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Yield and morphology of forage cactus cultivars under drip irrigation management based on soil water matric potential thresholds

Allan Radax Freitas Campos [a], Alisson Jadavi Pereira da Silva [b], Quirijn de Jong van Lier [c], Francisco Airdesson Lima do Nascimento [a], Rafael Dreux Miranda Fernandes [a,*], Jilcelio Nunes de Almeida [d], Vital Pedro da Silva Paz [a]

[a] Universidade Federal do Recôncavo da Bahia, Programa de Pós-Graduação em Engenharia Agrícola/Núcleo de Engenharia de Água e Solo, Cruz das Almas, BA, Brazil
[b] Instituto Federal de Educação, Ciência e Tecnologia Baiano, Campus Governador Mangabeira, Governador Mangabeira, BA, Brazil
[c] CENA/University of São Paulo, P.O. Box 96, 13416-900, Piracicaba, SP, Brazil
[d] Instituto Federal de Educação, Ciência e Tecnologia Baiano, Campus Senhor do Bonfim, Senhor do Bonfim, BA, Brazil

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ABSTRACT

The recent increase of irrigation practices in forage cactus crops makes appropriate irrigation management criteria necessary. In this study, the morphological and yield characteristics of forage cactus cultivars were evaluated for some soil-based irrigation management criteria. Five experiments were carried out simultaneously under semiarid conditions in a randomized block design, with forage cactus cultivars Orelha de Elefante (OE), IPA-Sertânia (IPA), Doce (DC), Gigante (GG), and Orelha de Onça (OO). For each cultivar, irrigation management was performed using four upper thresholds of matric potential (−0.2, −0.33, −1, and −3 atm), as well as a non-irrigated (rainfed) treatment. Forage cactus crop yield was evaluated after 12 months and responded positively and similarly to irrigation management using any of the thresholds, with a significant increase in the cladode area and, overall, a positive effect on growth and yield parameters. Very high irrigation water productivity up to 75 kg m^{-3} was obtained especially in the −3 atm threshold treatment, whereas an increase of the threshold potential caused a sharp reduction of water productivity. We conclude that irrigation management of forage cactus grown in semi-arid climates is highly beneficial and that unconventionally low matric potential thresholds may be used.

1. Introduction

Forage cactus (Opuntia spp. or Nopalea spp.) has morphophysiological adaptations that allow its growth and cultivation in areas with large water deficits. However, weather conditions, especially rainfall amount and distribution, highly affect cactus growth and yield (Consoli et al., 2013). When submitted to long periods of drought, physiological alterations of the cactus occur like reduced cladode photosynthesis due to a decrease in water content, reduced parenchyma thickness, and a loss of chlorophyll (Scalisi et al., 2016). This makes irrigation of cactus beneficial in regions prone to dry-spells (Flores-Hernández et al., 2004).

Irrigation management affects crop performance and may lead to qualitative and quantitative improvements in forage cactus production. Some recent studies focused on irrigation management optimization by direct measurements of the soil water status (Contreras et al., 2017; Létourneau et al., 2015). When irrigated, the yield of forage cactus becomes less dependent on the growing period and seasons, and one-year yields may be higher than the two-years yield obtained by Cavalcante et al. (2014) and Silva et al. (2015) under rainfed conditions.

Irrigation management aims at maintaining the soil water status within a range ideal for crop development which is usually defined by an upper and lower threshold of matric potential (Nolz et al., 2016). For common annual crops, these upper and lower thresholds are generally defined based on crop water availability. The upper threshold (target of irrigation) is considered to be the field capacity, corresponding to matric potentials between −0.06 atm and −0.33 atm (de Jong van Lier, 2017) and the lower threshold (triggering irrigation) is considered somewhere between −0.35 atm and −0.75 atm (Contreras et al., 2017; Létourneau

* Corresponding author.
E-mail addresses: allanradax@hotmail.com (A.R. Freitas Campos), alissonagr@gmail.com (A.J. Pereira da Silva), qdjvlier@usp.br (Q. de Jong van Lier), airdessonpai@hotmail.com (F.A. Lima do Nascimento), rafadreux@gmail.com (R.D. Miranda Fernandes), jilcelioalmeida@gmail.com (J. Nunes de Almeida), vpspaz@gmail.com (V. Pedro da Silva Paz).

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et al., 2015; Wang et al., 2007). However, for forage cactus with morphophysiological characteristics allowing its development under adversely dry conditions, no recommendations exist for the upper and lower matric potential thresholds.

Given the benefits of the irrigation of forage cactus and its special adaptations to dry conditions, we aimed to evaluate the sensitivity of crop traits and yield of forage cactus to different upper thresholds of matric potential in irrigation management. This information is not readily available and may be of help to improve irrigation strategies for this regionally important crop.

2. Material and methods

2.1. Experimental field

An experiment with forage cactus was conducted at the experimental fields of the Federal Institute Baiano (IFBaiano), Senhor do Bonfim campus, State of Bahia, Brazil, geographical coordinates 10°28′46″ S, 40°11′27″ W, at 520 m above sea level. Local average annual rainfall is 650 mm. The soil of the area is classified as a Yellow Red Latosol according to INEMA (2012), with 22.3% clay, 7.9% silt, and 69.8% sand (sandy clay texture). The experimental period covered the first cropping cycle of the forage cactus, with a duration of one year (September 2016 to August 2017).

