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Integrated management of agronomic practices in the forage cactus: maximizing productivity, biological efficiency and economic profitability

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Abstract. Forage cactus cropping systems that include a combination of agricultural practices (cloning, irrigation, mulching, and/or intercropping) can increase forage production and economic return in semi-arid environments. This study evaluated the effect on productivity, biological efficiency, and economic return of combining different practices with forage cactus cropping systems in the semi-arid region of Brazil. The research was conducted in four experimental areas, in a randomized block design with four replications, and included the following practices: 1) clones – irrigation - cover, 2) different irrigation depths, 3) intercropping - mulching, and 4) different levels of mulch. The treatments in experiment I consisted of three cactus clones (‘Orelha de Elefante Mexicana’—OEM; ‘Miúda’—MIU and ‘IPA-Sertânia’—IPA), two water regimes (rainfed and irrigated), and two levels of mulch (with and without mulch). Experiment II comprised four irrigation depths (0, 40, 80, and 120% of the crop evapotranspiration) and three cactus clones. In experiment III, three crop arrangements (single cactus, cactus intercropped with millet, and single millet) were evaluated under two levels of mulching (with and without mulching). In experiment IV, four levels of mulch were used (0, 5, 10, and 15 Mg ha^{-1}). The total number of cladodes per plant, fresh matter yield (YFM), dry matter yield (YDM), and final plant density were obtained when harvesting. Economic viability was assessed using the profitability index (PI). The rainfed systems showed greater yield. The use of mulch afforded greater productivity. The OEM clone (YFM = 310.76 Mg ha^{-1} and YDM = 29.87 Mg ha^{-1}) obtained a higher yield than did the IPA and MIU clones. The highest PI values were achieved under the rainfed systems. The MIU and IPA clones exhibited lower PI values. The cactus-millet intercrop achieved the best performance with the use of mulch. Cactus systems of 15.0 Mg ha^{-1} showed a greater PI value. It was concluded that the integrated management of such practices as intercropping, mulching, and the adoption of the OEM clone can increase the supply of forage. These practices can promote the sustainable intensification of forage input in Livestock Production Systems in semi-arid environments.

Keywords: *Opuntia, Nopalea, Competitive ability, Net present value*

Introduction

The world population is expected to increase to more than 9.5 billion people by the middle of the 21st century, with almost half located in developing countries The higher per capita income in these countries will intensify the search for food of animal origin (Bateki *et al.,* 2019). However, based on climate change scenarios, greater difficulty, and instability of production are expected, resulting in strong pressure on agricultural and livestock systems due to the increase in rainfall seasonality and in seasonal water deficit, especially in regions of dry climate (Ndiritu, 2020; Silva *et al.,* 2021a).

The semi-arid region of Brazil is one of the dry areas of the world which are highly susceptible to variations in climate (Silva *et al.*, 2020; Silva *et al.,* 2021b). The high number of goats, sheep, and cattle makes this region one of the most important in the country for production chains (Nunes et al. 2014). However, extensive breeding can limit the zootechnical performance of the animals and the supply of animal protein due to annual fluctuations in the supply of forage, which depends on the rainfall regime (Moraes *et al.,* 2019). In view of these problems, achieving forage stability is essential for improving livestock production and food security and generating income to reduce social inequality (Vieira *et al.,* 2015).

The integrated management of agricultural practices can be the solution to increasing the supply of forage in Livestock Production Systems in this type of dry environment using plants that are tolerant to water deficit (e.g., cacti) and practices for improving the soil-plant system, for example, intercropping, regular minimal use of irrigation, and mulching (Santos *et al.,* 2017; Martins *et al.,* 2018).

The forage cactus (*Opuntia* spp. and *Nopalea* spp.) is a cactus that is widely used in several semi-arid environments as a component of agricultural production systems that aim for an efficient supply of forage. This is possible due to the anatomical and physiological characteristics of the cactus, such as the crassulacean acid metabolism (CAM), which generally allows CO_2 to be captured at night, avoiding a large loss of water through transpiration, as well as the high water-use efficiency compared to C_3 and C_4 crops, which affords good yields (Amorim *et al.,* 2017; Cardoso *et al.,* 2019). Although tolerant to different types of environmental stress (i.e. water, heat, and salt) (Silva *et al.,* 2015a; Jardim *et al.,* 2021a), studies show that cactus crops respond well to irrigation (Queiroz *et al.,* 2015; Araújo Júnior *et al.,* 2021), mulching (Amorim *et al.,* 2017) and intercropping (Diniz *et al.,* 2017; Lima *et al.,* 2018a; Souza *et al.,* 2021; Jardim *et al.,* 2020; Jardim *et al.,* 2021b).

The yield of cactus production systems varies depending on the clone and species (Silva *et al.,* 2015b). As for water management, Queiroz *et al*. (2015) state that dry matter accumulation in the cactus does not increase with the application of irrigation depths from 976 to 1202 mm year^{-1}. Araújo *et al.* (2021) affirm that the application of 231 mm year^{-1} via irrigation is sufficient to increase the yield of cactus clones. For soil management, Amorim *et al.* (2017) found that when using 8.2 Mg ha^{-1} *Pennisetum purpureum* Schum. in a cactus plantation, dry matter production increased by 62%. Diniz *et al.* (2017), Lima *et al.* (2018a), Souza *et al.* (2021) and Jardim *et al.* (2021b) cite that intercropping the cactus with grasses (e.g. sorghum or millet) increases dry matter accumulation without harming the individual productivity of the cactus. These studies were carried out on crops from different harvests; as such, the simultaneous cultivation of crops with the adoption of different management practices can help in choosing production systems that offer the best support for forage.

The hypothesis, therefore, is that forage cactus cropping systems that include a combination of agricultural practices (cloning, irrigation, mulching, and/or intercropping) can increase forage production and economic return, improving the supply of forage in Livestock Production Systems in semi-arid environments. Thus, the aim of this study was to evaluate the effect of combining different practices under forage cactus cropping systems (1. clones – irrigation – mulching, 2.

clones – different irrigation depths, 3. intercropping – mulching, 4. different levels of mulch) on productivity, biological efficiency, and economic return in a semi-arid environment in Brazil.

Material and Methods

Study site: soil and climate conditions

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, altitude 431 m). According to the Köppen classification, the climate in the region is type BShw', with rainfall concentrated during the summer/autumn (Alvares *et al.,* 2013) totalling 642.1 mm year^{-1}, a relative humidity of 62%, and an average air temperature that ranges from 20.1 to 32.9 ºC, resulting in a negative water balance for most months of the year (Pereira *et al.,* 2015; Silva *et al.,* 2015b). The study was conducted in a soil classified as a typic Eutrophic Ta Haplic Cambisol (Jardim *et al.,* 2021b) of flat relief, with the following physical and chemical characteristics (0-0.2 m): bulk density = 1.58 g cm^{-3}, sand = 832 g kg^{-1}, silt = 126 g kg^{-1}, clay = 42 g kg^{-1}, electrical conductivity = 0.69 dS m^{-1}; pH = 6.8, cation exchange capacity = 7.8 cmol$_c$ dm^{-3} and base saturation = 92.4%.

