Acta Scientiarum. Agronomy
ISSN: 1807-8621
Editora da Universidade Estadual de Maringá - EDUEM

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Acta Scientiarum. Agronomy, vol. 44, e53016, 2022
Editora da Universidade Estadual de Maringá - EDUEM

DOI: https://doi.org/10.4025/actasciagron.v44i1.53016

Acta Scientiarum
http://periodicos.uem.br/ojs
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v44i1.53016

CROP PRODUCTION

Forage yield and structural responses of spineless cactus '*Orelha de Elefante Mexicana*' at different planting densities

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ABSTRACT. The objective was to evaluate the forage yield and structural responses of spineless cactus '*Orelha de Elefante Mexicana*' (OEM) (*Opuntia stricta* (Haw.) Haw) at different planting densities. The experimental design was a randomized block with five treatments and four replicates, during two production cycles of 12 months each. The evaluated densities were 20,000; 25,000; 33,333; 50,000; and 100,000 plants ha^{-1}. The increase in planting density caused a linear reduction in plant height, width, and mass, as well as in number of primary, secondary, tertiary, and overall cladodes. It also caused a linear increase in cladode area index, dry and green yield, water use efficiency, and forage accumulation rate. The increase in planting density promoted a quadratic effect on cladode thickness and dry matter content. Cladode thickness decreased with planting densities up to 47,500 plants ha^{-1} and increased from this point onwards. As for dry matter content, there was an increase up to the planting density of 61,428 plants ha^{-1} and a decrease from this point onwards. The increase in planting density of spineless cactus '*Orelha de Elefante Mexicana*' caused changes in structural responses and in forage yield. The use of greater planting densities increased forage yield.

Keywords: cropping density; forage; *Opuntia stricta* (Haw.) Haw; semi-arid.

Received on April 6, 2020.
Accepted on July 21, 2020.

Introduction

Spineless cactus (*Opuntia* sp. and *Nopalea* sp.) is an important forage crop for the Brazilian semi-arid region (Lédo et al., 2019; Mendoza et al., 2019) and widely used in the feeding of ruminants (Nogueira, Voltolini, Moreira, Lopes Júnior, & Oliveira, 2011; Knupp et al., 2019).

Some Brazilian semi-arid areas have restrictions to the cultivation of spineless cactus (Bezerra, Araújo, Pereira, Laurentino, & Silva, 2014; Souza et al., 2018). In the last years, the use of spineless cactus '*Orelha de Elefante Mexicana*' (OEM) (*Opuntia stricta* (Haw.) Haw) has been disseminated in livestock systems in the Brazilian Semi-arid region. Furthermore, additional applications of irrigation water and high-density planting of spineless cacti have also increased especially in drier regions (Rocha, Voltolini, & Gava, 2017).

According to Lima et al. (2016) and Rocha et al. (2017), irrigation water supply can promote changes in spineless cactus growth when compared to rainfed condition, which demands new management strategies for irrigated forage cacti, mainly in terms of planting density to increase forage yield. Despite its importance, the planting density of OEM under water supplementation has not been established yet.

A proper management system can increase plant yield and forage quality. For spineless cactus, planting density is an important component of management (Silva et al., 2016). Silva et al. (2014) evaluated the forage yield of Miuda, Gigante, and Redonda spineless cacti at different planting densities (10,000; 20,000; 40,000; and 80,000 plants ha^{-1}) and reported higher forage production at higher densities. Similarly, Cavalcante, Santos, Silva, Fagundes, and Silva (2014) reported larger forage yield and total digestible nutrients for spineless cactus genotypes (Miuda, Gigante and Redonda) at larger cropping densities.

Plant spacing can interfere with sunlight interception and hence OEM photosynthetic efficiency, as light is an important factor for carbohydrate biosynthesis. Therefore, photosynthetic efficiency can interfere directly with cactus development and yield (Cavalcante et al., 2014). Furthermore, higher crop densities may increase competition for water, light, and nutrients, affecting plant morphological traits, growth, and yield

(Dubeux Jr. et al., 2006). A low cladode area index (CAI), which is a parameter related to the photosynthesis capacity of spineless cactus, may be partially mitigated by increasing planting density (Lira et al., 2009).

