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The association between morphological characteristics and yield in forage cactus clones varies according to water regimes: a principal component analysis

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Abstract. Forage cactus species exhibit distinct morphological characteristics, which have a relationship to yield and can be affected by different water conditions. The objective was to analyze, with the principal components analysis (PCA), the association between morphological and productivity variables in forage cactus clones in different water regimes. We cultivated, in Serra Talhada, Brazilian semiarid, the Miúda (MIU), Orelha de Elefante Mexicana (OEM) and IPA Sertânia (IPA) clones under four water regimes based on crop evapotranspiration – ETc (0%, 40%, 80% and 120% ETc). Between the years 2016 and 2018, morphological and crop productivity data were obtained. Two main components explained >82% of the total variability of the data, and the relationship between morphological and production variables depended on the clone and the water regime. The production of fresh and dry matter was more influenced by the morphological characteristics in the MIU and OEM clones. The IPA clone showed no correlation between the variables analyzed, regardless of the water regime. PCA can be used to understand the growth dynamics of plants and to identify the water conditions that act in the production of cactus clones, favoring better management in the cultivation of culture.

Keywords: *Irrigation, multivariate statistics, Nopalea sp. Opuntia sp. Semi-arid region*

Introduction

The forage cactus (*Opuntia* and *Nopalea*), a xerophilic plant with a high capacity for storing water, is of great importance as a forage in the semi-arid region of Brazil (Lima *et al*., 2016; Scalisi *et al*., 2016). Like other CAM (Crassulacean Acid Metabolism) plants, the cactus opens its stomata to capture CO_2 at night, when the temperature is lower and the relative humidity is higher than those during the day, allowing less water to be lost to the atmosphere (Hassan *et al*., 2019; Liguori *et al*., 2013; Nefzaoui *et al*., 2014). This results in good biomass production, especially during dry periods, when there is a decrease in the supply of forage from the native Caatinga (Leite *et al*., 2014; Ramos *et al*., 2015; Araújo Júnior *et al*., 2021a) and, consequently, a reduction in feed for the animals.

The Miúda (*Nopalea cochenillifera* (L.) Salm-Dyck), IPA Sertânia (*Nopalea cochenillifera* (L.) Salm-Dyck) and Orelha de Elefante Mexicana (*Opuntia stricta*

(Haw.) Haw.) clones are widely cultivated in the Brazilian semi-arid region, because of their resistance to the cochineal scale bug (*Dactylopius opuntiae*) (Lopes *et al*., 2010). These species exhibit distinct morphological characteristics, such as size, quantity, and shape of the cladodes (Silva *et al*., 2014a; Pinheiro *et al*., 2014), which in turn determine differences relative to the plant canopy, influencing photosynthetic capacity and crop productivity (Barbosa *et al*., 2018a). In addition to characteristics inherent in the species, factors such as environmental conditions, planting density, irrigation management, and fertilization, can influence the architecture of these plants (Ramos *et al*., 2011; Silva *et al*., 2014b; Barbosa *et al*., 2018b; Araújo Júnior *et al*., 2021c).

One way of analyzing the influence of morphological characteristics on crop yield is via multivariate analyses (Neder *et al*., 2013). Among the techniques used, principal component analysis (PCA) generates new variables from the original set of data, maximizing the proportion of non-intercorrelated variance in successive principal components (PCs), in addition to significantly reducing the dataset (Silva and Sbrissia, 2010; Zhao, Meng and Xu, 2014). Using this technique, García-Nava *et al*. (2015) detected changes in the biophysical and physiological characteristics of *Opuntia cacti* induced by the water regime. Mendéz *et al*. (2015) found differences in cactus species because of their physical and chemical characteristics, with PC1 being associated with the morphological parameters and PC2 with the chemical traits of the clones.