Plant material and cultivation conditions

The study was carried out in four experimental areas (referred to as I, II, III, and IV) comprising multiple cropping systems of forage cacti (*Opuntia* spp. and *Nopalea* spp.) and one grass (*Pennisetum glaucum*). Each of the areas was cultivated in a randomized block design, with four replications and four crop rows. The same mechanized soil preparation was used in each area (i.e. ploughing, harrowing, and furrowing).

Experiment I: clones - water regimes - mulching

Three forage cactus clones were used: 'Orelha de Elefante Mexicana' - OEM (*Opuntia stricta* (Haw.) Haw.), 'IPA Sertânia' - IPA, and 'Miúda' - MIU (the latter two, *Nopalea cochenillifera* (L.) Salm-Dyck). The clones were evaluated from January 2017 to July 2018 (i.e. at the start of the treatments and at harvest). The treatments were applied in a 3 x 2 x 2 factorial scheme, combining the three cactus clones (OEM, IPA, and MIU) with two water regimes (rainfed and irrigated) and two levels of mulch (with and without mulch). Under the irrigated regime, irrigation was based on 100% of the ETc (crop evapotranspiration). Mulching consisted of 18 Mg ha^{-1} *Urochloa mosambicensis* straw placed at the beginning of the cycle only (with mulch, WM) and of exposed soil (no mulch, NM). The cultivated area consisted of plots of 20 m^2 with a spacing between rows of 1.0 x 0.2 m, giving a total stand of 50 thousand forage cactus plants per hectare. The area was fertilized by the application of 525 kg ha^{-1} formulation 14-00-18 + 16S. The meteorological conditions during the experimental period are shown in Fig. 1.

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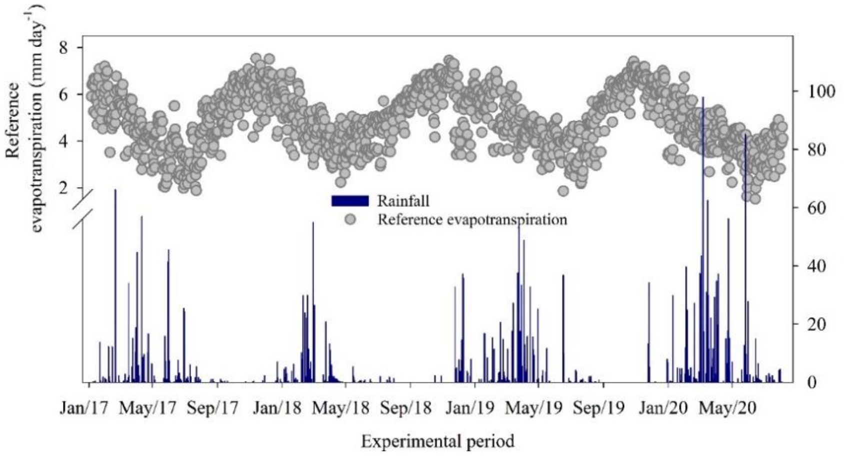

Figure 1. Reference Evapotranspiration and rainfall data from January 2017 to August 2020 including all study periods, for the district of Serra Talhada, Pernambuco, Brazil.

Experiment II: clones - irrigation depths

The ‘Orelha de Elefante Mexicana’, ‘IPA Sertânia’, and ‘Miúda’ clones were evaluated between March 2019 and May 2020, arranged in a 4 x 3 factorial scheme of subdivided plots. The experimental plots comprised three water regimes with depths of 40, 80, and 120% of the ETc, plus rainfed conditions (0% of the ETc); the subplots consisted of the different forage cactus clones. Each experimental plot was 60 m^2, while the subplots had an area of 20 m^2, with a spacing of 1.0 x 0.20 m between the rows and plants respectively (i.e. a total of 50 thousand plants per hectare). The meteorological data for the period under study are shown in Fig. 1.

Experiment III: crop arrangement - mulching

The ‘Orelha de Elefante Mexicana’ clone of the forage cactus, and the millet cultivar IPA Bulk-1-BF (*P. glaucum* [L.] R. Br.) were used in the experiment. The experimental period was from February 2019 to February 2020. A 3 x 2 factorial scheme comprising three crop arrangements was adopted, where each crop, under both single and intercropped systems, was submitted to two levels of mulch: NM and WM (using *U. mosambicensis* as mulching at a ratio of 18 Mg ha^{-1}, which was not replaced over time). The cactus plants were arranged at a spacing of 1.6 x 0.20 m, giving 31.25 thousand plants per hectare. The millet was sown at 0.20 m from the cactus rows, using 20 seeds per linear meter, and grown over two production cycles, the first crop was arranged in double rows (27 February 2019, 90-day cycle) with a stand of 250 thousand plants per hectare, and the second crop in a single row (10 October 2019, 126-day cycle). Each plot had an area of 25.6 m^2. The meteorological data are shown in Fig. 1 and Table 1, both of which aided irrigation management (120% of the ETc).

Table 1. Accumulated values for irrigation depth and meteorological variables in millimeters, during the experimental period, for each area under evaluation.

Variable	Irrigation-mulching-clones	--- Irrigation depths ---			Intercrop-mulching	Levels of mulching
	52%ET_0	40%ETc	80%ETc	120%ETc	120%ETc	42%ETc
Irrigation	684.82	212.47	433.23	658.22	585.45	305.35
Rainfall	1000.8		1342.2		711.8	1110.2
ET_0	2674.4		2051.87		1755.08	1759.73

ET_0 – Reference evapotranspiration; ETc – Crop evapotranspiration.

Experiment IV: levels of mulching

The 'Orelha de Elefante Mexicana' clone of the forage cactus was used, with treatments starting in August 2019 and ending in August 2020 (i.e. at harvest). The plots comprised three levels of mulch (5.0, 10.0, and 15 Mg ha^{-1}, WM) plus a condition with no mulch (0.0 Mg ha^{-1}, NM), all irrigated at 80% of the ETc. Each plot had an area of 16.0 m^2, and contained *U. mosambicensis* straw, which was not replaced over time. The meteorological conditions are shown in Fig. 1.

