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Association of morphological and water factors with irrigated forage cactus yield

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ABSTRACT

This study aimed to understand the relationship of morphological characteristics and actual evapotranspiration of forage cactus clones with their productive capacity under different water regimes. The data used in this study were collected between the years 2012 and 2013, in Serra Talhada, State of Pernambuco. The clones Sertânia IPA - IPA, Miúda - MIU and Orelha de Elefante Mexicana - OEM were submitted to three irrigation depths (2.5, 5.0 and 7.5 mm) and three irrigation intervals (7, 14 and 28 days). Cladode and plant morphology, accumulated actual evapotranspiration and yield were obtained at the moment of harvest. Pearson's correlation matrix was elaborated and, in the sequence, multicollinearity, canonical and path analysis were applied. There was no correlation of yield with the soil water supply and actual evapotranspiration of the clones ($p > 0.05$). Forage cactus yield was more associated with peculiarities of the morphological characteristics of the clones than with the different soil water supplies or the crop actual evapotranspiration. However, regardless of the water regime and clone, the vigor of the basal cladodes was highly decisive for the expression of the forage cactus productive capacity.

Palavras-chave:

evapotranspiração
Nopalea sp.
Opuntia sp.
Semiárido brasileiro

Associação de fatores morfológicos e hídricos com a produtividade da palma forrageira irrigada

RESUMO

Objetivou-se, neste trabalho, compreender a relação de características morfológicas e da evapotranspiração real de clones de palma forrageira com sua capacidade produtiva em diferentes regimes hídricos. Os dados usados nesta pesquisa foram coletados entre os anos de 2012 e 2013, em Serra Talhada, PE. Os clones IPA Sertânia - IPA, Miúda - MIU e Orelha de Elefante Mexicana - OEM foram submetidos a três lâminas (2,5; 5,0; e 7,5 mm) e três intervalos de irrigação (7; 14 e 28 dias). Dados morfológicos dos cladódios e da planta, evapotranspiração real acumulada e desempenho produtivo foram obtidos na ocasião da colheita. A matriz de correlação de Pearson foi elaborada e, em seguida, foram aplicadas análises de multicolinearidade, canônica e de trilha. Não houve correlação da produtividade com o suprimento de água e evapotranspiração real dos clones ($p > 0,05$). A produtividade da palma esteve mais associada a peculiaridades das características morfológicas dos seus clones do que aos diferentes suprimentos de água no solo ou à evapotranspiração real da cultura. Mas, independente do regime hídrico e do clone, o vigor do cladódio basal foi bastante decisivo para a expressão da capacidade produtiva da palma forrageira irrigada.



INTRODUCTION

Forage cactus has different varieties belonging to the genera *Opuntia* and *Nopalea*, and, despite having the same photosynthetic process, the crassulacean acid metabolism (CAM), has characteristics that differentiate them, such as morphology and, thus, water use efficiency (Silva et al., 2014a, 2015).

Different from C_3 and C_4 plants, CAM species open their stomata at night to capture the CO_2 necessary for their metabolism, which reduces water transfer to the atmosphere, i.e., evapotranspiration (ET). The ET varies between species, at the same time is affected by the crop management (Allen et al., 1998).

Studies conducted with forage cactus demonstrate that, although it tolerates extreme drought conditions, the application of supplementary irrigation events favors the productive performance, increasing the availability of food in semi-arid regions, especially in the drought period (Flores-Hernandez et al., 2004; Queiroz et al., 2015).

The contribution of morphological and environmental characteristics to the yield of forage cactus clones has been cited in the literature (Silva et al., 2010, 2015; Pinheiro et al., 2014), but it does not contemplate irrigated cultivation and does not meet water parameters, such as actual crop evapotranspiration.

Hence, the association of water-productive factors of the forage cactus planting system with morphological characteristics can establish new indicators of indirect selection of clones that are more productive and with higher water use efficiency for the different sites or that have wide interannual seasonality of rainfalls (Neder et al., 2013; Pinheiro et al., 2014).

This study aimed to understand the association of morphological and water factors of forage cactus clones with productive capacity under different water regimes.

MATERIAL AND METHODS

Morphological, water and production data of forage cactus were collected in an experimental area ($7^{\circ} 56' 20''$ S; $38^{\circ} 17' 31''$ W; 498 m) of the Agronomic Institute of Pernambuco, in Serra Talhada, PE, Brazilian semi-arid region, conducted between the years 2012 and 2013. The soil of the area was classified as Red Yellow Argisol.

The studied clones were IPA-Sertânia - IPA (*Napolea cochenillifera* (L.) Salm. Dick), Miúda - MIU (*Napolea cochenillifera* (L.) Salm. Dick) and Orelha de Elefante Mexicana - OEM (*Opuntia stricta* (Haw.) Haw.) planted in February 2010, at spacing of 1.6 x 0.2 m, with the crop rows along contour lines. The clones were arranged in a randomized block design, in $3 \times 3 \times 3 + 3$ factorial scheme, with three replicates, plus one control for each clone. Until March 2012, the clones were maintained under rainfed conditions, when plants were harvested, leaving only the basal cladode. From this date on, the data started to be collected for the present study, which ended in August 2013, totaling 532 days.

