, as the soils there are derived from limestone and have a very high clay content (Table 8) (Brasil, 1982). The contents of P-rem were very low in Morrinhos, low in Iuiu and very high in Riacho de Santana, Ceraíma and Maniaçu (Donato et al., 2017c).

The P-rem expresses the amount of P that remains in the equilibrium solution as a response to the concentration of P added to the soil. In more oxidic soils, a higher adsorption increase is expected, with a consequent decrease in P-rem contents. This decrease in P-rem values also occurs with SOM removal (Donagemma et al., 2008). This corroborates the importance of soil organic matter contents for enhancing soil characteristics, in this case, with higher P availability for the plants.

P-rem values higher than 30 mg L^{-1}, as the observed in all agroecosystems, indicate a relatively low P adsorption, compared to soils with high maximum P adsorption capacity, which normally show values lower than 20 mg L^{-1}. The interpretation class for P availability was very low in Riacho de Santana and very good in Iuiu (CFSEMG, 1999).

The highest contents of S and Mn, 8.13 e 101.82 mg dm^{-3}, respectively, were found in Iuiu, due to the influence of the origin material (Brasil, 1982). Acid soils, normally, show high contents of Al^{3+} and Mn, which can affect root development and, consequently, compromise plant shoot, decreasing crop productivity (Marschner, 2012; Alves et al., 2019b). Despite of that, in this work, the acid soils did not show high Mn contents, as it can be seen in Riacho de Santana and Maniaçu (Tables 8 and 3). Mn is the most extracted/exported nutrient in cactus pear dry matter (DM) (Donato et al., 2017c), ranging from 638.1 to 1968.23 g Mg^{-1} (Donato, 2011; Silva et al., 2016), depending on the environment and the fertilizer source employed.

The contents of Cu were higher in Morrinhos and Iuiu, 1.47 and 1.11 mg dm^{-3}, with good and average availability, respectively (CFSEMG, 1999). The highest Fe content occurred in Ceraíma (72.46 mg dm^{-3}), considered as high, and lowest in Morrinhos (25.06 mg dm^{-3}), considered as average. The highest contents of Zn occurred in Morrinhos (4.71 mg dm^{-3}) and Iuiu (3.85 mg dm^{-3}), both considered as high (Table 8) (CFSEMG, 1999). According to Donato (2011), Zn is the third most extracted/exported micronutrient in the DM, 58.3 g Mg^{-1}; on the other hand, Silva et al. (2016) points it as the second, with 65.1 g Mg^{-1}. These authors worked with ammonium sulfate as an acidifying source of the rhizosphere, which contributes to an increase of metallic cations availability, like Mn, Zn, Cu and Fe. The opposite occurred with Donato (2011), who worked with organic fertilization, which increases the adsorption of these cations and, consequently, decreases their extraction by plants. Zn deficiency affects the synthesis of auxin and proteins and hinders plant growth (Marschner, 2012).

Ceraíma, Maniaçu and Morrinhos did not show significant differences on the contents of P-Rem, S, B, Cu and Zn in their respective production systems and, in Iuiu, only B and Cu did not differ significantly ($p \leq 0.05$). When pH increases, the availability of some metallic cation micronutrients such as Cu, Fe, Mn and Zn, and B decreases. In a study carried out in the semiarid microregion of Guanambi, Donato (2011) detected the amounts extracted/exported in the following decreasing order: Mn (638.1 g Mg^{-1}), Fe (72.5 g Mg^{-1}), Zn (58.3 g Mg^{-1}), B (29.8 g Mg^{-1}) and Cu (0.07 g Mg^{-1}).