Irrigation management

A drip irrigation system was used, with the tapes at 0.20 m from the basal cladode of each cactus, and the emitters spaced 0.20 m apart. The system operated at a pressure of 101.32 kPa, with a mean flow rate of 1.60 L h^{-1} and distribution uniformity of 93%. Irrigation was based on both the reference evapotranspiration - ET_0, calculated using the Penman-Monteith method described in FAO bulletin 56 (Allen *et al.,* 1998), and on the crop evapotranspiration - ETc, based on a Kc of 0.52 throughout the cycle, as proposed by Queiroz *et al.* (2016). The meteorological data (Fig. 1) were collected from an automatic station of the National Institute of Meteorology that was located 20 m from the experimental areas. The areas under study received different irrigation depths due to the varying cultivation conditions, as well as to the different water regimes, which were adopted based on the period under evaluation, as shown in Table 1.

Collecting the experimental data

Forage production

The cactus was harvested at the end of the evaluation period in each area. Prior to this, the plants in the two central rows of each plot (i.e. experimental working area) were counted in order to establish the final plant density. The plants were then cut, and weighed on an electronic balance, thereby obtaining the total weight for each working plot (kg). Three representative cladodes from the central third of one plant were weighed to determine the fresh matter. The cladodes were then broken up, packed in paper bags, and dried in a forced air circulation oven at 65 ºC (Silva and Queiroz, 2005) to constant weight. Fresh matter yield at harvest (FM, Mg ha^{-1}) was determined from the final plant density and the average fresh weight of the plants in each working plot. Dry matter yield (DM, Mg ha^{-1}) was determined as the product of FM, and the dry matter content was derived from the ratio of fresh to dry matter in the three cladodes.

At the end of each millet production cycle (Experiment III), only the central rows of each working plot were evaluated ignoring the borders (four rows in the first cycle with double rows, and two rows in the second cycle with a single row). The number of plants in two linear meters was counted in order to define the final density. Ten plants from each row were then harvested, cut 0.10 m above the ground, and weighed on an electronic balance to obtain the fresh weight. From the harvested plants, three were selected and individually weighed, broken up, packed in paper bags, and placed in a forced air circulation oven at 65 ºC to obtain the values for dry matter. The final fresh matter yield of the millet (FM, Mg ha^{-1}) was extrapolated from the final plant density and the mean fresh weight of the plants in the working plot. Dry matter yield (DM, Mg ha^{-1}) was determined as the product of FM, and the dry matter content was derived from the ratio of fresh to dry matter in the three plants.

Indices of biological efficiency

The effect of intraspecific competition was obtained with the land equivalent ratio (LER) used to quantify the improvement in productivity of intercropped systems in relation to land use by single crops (Moghbeli *et al.,* 2019; Amanullah *et al.,* 2020; Jardim *et al.,* 2021b) (Eq. 1).

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$$LER=\left(\frac{Y_{ab}}{Y_{aa}}+\frac{Y_{ba}}{Y_{bb}}\right) \quad (1)$$

where Y_{ab} and Y_{ba} are the productivity of the cactus and millet in intercropped systems respectively; Y_{aa} and Y_{bb} correspond to the productivity of the cactus and millet as single crops respectively. When LER is equal to 1.0 it shows that intercropped production does not differ from that of the single crops. A value of less than 1.0 shows that yield was hampered by the intercrop, and an LER greater than 1.0 shows that there is an advantage to the intercrop.

The advantages of intercropping the cactus and millet were evaluated using the area time equivalent ratio (ATER), land equivalent coefficient (LEC), and system productivity index (SPI), calculated as per the procedures shown in Equations 2, 3, and 4 respectively (Diniz *et al.,* 2017; Amanullah *et al.,* 2020; Jardim *et al.,* 2021b).

$$ATER=\left[\frac{(LER_a\times t_a)+(LER_b\times t_b)}{t_{ab}}\right] \quad (2)$$

where LER_a and LER_b are the respective land equivalent ratios for the cactus and millet; t_a, t_b and t_{ab} represent the time in days of the cactus cycle (352 days), the millet cycle (216, days) and the total time of the cropping system respectively. Values differing from 1.0, upwards or downwards, represent advantages and disadvantages between the intercrops and the single crops (Diniz *et al.,* 2017; Amanullah *et al.,* 2020; Jardim *et al.,* 2021b).

$$LEC=LER_a\times LER_b \quad (3)$$

where LEC values greater than 25% show a productive advantage to the intercropping system, as per Diniz *et al.* (2017).

$$SPI=\left[\left(\frac{Y_{aa}}{Y_{bb}}\right)\times Y_{ba}\right]+Y_{ab} \quad (4)$$

showing the advantage of standardizing millet production relative to the forage cactus (Oseni and Aliyu, 2010).

Indices of competitive ability

The advantage of the intercropping system and the impact of the interspecific cactus-millet competition were evaluated using the following indices: coefficient of relative density (K), aggressivity (A), actual loss or gain in yield (ALGY), and the competitive ratio (CR), as per Equations 5, 6, 7 and 8 respectively (Diniz *et al.,* 2017; Li *et al.,* 2020; Jardim *et al.,* 2021b).

$$K=\left[\frac{Y_{ab}\times Z_{ba}}{(Y_{aa}-Y_{ab})\times Z_{ab}}\right]\times\left[\frac{Y_{ba}\times Z_{ab}}{(Y_{bb}-Y_{ba})\times Z_{ba}}\right] \quad (5)$$

where Z_{ab} and Z_{ba} represent the proportion of species *a* (forage cactus, 16%) and species *b* (millet, 84%) respectively. The K coefficient shows the dominance of one species over the other in the intercropping system. Values for K >1.0 show that the intercropping system is superior to the single crops.

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$$A_{ab}=\left(\frac{Y_{ab}}{Y_{aa}\times Z_{ba}}\right)-\left(\frac{Y_{ba}}{Y_{bb}\times Z_{ab}}\right) \qquad (6)$$

where the A_{ab} index is a response to interspecific competition in an intercropped system, showing how much the yield of one crop is superior to that of the other. For values of $A_{ab}>0.0$, the cactus is more competitive than the millet, while the reverse, $A_{ba}>0.0$, shows the superiority of the millet in relation to the cactus (Diniz *et al.,* 2017; Bi *et al.,* 2019; Jardim *et al.,* 2021b).

$$ALGY=\left[LER_{ab}\times\left(\frac{100}{Z_{ab}}\right)-1\right]+\left[LER_{ba}\times\left(\frac{100}{Z_{ba}}\right)-1\right] \qquad (7)$$

where a positive value for ALGY (ALGY >0.0), indicates cumulative benefits from the intercropping system in relation to the single crops.

$$CR_{ab}=\left(\frac{LER_{ab}}{LER_{ba}}\right)\times\left(\frac{Z_{ba}}{Z_{ab}}\right) \qquad (8)$$

where values for CR >1.0 indicate negative effects on the intercropping system compared to the single crops due to competition between the species; values <1.0 suggests positive benefits from associating the crops.

