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Combined agricultural practices in millet and cactus: phyllochron, structural characteristics and relations with yield

Gabriel Italo Novaes da Silva[1]*, Alexandre Maniçoba da Rosa Ferraz Jardim[1], Marcondes de Sá Souza[1], George do Nascimento Araújo Júnior[1], José Edson Florentino de Morais[2], Luciana Sandra Bastos de Souza[2], Carlos André Alves de Souza[1], Cleber Pereira Alves[1], Gherman Garcia Leal de Araújo[3], Abelardo Antônio de Assunção Montenegro[2], Breno Leonan de Carvalho Lima[4], Thieres George Freire da Silva[2]

[1]Universidade Federal Rural de Pernambuco – Depto. Engenharia Agrícola, R. Dom Manuel de Medeiros, s/n – 52171-900 – Recife, PE – Brasil.

[2]Universidade Federal Rural de Pernambuco/UAST – Av. Gregório Ferraz Nogueira – 56909-535 – Serra Talhada, PE – Brasil.

[3]Embrapa Semiárido, BR 428, km 152 – 56302-970 – Petrolina, PE – Brasil.

[4]Instituto Nacional do Semiárido (INSA), Av. Francisco Lopes de Almeida, s/n, Serrotão – 58434-700 – Campina Grande, PB – Brasil.

*Corresponding author <gabrielitalo.novaes@gmail.com>

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ABSTRACT: Variation in rainfall affects crops; therefore, agricultural practices become essential for forage production in semi-arid regions. This study aimed to evaluate the influence of different agricultural practices on phyllochron, structural characteristics of forage cactus and millet, and their relations with crop yield using the principal component analysis (PCA). The design was in randomized blocks, with six treatments: sole cropped cactus without straw mulching, sole cropped cactus with straw mulching, sole cropped millet without straw mulching, sole cropped millet with straw mulching, and cactus intercropping with millet, with and without straw mulching, each with four replicates. There were three cactus cycles and nine millet cycles (three cycles of cultivars BRS1501 and six of IPA Bulk-1-BF). Biometric parameters were evaluated monthly, while yield was determined after the crop harvest. Phyllochron was determined with the regression analysis. The PCA was applied to structural characteristics and yield. The systems adopted did not influence the structural characteristics of cactus and millet ($p > 0.05$), except for cladode thickness, which increased with straw mulching. Phyllochron of the millet reduced when the crop was intercropped. The structural characteristics of cladode length, width, and thickness influenced crop yield, mainly in systems with straw mulching. Straw mulching and intercropping alter phyllochron of cactus and millet. The adoption of straw mulching has a more significant relationship with cactus yield, whereas biometric variables influence crop yield for millet, not the cropping system.

Keywords: intercropping; straw mulching; principal component analysis; phyllochron; semi-arid region

Introduction

Livestock farming is an important activity in arid and semi-arid regions and is susceptible to the seasonality of the rainfall regime and the consequent reduction of forage supply (Jardim et al., 2021a; Souza et al., 2022). Therefore, expanding the options for the adaptation of forage crops and adopting agricultural practices, such as minimal irrigation, intercropping, and straw mulching, represents a form of coexistence with climatic adversities (Souza et al., 2019; Souza et al., 2021).

Forage cactus (*Opuntia* and *Nopalea*) is an alternative used in animal feed in semi-arid environments. It has good adaptation due to its anatomical and morphophysiological characteristics and high-water use efficiency (Araújo Júnior et al., 2021; Jardim et al., 2021b). However, forage cactus is a crop with low fiber content; thus, its exclusive use as animal feed should be avoided, since it can cause disturbances in animal metabolism (Diniz et al., 2017; Moraes et al., 2019). In this sense, adapted forage grasses, such as millet [*Penissetum glaucum* (L.) R. Br.], can complement to animal feed (Souza et al., 2019; Lira et al., 2020).

Agricultural resilience practices are studied for forage production in semi-arid regions (Jardim et al., 2021a). In this context, intercropping provides better use of the area and natural resources and improves soil properties (Hong et al., 2019; Li et al., 2019). Another strategy is using straw mulching, which increases soil moisture by reducing water loss through evaporation (Ibrahim et al., 2020; Wang et al., 2020). Finally, minimal use of irrigation promotes better crop growth and yield (Araújo Júnior et al., 2021).

The application of agrometeorological indicators in agricultural systems ensures better planning and decision-making. Among these parameters, morphogenesis and phyllochron are excellent options for understanding crop development and yield under different managements (Tenorio et al., 2017). The multivariate analyses, which include the principal component analysis (PCA), are widely used in several areas because they reduce the data set (Neder et al., 2013). Studies on the relationship between structural characteristics and yield of forage cactus and millet under different types of management are incipient in the literature (Jardim et al., 2020). Thus, the use of PCA can improve the understanding of the effects of adopting different managements to cactus and millet cropping systems.

To address these gaps in knowledge, we hypothesize that intercropping and straw mulching have advantages in the plant growth of forage cactus and millet. Therefore, this study aimed to evaluate: (i) these systems in the structural characteristics of forage cactus and millet, (ii) the phyllochron of these cultures, and (iii) the relationship of structural characteristics with yield in successive cycles in a semi-arid environment.

Materials and Methods

Study site

The study was carried out in the experimental field of the International Reference Center for Agrometeorological Studies of the Cactus and other Forage Plants, in the municipality of Serra Talhada (7°56′20″ S latitude; 38°17′31″ W longitude and 499 m altitude), in the semi-arid region of Pernambuco State, Brazil.

The climate of the municipality is BSwh′ with a rainy season in the summer, according to Köppen climate classification (Alvares et al., 2013). The average rainfall is 642 mm yr^{-1}, with potential evapotranspiration of 1,800 mm yr^{-1} and air temperature between 20.1 °C and 32.9 °C (Souza et al., 2022). The soil of the study site is a typical Eutrophic Ta Haplic Cambisol (Jardim et al., 2021a). Samples were collected to determine soil physical and chemical attributes at depths of 0.00-0.20 m (Table 1).