Many studies have shown an association between morphological and production characteristics in forage cactus clones (Silva *et al*., 2010; Neder *et al*., 2013; Barbosa *et al*., 2017a, b; Barbosa *et al*., 2018a, b), but little information is available about the effect of the water conditions on the growth environment (Araújo Júnior *et al*., 2021c). Such information is needed to help understand the growth dynamics of plants and identify factors that limit forage production in the cactus, which can aid in adapting management practices (Amorim *et al*., 2017; Silva *et al*., 2019; Araújo Júnior *et al*., 2021b). Based on the above, the aim of this study was to analyze the association between morphological and production variables in forage cactus clones on different controlled water regimes.

Materials and Methods

Description of the study site

The experiment was conducted at the International Reference Centre for Agrometeorological Studies of the Cactus and other Forage Plants, at the Serra Talhada Academic Unit of the Federal Rural University of Pernambuco, in Serra Talhada, Pernambuco, Brazil (7º59' S, 38º15' W and 431 m). According to the Köppen classification, the local climate is type BShw' (hot semi-arid), with an average rainfall of 642 mm yr^{-1}, average air temperature of 24.8 ºC, relative humidity of approximately 62%, and atmospheric demand >1,800 mm yr^{-1} (Alvares *et al*., 2013; Silva *et al*., 2015).

Setting up the experiment, plant material and treatments

On 6 January 2016, cladodes of the Miúda (MIU) (*Nopalea cochenillifera* (L.) Salm-Dyck), Orelha de Elefante Mexicana (OEM) (*Opuntia stricta* (Haw.) Haw.) and IPA Sertânia (*Nopalea cochenillifera* (L.) Salm-Dyck) (IPA) clones were planted, with 50% of their length buried in a typic Eutrophic Haplic Cambisol soil (Table 1), at a spacing of 1.0 m x 0.2 m (initial density of 50,000 plants ha^{-1}). In 2016, the crop was grown under rainfed conditions. From 1 January 2017, at the start of the present study, it was subjected to different water regimes until 30 June 2018, for a total of 567 days (~18 months).

Table 1. Chemical and physical attributes of soil cultivated with forage cactus clones under different water regimes (0% ETc - rainfed water regime, 40% ETc and 80% ETc - water regimes with a controlled water deficit, and 120% ETc - water regime greater than the crop requirement, where ETc = crop evapotranspiration).

Depth (m)	EC	pH	OC	OM	P	K	Na	Ca	Mg	CEC	V
	mS cm^{-1}		g kg^{-1}	g kg^{-1}	mg dm^{-3}	-------- cmolc dm^{-3} -------					%
0-10	0.87	6.9	5.8	10.0	78.1	1.3	0.04	4.0	1.6	7.4	94
10-20	0.52	6.7	4.8	8.3	66.5	0.7	0.03	4.5	2.2	8.2	91

Depth (m)	-- Density (g dm^{-3}) --		Total Porosity (%)	Particle Size (g kg^{-1})		
	Soil	Particle		Sand	Silt	Clay
0-10	1.58	2.43	34.8	833	128	38
10-20	1.60	2.53	36.7	830.4	118.8	50.8

EC: Electrical conductivity; **pH**: Potential of hydrogen in water (soil:solution ratio 1:2.5); **OC**: Organic carbon; **OM**: Organic matter; **P**: Available phosphorus; **K**: Potassium; **Na**: sodium; **Ca**: calcium; **Mg**: Magnesium; **CEC**: Cation exchange capacity and **V:** Base saturation.

The experiment was conducted using a split-plot design with four replications; water regimes were assigned to the main plots and clones to the sub-plots. The plots comprised four water regimes based on a percentage of the crop evapotranspiration (ETc) (0%, 40%; 80%, and 120% ETc). The water regime of 0% ETc was considered the control (i.e., rainfed cultivation), 40% ETc and 80% ETc were the regimes of a controlled water deficit, and 120% ETc was the regime greater than the crop requirement. In turn, the sub-plots comprised the three forage cactus clones (MIU, OEM, and IPA). Each experimental plot was 60 m^2 in area, consisting of four rows of 75 plants, with 25 plants of each clone in each row.