In this period, irrigation events were applied using a drip system (drippers spaced by 0.20 m), adopting three fixed water depths (L) for water replacement (2.5, 5.0 and 7.5 mm, plots)

with three frequencies (F) (7, 14 and 28 days, subplots). The three clones (IPA, MIU and OEM) formed the sub-subplots. Each one was composed of four rows of 20 plants, with total area of 25.6 m² and evaluation area of 11.52 m². Cultivation practices were performed along the vegetative cycle of the crop.

Irrigation depths and frequencies were established based on information surveyed in areas of forage cactus producers of the Rio Grande do Norte state, which irrigated the crop with events of 5.0 mm every 14 days.

The three forage cactus clones received the equivalent to (water supply): 756 (L7.5 F7), 672 (L5.0 F7), 622 (L7.5 F14), 586 (L2.5 F7), 579 (L5.0 F14), 555 (L7.5 F28), 536 (L2.5 F14), 535 (L5.0 F28), 514 (L2.5 F28) and 493 (Control) mm year⁻¹.

At harvest, the measurements of the cladodes (CT - thickness, CL- length, CW - width, CP - perimeter and CA - cladode area per order of appearance: B - basal; 1 - first order; 2 - second order; 3 - third order) and of the plant (TNC - total number of cladodes of the plant per order of appearance - NC1, NC2 and NC3, PH - height and PW - width of the plant, CAI - cladode area index) were obtained through biometric campaign. The adopted procedures were described in Pinheiro et al. (2014) and Silva et al. (2014b, 2015).

Subsequently, all plants of the evaluation area were harvested and weighed to determine the yield per sub-subplot. Five representative cladodes per sub-subplot were sampled to obtain the individual fresh biomass (CFB, g cladode⁻¹) and, after that, for dry biomass (CDB, g cladode⁻¹), the cladodes were dried in an oven at 65 °C, until constant weight. The ratio between CDB and CFB generated the dry matter content (DMC, %). The data of yield and final plant density were used to calculate the fresh matter yield (FMY, t ha⁻¹). The product between DMC and FMY resulted in dry matter yield (DMY, t ha⁻¹).

The actual evapotranspiration of the clones was calculated over time through the data of water content and physical-hydraulic properties of the soil, according to Silva et al. (2014a). In addition, the soil water balance (SWB) method was used for a control volume with depth of 0.70 m, in intervals of 14 days ($ET = P + I \pm Q \pm \Delta WS$, where P - pluviometric precipitation, I - irrigation, Q - vertical water flow in the soil, represented by capillary rise and deep drainage, and ΔWS - water storage variation in the soil, all in mm).

The data of soil water content were monitored using a capacitive sensor (Diviner 2000®, Sentek Pty Ltda., Australia). This sensor was inserted in access tubes installed at depth of 0.90 and 0.10 m away from the crop row, in each sub-subplot. The sensor was calibrated locally, as described by Araújo Primo et al. (2015).

ET values were related to the data of reference evapotranspiration (ET_o) to obtain the ET/ET_o ratio. ET_o was estimated through the Penman-Monteith method (Allen et al., 1998), using meteorological data of an automatic station of the National Institute of Meteorology - INMET, situated close to the area. At the end of the cycle, ET values were integrated (ΣET).

All data were subjected to the Lilliefors test, to verify normality, and subdivided into four groups: plant morphology

- "Plant" (PH, PW, TNC, NC1, etc.); Cladode morphology - "Cladodes" (CLB, CL1, CL2, etc.); evapotranspiration "ET" (ET and ET/ETo) and "YIELD" (CFB, CDB, FMY, DMY and DMC). The latter was considered as response group and the others as explicative groups.

The response variables ("YIELD") were correlated with the explicative variables ("Plant", "Cladodes" and "ET"), through the Pearson's correlation matrix (Cunha et al., 2011). Subsequently, multicollinearity test was applied to the data to detect if the variables within the same group were highly correlated. Then, variables that fitted this condition were removed from the data set as suggested by Toebe & Cargnelutti Filho (2013). Lastly, canonical analysis was applied to evaluate the association between explicative and response groups, and path analysis was applied, in the partitioning of the Pearson's correlation coefficient, to identify its direct and indirect effects (Cunha et al., 2011). The significance of the partial correlation was made through the chi-square test, at 0.01 probability level. All analyses were made in the statistical program "GENES" (Cruz, 2006).

RESULTS AND DISCUSSION

There was no correlation of water supply and actual evapotranspiration of forage cactus (ET and ET/ETo) with crop yield ($p > 0.05$).

The increment of forage cactus production did not respond directly to the increase in soil water supply, which varied between 493 and 756 mm year⁻¹. Hence, the morphological indicators of identification of the most productive clones are not dependent on the water regime of the cultivation environment.