Experiment, plant material, and cultural practices

Initial preparation consisted of one plowing and one harrowing operation. The forage cactus clone was 'Orelha de Elefante Mexicana' [*Opuntia stricta* (Haw.) Haw.], planted in July 2016 at a spacing of 1.6 × 0.2 m (31,250 plants ha^{-1}). Millet [*Pennisetum glaucum* (L.) R. Br.], cultivar BRS 1501, was sown on February 12, 2017, at a distance of 0.4 m from the cactus crop. At 15 days after sowing (DAS), thinning was performed, leaving 20 plants per linear meter (150,000 plants ha^{-1}).

The experimental trial lasted four years, with three production cycles of forage cactus and nine cycles of millet: the first cycle of cactus lasted two years (July 2016 to June 22, 2018), associated to six cycles of millet, using cultivar BRS 1501 (sown on February 12, 2017), with one sowing and two regrowth events, and three more cycles with cultivar IPA Bulk-1-BF (sown on September 15, 2017), represented by: Cactus(I)-BRS1501(I), Cactus(I)-BRS1501(II), Cactus(I)-BRS1501(III), Cactus(I)-IPA Bulk-1-BF(IV), Cactus(I)-IPA Bulk-1-BF(V), and Cactus(I)-IPA Bulk-1-BF(VI), respectively. The second cycle of cactus lasted one year, starting after thinning of second-order up cladodes on February 25, 2019, and ending on January 20, 2020, with two cycles of millet cultivar IPA Bulk-1-BF (*i.e.*, sown on February 27, 2019, and October 10, 2019): Cactus(II)-IPA Bulk-1-BF(VII), Cactus(II)-IPA Bulk-1-BF(VIII), respectively. The third cycle of cactus lasted five months (January 20 to June 26, 2020) due to the harvest of the millet cultivar IPA Bulk-1-BF: Cactus (III)-IPA Bulk-1-BF(IX).

The experiment was carried out in a randomized block design, with six treatments (*i.e.*, sole cropped cactus without straw mulching—CNM, sole cropped cactus with straw mulching—CWM, sole cropped millet without straw mulching—MNM, sole cropped millet with straw mulching—MWM, cactus-millet intercropping with straw mulching—CMWM and without mulch—CMNM) and four replicates. The straw mulching consisted of *Urochloa mosambicensis* (Hack.) Dandy obtained near the experimental site. A decomposition rate of 0.0049 t ha^{-1} d^{-1} was applied in January 2017, February 2019, and January 2020 for the first, second, and third cycles of forage cactus, respectively, totaling 17.6 t ha^{-1} on a dry basis. During the forage cactus cycle, there was no replacement for straw mulching.

Manual weeding and cultural practices were performed whenever necessary. Fertilization of the first cactus cycle was based on the formulation 14-00-18 (NPK) + 16S, with an application of 525 kg ha^{-1} as basal and top-dressing (73.5 kg ha^{-1} N, 94.5 kg ha^{-1} K_2O and 84.0 kg ha^{-1} S), according to Diniz et al. (2017). In the second cycle, the amounts applied were 234.3 kg ha^{-1} N, 46.8 kg ha^{-1} P, and 76.1 kg ha^{-1} K_2O, according to the soil analysis.

Irrigation began in the experiment in January 2017 three times a week on alternate days using a drip system. The irrigation water was obtained from an artesian well, with electrical conductivity of 1.62 dS m^{-1} and classified as C3, with high salinity and sodium (Na) and potassium (K) concentrations of 168.66 and 22.17 mg L^{-1}, respectively. The flow rate of the drippers was 1.25 L h^{-1} with a working pressure of 100 kPa, uniformity coefficient of 93 %, and spacing between emitters of 0.4 m.

Irrigation was scheduled based on replacing 120 % of crop evapotranspiration (ET_c), adopting a K_c of 0.52 for cacti. ET_c was obtained by the product between reference evapotranspiration (ET_0) and K_c,

Table 1 – Physical and chemical properties of a typical Eutrophic Ta Haplic Cambisol in the 0.00-0.20 m layer in the municipality of Serra Talhada, Pernambuco, Brazil.

ρ_d	Ø	Sand	Silt	Clay
kg dm^{-3}	%	g kg^{-1}		
1.45	42.27	828.6	148.3	23.2

Soil chemical properties

ECe	pH	OC	P	K	Na	Ca	Mg	CEC	V
dS m^{-1}		g kg^{-1}	mg dm^{-3}	$cmol_c$ dm^{-3}					%
0.33	6.0	4.6	168.96	13.8	1.09	3.5	1.9	20.9	97.2

ρ_d: Soil bulk density; Ø: Total soil porosity; ECe: Electrical conductivity of the saturated soil extract; CEC: Cation exchange capacity; P: Phosphorus; OC: Organic carbon; K: Potassium; Na: Sodium; Ca: Calcium; Mg: Magnesium; and V: Base saturation.

while ET_0 was obtained by the Penman-Monteith method, parameterized by the FAO-56 bulletin (Allen et al., 1998). For that, meteorological variables: global solar radiation (R_g, MJ m^{-2} d^{-1}), average air temperature (T_a, °C), average relative humidity (RH, %), wind speed (u, m s^{-1}), atmospheric pressure (P_a, kPa) and rainfall (R, mm) were obtained daily through an automatic weather station of the National Institute of Meteorology and located 40 m away from the experiment. ET_0, rainfall and irrigation were equal to 4.96 mm d^{-1}, 1,069.20 mm and 1,008.73 mm, in the first cycle, 4.93 mm d^{-1}, 748.20 mm and 573.46 mm in the second cycle, and 3.56 mm d^{-1}, 975.8 mm and 0 mm in the third cycle, respectively (Figure 1).

Structural characteristics of cactus and millet

Biometric campaigns were carried out monthly in one plant per plot to obtain the structural characteristics of cactus. We recorded plant height (measurement from the soil surface to the highest cladode), plant width (average horizontal distances between the most extreme cladodes), and the total number of cladodes (TNC). A representative branch of the plant was selected to measure the cladode data. Cladode length (CL), width (CW), perimeter (CP), and thickness (CT) were measured with a measuring tape and a caliper.