Irrigation was carried out three times a week using a drip system, with a uniform water application of 93%; emitters were spaced 0.20 m apart and the flow rate was 2.25 L h^{-1} at a pressure of 100 kPa. Irrigation was always carried out when the accumulated ETc between irrigation days was greater than the rainfall for the period. The water came from an artesian well and had an electrical conductivity of 1.51 dS m^{-1}, with a sodium and potassium concentration of 168.66 mg L^{-1} and 28.17 mg L^{-1}, respectively. To apply the irrigation depths, the daily ETo was calculated using the Penman-Monteith equation (Allen *et al*., 1998), the meteorological variables being monitored by means of an automatic weather station located 30 m from the experimental area.

The mean ETo was equal to 4.72 mm day^{-1} (Figure 1A), whereas the irrigation depths in the treatments of 40%, 80% and 120% ETc were equal to 347, 738 and 1,132 mm, respectively, which was added to the rainfall, resulting in 1,005 mm (rainfed), equivalent to 647 mm yr^{-1}; 1,352 mm (40% ETc), equivalent to 870 mm yr^{-1}; 1,743 mm (80% ETc), equivalent to 1,122 mm yr^{-1} and 2,137 mm (120% ETc), equivalent to 1,376 mm yr^{-1} (Figure 1B). Throughout the period, cropping treatments were used to control diseases and weeds. Chemical fertilization (50 kg ha^{-1} N-P-K formulation of 14-00-08) was carried out every three months.

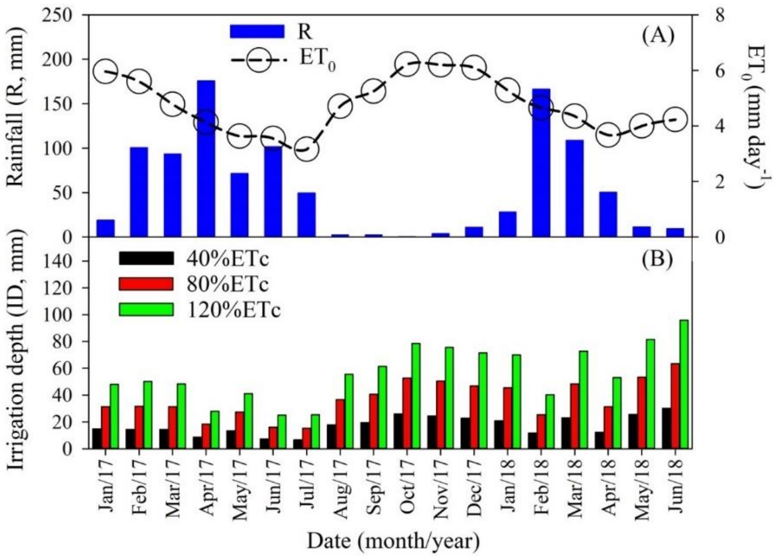

Figure 1. Rainfall, reference evapotranspiration (ET_0) and applied water depths in an area cultivated with forage cactus clones grown under different controlled water regimes (40% ETc, water deficit; 80% ETc - water deficit; and 120% ETc - full irrigation greater than the crop water requirement) plus the rainfed regime (0% ETc).

Morphological variables

During the 567 days of the experiment (~18 months), eight morphological analyses were performed every three months. On these occasions, two plants per subplot were analyzed to determine plant height (PH (cm), measured from the soil surface to the highest cladode on the plant); plant width (PW (cm) - the two largest extremities of the plant); cladodes total number (CTN); cladode length (CL (cm) - from the base of the cladode to its apex); cladode width (CW (cm) - from one side to the other, in the central region of the cladode); cladode perimeter (CP (cm) - circumference of the cladode), using a tape measure; and cladode thickness (CT (mm) - thickness of the median region of the cladode), with the aid of a caliper. Based on the mathematical models adjusted by Silva *et al*. (2014a), the cladode area (CA) was calculated in order of appearance (i.e., first-order, second-order, etc.) and per plant. Subsequently, the mean CA value per clone was determined. The cladode area index (CAI) was calculated from the ratio between the total cladode area and the spacing used (Pinheiro *et al*., 2014).