A less dense planting is important for pest control and facilitates cultivation (Cavalcante et al., 2014). Under environments without water and nutrient restrictions, plant population density increases can raise productivity due to a larger number of plants per area (Silva et al., 2014).

Despite the advances in science regarding the management of spineless cactus and its influence on morphological characteristics and productive responses, studies on the crop spacing and planting density of OEM plants under supplemental irrigation are scarce. Therefore, this study aimed to evaluate the growth and yield of spineless cactus cultivated at different planting densities.

Material and methods

The study was carried out at *Embrapa Semiárido* (Brazilian Agricultural Research Corporation - 9°23'35" S and 40°30'27" W, 365-m altitude), in Petrolina, Pernambuco State, Brazil. The genotype used was '*Orelha de Elefante Mexicana*' (*Opuntia stricta* [Haw.] Haw), which were assessed in two 12-month crop cycles.

The first cycle was between June 2016 (planting) and June 2017, with a mean temperature of 27.23°C, mean relative humidity of 54.56%, accumulated rainfall of 152.90 mm, and reference evapotranspiration (ETo) of 1,936.29 mm. Over this cycle, the crop was supplied with 546 mm water depth by drip irrigation. Combined rainfall and irrigation water inputs totaled 698.9 mm. Irrigation was based on the reference evapotranspiration complementary to rainfall.

The second cycle lasted from August 2017 (standardization cutting) to August 2018. Along this cycle, rainfall was 341 mm, ETo 1,840 mm, mean temperature 26.4°C, and mean relative humidity 59.3%. This time irrigation totalized 779.48 mm via drip irrigation. The chemical composition of irrigation water in both cycles was: Ca^{2+} 0.43 mmol L^{-1}, Mg^{2+} 0.52 mmol L^{-1}, Na^{+} 0.14 mmol L^{-1}, K^{+} 0.05 mmol L^{-1}, $CO3^{2-}$ 0.00 mmol L^{-1}, HCO^{3}- 0.62 mmol L^{-1}, $SO4^{2-}$ 0.34 mmol L^{-1}, Cl^{-} 1.60 mmol L^{-1}, pH 8.05, CE 0.06 dS m^{-1}, and hardness 4.76 mg L^{-1}.

The experimental design was a randomized block with five treatments and four replicates. The assessed densities were 20,000; 25,000; 33,333; 50,000; and 100,000 plants ha^{-1}, which were achieved by using varied plant spacings (0.50, 0.40, 0.30, 0.20, and 0.10 m, respectively) in a row, while row spacings were all one meter for all densities. The useful area comprised the five plants within the center of each plot, totaling 100 plants evaluated, whose cladodes were measured individually.

Organic fertilization (tanned cattle manure) rate of application was equivalent to 40 t ha^{-1} in both cycles, and manual weeding was performed twice.

For both harvests, forage yield (FY) (kg of green mass [GM] ha^{-1} and kg of dry mass [DM] ha^{-1}) was evaluated by cutting and weighing of five plants per plot, in which all cladodes were weighed, thus obtaining total weight per plant. The forage yield was estimated considering plant mass multiplied by number of plants ha^{-1}, based on GM and DM. The DM content was determined using a forced-air oven at 55°C until constant weight (pre-drying).

Structural measurements were carried out on five plants from the useful area at harvest time. Plant height (cm) and width (cm) were measured using a tape measure. The number of cladodes per order was counted, obtaining the overall number of cladodes per plant (NOC) and numbers of primary cladodes (NPC), secondary cladodes (NSC), tertiary cladodes (NTC), and quaternary cladodes (NQC). All cladodes were also measured with a tape measure for length (cm) and width (cm), and hence determining cladode area index (CAI). A caliper was used to measure cladode thickness (cm).