Cladode area (CA) and cladode area index (CAI) were obtained by following the methodologies of Silva et al. (2014) and Pinheiro et al. (2014), respectively (Equations 1 and 2).

$$CA = 0.7086 \frac{\left(1 - \exp\left(0.000045765 - CL - CW\right)\right)}{0.000045765} \quad (1)$$

$$CA = \frac{\dfrac{\left(\sum_{n}^{i=1} CA\right)}{10,000}}{S1 \times S2} \quad (2)$$

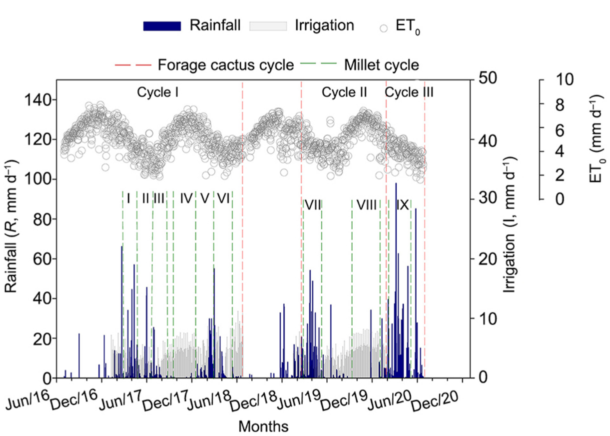

Figure 1 – Rainfall (R), reference evapotranspiration (ET_0) and irrigation (I) from June 2016 to June 2020 in an experimental area of forage cactus as sole crop and intercropped with millet with and without straw mulching in Serra Talhada, Pernambuco State, Brazil.

where: CA: cladode area (cm^2); CL: cladode length; and CW: cladode width (cm); CAI: cladode area index (m^2 m^{-2}) obtained through the sum of cladode area; 10,000: conversion factor from cm^2 to m^2; S1 and S2: spacing between rows and plants (1.6 × 0.2 m), respectively.

Biometric data of millet were obtained at harvest and in the cycle of IPA Bulk-1-BF(VII) collected every 15 days. Plant height (PH) was measured from the base of the main stem to the base of the panicle. We recorded plant width (PW), stem thickness (ST), number of live leaves (NLL, *i.e.*, fully expanded), dead leaves (NDL, *i.e.*, with more than 50 % of the compromised photosynthetic area), number of tillers (NTill), panicle length (PanL), panicle width (PanW), leaf 3+ length (LL, *i.e.*, the third-uppermost fully expanded leaf) and leaf 3+ width (LW). Leaf area (LA) was determined according to Leite et al. (2019) using Equation 3 and leaf area index (LAI) was obtained by Equation 4 (Souza et al., 2021).

$$LAI = 0.879 \cdot L \cdot W^{0.971} \quad (3)$$

$$LAI = \frac{\left\{\dfrac{\left[\left(0.879 \cdot LW\right)^{0.971}\right]\left(NLL \cdot FPD\right)}{10,000}\right\}}{\left(S1 \cdot S2\right)} \quad (4)$$

where, LA: leaf area (cm^2); $L \cdot W$: product of leaf blade length and width; LL: leaf length (cm); LW: leaf width (cm); NLL: number of live leaves (units); FPD: final plant density; and S1 and S2: spacings of the millet crop (1.6 × 0.05 m).

Cactus and millet yield

Cactus yield was obtained at the end of each cycle by weighing the cladodes harvested from the usable plot, except for the basal and first-order cladodes. Cladodes from a representative plant were counted and weighed on a scale. Then, two cladodes of the middle third were selected for weighing, fractionated, placed in identified paper bags, and taken to a forced air circulation oven at 55 °C. They remained until reaching constant weight. The dry matter (DM) content was obtained by the ratio between the values of dry and fresh matter (Alves et al., 2022).

The number of plants in two linear meters within the usable area was counted or millet yield. Then, ten plants were harvested per plot and weighed to obtain fresh biomass. After weighing, two plants per plot were selected, divided into living leaves, dead leaves, stem, and panicle, and placed in paper bags. Subsequently, they were weighed to obtain the fresh matter weight and placed in a forced air circulation oven at 55 °C to obtain the DM weight (Alves et al., 2022).

Phyllochron

The cladode appearance rate (CAR, cladode °C d^{-1}) of cactus in cycle I and the leaf appearance rate (LAR, leaf °C d^{-1}) of millet in cycle VII were quantified by the angular coefficient of the line from the linear regression, with the accumulated degree-days (ADD) as the independent variable and the total numbers of cladodes and leaves (TNC and TNL, respectively) as the dependent variable. For cactus, two values of phyllochron were determined for phases I and II (fast growth and slow growth, respectively). The ADD were obtained by the difference between the average air temperature and lower base temperature (Tb) equal to 22 °C for cactus per analysis (Souza et al., 2021) and 10 °C for millet (Norman et al., 1995). Phyllochron was determined by the inverse of CAR or LAR (PHYLL = 1/CAR or 1/LAR).

Statistical analysis

Data on structural characteristics in each cycle of forage cactus and millet of all cropping systems were subjected to the normality test (Shapiro-Wilk test), homoscedasticity (previously established by Bartlett's test), and analysis of variance by the F-test ($p < 0.05$). In addition, the hypothesis is tested, and if the significance value is < 0.05, then H_0 is rejected, H_1 is accepted, and vice versa. If the value of significance is > 0.05, then H_0 is taken. When the significance value was significant, the Tukey test was carried out at 5 % probability level ($p < 0.05$). Linear regressions were fitted to the data of phyllochron using linear models of the form $y = \beta_0 + \beta_1 x$, where y is the dependent variable (*i.e.*, the total number of cladodes and leaves of forage cactus and millet, respectively), x is the independent variable (accumulated degree-days), β_0 (intercept) and β_1 (slope) are coefficients that quantify the degree and direction of the effect of x over y (Jardim et al., 2022). The relationship between biometric variables and biomass was analyzed by the principal component analysis (PCA), considering only eigenvalues above 1.0 (Kaiser, 1960), due to the significance of their responses in relation to the variables analyzed. In the PCA, each principal component represents a proportion of the total variation in the dataset. All statistical analyses were performed using the R software (version 4.1.3) with the 'FactoMineR' and 'factoextra' packages.