The study consisted of five simultaneous experiments in a randomized complete block design with four replications. The total area of 1200 m^2 was divided into five plots of 240 m^2 each, one for each experiment. Interrow spacing was 1.0 m, and the distance between cactus plants in a row was 0.5 m, corresponding to a plant density of 20,000 ha^{-1}. In all the experiments, the sources of variation and variable responses were the same, and the only factor of variation was the cultivar. The five studied cultivars were (1) Orelha de Elefante Mexicana (OE), a cultivar of *Opuntia stricta;* (2) IPA-Sertânia (IPA) and (3) Doce (DC), cultivars of *Nopalea cochenillifera* SalmDyck; (4) Gigante (GG) and (5) Orelha de Onça (OO), cultivars of *Opuntia ficus-indica* L. (Mill.). It was not our goal to compare the cultivars, but to evaluate the performance of soil-based irrigation management concerning cactus growth and yield using different upper irrigation threshold matric potentials. For each cultivar, five irrigation management treatments were applied: a control treatment under rainfed conditions and four irrigated treatments with respective upper irrigation thresholds of −0.2 atm, −0.33 atm, −1 atm, and −3 atm.

The area was prepared by mechanized plowing and harrowing. Subsequently, lime and fertilizers were applied based on the soil chemical analysis (Table 1). The amount of 50-60-50 kg ha^{-1} of NPK mineral fertilizer was applied in the form of urea, simple superphosphate, and potassium chloride, following regional recommendations by Dubeux et al. (2006).

Undisturbed soil samples were collected at the depths of 0.15 and 0.45 m at five random locations in each experimental area to determine the soil water retention curve (Table 2). The stepwise outflow method using a pressure chamber with a porous plate was used to measure the water content θ at specific values of matric potential (Table 2). The soil water retention curve was described fitting the Van Genuchten (1980) equation to the measured data.

Table 2
Soil water contents at specific values of matric potential Ψ_m at two depths in the soil from the experimental area.

Depth (m)	Water content (cm^3 cm^{-3})				
	Ψ_m −0.1 atm	Ψ_m −0.33 atm	Ψ_m −1 atm	Ψ_m −3 atm	Ψ_m −15 atm
0.15	0.191	0.135	0.118	0.112	0.110
0.45	0.186	0.145	0.128	0.114	0.108

2.2. Soil-water monitoring and measurement

In each experimental plot (5 cultivars) and each irrigation treatment (rainfed + 4 thresholds), the water content near three cactus plants was monitored at 0.15 and 0.45 m depth using TDR probes installed at 0.2 m from the plant center. The TDR probes were previously calibrated based on the measured apparent dielectric constant of the soil (Ka) and soil water contents (θ) obtained simultaneously by oven drying and weighing. The obtained calibration equation was:

$$\theta = 0.00005Ka^3 - 0.0026Ka^2 + 0.0504Ka - 0.2604 \; ; \; R^2 = 0.99 \qquad (1)$$

TDR readings were obtained every 3 days to calculate if and how much water was to be applied. During the experimental year, 10,950 values of θ (3 plants/treatment x 2 sensors/plant x 5 treatments x 5 cultivars x 73 reading dates) were obtained. The volume of water to be irrigated (I_v, m^3) to return the soil to the threshold water content $\theta_{threshold}$ was calculated according to equation (2):

$$I_V = \left(\theta_{threshold} - \overline{\theta}_{actual}\right) \frac{\pi \;\; {d_w}^2 z_e}{4E} \qquad (2)$$

In this equation, $\overline{\theta}_{actual}$ is the mean soil water content obtained from TDR readings, d_w (m) represents the wet-bulb diameter (0.5 m in the present experiment), z_e (m) is the effective rooting depth (we used 0.45 m) end E is the irrigation system efficiency, considered equal to 0.95. The threshold water content $\theta_{threshold}$ was calculated for each of the applied threshold matric potentials (−0.2, −0.33, −1 and −3 atm) using the fitted Van Genuchten (1980) equation, yielding 0.155, 0.137, 0.119, and 0.113 m^3 m^{-3}, respectively.

Drip irrigation was performed using one self-compensating online dripper per plant with a flow rate of 2.3 L/h. The system operated at a pressure of 1.0 atm, resulting in an average coefficient of uniformity of 92%. The irrigation water was obtained from a nearby rainwater capture and storage system.

2.3. Crop growth measurements

In the 5 × 5 x 3 = 75 cactus plants with TDR sensor monitoring, a monthly measurement of the cladode length, width, and thickness, number of cladodes, plant height, and plant width was made. The cladode area for each cultivar was estimated using the mathematical models proposed by Silva et al. (2014) for cultivars OE, IPA, and DC. For cultivars GG and OO, the model proposed by Cortázar and Nobel (1991) was used. The area of cladodes per plant was obtained by multiplying the cladode area by the number of cladodes per plant.

At the end of the experimental period (365 days after planting), harvest consisted of removing all cladodes of each plot, leaving only the basal cladode in the field. The cladodes were cut at the junction between themselves so as not to cause damage to the basal part. The harvested

Table 1
Chemical attributes of the studied soil, municipality of Senhor do Bonfim, Bahia, Brazil. (BC = Base Cations; CEC = Cation Exchange Capacity; V = Base saturation; OM = Organic Matter content).

pH	P	K	Ca+Mg	Al	H+Al	Na	BC	CEC	V	OM
1:2.5	mg/dm^3		$cmol_c/dm^3$						%	g/kg
5.41	20	60	2.40	1.90	2.40	0.15	2.70	5.10	52.94	1.07

cladodes were weighed to determine the green mass (GM) per plant. The GM per cladode was obtained dividing GM by the number of cladodes per plant. GM yield (kg ha^{-1}) was estimated by the product of GM per plant and the number of plants per hectare according to the planting density.