Economic indicators

The economic analysis considered 34 different cropping systems, resulting from combining the various systems in the four experimental areas, employing the values for gross and net yield, and considering depreciation of the system components, interest on the capital invested, energy costs, labour costs, maintenance of the system components, and contingency reserve, as described by Lima *et al.* (2018b). With these data, the profitability index (PI) was calculated from the net present value (NPV) and the internal rate of return (IRR) as per Equations 9, 10, and 11 (Basavaraj *et al.,* 2013; Sharma and Irmak, 2020; Jardim *et al.,* 2021b).

$$NPV=\sum_{n=0}^{N}\left[\frac{B_n-C_n}{(1+d)^n}\right] \qquad (9)$$

where $B_n = P_n \times Q_n$, B_n represents the return from production when sold as forage (cactus and millet) and when sold as seed (cactus); P_n is the selling price of the crops (cactus as forage - BRL 150.00 Mg^{-1}; cactus seed - BRL 0.10 $unit^{-1}$; millet as forage - BRL 450.00 Mg^{-1}); Q_n is the volume produced per crop (Mg ha^{-1}) during year *n*; C_n represents the production cost for the different systems (BRL ha^{-1}) during year *n*; d is the required rate of return (discount rate); n is the economic life of the investment. The use of this index is of great importance in decision-making in investment projects. Positive values point to economic viability.

$$IRR \Rightarrow \sum_{n=0}^{N}\left[\frac{B_n-C_n}{(1+d)^n}\right]=0 \qquad (10)$$

where this rate demonstrates the mean earning ability of the invested capital per project for a given period. The IRR calculates the discount rate that a cash flow must have for the NPV to be equal to zero. For the investment to be viable, the IRR must be greater than the discount rate of the project.

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$$PI=\frac{\sum_{n=0}^{N} NPV}{\text{Initial investment}} \quad (11)$$

where PI simulates the potential of the project to generate profit. PI values ≤1.0 indicate the non-viability of the project.

Statistical analysis

The production data of each system, the number of cladodes, and biological and competitive indices for the intercropping system were compared within each study area. These were subjected to tests of normality and homoscedasticity. When the assumptions were met, ANOVA was carried out using the F-test ($p<0.05$); when the test was significant, the mean values were compared using Tukey's test at a level of 5%. The statistical analysis was carried out using the R software (R Core Team, 2019).

Results

Productive performance

Systems with clones - water regimes - mulching

No interaction was seen between the factors clone, irrigation, or mulching ($p>0.05$) for fresh matter yield, dry matter yield, or the total number of cladodes (Y_{FM}, Y_{DM}, and TNC respectively) (Table 2 and 3). There was an isolated effect from the factors clone, water regime (rainfed and irrigated), and mulching (with and without mulch) for Y_{FM}, Y_{DM}, and TNC ($p<0.05$). The 'Orelha de Elefante Mexicana' clone (OEM) of *Opuntia stricta* (Haw.) Haw showed greater Y_{FM} and Y_{DM}, while 'Miúda' (MIU) displayed greater cladode emission ($p<0.05$). For the factor water regime, the rainfed conditions showed a greater value for Y_{FM}, Y_{DM} and TNC compared to the irrigated conditions ($p<0.05$). The system that included mulch showed a higher return for Y_{FM}, Y_{DM} and TNC compared to that with no mulch ($p<0.05$) (Table 3).

Table 2. Performance of forage cactus clones (*Opuntia* and *Nopalea*) under the mulching-irrigation-clone production system.

Variable	----- Clones -----			--- System 1 ---		--- System 2 ---		CV (%)
	OEM	MIU	IPA	I	R	CC	NC	
Y_{FM}	310.76 a	152.10 b	153.87 b	188.97 b	222.19 a	234.82 a	176.33 b	1.09
Y_{DM}	29.87 a	15.45 b	12.44 b	17.39 b	21.19 a	21.50 a	17.08 b	13.71
TNC	12.13 b	30.93 a	16.18 b	18.00 b	21.50 a	21.81 a	17.68 b	12.4

Rate of plant mortality (%)					
	Clones x Water Regime			Water Regime x Mulching	
	OEM	MIU	IPA	No-mulch	With-mulch
Irrigated	24.72 c	52.71 bA	77.16 aA	59.23 aA	43.83 bA
Rainfed	18.76 b	31.25 abB	45.38 aB	31.70 B	31.89 B

Mean values followed by the same lowercase letters on the lines and uppercase letters in the columns within each clone, for systems 1 and 2 and for the interaction between the two, do not differ statistically by Tukey's test at a level of 5%. OEM – 'Orelha de Elefante Mexicana'; MIU – 'Miúda'; IPA – 'IPA Sertânia'; I - Irrigated cultivation; R - Rainfed cultivation; CC - Cultivation with mulch; NC - Cultivation with no mulch; CV - Coefficient of variation; TNC - Total number of cladodes (Units); Y_{FM} - Fresh matter yield (Mg ha^{-1}); Y_{DM} - Dry matter yield (Mg ha^{-1}).

There was an interaction between the clones, water regimes, and mulching for the rate of plant mortality (RPM) ($p<0.05$). The highest rate of plant mortality was seen in the 'IPA Sertânia' clone

(IPA) under irrigation (Table 3). The lowest values for RPM were seen in *O. stricta*, with a mean value 65% less than that of the IPA clone. In the water regime x mulching interaction, it was found that for irrigation with no mulch the RPM was greater compared to the use of mulching ($p<0.05$). Under rainfed conditions, there was no difference in RPM for the use of mulching ($p>0.05$). There was an effect from irrigation on the crops with and without mulching compared to the rainfed crop ($p<0.05$).

Table 3. Productivity and plant mortality in the cactus under different water regimes.

Variable	------- Clone (C) -------			----- p-value (0.05) -----			CV (%)
	OEM	MIU	IPA	C	WR	C x WR	
Y_{FM}	321.76 a	67.97 b	101.26 b	0.00**	0.40^{ns}	0.32^{ns}	33.34
Y_{DM}	28.41 a	5.27 b	7.33 b	0.00**	0.67^{ns}	0.09^{ns}	30.25
TNC	13.56 a	14.68 a	9.31 b	0.00**	0.53^{ns}	0.27^{ns}	26.51
RPM	6.00 b	60.00 a	63.00 a	0.00**	0.81^{ns}	0.89^{ns}	23.80

Mean values followed by the same letters on the lines do not differ statistically by Tukey's test at a level of 5%. **, * and ns - significant at 1%, 5% and non-significant respectively. OEM - 'Orelha de Elefante Mexicana'; MIU - 'Miúda'; IPA - 'IPA Sertânia'; WR - Water regime; CV - Coefficient of variation; Y_{FM} - Fresh matter yield (Mg ha^{-1}); Y_{DM} - Dry matter yield (Mg ha^{-1}); TNC - Total number of cladodes; RPM - Rate of plant mortality (%).