Forage yield of the forage cactus clones

To determine the productivity of the crop, three plants per plot were cut on the same dates as to when the morphological analyses were conducted, giving a total of 48 plants per date. On those occasions, only the basal cladode was left. The other cladodes were weighed to obtain the fresh weight of the plot. Of these, two representative cladodes from each clone per plot were chosen and weighed to obtain fresh weight. The cladodes were then sliced up, placed in paper bags, and dried in a forced air circulation oven at 55°C to constant weight (Silva & Queiroz, 2005). The ratio between the values for fresh and dry weight gave the dry matter content of the cladodes. Fresh matter yield (FMY, Mg ha^{-1}) was estimated by extrapolating the mean fresh weight of one plant and the final plant density. The dry matter yield (DMY, Mg ha^{-1}) was determined as the product of the dry matter content (DMC) and the FMY.

Statistical analysis

The mean data on the morphological variables and forage yield obtained from the eight biometric and biomass campaigns were subjected to a PCA to establish the relationship between the morphological and production of the forage cactus clones as a function of the different water regimes. Statistical procedures for PCA were carried out using the tool XLSTAT v2018 (Addinsoft, 2020).

Results and Discussion

The PCA revealed that the morphological variables were associated with the production variables of the cactus clones. However, it can be seen that the relationship between these variables depends on the cactus clones and the water regimes applied. Morphological differences such as growth habit, size, shape, and amount of cladodes present in each species significantly influence the cactus-environment interface, which results in distinct responses of these clones to the cultivation environment (Araújo Júnior *et al*., 2021c).

Figure 2 represents the PCA of the morphological and production variables in the MIU clone, grown under different controlled water regimes. Three components were sufficient to explain the total variability present in the original data. Component 1 (PC1), responsible for explaining 44% of the variation, showed a positive correlation between HP, CW, and CT and a negative correlation between PW, CTN, and DMC (Figure 2A). Therefore, it is clear that PC1 is responsible for explaining the growth and development of the plant, as well as for the variation of the DMC. CTN and PW were the morphological variables that showed the strongest association with DMC. Pinheiro *et al*. (2014) also found a significant correlation between morphological variables and productivity in the MIU clone, especially the height and width of the plant, and the total number of cladodes. On the other hand, CL, CP, and CAI were positively correlated with each other, with weight in component 2 (CP2), which accounted for 31% of the variance of the data matrix. CAI showed a low correlation with CTN. FMY and DMY showed a high positive correlation with each other, but a negative correlation with CA, in component 3 (PC3), which explained 25% of the total variability (Figure 2C). Of the clones under study, the MIU has the lowest CA, which reflects significantly for a lower CAI and, consequently, DM, as also verified by Silva *et al*. (2015). However, the high CTN, mainly in the upper orders, favors the lateral growth of the plant and, consequently, better photosynthesis, resulting in an increase in the dry matter content (Pinheiro *et al*., 2014; Barbosa *et al*., 2018a; Araújo Júnior *et al*., 2021a).

The PC1 consisted of the rainfed regime (0% ETc) and water regime greater than the need for the crop (120% ETc), which showed a negative correlation with each other, while PC2 comprised the conditions of controlled water deficit (40% ETc and 80% ETc) (Figure 2B). The conditions of 40% ETc and 80% ETc also showed a negative correlation with each other. This indicates that PC1 was more related to extreme water conditions (i.e., 0% ETc and 120% ETc) and modeled plant growth and dry matter accumulation in the MIU clone. Freire *et al*. (2018) observed a significant influence of the amount of irrigation on the growth and productive performance of the MIU clone. When grown in environments with more water available, the plants of the MIU clone tend to show similar yields to those of the clones that are generally more productive (e.g., *Opuntia* genus). However, under water restriction, the clone has difficulty adapting, and, consequently, the yields are below its production potential (Silva *et al*., 2015).