After determining the GM per cladode, they were sliced and representative samples of 1 kg per plant were collected. The samples were submitted to pre-drying in the open-air followed by a forced air circulation oven at 55 °C until reaching constant weight, and subsequently, they were taken to a forced-air circulation oven at 105 °C for the calculation of the DM fraction. DM yield was obtained by multiplying GM yield by DM fraction.

2.4. Statistical analyses

All variables were submitted to analysis of variance, and a comparison of means was performed using the Tukey test at a 5% significance level.

3. Results and discussion

The total observed rainfall during the experimental year was 345 mm, with higher amounts during the last three months. The rainfall amount during these months was sufficient to maintain the matric potential above the upper threshold of the −3 atm and −1 atm treatments (Fig. 1), and irrigation was not necessary for these treatments in this period.

The average total irrigation depth applied to the forage cactus cultivars was 326 mm, 237 mm, 94 mm, and 52 mm respectively for irrigation treatments with the upper threshold of −0.2 atm, −0.33 atm, −1 atm, and −3 atm. The corresponding amounts of water applied by drip irrigation to each of the cultivars are listed in Table 3.

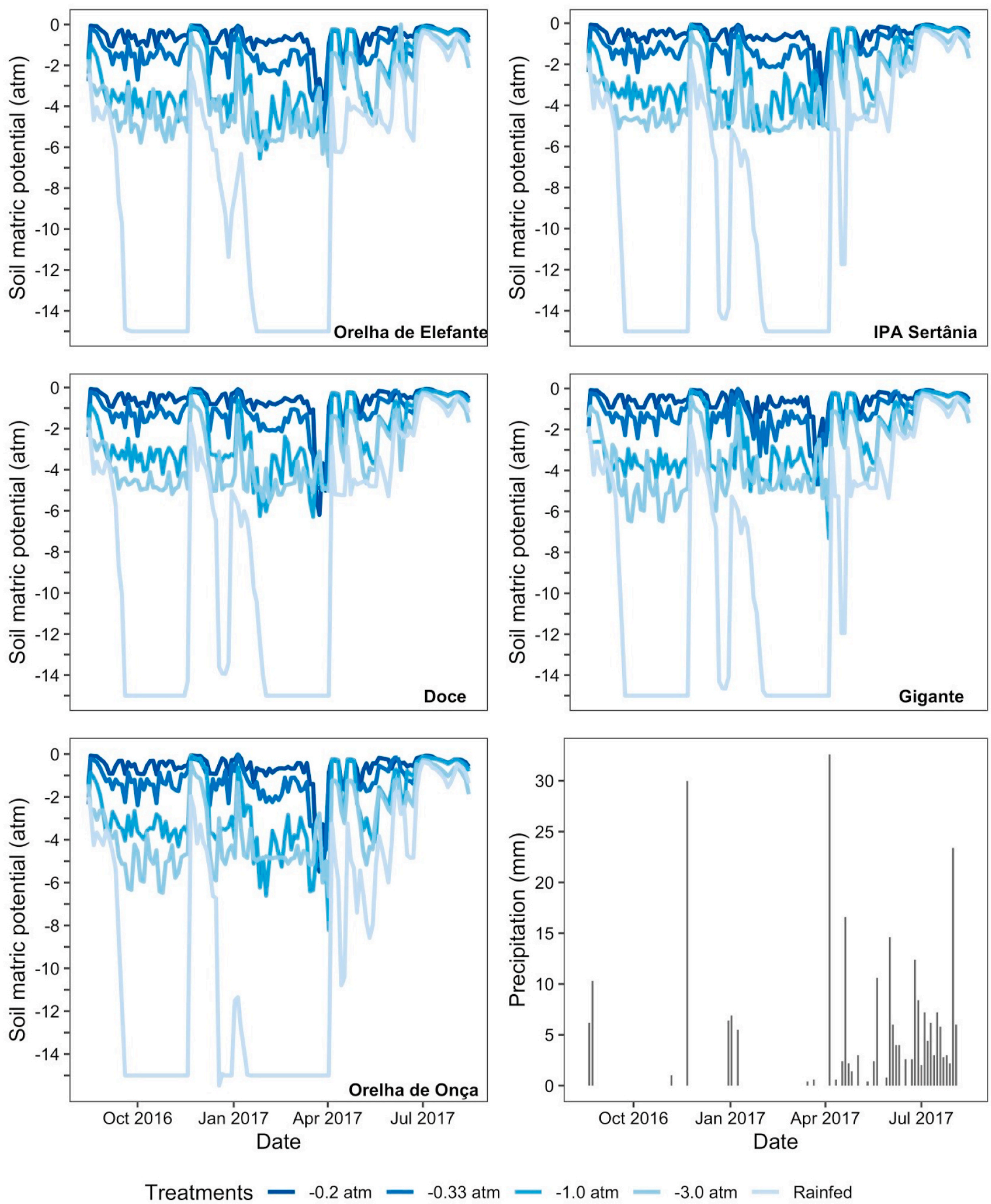

Fig. 1. Matric potential measured shortly before irrigation and rainfall events during the experimental period in the semi-arid region of Bahia, Brazil.

Table 3
Total volume of water applied by drip irrigation to each of the cultivars during the experimental period.

Irrigation treatment	Orelha de Elefante (OE)	IPA Sertânia (IPA)	Doce (DC)	Gigante (GG)	Orelha de Onça (OO)
	$m^3\ ha^{-1}$				
−3 atm	220.9	190.4	180.7	225.5	222.6
−1 atm	387.1	362.3	374.8	382.7	373.2
−0.33 atm	966.0	942.0	964.7	956.2	911.1
−0.2 atm	1251.6	1324.9	1315.5	1350.7	1277.4

The average lower matric potential thresholds measured in the dry period, shortly before the irrigation events, were about −0.75 atm, −1.5 atm, −3.5 atm, and −5.0 atm, respectively for the upper thresholds of −0.2 atm, −0.33 atm, −1 atm and −3 atm (Fig. 1). These lower thresholds are well below those recommended for other common crops, usually in the range between −0.35 atm and −0.75 atm (Contreras et al., 2017; Jong van Lier, 2017; Létourneau et al., 2015; Nolz et al., 2016; Wang et al., 2007).