Results

Analysis of structural characteristics of forage crops

The use of the intercropping system and the straw mulching did not influence plant height (PH) and width (PW), as well as the total number of first-, second- and third-order cladodes and cladode area index of forage cactus in the three production cycles ($p > 0.05$) (Table 2). Although the variables did not show statistical differences, the mean values of PH and PW tended to decrease with intercropping, regardless of using straw mulching.

In the structural analysis of cactus cladodes, there was a significant difference only for the thickness of the second-order cladode in the first production cycle ($p < 0.05$), which increased when straw mulching was used, regardless of the cropping system (Figure 2A), with an increase of 26 % compared to CMNM, but with no significant difference from the CNM treatment.

For millet, the structural analysis showed a significant difference ($p < 0.05$) in all variables studied only in cycle VI, because there was no regrowth when the crop was intercropped (Figures 2B and 2C). In the other cycles, there was no significant difference ($p > 0.05$), except for stem thickness in cycles II and VII (Figure 2D). When millet was subjected to the intercropping system, there were reductions of 21 % and 35 % compared to the sole cropping system for cycles II and VII, respectively.

Phyllochron of forage crops

In the first phase, there was a higher rate of appearance of cladodes, with values of 0.0050, 0.0051, 0.0067, and 0.0054 cladode °C d^{-1} for CWM, CNM, CMWM, and CMNM, respectively, with an interruption point between 10 and 12 units of cladodes (Figure 3). In the regression analysis, phyllochron was higher in cactus when grown as a sole crop, regardless of straw mulching, with 200 and 196 °C d^{-1} per cladode (CWM and CNM,

Table 2 – Plant height (PH), plant width (PW), total number of cladodes (TNC), number of first-, second- and third-order cladodes (N1, N2, and N3, respectively) and cladode area index (CAI) of the cactus clone 'Orelha de Elefante Mexicana' cultivated under different cropping systems in a semi-arid environment.

Cropping systems	1st Cycle							2nd Cycle						3rd Cycle					
	PH	PW	TNC	N1	N2	N3	CAI	PH	PW	TNC	N1	N2	CAI	PH	PW	TNC	N1	N2	CAI
CNM	71.8 a	78.6 a	13.6 a	4.1 a	7.6 a	0.8 a	1.84 a	75.7 a	73.1 a	19.5 a	5.2 a	13.2 a	2.61 a	75.7 a	60.7 a	19.0 a	4.7 a	13.2 a	2.26 a
CWM	73.4 a	68.6 a	12.2 a	4.3 a	5.7 a	1.2 a	1.63 a	70.7 a	74.2 a	17.5 a	4.2 a	11.7 a	2.14 a	80.0 a	47.0 a	18.0 a	4.2 a	12.7 a	2.26 a
CMWM	67.5 a	73.5 a	13.5 a	4.6 a	6.3 a	1.6 a	1.73 a	71.2 a	64.3 a	16.2 a	5.0 a	9.7 a	1.96 a	76.7 a	64.3 a	21.2 a	4.2 a	16.0a	2.30 a
CMNM	66.0 a	59.8 a	12.7 a	4.3 a	6.3 a	1.0 a	1.33 a	67.2 a	62.6 a	16.0 a	5.5 a	9.5 a	1.95 a	72.7 a	52.0 a	17.2 a	4.2 a	12.2 a	1.89 a
Mean	69.6	70.1	13.0 a	4.3	6.5	1.2	1.63	71.3	68.5	17.1	5.0	11.0	2.16	76.3	56.0	18.9	4.3	13.5	2.18
p-value	0.88	0.41	0.96a	0.95	0.88	0.81	0.79	0.65	0.30	0.71	0.75	0.59	0.73	0.49	0.31	0.81	0.91	0.79	0.82

Abbreviations: sole cactus without straw mulching (CNM); sole cactus with straw mulching (CWM); intercropped cactus-millet with straw mulching (CMWM); and intercropped cactus-millet without straw mulching (CMNM). Note: PH and PW – cm; TNC, N1, N2 and N3 – units; CAI – m^2 m^{-2}.