The PC2, in turn, was better related to the characteristics of the cladodes (e.g., CL, CP), contributing significantly to the CAI. On the other hand, CTN and CAI showed a low correlation with each other, showing that although the MIU clone has many cladodes (Araújo Júnior *et al*., 2021a), CTN had little weight in CAI. Thus, the intrinsic characteristics of the cladode (e.g., CL and CP) are, therefore, more important for variations in the CAI than the characteristics of the plant (for example, PH and PW), both under the conditions of a controlled deficit and under the rainfed regime, as reported by Pinheiro *et al*. (2014). PC3 showed no correlation with any of the regimes imposed on the MIU clone, showing that the morphological variable CA and the production variables FMY and DMY were not influenced by the water conditions in the present study (Figure 2D).

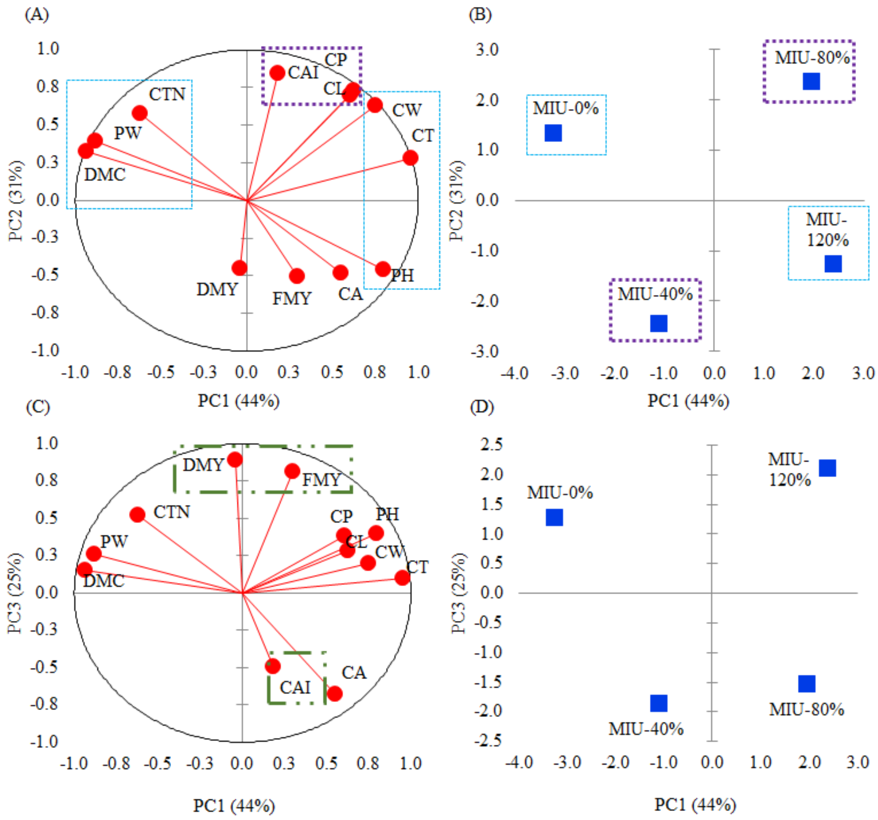

Figure 2. Principal component analysis (**PC**) of morphological and production variables in the Miúda clone (MIU), subjected to different controlled water deficit regimes based on a percentage of the crop evapotranspiration (ETc) (0%, 40%; 80% and 120% ETc). **(A)** Eigenvectors and **(B)** eigenvalues of the first PC, and **(C)** eigenvectors and **(D)** eigenvalues of the second PC. Abbreviations: **PH** - plant height; **PW** - plant width; **CTN** - cladodes total number; **CL** - cladode length; **CW** - cladode width; **CP** - cladode perimeter; **CT** - cladode thickness; **CA** - cladode area; **CAI** - cladode area index; **FMY** - Fresh matter yield; **DMY** - dry matter yield; **DMC** - dry matter yield. The dashed rectangles indicate the groups formed.