Forage cactus growth was significantly influenced ($p < 0.05$) by the irrigation treatments (Table 4). The average plant width in the four irrigated treatments was not statistically different but it was significantly higher than under rainfed conditions. The plants in the rainfed treatment suffered from two long periods (63 and 85 days) without rain. In these periods, the matric potential measured under rainfed conditions fell below −10 atm (Fig. 1). Long dry spells like these, of the order of two to three months, are reported to negatively affect the physiology of forage cactus plants, including a reduction in photosynthesis rate, nighttime stomatal closure, accumulation of malic acid, and reduced water content of the parenchyma and the chlorenchyma, resulting in a decrease of the cladode size (Pimienta-Barrios et al., 2007; Scalisi et al., 2016). In our experiments, negative effects on the biometric dimensions were observed in all cultivars under rainfed conditions (Figs. 2–4).

Table 4
Average height, width and number of cladodes per plant of five forage cactus cultivars (OE, IPA, DC, GG and OO), rainfed and under irrigation treatments with four different upper thresholds of matric potential in the semi-arid region of Bahia, Brazil, August 2017.

Variable	CV (%)	Irrigation treatment				
		Rainfed (control)	−3 atm	−1 atm	−0.33 atm	−0.2 atm
ORELHA DE ELEFANTE (OE)						
Height (cm)	19.35	44.49 a[a]	48.12 a	49.96 a	55.66 a	54.00 a
Width (cm)	20.12	58.83 a	70.58 b	72.16 b	75.66 b	71.58 b
Cladodes/plant	20.94	4.67a	8.20b	8.60b	8.80b	9.54b
IPA Sertânia (IPA)						
Height (cm)	16.36	38.75 a	45.61 ab	46.16 ab	59.58 c	52.58 bc
Width (cm)	20.36	34.91 a	62.91 b	64.58 b	71.83 b	78.91 b
Cladodes/plant	20.74	3.83	11.58	11.33	13.17	13.07
DOCE (DC)						
Height (cm)	17.65	33.16 a	44.45 b	45.00 b	48.50 b	52.58 b
Width (cm)	18.57	44.25 a	71.33 b	68.16 b	74.91 b	78.91 b
Cladodes/plant	15.14	8.92a	18.92b	19.33b	21.42b	21.01b
GIGANTE (GG)						
Height (cm)	11.23	33.16 a	44.45 b	45.00 b	48.50 b	52.58 b
Width (cm)	12.36	44.25 a	71.33 b	68.16 b	74.91 b	78.91 b
Cladodes/plant	18.91	4.26a	10.04b	10.38b	10.76b	10.62b
ORELHA DE ONÇA (OO)						
Height (cm)	21.63	28.50 a	45.00 b	45.08 b	47.25 b	50.58 b
Width (cm)	22.36	42.33 a	68.66 b	69.41 b	76.25 b	78.08 b
Cladodes/plant	19.89	3.83a	7.75b	8.00b	9.33b	9.17b

[a] Means followed by the same letter in the row do not differ by the Tukey test at a 5% significance level.

Only cultivar OE showed no significant difference in height between treatments (Table 4). Specific growth characteristics of this cultivar, that presents the longest Phenophase I and more frequent sprouting of primary cladodes (Amorim et al., 2017) may have caused this insensitivity of height to irrigation.

From the fourth month (or 7th month for cultivar OE), the irrigated plants showed a significant increase of the number of cladodes (Fig. 2). All cultivars, even when irrigated using a very low upper matric potential threshold of −3 atm, presented an increase in the number of cladodes per plant when compared to those rainfed.

Under rainfed conditions, the number of cladodes per plant remained lower than under irrigation, although it increased at the beginning of the rainy season (Fig. 2). Irrespective of the upper threshold, the irrigated plants yielded about twice (cultivar DC even thrice) as many cladodes as those rainfed by the end of the 12-month growing season. Under drought stress, forage cactus reduces metabolic activities and suppresses the appearance of new cladodes. The number of cladodes per plant obtained in our study is consistent with observations by Queiroz et al. (2015) who studied the effect of irrigation on morphophysiological characteristics and productivity of forage cactus. They observed an increase in the number of cladodes with increasing irrigation depths. In our experiment, the differences in average cladode area were significant from the second month of evaluation for the five cultivars under study (Fig. 3).

Comparing the average cladode area per plant (Fig. 3), irrigated plants showed higher and always increasing values during the entire 1-yr crop cycle, whereas the rainfed plants showed a decreasing cladode area during the dry period. This reduction is caused by a loss of water from parenchyma and chlorenchyma cells to the atmosphere, reducing cladode turgidity, width, and length. Long periods of drought caused a decline in cladode growth, a change in coloration, and wrinkling. Some plants presented abscission of cladodes or mortality with a direct impact on crop yield. Such symptoms were observed visually and are similar to observations by Cushman et al. (2015), Nobel and Bobich (2002), and Scalisi et al. (2016).

Although plant growth under non-irrigated conditions resumed at the onset of the rainy season, the mean cladode area per plant remained higher in the irrigated treatments until the last month. These observations make it clear that irrigation positively affects forage cactus growth, even with the lowest upper threshold. Hence, the classical values of field capacity as the upper threshold for irrigation management do not apply to forage cactus management. The crop responded similarly to upper thresholds of −0.2 atm and −3 atm, showing its high adaptation to drought.