The highest contents of B were found in soils of Morrinhos (0.81 mg dm^{-3}), Maniaçu (0.68 mg dm^{-3}), Iuiu (0.62 mg dm^{-3}) and Ceraíma (0.47 mg dm^{-3}). The class which considers as average a B content ranges from 0.36 to 0.60 mg dm^{-3} (CFSEMG, 1999). B was the second last micronutrient in order of extraction/export by the cactus pear in the DM, 29.8 g Mg^{-1} (Donato, 2011) and 22.8 g Mg^{-1} (Silva et al., 2016). Donato et al., 2017d consider it compatible with the lowest level of association between contents in the cladode and B extraction (0.36).

Based on the correlation analysis of the variables shown in Table 9, the contents of S in the soil showed higher significant and positive correlations with the contents of S (0.43) and Mn (0.41) in cactus pear tissues, both of moderate magnitude. The content of B in the soil correlated in a positive, significant way, with moderate magnitude, with the contents of Cu (0.62) and Zn (0.59) in the soils and with the contents of Cu (0.45) in the plant tissues; also, a weak correlation with NDF was found (0.30). The highest significant and positive correlation of the contents of Zn in the soil with micronutrients in plant tissues was registered for the contents of B (0.28); however, the magnitude was weak. These results corroborate with the dynamics of B when related to other elements and establish itself in the processes of extraction and export of nutrients by the plants.

The contents of Cu in the soil showed a significant, positive and moderate correlation with Mn and Zn in the soil and with Cu in plant tissues, in addition to a weak association with NDF. The contents of Mn in the soil registered a significant, positive and moderate correlation with Zn in the soil and with the S contents in plant tissues (Table 7). In plant tissues, S registered a significant and positive correlation with Zn (0.47) and DMP (0.35). The Fe of the plant tissues registered higher significant and positive correlation with the Zn (0.30) in the plant, even so, with low magnitude (Table 9).

In determining micronutrient sufficiency ranges for the cactus pear, Alves et al. (2019) detected positive correlations between the contents of nutrients in the tissues of the cladodes and those of the soil, such as Zn with P (0.26). However, the contents of Mn in the cladodes correlated

Table 9
Correlation between contents of sulfur and micronutrients in soil and plant tissues, dry matter productivity (DMP) and neutral detergent fiber (NDF) of 'Gigante' cactus pear from 20 traditional production systems distributed in five agroecosystems from the semi-arid region of Bahia - microregion of Guanambi-BA.

Variable	S	B	Cu	Mn	Fe	Zn	CMS	CMB	CMCu	CMMn	CMFe	CMZn	PMS
B	0.05^{ns}	1.00											
Cu	−0.01^{ns}	0.62**	1.00										
Mn	0.11^{ns}	0.45**	0.45**	1.00									
Fe	0.03^{ns}	−0.20^{ns}	−0.20^{ns}	−0.06^{ns}	1.00								
Zn	−0.03^{ns}	0.59**	0.66**	0.62**	−0.19^{ns}	1.00							
CMS	0.43**	0.09^{ns}	0.09^{ns}	0.42**	0.20 ^{ns}	0.17 ^{ns}	1.00						
CMB	−0.02^{ns}	0.04^{ns}	0.19^{ns}	0.21^{ns}	−0.16 ^{ns}	0.28*	0.17 ^{ns}	1.00					
CMCu	0.17^{ns}	0.45**	0.51**	0.16^{ns}	−0.04 ^{ns}	0.15 ^{ns}	0.24*	0.05 ^{ns}	1.00				
CMMn	0.41**	−0.24*	−0.09^{ns}	0.24*	−0.01 ^{ns}	−0.11 ^{ns}	0.18 ^{ns}	−0.05 ^{ns}	0.22*	1.00			
CMFe	−0.04^{ns}	0.27*	0.10^{ns}	0.23*	−0.13 ^{ns}	0.10 ^{ns}	0.11 ^{ns}	−0.03 ^{ns}	0.26*	−0.02 ^{ns}	1.00		
CMZn	0.12^{ns}	−0.03^{ns}	0.11^{ns}	0.21^{ns}	−0.03 ^{ns}	0.11 ^{ns}	0.47**	−0.07 ^{ns}	0.18 ^{ns}	0.07 ^{ns}	0.30**	1.00	
PMS	0.15^{ns}	0.23*	0.15^{ns}	0.23*	0.24*	0.22*	0.35**	0.10 ^{ns}	0.20 ^{ns}	0.07 ^{ns}	−0.03 ^{ns}	0.13 ^{ns}	1.00
FDN	−0.13^{ns}	0.30*	0.32**	0.05^{ns}	−0.07 ^{ns}	0.14 ^{ns}	−0.11 ^{ns}	0.21 ^{ns}	0.12	−0.06 ^{ns}	0.14 ^{ns}	−0.20 ^{ns}	0.27*