Two components explained 82% of the total variability of the OEM clone data, with PC1 and PC2 accounting for 58% and 24%, respectively (Figure 3A). The results of PC1 showed a strong association between the morphological variables (PH, PW, CTN, CL, CW, CP, CA, and CAI). DMY showed a negative correlation with these variables, mainly with the characteristics of the cladode (i.e., CL, CW, CT, CP, and CA). When considering the weight of the water regimes in the components, PC1 consisted of the regimes of 80% ETc and 120% ETc (Figure 3B); therefore, larger water applications have a greater influence on the morphological characteristics of the OEM clone.

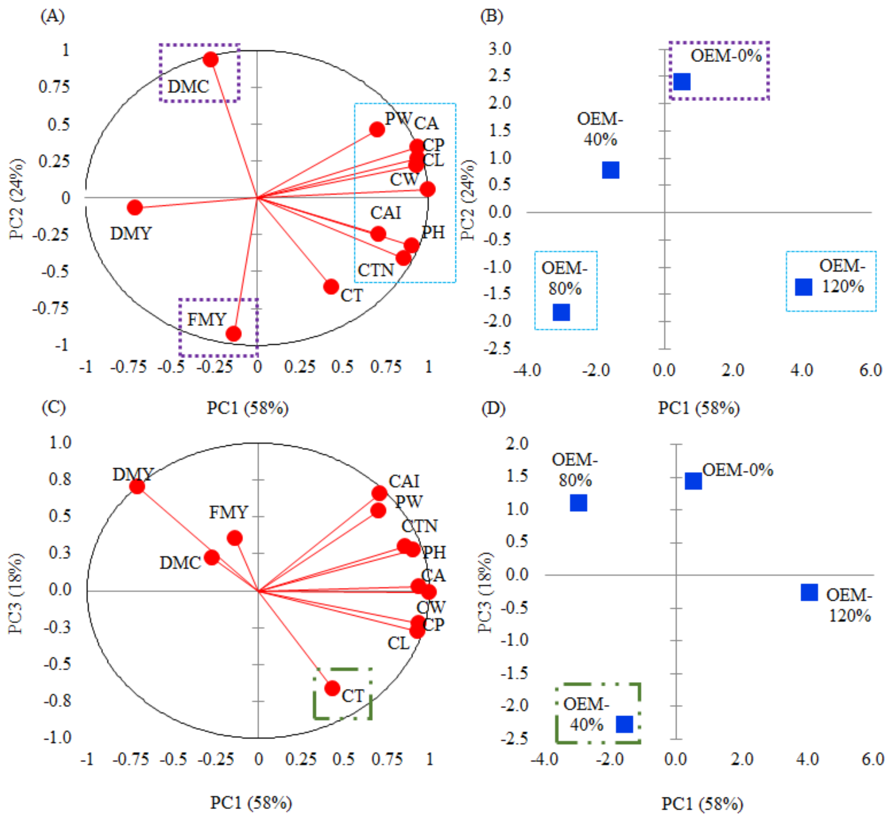

Figure 3. Principal component analysis (**PC**) of morphological and production variables in the Orelha de Elefante Mexicana clone (OEM), subjected to different controlled water deficit regimes based on a percentage of the crop evapotranspiration (ETc) (0%, 40%; 80% and 120% ETc). **(A)** Eigenvectors and **(B)** eigenvalues of the first PC, and **(C)** eigenvectors and **(D)** eigenvalues of the second PC. Abbreviations: **PH** - plant height; **PW** - plant width; **CTN** - cladodes total number; **CL** - cladode length; **CW** - cladode width; **CP** - cladode perimeter; **CT** - cladode thickness; **CA** - cladode area; **CAI** - cladode area index; **FMY** - Fresh matter yield; **DMY** - dry matter yield; **DMC** - dry matter yield. The dashed rectangles indicate the groups formed.