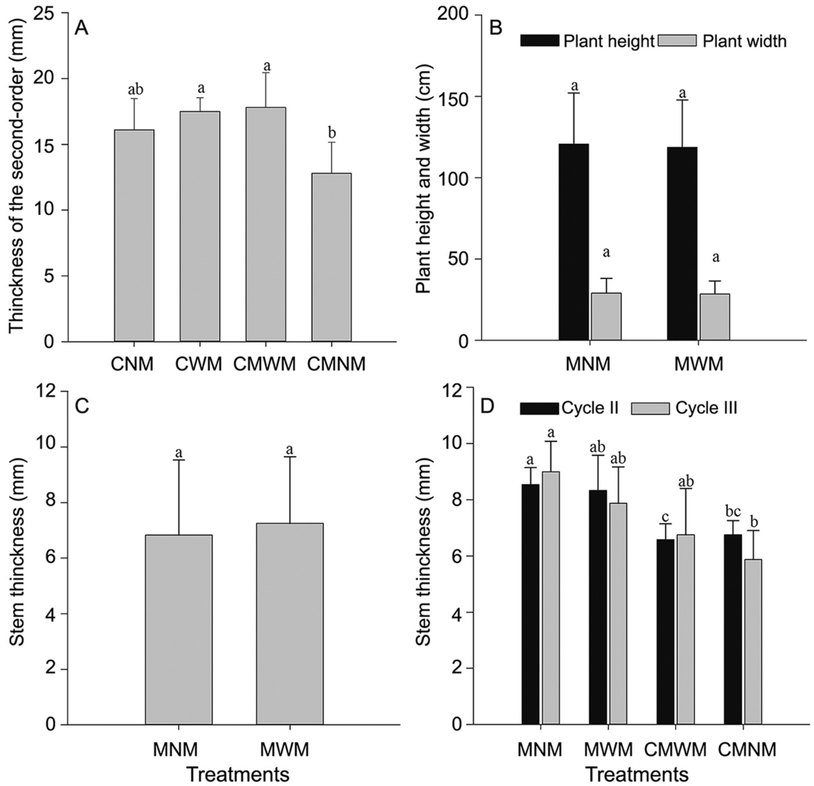

Figure 2 – (A) Thickness of the second-order cladode of the first cycle of forage cactus, clone 'Orelha de Elefante Mexicana'; (B) height and width of the millet plant and (C) stem thickness of VI production cycle; and (D) stalk thickness of millet cycle II and VII. Abbreviations: sole cactus without straw mulching (CNM); sole cactus with straw mulching (CWM); intercropped cactus-millet with straw mulching (CMWM); intercropped cactus-millet without straw mulching (CMNM); sole millet without straw mulching (MNM), and sole millet with straw mulching (CWM).

respectively). CMWM and CMNM cropping systems showed phyllochron values of 149 and 185 °C d^{-1} per cladode, respectively.

The cladode appearance rate was lower in the second phase compared to the first phase, with 0.0017, 0.0020, 0.0007, and 0.0011 cladodes °C d^{-1} for CWM, CNM, CMWM, and CMNM, respectively. Phyllochron was higher in treatments with intercropping cactus, with 1,429 and 909 °C d^{-1} per cladode for CMWM and CMNM, respectively, while the sole-crop cactus had lower phyllochron (588 and 500 °C d^{-1} per cladode, for CWM and CNM, respectively).

The relationship between the total number of leaves and accumulated degree-days generated a coefficient of determination (R^2) of 0.82 for millet as sole crop with straw mulching. At the same time, R^2 was higher than 0.90 for millet intercropping without straw mulching, millet as a sole crop without straw mulching, and millet intercropping with straw mulching, respectively (Figure 4). Millet showed leaf appearance rates (LAR) of 0.0050, 0.0073, 0.0078, and 0.0092 for MWM, CMNM, MNM, and CMWM, respectively.

Phyllochron was obtained as the inverse of LAR. In this experiment, values of 108.7, 128.2, 136.9, and 200.0 °C d^{-1} per leaf were found for CMWM, MNM, CMWM, and MNM, respectively.

Principal component analysis

The principal component analysis (PCA) was performed to investigate the influence of biometric variables on cactus yield in different cropping systems (Figure 5).

The variables closer to the origin horizontally showed lower weights for the principal components 1 and 2 (PC1 and PC2, respectively) (Figures 5A and 5B) in the analysis, for example, the length of the basal cladode (CLB), N2, and TNC. The PCA allowed us to identify the separation of three distinct groups (Figure 5A). PC1 explained 55 % of the total variation of the data and contained CNM and CWM cropping systems (Figure 5A), along with the variables with the highest loading (*i.e.*, vectors with loadings greater than 0.8); in general, this explanation is due to the biometric variables of third-order cladodes (Figure 5B).

With 27 % of the total variance, principal component 2 (PC2) explained this variation and comprised the CMWM system. The variables first-order cladode length (CL1) and number of first-order cladodes (N1), along with N3, had higher loadings (0.80, 0.68, and 0.89, respectively).

The CMNM system was included in principal component 3 (PC3), although it was not presented in the biplots. PC3 had an eigenvalue above 1.0, as established

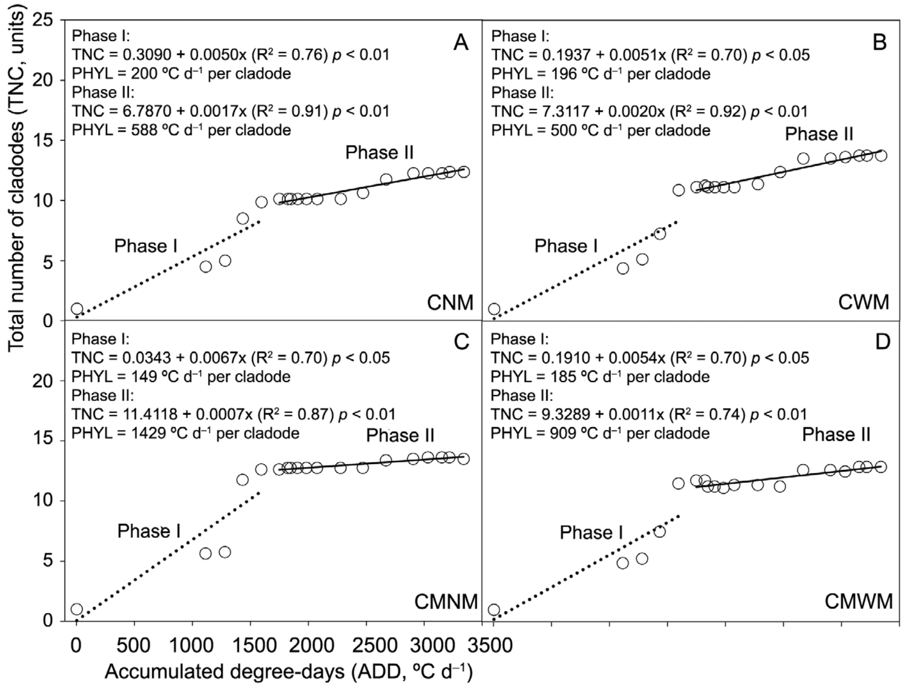

Figure 3 – Cladode appearance rate (cladodes °C d^{-1}) and phyllochron (°C d^{-1} per cladode) of forage cactus, clone 'Orelha de Elefante Mexicana', as sole crop with straw mulching (A), as sole crop without straw mulching (B), intercropped with millet with straw mulching (C) and intercropped with millet without straw mulching (D) as a function of accumulated degree-days (ADD, °C d^{-1}), for the first production cycle of forage cactus. All regression lines are significant at a *p*-value of 0.01.

by the criterion of Kaiser (1960) for use of explanatory variables; however, few variables were grouped in this component (*e.g.*, the thickness of the basal cladode—CTB), not influencing the response of the main components. Forage yields and the other variables, that is, second-order cladode length, width, perimeter, and area (CL2, CW2, CPO2, and CA2, respectively) and CAI were not grouped with some cropping system. However, they were included in PC2 and the CMWM system was included in this component, with a higher correlation with forage yield for this system, but a negative correlation (-0.59) with the dry matter content (DMC).