Note: S = sulfur content in the soil; B = boron content in the soil; Cu = copper content in the soil; Mn = manganese content in the soil; Fe = iron content in the soil; Zn = zinc content in the soil; CMS = sulfur content in the plant tissue; CMB = boron content in the plant tissue; CMCu = copper content in the plant tissue; CMMn = manganese content in the plant tissue; CMFe = iron content in the plant tissue; CMZn = zinc content in the plant tissue; PMS = dry matter productivity; PB = crude protein; FDN = neutral detergent fiber. ^{ns} = non-significant; significance level: ** = 1% and * = 5%.
Source: Authors' elaboration.

negatively with the contents of Ca^{2+} in the soil (−0.29) (Galizzi et al., 2004; Alves et al., 2019b).

4.6. Crop yield and forage quality

The highest annual productivities occurred in Ceraíma (131.73 Mg ha^{-1} year^{-1}) and Iuiu (101.74 Mg ha^{-1} year^{-1}). In addition to being

Table 10
Bromatological characteristics of the cladodes and average yield of 'Gigante' cactus pear cultivated in 20 traditional production systems in five agroecosystems in the semiarid of Bahia - micro-region of Guanambi-BA.

Agroecossystem		PANNUAL (Mg ha^{-1})	DENS (plants ha^{-1})	DMP (Mg ha^{-1})	DM (g kg^{-1})	CP (g kg^{-1})	NDF (g kg^{-1})
		------------------------------ Agroecossystem (environment) ------------------------------					
Ceraíma		131.74a	14.617b	11.46a	105,4 b	67,4 bc	185,0 b
Iuiu		101.75ab	26.603a	9.89a	92,6 b	68,0 bc	184,7 b
Maniaçu		88.58b	9.317c	9.77a	93,4 b	87,1 a	221,2 a
Riacho de Santana		15.12c	6.657d	3.79b	161,9 a	69,4 b	170,3 b
Morrinhos		68.43b	6.621d	6.10b	97,4 b	59,3 c	199,2 ab
Means		81.12	12.763	8.20	110,1	70,2	192,1
SD		28.68	1734.10	2.02	20,1	8,0	25,2
CV (%)		35.36	13.59	24.66	18,23	11,46	13,12
Agroecossystem	P	------------------- Production system (producer / agroecossystem) -----------------					
Ceraíma	1	202.64a	14.067ab	11.99ab	61,8 b	67,4 ab	208,3
	2	75.76b	10.692b	10.32ab	134,5 a	61,6 b	180,9
	3	182.53a	16.863a	14.31a	84,3 b	82,3 a	179,7
	4	66.03b	16.846a	9.21b	141,1 a	58,1 b	171,0
Iuiu	5	65.80b	12.126d	12.63a	192,8 a	64,6	231,7 a
	6	55.86b	42.222a	3.04b	55,0 b	59,5	178,2 ab
	7	173.39a	24.113c	11.19a	65,7 b	75,0	159,9 b
	8	111.93ab	27.949b	12.68a	56,7 b	72,7	169,0 b
Maniaçu	9	51.54b	11.238	5.39b	105,8 ab	70,0 c	165,3 b
	10	116.05a	7.743	14.78a	63,3 b	78,0 bc	265,4 a
	11	106.69ab	9.004	11.92a	112,6 a	89,9 b	219,8 ab
	12	80.05ab	9.284	7.00b	91,7 ab	110,7 a	234,3 a
Riacho de Santana	13	14.78	2.571b	3.38	130,8 b	78,4 a	158,7
	14	8.52	9.308a	2.60	166,3 ab	77,9 a	202,1
	15	14.85	7.542a	5.23	174,4 ab	52,0 b	164,8
	16	22.33	7.208a	3.96	176,0 a	69,3 ab	155,8
Morrinhos	17	44.08	5.261b	6.20	140,6 a	62,0 a	174,1
	18	71.56	12.067a	7.56	109,1 ab	44,0 b	183,7
	19	102.00	5.010b	6.70	69,1 b	69,5 a	221,0
	20	56.08	4.144b	3.97	70,8 b	61,6 ab	217,9