It was observed that PC2 was related to DMC, while FMY had a negative weight (Figure 3B). For this component, the rainfed regime (0% ETc) had a greater influence on DMY and FMY. This means that, when grown without complementary irrigation, the OEM clone tends to have a higher DMC than under irrigation conditions, while the FMY is reduced. The negative relationship between the production variables observed in this study differs from the results reported by Neder *et al*. (2013), whose research was carried out under a rainfed regime, verifying that DMC and FMY had a high association.

The controlled water deficit of 40% ETc was related to PC3. Considering the low contribution of PC3 (18%) to the total variability, the 40% ETc regime had little influence on the morphological or production characteristics of the OEM clone (Figure 3D). However, the negative relationship observed between DMC and CT (Figure 3C) may have occurred due to water conditions imposed by treatment with 40% ETc (347 mm via irrigation) (Figure 3D). In favorable conditions of soil moisture, the cladodes become thicker due to the amount of water present in the parenchyma (Liguori *et al*., 2013), which causes a decrease in the dry matter content of the cladode (Queiroz *et al*., 2015).

For the IPA clone, two components were responsible for 95% of the data variability, with PC1 and PC2 being responsible for 74% and 21%, respectively (Figure 4A). The morphological variables evaluated correlated with each other, with a positive weight in CP1, but showed a weak relationship with the production variables, which were shown to be correlated with each other, with a positive weight in CP2 (Figure 4A). The strong correlation between FMY and DMY shows that there is the possibility of selecting the IPA clone based on the production of fresh matter, with possible proportional gains in dry mass. A similar result was found by Neder *et al*. (2013) for *Opuntia ficus indica*.