Water-use efficiency (WUE) was calculated considering FY (kg DM ha^{-1}) and rainfall plus irrigation inputs during 12 months (FY / total water [irrigation + rainfall]). Whereas forage accumulation rate (FAR) was estimated considering FY (Kg DM ha^{-1}) and the evaluation time.

Data were submitted to linear and quadratic regression analyses at 5% significance ($p < 0.05$). The statistical analyses were performed using the Statistical Analysis System (SAS, 2015). The statistical model was $Y_{ij} = \mu + d_i + e_{ij}$; where: μ is the general constant, d_i is the planting density effect, and e is the random error of observations.

Results and discussion

Increasing planting density reduced plant height and width, NOC, NPC, NSC, and NTC. Planting density had a quadratic effect on cladode thickness. Increasing planting density also promoted greater CAI (Table 1).

Table 1. Structural characteristics of spineless cactus Orelha de Elefante Mexicana in different planting densities as average of two12 months crop cycles.

Variable	Planting density (plants ha^{-1})					ER	R^2
	20,000	25,000	33,333	50,000	100,000		
PH (cm)	73.91	80.23	72.96	76.24	69.98	$Y = -0.00008x + 78.16$	0.42
PW (cm)	90.22	87.80	84.81	76.63	65.41	$Y = -0.0003x + 94.98$	0.97
NOC	15.5	15.5	11.6	9.8	7.0	$Y = -0.0001x + 16.64$	0.84
NPC	6.3	5.9	5.2	4.4	3.6	$Y = -0.00003x + 6.53$	0.88
NSC	7.8	7.7	5.3	4.5	2.7	$Y = -0.00006x + 8.41$	0.83
NTC	0.9	1.5	0.5	0.4	0.1	$Y = -0.00001x + 1.26$	0.57
CT (cm)	1.41	1.24	1.24	1.14	1.37	$Y = 0.0000000002x^2 - 0.000019x + 1.68$	0.85
CAI	1.28	1.58	1.59	2.00	2.84	$Y = 0.00002x + 1.02$	0.98

Plant height (PH), plant width (PW), mumber of overall cladodes (NOC), number of primary cladodes (NPC), number of secondary cladodes (NSC), number of tertiary cladodes (NTC), cladode thickness (CT), and cladode area index (CAI). ER = equation of regression, R^2 = coefficient of determination.

Higher plant densities intensified competition for water, nutrients, and light, decreasing individual plant growth, cladode weight, plant height and width, and cladode number. Furthermore, according to Dubeux Jr. et al. (2006), higher numbers of cladodes in lower density plantations are due to a larger area of soil explored. Therefore, a reduction in the surface to be explored can reduce new cladode emissions. Exploring a larger soil area increases plant ability to obtain water and nutrients and direct them to its growth.

Planting density promoted changes in structural responses of OEM plants. At a density of 100,000 plants ha^{-1}, NOC reduced by 55% compared to that of 20,000 plants ha^{-1}. All cladode orders (primary, secondary, and tertiary) showed lower numbers of cladodes as plant density increased, showing that plants under less competitive pressure produced more cladodes. Secondary cladodes corresponded to 50% of total cladodes at 20,000 plants ha^{-1}, but only 38.5% at 100,000 plants ha^{-1}; therefore, planting densification reduces cladode numbers of this specific order. Higher cladode emissions, increasing plant height and width, is a plant strategy to capture light for its development.

Cladode thickness decreased up to a density of 47,500 plants ha^{-1}, probably due to greater absorption of water and nutrients. However, when planting density was raised up to 100,000, plants showed lower cladode numbers and directed more water and nutrients for them, promoting an increased thickening.

The increase in CAI is due to a greater number of plants in plots at higher planting densities. The CAI is directly related to cactus yield since cladodes are responsible for harnessing solar radiation, it is used as chemical energy in the photosynthesis process, favoring the photosynthetic efficiency per area and interfering directly with crop development and yield (Cavalcante et al., 2014). According to Cortázar and Nobel (1991), the CAI for a maximum spineless cactus yield ranges between 2 and 2.5 (Cortázar & Nobel, 1991). In the current study, the CAI was 2.84 for a plant density of 100,000 plants ha^{-1} and ranged from 1.28 to 2.00 for plant densities up to 50,000 plants ha^{-1} at harvest time.