Systems with clones - irrigation depths

There was no interaction between the clones or irrigation depths for Y_{FM}, Y_{DM}, TNC, or RPM (Table 4). Effects were found only between the *O. stricta* clones, with species *Nopalea cochenillifera* (MIU and IPA clones) being superior for fresh and dry matter yield; whereas the MIU and OEM clones showed higher values for TNC compared to the IPA clone ($p<0.05$). There was a difference between the plants of *Nopalea* and *Opuntia* for RPM ($p<0.05$), where, on average plants of *Nopalea* displayed an RPM 90% higher than those of *Opuntia*.

Systems with intercropping - mulching

There was no interaction between the arrangements (intercropping vs single crops) and the mulching (with and without mulch) (Table 5). There was an isolated effect from *Pennisetum glaucum* on the system for Y_{FM} in cycle 1, with the single crop exceeding the intercrop by 39% ($p<0.05$). There was no significant difference between treatments with and without mulch for Y_{FM} in the millet in cycle 1, nor for the systems or treatments in cycle 2, or the sum of both cycles ($p>0.05$). In terms of dry matter productivity, *P. glaucum* showed an isolated effect between the systems and treatments in cycle 1, and for the sum of cycles 1 and 2 ($p<0.05$). In cycle 1 of the millet, the system that included mulch had a Y_{DM} 2.13 times greater than the system with no mulch. The highest value for Y_{DM} was found in cycle 1 of the single millet, which was 2.5 times higher compared to its intercrop with the cactus.

There was no interaction between the crop arrangement and mulching for Y_{FM} and Y_{DM} in the cactus (Table 5). For the cropping systems, Y_{FM} and Y_{DM} showed no difference between the single crop or the intercrop of cactus and millet. The same occurred for the treatments with and without mulch ($p>0.05$). There was no difference in the sum of Y_{FM} or Y_{DM} for either crop between the systems with no mulch and those with mulching of straw. No effects were found on TNC within the systems or treatments ($p>0.05$).

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Table 4. Fresh and dry matter yield per millet and cactus cycle, and the total number of cladodes (TNC).

Fresh matter (Mg ha^{-1})								
Variable	------ System ------			- Treatment -		--- p-value (0.05) ---		CV (%)
	$P_{Sng.}$	$M_{Sng.}$	P-M	CC	NC	System	Treatment	
Y_{MC1}	–	13.97 a	8.46 b	12.91	9.52	0.04*	0.18^{ns}	41.71
Y_{MC2}	–	5.18	4.97	5.15	5.01	0.88^{ns}	0.92^{ns}	54.40
$\sum_{Cycles}$	–	19.15	13.44	18.06	14.53	0.07^{ns}	0.25^{ns}	35.39
Y_P	360.57	–	360.25	374.43	346.39	0.99^{ns}	0.55^{ns}	25.58
Y_{PM}	360.57 a	19.15 b	373.69 a	261.66	240.61	0.00**	0.50^{ns}	30.28
Dry matter (Mg ha^{-1})								
Variable	------ System ------			- Treatment -		--- p-value (0,05) ---		CV (%)
	$P_{Sng.}$	$M_{Sng.}$	P-M	CC	NC	System	Treatment	
Y_{MC1}	–	5.16 a	2.06 b	4.91 a	2.30 b	0.01*	0.03*	59.01
Y_{MC2}	–	1.32	1.28	1.31	1.30	0.89^{ns}	0.97^{ns}	52.57
$\sum_{Cycles}$	–	6.49 a	3.34 b	6.22 a	3.60 b	0.02*	0.054^{ns}	47.46
Y_P	27.33	–	31.78	29.03	30.08	0.39^{ns}	0.83^{ns}	33.60
Y_{PM}	27.33 a	6.49 b	35.12 a	23.50	22.45	0.00**	0.75^{ns}	35.82
TNC	18.50	–	16.12	16.87	17.75	0.36^{ns}	0.73^{ns}	28.53

Mean values followed by the same letters on the lines within each system and treatment do not differ statistically by Tukey's test at a level of 5%. $P_{Sng.}$ – Single cactus; $M_{Sng.}$ – Single millet; P-M – Cactus-millet intercrop; CC – Cultivation with mulch; NC – Cultivation with no mulch; CV – Coefficient of variation; Y_{MC1} and Y_{MC2} – Millet yield in cycles 1 and 2 respectively; $\sum_{Cycles}$ – Sum of millet cycles; Y_P – Cactus yield; Y_{PM} – Cactus + millet yield; TNC – Total number of cladodes.

Table 5. Productivity in the 'Orelha de Elefante Mexicana' clone of the forage cactus under different levels of mulch on the soil.

Variable	----- Treatment (T) -----				p	CV (%)	Equation	R^2
	0	5	10	15				
Y_{FM}	449.5	510.87	715.75	871.25	0.0183	36.13	Y_{FM}=29.3024·(T)+415.827	0.95
Y_{DM}	28.22	41.74	65.46	66.09	0.0361	43.13	Y_{DM}=2.7466·(T)+29.783	0.86
TNC	14.5	10.0	13.75	13.75	0.0681	17.01	†	†

Mean values followed by the same letters on the lines do not differ statistically by Tukey's test at a level of 5%. **, * and ns - significant at 1%, 5% and non-significant respectively. p - significance level of the p-value; R^2 - coefficient of determination. Y_{FM} - Fresh matter yield (Mg ha^{-1}); Y_{DM} - Dry matter yield (Mg ha^{-1}) (Mg ha^{-1}); TNC - Total number of cladodes. Note: † value not shown; treatment values relative to 0, 5, 10, and 15 Mg ha^{-1}.

The use of straw mulch had a positive effect on the land equivalent ratio (LER) and the area time equivalent ratio (ATER) compared to the control crop with no mulch ($p<0.05$) (Table 6). The present study showed no effect from the mulching on the land equivalent coefficient (LEC) in the intercrop, nor on the productivity index of the system ($p>0.05$). The total land equivalent ratio (LER_t) was 41.9% higher in the system with straw. An effect from the use of straw mulch on the soil was found for the following indices: relative density (K), aggressivity (A), and actual loss or gain in yield (p<0.05) (Table 6). There was no difference in the competitive ratio (CR) between the systems with and without straw, both for the cactus over the millet or the millet over the cactus (p>0.05).