An increase in the cladode area per plant was observed from month 4 for cultivars DC and OE, and from month 6 for the other cultivars (Fig. 3). During this development stage, a change in the phenophase of forage cactus plants occurs, characterized by sprouting and growth of secondary and tertiary cladodes, leading to a large increase in cladode area per plant.

The cladode thickness (CT) was significantly higher in the irrigated plants than rainfed but did not significantly differ between the irrigated treatments (Fig. 4). CT was about 10 mm higher in the irrigated plants than in those rainfed, with a somewhat lower difference for OE cultivar. Turgidity of the forage cactus is measured by CT which is directly related to the water status of the plant (Consoli et al., 2013; Cushman et al., 2015; Silva et al., 2005a). In the rainfed treatment, CT varied with soil water status (Fig. 1) between the third and the seventh months of cultivation (Fig. 4). This variation was due to the natural wilting process in which the thickness of the cladodes decreased due to the loss of water to the atmosphere. Although it is a species with CAM photosynthesis that closes stomata during the daytime to avoid water loss to the dry

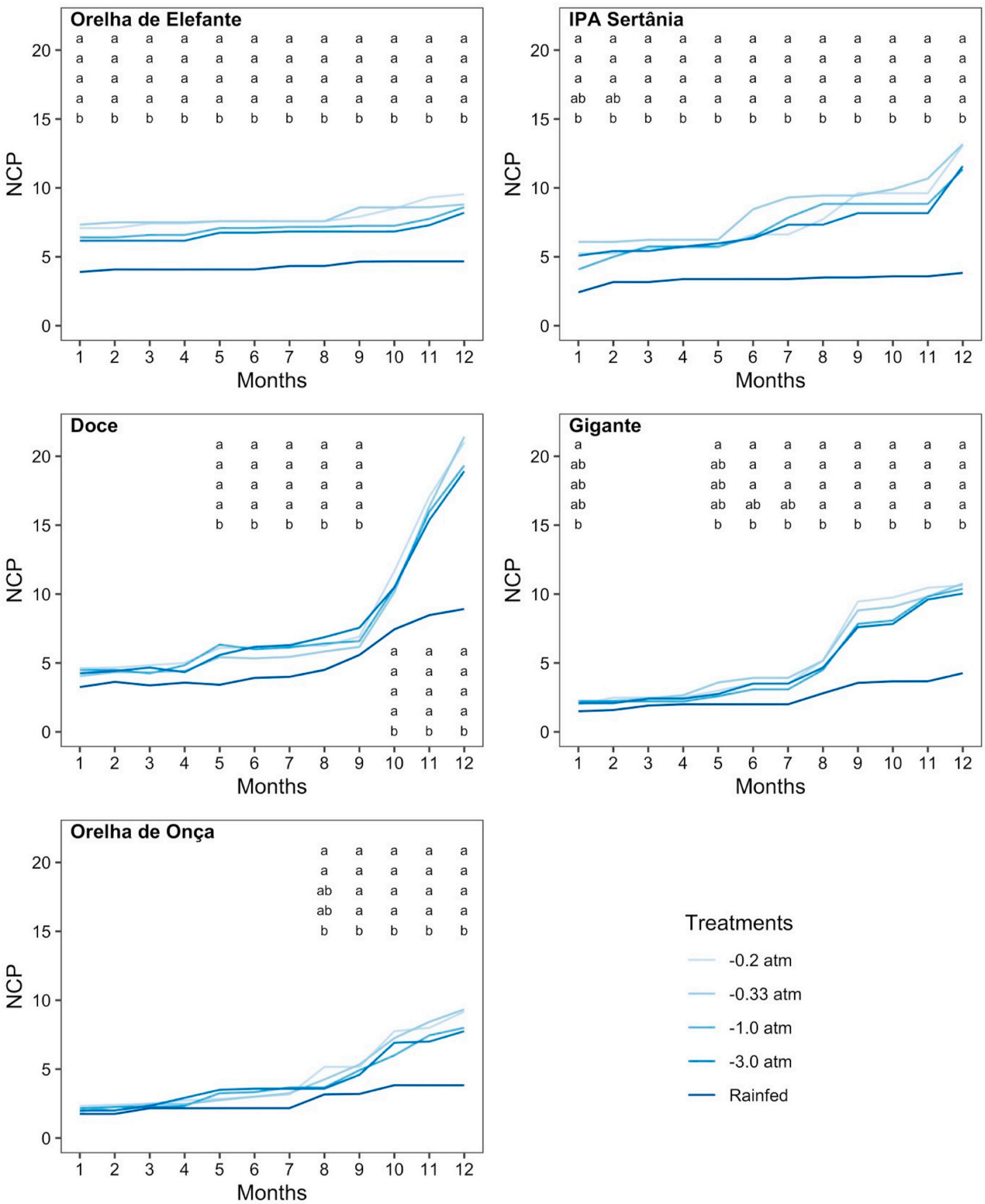

Fig. 2. Average number of cladodes per plant (NCP) during the experimental period (month 1 = August 2016) for the five forage cactus cultivars (OE, IPA, DC, GG and OO). The same letter indicates no significant difference in values for the respective month by the Tukey test at 5% significance.

atmosphere and opens stomata during the night at low water vapor pressure deficit, some water is lost and physiological activity enters into latency when a critical water status is reached (Nobel and Bobich, 2002; Cushman et al., 2015).