The increase in planting density led to a linear increase in green and dry mass yields, and in forage accumulation rates (Table 2), but it decreased plant mass and had a quadratic effect on DM levels. DM contents increased up to a density of 61,248 plants ha^{-1}, which may have been due to the greater number of young cladodes at the lower planting densities. In contrast, at 100,000 plants ha^{-1}, plants produced less cladodes, increasing the number of cladodes with a more advanced physiological stage and hence DM contents. This is because young cladodes have more water contents.

Lower plant mass resulting from planting densification can be attributed to a greater competition among plants for water, light, and nutrients. Overall, an increase in planting density from 20,000 to 100,000 plants ha^{-1} reduced plant weight by 61.2%.

Table 2. Forage yield, plant mass, dry matter content (DM) and water use efficiency of Spineless cactus Orelha de Elefante Mexicana in different planting densities as average of two 12 months crop cycles.

Variable	Planting density (plants ha^{-1})					ER	R^2
	20,000	25,000	33,333	50,000	100,000		
DM (%)	9.19	10.15	10.05	10.50	9.53	$Y = 0.0000000007x^2\ 0.000086x + 8.03$	0.77
PM (kg)	9.44	8.60	6.56	5.00	3.66	$Y = -0.00007x + 9.7$	0.80
FY (t GM ha^{-1})	188.9	215.1	218.8	250.2	366.6	$Y = 0.0021x + 150.15$	0.98
FY (t DM ha^{-1})	17.45	21.96	22.11	25.78	35.39	$Y = 0.0002x + 15.20$	0.96
WUE (kg DM ha^{-1} mm^{-1})	19.51	25.49	25.65	28.38	38.24	$Y = 0.0002x + 18.16$	0.93
FAR (kg DM ha^{-1} mm^{-1})	47.81	60.16	60.56	70.63	96.95	$y = 0.0006x + 41.66$	0.96

Dry matter (DM), plant mass (PM), forage yield (FY), GM (green matter), DM (dry mass), water use efficiency (WUE), and forage accumulation rate (FAR). ER = equation of regression, R^2 = coefficient of determination.

Higher FY (kg GM ha^{-1} and kg DM ha^{-1}) can be attributed to a larger number of plants within the area. According to Silva et al. (2014), although larger planting densities reduce cladode numbers and plant weights (kg DM), planting densification may raise forage yield due to an increase in plant numbers. As crop density increased, FAR increased linearly, which can be explained by the higher CAI. Nutrient use efficiency can be maximized by planting densification as it increases the soil surface explored by the roots. Sales, Alves, Ramos, Nascimento, and Leite (2012) reported increases in organic fertilizer use efficiency when the planting density of spineless cactus 'Gigante' was raised from 50,000 to 100,000 plants ha^{-1}.

Similar results on forage yield of spineless cactus at different crop densities were reported by Silva et al. (2014), who evaluated densities from 10,000 to 80,000 plants ha^{-1} and found yields from 100 to 400 t ha^{-1}, respectively, with a cutting interval of 12 months. Cavalcante et al. (2014) studied three cactus genotypes and reported yield increase, ranging from 200 to about 650 t ha^{-1}, with a cutting interval of 24 months in three genotypes.

The larger FY (t ha^{-1}) promoted by planting densification also increased WUE, which can be justified by higher exploitation of the soil surface. Such a high WUE is one of the factors that contributed to spineless cactus productive responses.

Conclusion

An increase in planting density of spineless cactus '*Orelha de Elefante Mexicana*' (*Opuntia stricta* [Haw.] Haw), with supplementary irrigation, alters plant structural traits, reducing height and width and number of cladodes, besides increasing forage yield (t ha^{-1}).

Acknowledgements

This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (Capes) – Finance Code 001, as well as with the support of the *Embrapa Semiárido* through research aid (action plan n° 02.16.04.28.00.07).

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