During cycle II of cactus, the biometric and forage yield variables were more grouped with the CNM, CWM and CMNM systems (Figures 5C and 5D). The systems with the highest contributions in PC1 were CNM and CMNM. In PC2, data variances were explained with 33 %. The CWM system was included in this PC, with more significant loadings, in particular for the variables of basal cladodes. The CMWM system had more weight in PC3 and it was not presented because there was no significance of the variables in this component.

Figures 5E and 5F show the PCA of cycle III of cactus in its cropping systems. PC1 explained 45 % of the variance of the data presented, while PC2 explained 41 %, totaling a contribution of 86 % to the total variation. The variables included in PC1 showed higher contributions with negative correlations with the CMNM system. The systems with the use of straw mulching were more significant in PC2 (*i.e.*, CWM and CMWM), with variables of higher weight for first-order and basal cladodes.

The evaluation of millet crops in the different cropping systems showed a dispersion of the scores of the results. Figure 6 shows the biometric and yield variables of the millet crop in its nine cycles. PC1 and PC2 explained 49 % and 12 % of the data variance, respectively, contributing to a total data variance of 61 %. Among the principal components evaluated, cycles I and VI were more significant in PC1 and cycles V and VIII were more significant in PC2. The other cycles showed dispersions in the other components with low contributions. Most structural variables of biometric and yield characteristics (fresh matter—FMY and dry matter—DMY) were more significant in PC1 (Figures 6A and 6B), while the number of living leaves of the plant (NLLP) and FPD were more significant in PC2. The NDL variable showed low contribution in the analysis.

Discussion

Analysis of structural characteristics of forage crops

The cropping system (intercropping or sole cropping) and straw mulching (with and without) had no effects on the structural characteristics of cactus. This type of response is attributed not only to the environment and management used, but also to an inherent effect to plant genetics (Dubeux Júnior et al., 2006; Queiroz et al., 2015),

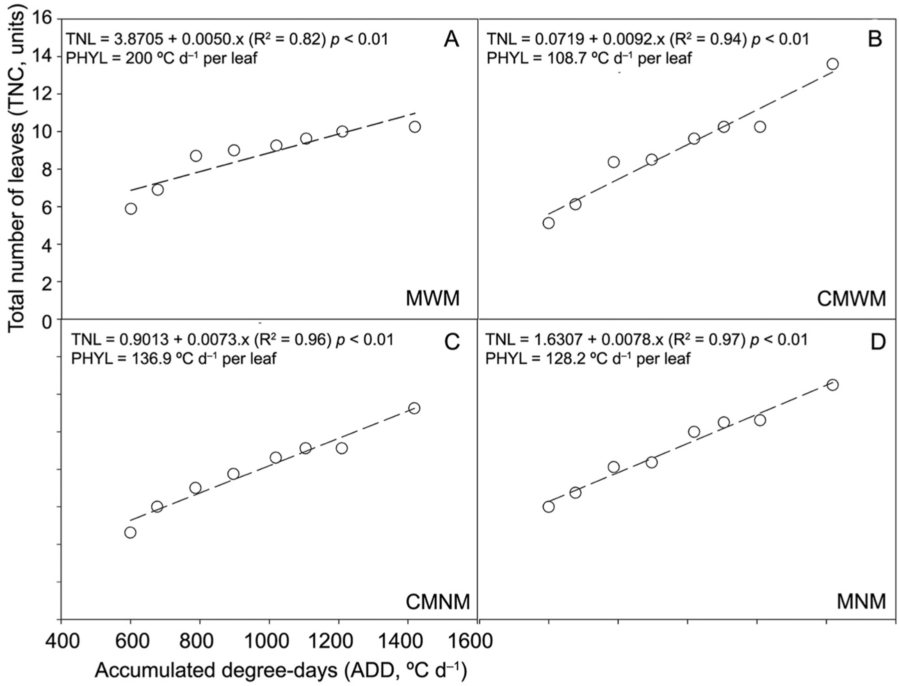

Figure 4 – Leaf appearance rate (leaf ºC d^{-1}) and phyllochron (ºC d^{-1} per leaf) of millet as sole crop with straw mulching (A), intercropped with straw mulching (B), intercropped without straw mulching (C) and as sole crop without straw mulching (D) as a function of accumulated degree-days (ADD, ºC d^{-1}), for the seventh production cycle of millet. All regression lines are significant at a *p*-value of 0.01.

the type of intercropping (Lima et al., 2018), in this case, millet has low aggressiveness in relation to forage cactus culture (Souza et al., 2021).

The higher production of second-order cladodes in relation to first and third-order cladodes is mainly due to the genetic characteristic of the clone 'Orelha de Elefante Mexicana', which allocates more energy to the production of these cladodes. Moreover, there was an influence of solar radiation on the plant, where young cladodes presented a more significant stimulus to photosynthesis, affecting plant growth, the appearance of new cladodes, and consequently, their productivity (Barbosa et al., 2018; Araújo Júnior et al., 2021; Jardim et al., 2021b). First-order cladodes support plant architecture (Queiroz et al., 2015). Souza et al. (2021) investigated intercropping of forage cactus with clone 'Orelha de Elefante Mexicana' with millet and did not observe a significant difference between the production systems, with an average of cladodes of 13.3 units.

The third-order cladodes had a lower appearance rate and required a more accumulateddegree-days (Souza et al., 2021). According to Amorim et al. (2017), production of third-order cladodes may start from the nineth month of the crop cycle depending on the management adopted; however, it may not be advantageous, as they have a small photosynthetic area, which does not significantly influence biomass production, serving more as a sink for photoassimilates.