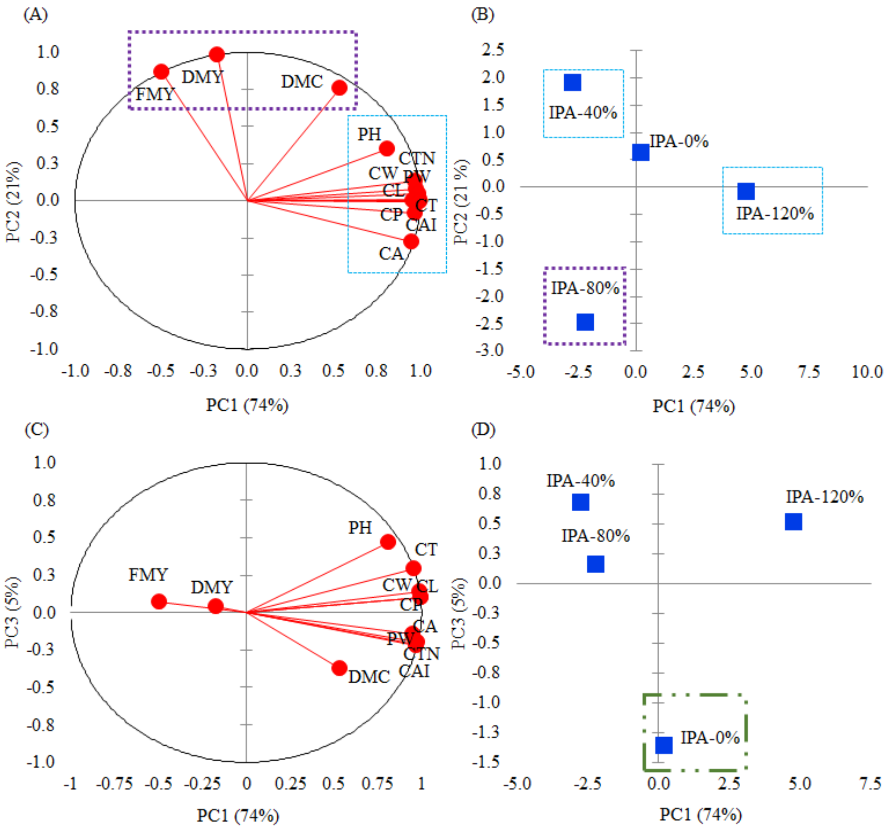

Figure 4. Principal component analysis **(PC)** of morphological and production variables in the IPA Sertânia clone (IPA), subjected to different controlled water deficit regimes based on a percentage of the crop evapotranspiration (ETc) (0%, 40%, 80% and 120% ETc). **(A)** eigenvectors and **(B)** eigenvalues of the first PC, and **(C)** eigenvectors and **(D)** eigenvalues of the second PC. Abbreviations: **PH** – plant height; **PW** – plant width; **CTN** – cladodes total number; **CL** – cladode length; **CW** – cladode width; **CP** – cladode perimeter; **CT** – cladode thickness; **CA** – cladode area; **CAI** – cladode area index; **FMY** – Fresh matter yield; **DMY** – dry matter yield; **DMC** – dry matter yield. The dashed rectangles indicate the groups formed.

It can be seen in Figure 4B that PC1 was formed by regimes of 40% ETc and 120% ETc, while PC2 by the regime of 80% only. This shows that the 40% ETc and 120% ETc regimes are mainly related to the growth characteristics of the plant, while the controlled water deficit of 80% ETc has a direct influence on the yield of the IPA clone. These effects may be associated with the presence of more available water, favoring greater development and the emission of cladodes (Arba *et al*. 2018). Although there is no strong association, the CTN influences the productivity of the forage cactus, mainly in the dry matter gain; a similar trend was observed by Neder *et al*. (2013). The 0%

ETc regime involved PC3, which in turn contributed little to the culture's morphological and production variables (Fig. 4 C, D).

Conclusions

The PCA revealed a strong association between the morphological variables and the productive variables of the cactus clones; however, this relationship depends on the species of cacti and the imposed water condition. Controlled water regimes influenced the relationship between the variables analyzed, mainly for the Miúda (*Nopalea cochenillifera* (L.) Salm-Dyck) and Orelha de Elefante Mexicana (*Opuntia stricta* (Haw.) Haw.) cacti. For these clones, the PCA showed that the dry matter gain and the variation of the dry matter content were the production variables most influenced by the morphological characteristics. On the other hand, the IPA Sertânia clones (*Nopalea cochenillifera* (L.) Salm-Dyck) showed no correlation between morphological and production variables, regardless of the water regime. However, the strong relationship observed between the production variables, mainly, the productivity of fresh matter with the productivity of dry matter, makes it possible to choose this clone based on its yield of fresh mass, with possible proportional gains in dry matter. The PCA showed a statistical alternative of easy practical use, which can be used to understand the growth dynamics of the plants and to identify the water conditions that act in the production of forage cactus clones, favoring, thus, a better management in the cultivation of this culture, and the increase of forage input in a semi-arid environment.

ETHICS STATEMENT

Not applicable

CONSENT FOR PUBLICATION

Not applicable

AVAILABILITY OF SUPPORTING DATA

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

COMPETING INTERESTS

The authors declare that they have no competing interests.

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AUTHOR CONTRIBUTIONS

Conceptualization, **Araújo Júnior, G.N.** and **Silva, T.G.F.**; methodology, **Araújo Júnior, G.N.** and **Silva, T.G.F.**; formal analysis, **Araújo Júnior, G.N., Souza, L.S.B., Silva, T.G.F.** and **Jardim, A.M.R.F.**; investigation, **Araújo Júnior, G.N., Silva, T.G.F., Jardim, A.M.R.F., Alves, C.P., Assis, M.C.S., Silva, J.O.N., Souza, C.A.A.** and **Pinheiro, A.G.**; resources, **Silva, T.G.F.**; data curation, **Araújo Júnior, G.N.** and **Silva, T.G.F.**; writing—original draft preparation, **Araújo Júnior, G.N.**; writing—review and editing, **Araújo Júnior, G.N., Silva, T.G.F., Souza, L.S.B.** and **Oliveira, A.C.**; visualization, **Silva, T.G.F.**; supervision, **Silva, T.G.F.** and **Souza, L.S.B.**; project administration, **Silva, T.G.F.**; funding acquisition, **Silva, T.G.F.**

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