Fig. 4 shows the rapid responses of CT to the increase in soil water content of the plants under rainfed conditions. At the first occurrence of significant rainfall events after a dry period, rainfed plants show a rapid increase in CT. Variations in CT are related to the water status of the forage cactus crop which rehydrates quickly after long periods of drought (Scalisi et al., 2016). Despite the increase in CT at the onset of rainfall in the seventh month, for all cultivars the it remained lower than in the irrigated plants. The mean CT for irrigated plants are close to those observed by Queiroz et al. (2015) and Pereira et al. (2015) with the use of drip irrigation under semi-arid conditions.

The mean growth parameters for the irrigated treatments (Figs. 2–4) are higher than observed by Flores-Hernández et al. (2004) and Queiroz et al. (2015) who applied irrigation management based on reference evapotranspiration. Variables GM per plant, GM per hectare, DM percentage, DM per plant, and DM per hectare were significantly influenced by irrigation (Table 5). The GM of cladode presented a significant difference only for OE and GG cultivars, with irrigated means about 60% higher than rainfed.

The cultivars showed a higher GM per plant under irrigation than rainfed (Table 5). The greatest GM yield for the cultivars was verified using matric potential thresholds of −1 atm or higher, but even when irrigated with the lowest −3 atm matric potential threshold, GM was more than twice as high than under rainfed conditions. The threshold of −3 atm corresponds to about 200 m^3 ha^{-1} y^{-1} of irrigation, much less than the approximately 370 m^3 ha^{-1} y^{-1} needed for the threshold of −1 atm (Table 3). The water productivity of irrigation WP_I (kg m^{-3}) allows

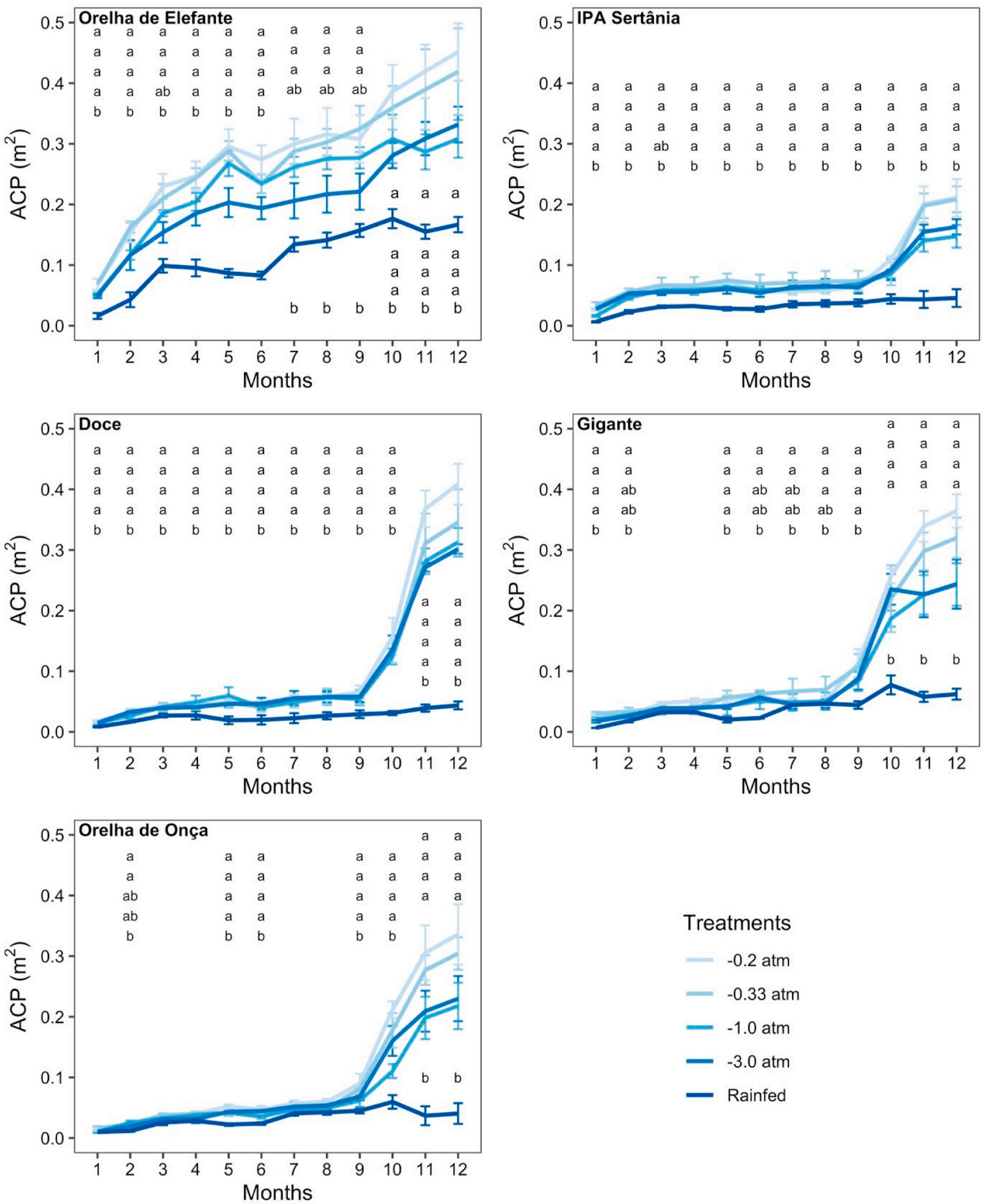

Fig. 3. Average cladode area per plant (ACP) during the experimental period (month 1 = August 2016) for the five forage cactus cultivars (OE, IPA, DC, GG and OO). The same letter indicates no significant difference in values for the respective month by the Tukey test at 5% significance.