Note: Agroecosystem = cactus pear cultivation environment; Producer/agroecosystem = each production system in its respective cultivation environment; P = cactus pear production system for each traditional producer; PANNUAL = annual productivity of cactus pear in each production system; DENS = density, corresponds to the number of plants per hectare; DMP = dry matter productivity; DM = dry matter content in the cladodes; CP = crude protein; NDF = neutral detergent fiber. With the exception of producers 8, 10, 13, 14 and 15, who harvested the cladodes at the age of two, the others did so with an interval of just one year after the last harvest. Means followed by the same letter in the column for each environment do not differ from each other, by the Tukey test ($p \leq 0.05$). The absence of letters in the column, indicates that the variable did not present significant differences for the referred environment.

Source: Authors' elaboration.

agroecosystems with better natural fertility soils, these regions were the only ones in which the farmers irrigated the fields and, thus, provided conditions for achieving higher green mass yields of the cladodes (Table 10). Iuiu and Ceraíma also had the highest cladode area indexes, with 3.92 and 3.11 m^2 of cladode per m^2 of soil, respectively.

On the other hand, in Riacho de Santana, the lowest annual yields were recorded, with an average of 15 Mg ha^{-1} $year^{-1}$ (Table 10). Riacho de Santana and Maniaçu correspond to agroecosystems with less naturally fertile soils. However, even with soils with greater restrictions on fertility and storage capacity of water and organic matter, Maniaçu stood out in yields and better bromatological characteristics of the cladodes for use in animal feed.

Considering the morphometric characteristics of the plant, Maniaçu produced cladodes with greater width (17.10 cm) and, together with Ceraíma, had the cladodes with greater length (31.72 and 32.15 cm, respectively). The width is 49.90% affected by the cultivation agroecosystem. The highest numbers of cladodes produced per plant were in Morrinhos and Ceraíma, with 28 and 24, respectively.

The highest average crude protein (CP) content was detected in Maniaçu (87.1 g kg^{-1}) and the lowest in Morrinhos (59.3 g kg^{-1}). The production systems affected to a greater extent (49.17%) the CP contents in the cladodes (Table 10). Other authors agree when considering the influence of the application of manure in increasing doses (0, 30, 60 and 90 Mg ha^{-1}), as this practice increases the contents of total N and CP of the 'Gigante' cactus pear (Donato et al., 2014b; Barros et al., 2016; Lédo et al., 2019), in addition to mineral fertilization with a supply of N and P (Silva et al., 2013).

The average NDF contents remained low, 192.1 g kg^{-1}. Other authors have detected averages ranging from 283.0 to 318.7 g kg^{-1} of NDF (Cavalcante et al., 2014). The cactus pear fields of Maniaçu and Morrinhos presented the highest average NDF contents, with 221.2 and 199.2 g kg^{-1}, respectively (Table 10).