The CAI is directly related to the morphological variables, cladode length, width and area (Pinheiro et al., 2014). The CAI allows for estimating the photosynthetic capacity of cactus, besides contributing to the measurement of vegetative growth (Pinheiro et al., 2014); Silva et al., 2014). The increase in the turgor of the second-order cladode may be due to the use of straw mulching, as it reduces water evaporation in the soil, altering the soil-water-atmosphere ratio, in addition to avoiding direct exposure to solar radiation, increasing water storage in the soil through precipitation and irrigation, which is used for plant growth (Qin et al., 2021; Li et al., 2022).

In the millet crop, although intercropping favors a better use of natural resources, in this study, the structural characteristics of the plant cycle tended to decrease when the millet crop was intercropped, due to greater competition for natural resources (*i.e.*, water, light, and nutrients), since cactus is a more aggressive crop than millet (Souza et al., 2022). In the regrowth cycles, in addition to the intercropping effect, the reduction is also linked to an intrinsic characteristic of the millet crop because, after harvest, there is a more significant investment in the development of tillers. of tillers. Millet is a drought-tolerant and low fertility-tolerant crop; nevertheless, a good initial establishment is necessary to ensure good crop growth (Havilah, 2011). An evaluation of the intercropping system of forage cactus with millet showed an average plant height of 143.6 cm (Souza et al. 2021), similar to the findings in our study.

Intercropping influenced the reduction in stem thickness. Millet stem diameter is one of the main

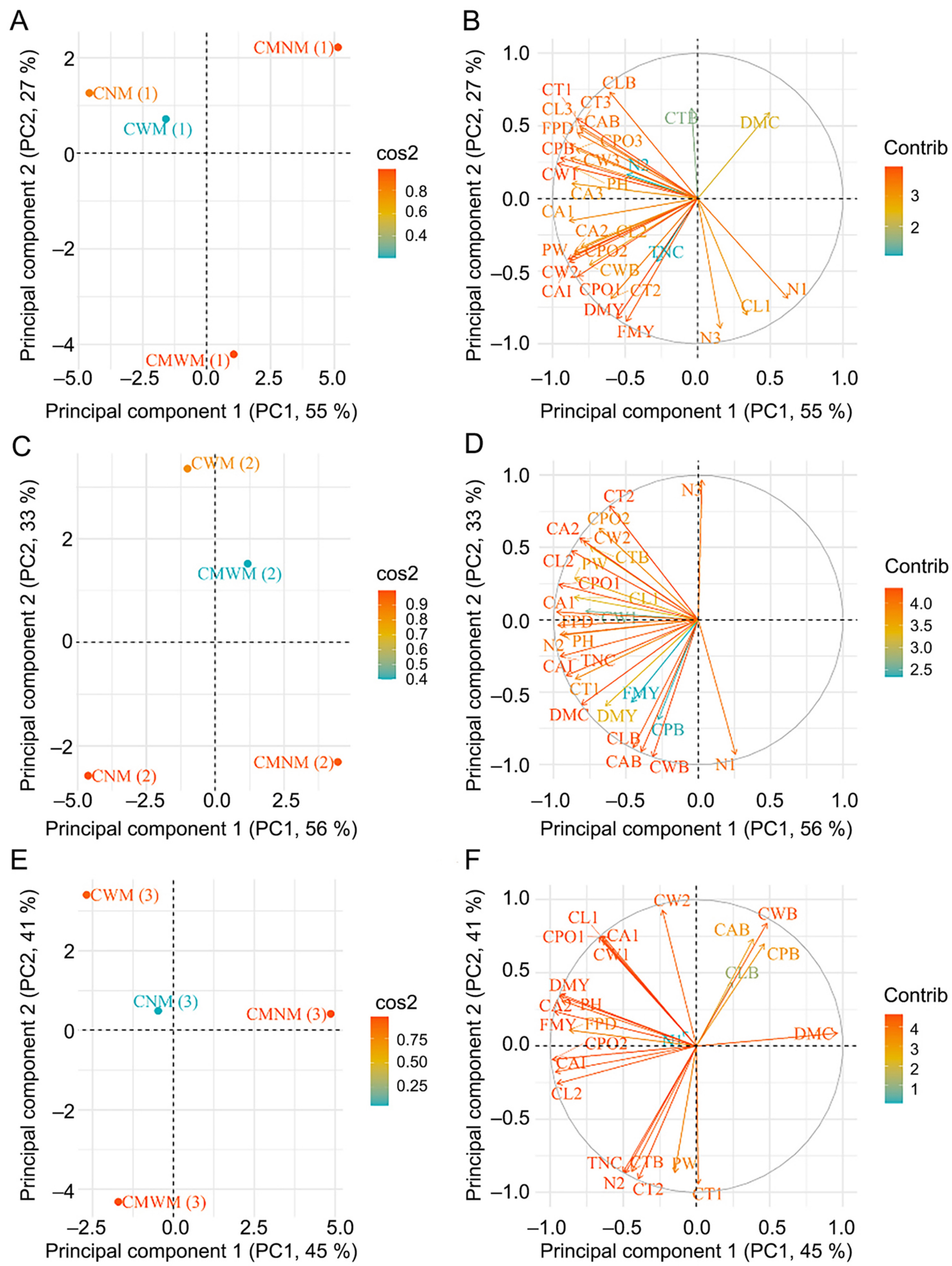

Figure 5 – Principal component analysis (PCA) of biometric and yield variables for the three cycles of cactus in different cropping systems. Note: A, C and E are the plots of PCA scores in cycles I, II and III, respectively. B, D and F are the plots of loadings for cycles I, II and III, respectively. Percentage values between parentheses (x- and y-axes) indicate the proportion of variance explained for each principal component (PC1 and PC2).

morphological characteristics since it serves as a structure of support for the leaves and is also related to the physiological factor. Stems are structures that store soluble solids, which are converted to produce carbohydrates in the grains during the reproduction stage; therefore, plants with greater stem thickness tend to be more vigorous and productive (Fancelli and Dourado Netto, 2000; Souza et al., 2021).