evaluating the gain in dry matter production per volume of irrigation water. It is calculated based on irrigated dry matter yield (DM_I, kg ha^{-1}), rainfed dry matter yield (DM_0, kg ha^{-1}), and applied volume of irrigation water V_I (m^3 ha^{-1}) according to equation (3):

$$WP_I = \frac{DM_I - DM_0}{V_I} \quad (3)$$

Table 5 shows values of WP_I obtained in our experiment based on the values of V_I from Table 3. WP_I increases from irrigation thresholds of −3 to −0.2 atm showing that, depending on the cultivar, between 23 (Orelha da Onça) and more than 75 (Gigante) kg of dry matter are produced per m^3 of water applied in the −3 atm threshold treatment. Conventionally high threshold potentials of −0.2 atm, although leading to an increased yield, have a much lower gain of dry matter production per volume of irrigation water (of the order of 4–12 kg m^{-3}, depending on the cultivar). Cultivars IPA and OO, when managed with a matric potential threshold higher than −3 atm showed average GM yields of 254 and 182 Mg ha^{-1}, about 4 and 2.5 times higher than the non-irrigated plants. Cultivars OE, DC, and GG had the best performance with irrigation management under matric potential thresholds between −1 and −0.2 atm (Table 5). Nevertheless, even with the upper threshold of −3 atm their yield significantly exceeded the plants of the control treatment.

The GM per plant and the yield (GM ha^{-1}) found in the present study for irrigated forage cactus crops support the results found by Rocha et al. (2017) who evaluated the productive and structural characteristics of forage cactus genotypes at different cutting intervals. However, our values are higher than those reported by Silva et al. (2015) for clones of forage cactus (OE, IPA, DC) two years after planting, grown under rainfed conditions. Our study shows that unconventional upper matric

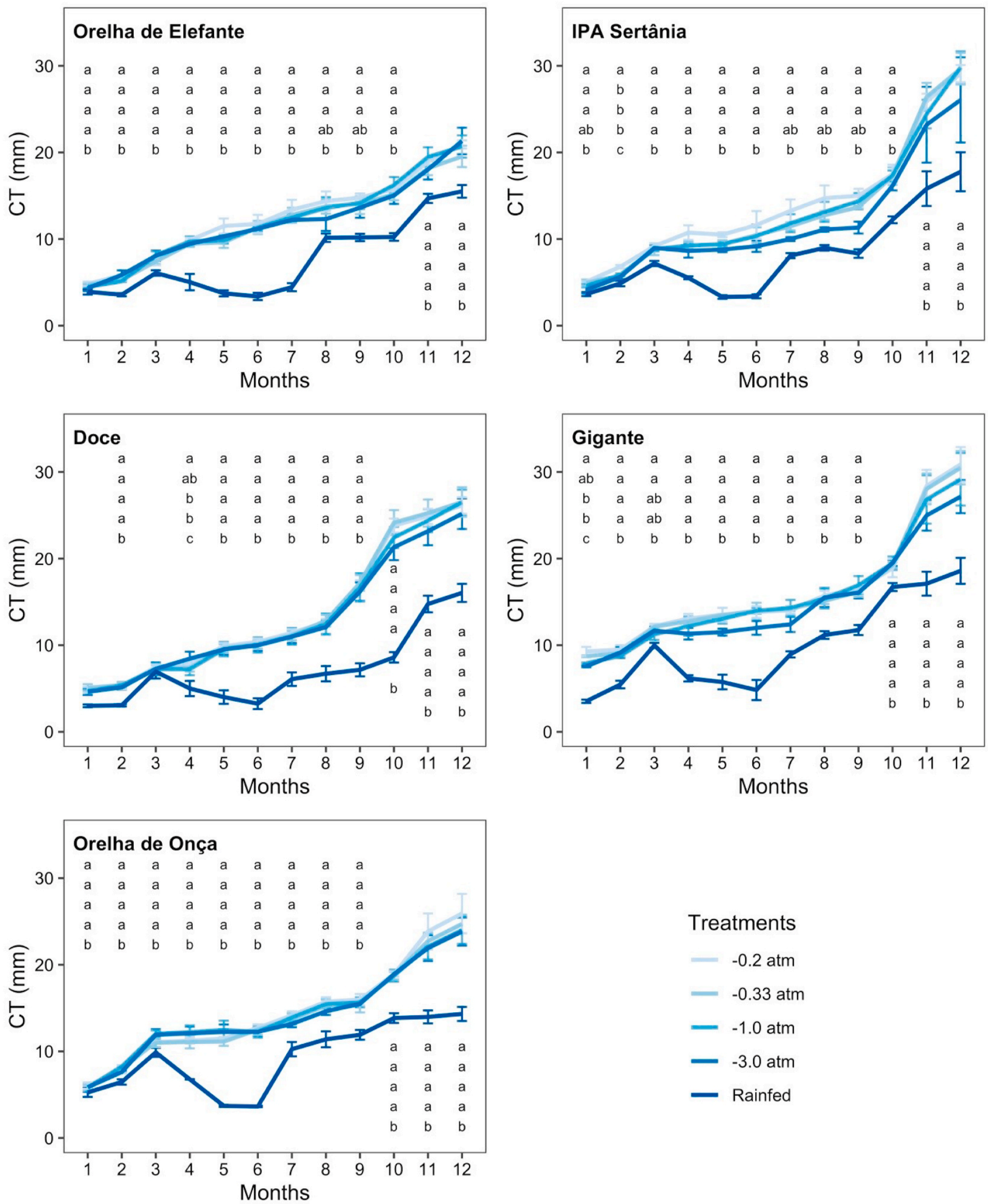

Fig. 4. Average cladode thickness (CT) during the experimental period (month 1 = August 2016) for the five forage cactus cultivars (OE, IPA, DC, GG and OO). The same letter indicates no significant difference in values for the respective month by the Tukey test at 5% significance.

potential thresholds of −1 and −3 atm can be adopted as a water-saving form of irrigation management with a significantly positive effect on the growth and yield of forage cactus crops and resulting in a very high water use efficiency.