The dry matter (DM) content was higher in the cactus pear fields in Riacho de Santana (161.9 g kg-1); in the other agroecosystems, it varied from 92.6 to 105.4 g kg-1 of DM, being most affected by the production system adopted on the property (63.21%) (Table 10). The higher DM content in the plant tissues of the fields in Riacho de Santana is justified by the lower turgidity of the plants due to the higher water deficit and less supply of nutrients in the soil. This situation is aggravated by the higher albedo caused by sandy soils, with 600 g kg-1 of coarse sand (Table 4), and the wider spacing, as observed in Riacho de Santana, with up to 2.5 × 1.5 m (Table 2).

The dry matter productivity (DMP) was also higher for 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 with 6.10 Mg ha^{-1} $year^{-1}$, and Riacho de Santana, with 3.79 Mg ha^{-1} $year^{-1}$, presented the plants with the lowest DMP (Table 10).

The low productivity per plant of the fields in Iuiu, 5.54 kg per harvest, was equivalent to that of Riacho de Santana, with 5.03 kg. However, productivity in Iuiu surpassed due to the higher density used in cultivation, 26,603 plants ha^{-1}, while Riacho de Santana had an average of 9317 plants ha^{-1} (Table 10).

A higher density of plants in cultivation to increase DM productivity causes higher extraction of nutrients from the soil, initially, mainly for mobile elements, such as N and Ca (Novais et al., 2007). Furthermore, the cultivation of cactus pear presents high nutrient extraction/export (Donato et al., 2017b).

In addition to presenting the best yields in the number of cladodes per plant, Maniaçu stood out with the highest average content of PB and NDF (Table 10). This better performance of the 'Gigante' cactus pear cultivation in Maniaçu is related to the fact that the plant benefits from the milder nighttime temperatures in the region (ecophysiological requirement), due to the higher local altitude (936 m). This constitutes a non-nutritional factor that translates into milder temperatures (Table 1), compatible with the temperatures in the region of the center of origin of the cactus pear (Santos et al., 2013), associated with fertilization. The altitude of the cactus pear cultivation areas showed the highest positive correlations with the contents of OM, NDF and ADF in 47, 46 and 41%, respectively.

Although the clones are used regionally and belong to the same cultivar, somaclonal variation in the genetic material may have occurred, which implies variations in its potential, and, for example, the NDF content is partly influenced by the plant as well, genetic factor. Additionally, it is noteworthy that all cactus pear production systems in Maniaçu were fertilized, a practice that influences the productivity and nutritional value of cactus pear (Silva et al., 2013; Lédo et al., 2019).

The critical level of a nutrient in the soil and in the plant varies according to its availability and the maximum adsorption capacity of the soil (Novais et al., 2007). Chemical (Silva et al., 2013) and organic (Donato et al., 2014b; Barros et al., 2016) fertilizers cause a reduction in DM contents and contribute to the increase in CP contents and productivity of the 'Gigante' cactus pear (Silva et al., 2017). Fertilization increases nutritional efficiency, with organic and organomineral fertilizations providing greater nutritional efficiency of N, S, P, Mn and Zn. In 'Gigante' cactus pear, these nutrients are associated with higher dry matter yields; on the other hand, K is higher with mineral fertilization, for the same amounts of applied nutrients (Lédo et al., 2020).

Therefore, according to the case of Maniaçu, the fertilization recommendation should not only consider plant requirement of a certain nutrient and soil availability, but also the interrelationship of other factors, as well as the socioeconomic and cultural issues of the plant producer and the ecophysiological conditions of plants and their consonance with the environment, which, thus, can provide better conditions for adaptation and crop production (Curi and Kämpf, 2015; Donato et al., 2017c).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

To the State University of Montes Claros - Unimontes, the National Institute of Colonization and Agrarian Reform - INCRA, the Federal Institute of Bahia - Campus Guanambi, the Federal University of Viçosa - UFV, the Unions of Rural Workers of Guanambi and Caetité, for contributing to the feasibility of the research project.

This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001.

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