Table 6. Indices of biological efficiency and competitive ability in the intercrop between *Opuntia stricta* and *Pennisetum glaucum* (cactus-millet) with and with no mulch on the soil, in a semi-arid environment.

Indices of biological efficiency						
Treatment	LER_{ab}	LER_{ba}	LER_t	ATER	LEC	SPI
P/M NC	0.99 b	0.56	1.55 b	1.33 b	0.63	47.54
P/M CC	1.77 a	0.52	2.29 a	2.09 a	0.69	47.12
SL	*	ns	*	*	ns	ns

Indices of competitive ability										
Treatment	K_{ab}	K_{ba}	K_t	CR_{ab}	CR_{ba}	A_{ab}	A_{ba}	$ALGY_{ab}$	$ALGY_{ba}$	ALGY
P/M NC	-5.10b	0.69	-3.26	33.48	0.10	5.72b	-5.72a	637.53b	66.58	704.11 b
P/M CC	3.70a	-0.29	-1.07	29.46	0.10	10.77 a	-10.77b	1138.76a	62.21	1200.98a
SL	*	ns	ns	ns	ns	*	*	*	ns	*

P/M NC - cactus-millet intercrop with no straw mulch; P/M CC - cactus-millet consortium with straw mulch. LER – land equivalent ratio; ATER - area time equivalent ratio; LEC - land equivalent coefficient; SPI - system productivity index; LER_{ab} - partial land equivalent ratio for the cactus; LER_{ba} - partial land equivalent ratio for the millet; LER_t - total land equivalent ratio. K - coefficient of relative density; CR - competitive ratio; A - aggressivity; ALGY - actual loss or gain in yield; ab - partial for cactus over millet; ba - partial for millet over cactus; t - total; SL. - significance level; ** - significant at 1% probability; * - significant at 5% probability; ns - not significant by F-test.

Systems with different levels of mulching

The system that included different levels of mulching showed significance between the various amounts applied (Table 6). An upward linear trend was seen for the production parameters (Y_{FM} and Y_{DM}). There was no effect from the straw on TNC (p>0.05).

Economic analysis

The profitability index (PI) varied according to the cropping system and the commercial use of the cactus (Table 7). In the systems with clones, irrigation, and mulching, the maximum value for the profitability index when selling forage (PIf) was achieved under the OEM system with no mulch. The *Nopalea* plants showed negative values for PIf under the irrigated systems with no mulch. When selling seeds, the MIU clone gave the best return, with a maximum value for PIs under the rainfed systems with and with no mulch. The IPA clone gave the lowest results, with a negative value under no mulch.

Under the systems with different irrigation depths, the plants of *Nopalea* had the worst results for PIf (Table 7) both with and without irrigation. The best performance for PIf was found in the OEM clone under the rainfed system (0% ETc). For the profitability index when selling seeds (PIs) the rainfed system had the best values regardless of the clone. For the systems with intercropping and mulching, PIf was negative for the single millet, both with and without mulching. The single cactus and the cactus intercropped with millet showed no great variation in PI value, whether selling forage or seed. The cactus crop under different levels of straw showed a positive PI for all treatments. There was an increase in PIf as the level of straw increased. For selling seeds, the values differed from the pattern for selling forage.

Table 7. Profitability index for different cactus production systems in a semi-arid environment.

Clones-irrigation-mulching								
Clone/ System	-------- Sold as forage --------				-------- Sold as seed --------			
	IWM	RWM	INM	RNM	IWM	RWM	INM	RNM
OEM	1.39	3.78	0.97	2.97	1.15	4.36	0.51	2.8
MIU	0.62	1.18	-0.3	1.02	3.5	8.92	0.83	8.29
IPA	0.12	1.81	-0.36	1.57	0.06	2.89	-0.4	3.32
Irrigation depth								
Clone/ System	-------- Sold as forage --------				-------- Sold as seed --------			
	0%ETc	40%ETc	80%ETc	120% ETc	0%ETc	40%ETc	80%ETc	120% ETc
OEM	3.57	1.73	1	1.21	6.13	2.07	1.14	2.15
MIU	-0.38	-0.4	-0.27	-0.43	1.81	0.71	0.46	0.38
IPA	0.19	-0.15	-0.22	-0.1	0.96	0.03	-0.19	0.3
Intercrop-mulching								
System	----- Sold as forage -----					----- Sold as seed -----		
	$P_{Sng.}$	P-M	$M_{Sng.}$			$P_{Sng.}$	P-M	M_{Sng}
No-mulch	2.42	1.92	-0.19			2.44	1.82	-
With-mulch	2.14	2.71	-0.09			2.14	2.02	-

Levels of mulching				
System	No-mulch	5 Mg	10 Mg	15 Mg
Sold as forage	2.26	2.69	4.1	5.23
Sold as seed	2.26	1.44	2.08	2.08

OEM - 'Orelha de Elefante Mexicana'; MIU - 'Miúda'; IPA - 'IPA Sertânia'; IWM - irrigated with mulch; RWM - rainfed with mulch; INM - irrigated with no mulch; RNM - rainfed with no mulch; ETc - crop evapotranspiration; P_{Sng} - single cactus; P-M – cactus-millet intercrop; M_{Sng} - single millet.

Discussions

Productive performance

Only isolated effects were found on fresh and dry matter yield in the mulching–irrigation-clone systems (Tables 2 and 3). Within the factor clone, the greatest productivity was in the genus *Opuntia* (OEM clone). This is linked to the RPM, which was high in plants of genus *Nopalea* (MIU and IPA clones), which had a mean RPM of 62%, reducing plant density and having a direct effect on end productivity. Silva *et al.* (2015b) and Jardim *et al.* (2021b) state that plants of the genus *Nopalea* have greater difficulty in becoming established, and exhibit high mortality compared to plants of *Opuntia*.

For the water regimes within the clone-water regime-mulching systems, the rainfed crops showed better productive performance (OEM, MIU, and IPA). This result is related to the high availability of rainfall water, with 628.4 mm during the first year and 372.4 mm during the remainder of the cycle (a further six months), promoting satisfactory crop development. In the irrigated crops, where 40.6% more water was applied to the plants, there was a reduction in yield. Oliveira *et al.* (2010) report that in places with rainfall greater than 1000 mm year^{-1} there is a tendency for forage cactus production to decrease. Queiroz *et al.* (2015) found a reduction in forage cactus development when the increase in water was greater than 1,048 mm. However, the amount of water required depends on the crop, the stage of development, and the soil and climate conditions (Yavuz *et al.,* 2015).