Dry matter contents were reduced under irrigation as a result of the greater degree of turgidity. Similar results were found by Consoli et al. (2013). Nevertheless, the production of dry mass (DM) per hectare was highly correlated to GM per hectare. The observed values are in agreement with Scalisi et al. (2016), who investigated the effect of soil water deficit and temperature on daily cladode growth mechanisms and observed that under high water stress the cladode growth rate, the relative water content, and physiological factors of cactus forage crops were adversely affected.

4. Conclusions

1. Forage cactus irrigation management using upper thresholds of matric potential equal to or greater than −3 atm resulted in increased productivity (plant width, number of cladodes per plant, cladode thickness, and green and dry mass per hectare).
2. The classical values of field capacity (usually of the order of −0.1 atm), used as upper threshold (target) in irrigation management, do not apply to forage cactus management, which gave similar yields for any upper threshold between −0.2 atm and −3 atm.
3. High irrigation water productivity (between 23 and 75 kg of dry matter per m^3 of irrigation water, depending on the cultivar) was obtained in the −3 atm threshold treatment. Conventionally high threshold potentials of −0.2 atm showed much lower irrigation

Table 5
Average GM per cladode and per plant, green mass (GM) and dry mass (DM) yield per ha, DM content (%) and irrigation water productivity (WP_I) of five cultivars of forage cactus (OE, IPA, DC, GG and OO) submitted to different upper thresholds of matric potential and under rainfed conditions in the semi-arid region of Bahia, Brazil.

Irrigation treatment	GM per cladode (kg)	GM per plant (kg)	GM (Mg ha^{-1})	DM content (%)	DM (Mg ha^{-1})	WP_I (kg m^{-3})
Orelha de Elefante (OE)						
Rainfed (control)	1.033 a	4.787 a	95.741 a	9.97 b	9.545 a	
−3 atm	1.497 b	12.275 b	245.500 b	8.30 a	20.376 b	49.0
−1 atm	1.740 b	14.964 c	299.280 c	8.22 a	24.600 c	38.9
−0.33 atm	1.840 b	16.192 c	323.840 c	8.12 a	26.200 c	17.2
−0.2 atm	1.637 b	15.632 c	312.640 c	8.05 a	25.167 c	12.5
IPA Sertânia (IPA)						
Rainfed (control)	0.840	3.217 a	64.340 a	9.70 b	6.240 a	
−3 atm	1.080	12.506 b	250.120 b	7.47 a	18.683 b	65.4
−1 atm	1.075	12.179 b	243.580 b	7.99 a	19.462 b	36.5
−0.33 atm	1.034	13.617 b	272.340 b	8.24 a	22.440 b	17.2
−0.2 atm	0.902	12.447 b	248.940 b	8.25 a	20.537 b	10.8
Doce (DC)						
Rainfed (control)	0.232	2.069 a	41.388 a	9.73 b	4.200 a	
−3 atm	0.335	6.338 b	126.760 b	8.60 ab	10.901 b	37.1
−1 atm	0.400	7.732 c	154.640 c	8.30 a	12.820 c	23.0
−0.33 atm	0.377	8.075 c	161.500 c	8.40 a	13.566 c	9.7
−0.2 atm	0.400	8.404 c	168.080 c	8.13 a	13.664 c	7.2
Gigante (GG)						
Rainfed (control)	0.970 a	4.132 a	82.644 a	10.48 b	8.661 a	
−3 atm	1.497 b	15.029 b	300.580 b	8.52 a	25.609 b	75.2
−1 atm	1.682 b	17.324 c	346.480 c	8.20 a	28.441 c	51.7
−0.33 atm	1.590 b	17.108 c	342.168 c	8.30 a	28.399 c	20.6
−0.2 atm	1.543 b	16.386 c	327.732 c	8.21 a	26.906 bc	13.5
Orelha de Onça (OO)						
Rainfed (control)	0.888	3.401 a	68.020 a	7.43 b	5.053 a	
−3 atm	1.072	8.308 b	166.160 b	6.20 a	10.301 b	23.6
−1 atm	1.107	8.856 b	177.120 b	6.03 a	10.680 b	15.1
−0.33 atm	1.175	9.962 b	219.240 b	6.20 a	13.592 b	9.4
−0.2 atm	0.903	8.280 b	165.610 b	6.38 ab	10.565 b	4.3

Means followed by the same letters in the column do not differ from each other by the Tukey test at a 5% significance level.

water productivities of the order of 4–12 kg m^{-3}, depending on the cultivar.

4. Cultivars Orelha de Elefante, Doce, and Gigante responded slightly better to an upper threshold of matric potential of −1 atm than to −3 atm. For cultivars IPA Sertânia and Orelha de Onça, the yield using an upper threshold matric potential of −3 atm was the same as for higher thresholds.

CRediT authorship contribution statement

Allan Radax Freitas Campos: Conceptualization, Investigation, Data curation, Writing – original draft. **Alisson Jadavi Pereira da Silva:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Quirijn de Jong van Lier:** Writing – review & editing, Supervision. **Francisco Airdesson Lima do Nascimento:** Investigation, Data curation, Methodology. **Rafael Dreux Miranda Fernandes:** Visualization, Writing – original draft. **Jilcelio Nunes de Almeida:** Conceptualization, Writing – original draft, Supervision. **Vital Pedro da Silva Paz:** Writing – original draft, Supervision, Project administration.

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.

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