Phyllochron of forage crops

The relationship between the number of cladodes and the accumulated degree-days (ADD) pointed to a biphasic linear relationship. The same behavior has been observed in long-cycle crops, such as sugarcane (Streck et al., 2010). In the first phase, the use of the intercropping cactus reduced its thermal sum to obtain

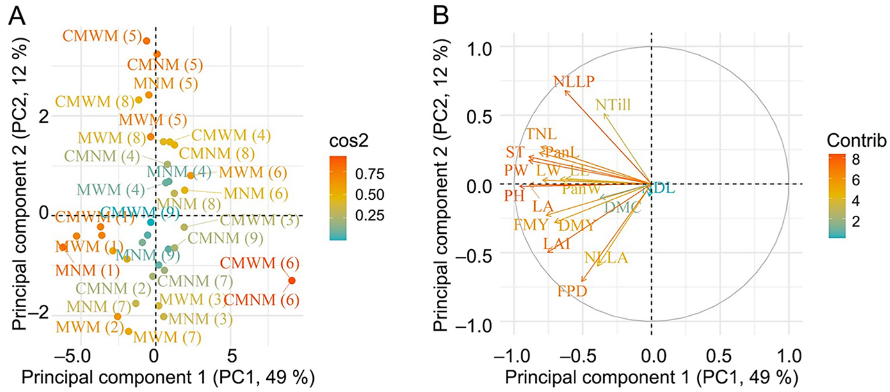

Figure 6 – Principal component analysis (PCA) of biometric and yield variables of the nine cycles of millet in different cropping systems. Note: A and B are the plots of PCA scores and loadings, respectively. Percentage values between parentheses (x- and y-axes) indicate the proportion of variance explained for each principal component (PC1 and PC2).

a new cladode unit due to the temperature difference during the experiment.

Millet phyllochron was shorter in intercropping and without straw mulching; that is, the plant needed fewer ADD to produce a new leaf (Figure 3). The interaction between species can influence the variation and distribution of light energy in intercropping and straw mulching, changing the time of onset and duration of phenology (Jardim et al., 2021c). This study attributed this reduction to competition with forage cactus and millet plants (Souza et al., 2022).

Principal component analysis

The analyses above 60 % of the total variation in the first and second principal components can be used to identify the association between structural characteristics and yield (Jardim et al., 2020) or they can also be explained when their eigenvalues are above 1 (Kaiser, 1960). Third-order cladodes do not significantly influence yield because they are found in smaller numbers and have a smaller photosynthetic area (Amorim et al., 2017).

The influence of second-order cladode is due to the genetic characteristics of the 'Orelha de Elefante Mexicana' clone, as it forms a more open canopy to provide a greater capture of solar radiation (Queiroz et al., 2015). The PCA applied to cactus crop in different configurations showed that structural characteristics (*i.e.*, cladode length, width, perimeter, and area) are the variables that determine cactus biomass accumulation (Jardim et al. 2020).

The contribution to the total variance in cycle II of cactus was 88.58 %. PC1 explained 55.86 % of the data variance, with vector loadings ≥ 0.6 for plant variables, for first-order and second-order cladode variables, as well as DMC and dry matter yield (DMY), as first-order and second-order cladodes are the main responsible to perform the biochemical and physiological processes (Silva et al., 2014; Jardim et al., 2021b).

In cycle III of cactus, the benefits of using straw mulching regardless of the system (*i.e.*, intercropping or sole cropping) became more evident, as it promoted a lower effect of direct radiation on the soil surface, creating a microclimate that favored soil water storage, root growth, water absorption by plants, and consequently, their development (Amorim et al., 2017).

Yield of millet crop was influenced by the structural characteristics (*i.e.*, plant height and width, stem thickness, panicle length and width, leaf area, and leaf area index) due to a greater interception of solar radiation and, consequently, the biochemical and physiological activities carried out by the plant. Dead leaves were not correlated to the other variables and showed low weight in the analysis. Their contributions were less pronounced, as they do not have significant influence on photosynthesis.

Conclusion

The structural characteristics of forage cactus (plant and cladodes) and millet were not influenced by intercropping and straw mulching. The rate of leaf appearance and phyllochron of millet was altered using cropping systems. Straw mulching and intercropping promoted a smaller number of accumulated degree-days in forage cactus phase I, but ADD increased in phase II. In forage cactus, the straw mulching was better grouped with the variables length, width, and cladode thickness, thus influencing yield. Millet yield was affected only by structural characteristics variables and not by the cropping systems. The findings of this analysis provide a better understanding of the relationship between structural and yield characteristics in forage plants. Future research is needed to investigate the performance of both crops in other environments and planting configurations.

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Authors' Contributions

Conceptualization: Silva, G.I.N.; Silva, T.G.F.; Jardim, A.M.R.F.; Morais, J.E.F. **Data curation:** Silva, G.I.N.; Jardim, A.M.R.F.; Souza, M.S.; Araújo Junior, G.N.; Alves, C.P. **Formal analysis:** Silva, G.I.N., Silva, T.G.F.; Jardim, A.M.R.F. **Funding acquisition:** Silva, T.G.F. **Investigation:** Silva, G.I.N.; Jardim, A.M.R.F.; Souza, M.S.; Araújo Junior, G.N.; Alves, C.P. **Methodology:** Silva, G.I.N.; Jardim, A.M.R.F.; Souza, M.S.; Araújo Junior, G.N. **Project administration:** Silva, T.G.F.; Souza, M.S. **Resources:** Silva, T.G.F. **Supervision:** Silva, T.G.F.; Silva, G.I.S. **Writing – original draft:** Silva, G.I.N.; Silva, T.G.F.; Jardim, A.M.R.F.; Morais, J.E.F.; Souza, L.S.B.; Souza, C.A.A.; Araújo, G.G.L.; Montenegro, A.A.A.; Lima, B.L.C.. **Writing-review & editig:** Silva, G.I.N.; Silva, T.G.F.; Jardim, A.M.R.F.; Morais, J.E.F.

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