An evaluation of the mulching within the clone-water regime-mulching systems showed Y_{FM}, $Y_{DM,}$ and TNC to be more satisfactory when using straw, exceeding the system with no mulch by 25%, 21%, and 19% respectively. This can be explained by the benefits inherent to using straw, such as an improvement in the distribution of soil moisture, and a reduction in temperature, thermal amplitude, and evaporation, in addition to an increase in organic matter and the subsequent availability of nutrients (Paul *et al.,* 2020; Souza *et al.,* 2021). This practice is widely used for increasing crop yields, as it is easily implanted without the need for intensive labour and/or a high degree of technification and helps to conserve the soil in dry regions (Jiménez *et al.,* 2017; Chen *et al.,* 2019). In studies with *O. stricta* in a semi-arid environment, Amorim *et al.* (2017) found a 62% greater dry matter yield in crops with a cover of mulch compared to unprotected soil.

Within the systems that include different irrigation depths and clones (Table 4), Y_{FM} and Y_{DM} only varied for the clones. Comparing the plants of genus *Nopalea*, those of *O. stricta* showed better fresh and dry matter yields. This was due to the high mortality rate of the plants from the clones of *Nopalea* (Table 3), reducing the final stand and compromising the productivity of the system. According to Morais *et al*. (2017), who studied water efficiency in plants of *Opuntia* and *Nopalea* under irrigation in a region of climatic water deficit and found that plants of *O. stricta* showed better use of the water resources, inferring a greater capacity for converting water into dry matter compared to the plants of *N. cochenillifera*.

The lack of any effect from irrigation depth (Table 4) in the forage cactus can be associated with the amount of rainfall during the period under evaluation, which totaled 1342.2 mm (Table 1) and resulted in greater water availability than required for proper crop growth (Oliveira *et al.,* 2010; Araújo Júnior *et al.,* 2021). Cacti show a great capacity for storing water in their cladodes, thereby maintaining their metabolic pathways, and stable growth and development during periods of water deficit (Morais *et al.,* 2017). As such, small increases in water above that required by the plant, may not show an adequate response (Queiroz *et al.,* 2015). Diniz *et al.* (2017) found that the yield of *O. stricta* plants did not change for irrigation depths of between 355 and 1011 mm year^{-1}, making the application of smaller depths more economical. Studying the association of water factors with biomass production in forage cactus clones, Barbosa *et al.* (2017) found no effects from the different levels of water.

There was no interaction between the system and treatments in the intercropping-mulching systems (Table 5). In the first production cycle, there was a reduction in Y_{FM} and Y_{DM} in *P. glaucum* intercropped with *O. stricta* of 39.4% and 60.1% respectively compared to the single crop. This decrease is related to interspecific competition, where crops compete for the same ecological niche (i.e. light, water, and nutrients) (Gong *et al.,* 2020a). This may have been intensified due to the main crop (forage cactus) being in its third year of cultivation. Despite the plants being uniformly cut, the primary cladodes were maintained, the plants remaining fully established in the field, with a well-developed canopy and root system, increasing the competition for radiation, water, nutrients, and space, and hindering the initial growth of the millet.

Gong *et al.* (2020b) show that radiation is a crucial factor in plant productivity, however, in intercropped systems, there may be restrictions to productivity due to the growth habit of the competing crops or the stage of development of the main crop. In addition to radiation, water availability is crucial to promoting satisfactory yields (Bhattarai *et al.* 2020). However, in the present study, irrigation was based on the water requirements of the cactus, which are lower than that of

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the millet, promoting a water deficit in the second crop. A combination of these factors helps in understanding the lower yields of millet intercropped with cactus compared to the single crop; the use of an intercropping system during periods of acute water deficit or under reduced irrigation offers no advantages to the producer.

The lowest yields in the millet were found during the second production cycle, with no difference between the single crop and the intercrop (Table 5). This is related to the time the crop was sown (i.e. spring), with no rain and high atmospheric demand (Fig. 1), and an insufficient supply of irrigation water (based on the need of the cactus) generating unfavourable environmental conditions. The limited availability of water in the soil can prevent the plants from solubilizing and absorbing nutrients, restricting the formation and growth of tissue, and resulting in low productivity (Lobato *et al.,* 2020). Although millet is widely grown in arid and semi-arid regions, it needs a reasonable amount of water, radiation, and nutrients to achieve good productivity (Meng *et al.,* 2020; Tounkara *et al.,* 2020).

In the *O. stricta* cactus, the treatments and systems had no effect on Y_{FM}, Y_{DM}, or TNC. The genotype of the *Opuntia* plants is easily adaptable to different environmental conditions, resulting in great phenotypic plasticity, allowing the cactus to become established under the most varied environmental conditions (Erre *et al.,* 2009; Jardim *et al.,* 2021a), in addition to the crassulacean acid metabolism (CAM), which consists in opening the stomata at night, facilitating CO_2 absorption with the minimum of transpiration, contributing to water use efficiency, and promoting dry matter production in hostile environments (Moraes *et al.,* 2019; Jardim *et al.,* 2022). According to Lima *et al.* (2018a), a study of a cactus-sorghum intercropping system showed no interference from the second crop (sorghum) on the characteristics of the forage cactus. Similar results were found in studies with cacti by Diniz *et al.* (2017), Souza *et al.* (2021), and Jardim *et al.* (2021b).

The cactus-millet systems, despite not showing any significant difference from the single cactus, showed a slight increase in Y_{FM} and Y_{DM}. This is due to the low performance of the millet, with its extremely small contribution to the end productivity of the system. Amorim *et al.* (2017) found similar results to those of the present study, where the final yield of the cactus-sorghum system showed no difference from that of the single cactus. Diniz *et al.* (2017), however, found greater productivity in a cactus-sorghum intercropping system in a semi-arid environment than in single crops. Nonetheless, the response of the cactus may vary because of the intercropping system (Silva *et al.*, 2013).

Intercropping is a promising practice for the advancement of production systems, helping to optimize resources, such as increased efficiency in the use of radiation, water, and nutrients due to the different niches exploited by the component crops (Zhang *et al.,* 2019; Jardim *et al.,* 2021c). This is a widely accepted practice for environmental and socio-economic improvement in arid and semi-arid environments, contributing to the food security of developing populations (Qian *et al.,* 2018). However, the response of the production system may be different, depending on the environmental conditions and the species being used. Due to the wide range of conditions under study, the present work can help producers in choosing production systems that suit their reality.

An increase in productivity (Y_{FM} and Y_{DM}) was seen in the *O. stricta* cactus for increases in the levels of straw (Table 6). The use of crop remains on the soil surface is reported to be a sustainable agronomic practice, bringing improvements to the physical and chemical properties of the soil, improving the infiltration and distribution of water, reducing large variations in temperature, increasing organic matter, making nutrients available to the plants, and intensifying microbial activity (Qiu *et al.,* 2020; Souza *et al.,* 2021). Clearly, mulching results in improvements to

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production systems; however, an important factor is the amount of straw used, since small amounts can result in the soil being partially covered and not receiving all the benefits of mulching (Pereira *et al.,* 2002). As the layer of straw on the soil increases, there is a reduction in the direct incidence of the radiation, reducing the temperature and consequently evaporation from the soil, and favouring an increase in the water available for plant transpiration (Wang *et al.,* 2018).

According to Lüttge (2004) and Jardim *et al.* (2021b), various CAM plants can opt between CAM in the absence of water (limited conditions), and C_3 or C_4 when the water supply is adequate, thereby improving the capture of CO_2. Silva *et al.* (2015a) mention that at certain stages of its development some of the structures of the forage cactus present stomatal opening during the day. Scalisi *et al.* (2016) point out that despite its high water-use efficiency the forage cactus shows greater transpiration and CO_2 uptake at night under suitable conditions of water availability compared to water deficit, which favours performance. As such, the use of higher levels of mulch resulted in a more adequate environment (e.g. greater distribution of the soil moisture), favouring metabolic activity in the cactus, and promoting higher yields.

The integrated management of agronomic practices is therefore of great importance for improving the productivity of agricultural systems in environments driven by climate seasonality, as is the case of the semi-arid region of Brazil, affording stability to forage production and improving the agricultural sector, with a strong impact on the socio-economic and environmental development of the region.

Indices of biological efficiency and competitive ability (forage cactus vs millet)

The values for LER_t show that the intercropping system presented advantages in land use over the single crops (Table 7). Production in the system with mulch increased 1.29 times; it is, therefore, possible to produce the same quantity as the single crops using less land or increase the production of the area cultivated with single crops (Xu *et al.,* 2020). Despite giving satisfactory results, LER_t can overestimate the response of the intercrop when the production cycles of the crops are completely different (Diniz *et al.,* 2017). The same authors suggest that this indicator can be complemented by the area time equivalent ratio (ATER), where values greater than one indicate advantages that compensate for the length of each crop cycle.

In the present study, the values for ATER reflect the advantages of using the cactus-millet intercropping system for production systems in a semi-arid environment. Furthermore, the intercropping system that included mulching exceeded the system with no mulch by 35%. Diniz *et al.* (2017), studying a cactus-sorghum intercrop in a semi-arid environment, found a 51% and 30% advantage in LER and ATER over the single crops respectively. Therefore, the use of mulching and the adoption of a cactus-millet intercropping system can help to maximize production in a semi-arid environment without the need to expand the agricultural frontier, minimizing impacts on the environment and contributing to the socio-economic improvement of these locations (Gitari *et al.,* 2020).

The production system is more advantageous when the LEC is greater than 25%. From the present results, the production systems exceed this expectation. With the SPI, it was possible to match dry matter production in the millet with that of the cactus, with the cactus-millet intercrop exceeding the single cactus by 42%.

The coefficient of relative density (K) is a measurement used to compare the competitive ability of each species, where positive values indicate greater interspecific competition, while negative values show greater intraspecific competition (Xu *et al.,* 2013). In the present study, K displayed

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negative values (Table 8), showing that the cactus grown on millet in the system with no mulch (K_{ab}) showed greater intraspecific than inter-specific (cactus-millet) competition from the cactus, whereas, with mulch, the values for K were positive, showing that there was no intraspecific competition from the cactus. In general, the intercropped systems showed intraspecific competition, which was more pronounced in the system with no mulch.

The competitive ratio of the forage cactus (CR_{ab}) was on average 31.47 times greater than that of the millet, whether the cropping system included the use of straw; this shows the superior competitive ability of the cactus compared to the millet. Values consistent with this research were found by Diniz *et al.* (2017) in a cactus-sorghum intercropping system, where the cactus was more than 16.27 times greater than the sorghum. Reinforcing the CR, the aggressivity index (A) shows the cactus to be superior to the millet. Relating the actual loss or gain in yield (ALGY), the cactus showed a high productive return, especially when grown under straw, while the millet proved to be more vulnerable to a loss in yield, showing the cactus to be the dominant species in the system (Bi *et al.,* 2019; Jardim *et al.,* 2021b). However, according to the same authors, ALGY indicates an advantage to the intercropping system compared to single crops.

Economic analysis

The profitability index (PI) is used to measure the economic viability of a project, i.e. the return achieved on the capital invested in setting up the project, demonstrating the capacity of an enterprise to generate profit. The higher the PI value, the more promising is the project for generating profit (Barbieri *et al.,* 2016). The highest PI values were achieved by the OEM clone under the systems with no irrigation in experiment I when sold as forage; in the same area, the MIU clone had the highest PI value in the rainfed system with mulch when sold as seed. In experiment II (different irrigation depths), the lowest values were reported in the systems that invested in irrigation. The systems that included cactus of genus *Nopalea* with irrigation showed less economic return when sold as forage due to low productivity and the high cost of setting up the system and required more production cycles to amortize the initial costs. The use of the OEM clone proved to be quite promising in increasing economic return, especially when combined with mulch.

Conclusion

The environment shapes the crop response, affecting the yield and economic return of production systems, especially in semi-arid environments, where there is high atmospheric demand and a large spatio-temporal variation in rainfall, which limits traditional cropping systems. Adopting appropriate agronomic practices helps to improve the use of available resources. The productive advantages of the forage cactus were evaluated for the adoption of joint management practices: clone-irrigation-mulching, clone-different irrigation depths, intercropping-mulching, and different levels of mulch. Under the combined practice of clone-irrigation-mulching, the plants are more sensitive to irrigation, reducing productivity and increasing the rate of plant mortality. The best yields were achieved by the 'Orelha de Elefante Mexicana' clone, where the rainfed systems and those with straw proved to be the most promising. For crops under different irrigation depths, the irrigated systems did not contribute to an increase in yield or to the economic return of the clones. The highest productivity was achieved by the 'Orelha de Elefante Mexicana' clone. The intercropping systems that included mulching improved the profitability of the system in relation to the single crops. Cultivating millet under a water-deficit regime is not feasible during periods of acute water shortage since the return on invested capital is low. The plants responded satisfactorily to the different levels of mulching, with increased production and economic return. In years with more rainfall, it is generally advisable to adopt the 'Orelha de Elefante Mexicana' clone intercropped with millet with greater levels of mulch to improve productive yield and economic profitability in stressful environments.

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