Flores-Hernandez et al. (2004) and Queiroz et al. (2015), applying increasing water depths from 760 to 1380 mm year⁻¹ and from 976 to 1202 mm year⁻¹, respectively, also did not find response of forage cactus production. Queiroz et al. (2015) cite that, under full water availability, the immediate response of the forage cactus may not be observed due to its high capacity of water storage in the cladodes, low water demand and reduced conversion into dry matter. Thus, Scalisi et al. (2016) suggest that controlled reductions in the irrigation depths may not affect the biomass of the plants.

The ET of the clones showed no correlation with their yields, which is justified by the crassulacean mechanism of forage cactus, which, besides minimizing transpiration, increases the importance of the evaporation component (Han & Felker, 1997) so that the increment in ET does not increase yield proportionally.

The morphological factors showed the highest correlation with the productive expression of the clones.

Significant correlation coefficients for the clones IPA and OEM were obtained of the production variables (IPA: DMY, DMC and CFB; OEM: DMY, DMC, CFB and CDB) with plant morphology (IPA: PW, NC2 and NC3; OEM: PW, NC1 and NC2) and cladode morphology (IPA: CL2, CTB, CT3 and CP2; OEM: CLB, CL1, CW1, CTB, CT2 and CAB). Thus, canonical analysis was applied between these groups, per clone (IPA and OEM).

Only one production variable of the MIU showed correlation with PH and cladode morphology (CLB, CL2, CPB and CAB). Thus, the association between the groups "YIELD" and "Plant" was not evaluated and there was no significant canonical axis between the groups "YIELD" and "Cladode".

The association between the groups "YIELD" and "Cladode" (Table 1) of IPA demonstrated that plants with higher CTB and of third-order showed higher CFB, but in detriment of DMC. There was no significant canonical axis with the group "Plant", indicating that "YIELD" is independent of this group and the effects of their variables occurred separately.

For OEM (Table 1), two canonical axes were significant in the association between the groups "YIELD" and "Plant", and there was no correlation with the group "Cladode".

In the first axis, the highest DMY and DMC occurred in plants with greater dimensions of the basal cladodes (CAB). However, in this condition, there was a reduction in CFB and CDB, when plants with larger basal cladodes (CLB, CAB) also had greater dimensions of the first-order cladode (CL1), according to the second axis (0.994*).

In the partitioning of the correlation coefficients through the path analysis, the NC3 showed the highest positive explanation for the CFB of IPA (Table 2), with direct and indirect effect (via NC2), followed by PW, explaining together 60.7% of its variability. In terms of cladode, the perimeter of those of second-order (CP2) contributed to the increment in DMY, reaching 60.3%.

In turn, the accumulation of CFB was favored in plants with larger second-order cladodes and thicker third-order cladodes,

Table 1. Canonical correlations between the groups "YIELD" and "Cladode" of IPA Sertânia (IPA) and "YIELD" and "Plant" of Orelha de Elefante Mexicana (OEM)

Groups	Variables	Canonical factors			
		1°	2°	3°	4°
IPA Sertânia					
I - Yield	DMY	0.013	0.850	-0.526	-
	DMC	-0.721	0.034	0.692	-
	CFB	0.716	0.694	-0.081	-
II - Cladode	CL2	0.431	0.833	-0.260	-
	CTB	0.743	0.131	-0.633	-
	CT3	0.801	0.433	0.334	-
	CP2	0.004	0.704	-0.703	-
	CC	0.995**	0.893	0.311	-
	χ^2	31	8	1	-
	DF	12	6	2	-
Orelha de Elefante Mexicana					
I - Yield	DMY	0.569	0.266	0.236	-0.741
	DMC	0.539	-0.167	-0.589	0.578
	CFB	-0.402	0.651	0.496	-0.411
	CDB	0.091	0.846	-0.477	-0.220
II - Plant	CLB	0.202	-0.522	0.775	0.178
	CL1	-0.239	-0.769	0.543	0.065
	CW1	-0.177	0.302	0.781	-0.471
	CTB	0.223	-0.311	0.178	-0.875
	CT2	0.154	0.059	0.649	-0.607
	CAB	0.389	-0.583	0.541	0.244
	CC	0.999*	0.994*	0.951	0.849
	χ^2	76	28	13	4
	DF	24	15	8	3

DMY - Dry matter yield, DMC - Dry matter content, CFB, CDB - Cladode fresh and dry biomass, CLB, CL1, CL2 - Length of basal, first- and second-order cladodes, CW1 - Width of first-order cladode, CTB, CT2, CT3 - Thickness of basal, second- and third-order cladodes, CP2 - Perimeter of second-order cladode, CAB - Area of basal cladode. **, *Significant at 0.01 and 0.05, respectively, by Chi-square test; CC - Canonical correlation, DF - Degrees of freedom

Table 2. Partitioning of the correlation coefficient in direct and indirect effects between the variables of the groups "YIELD", "Plant" and "Cladode" of IPA Sertânia (IPA)

Variable	Effect	DMY	DMC	CFB
"Plant" Group				
PW	Direct effect PW	-	-	0.303
	Indirect effect via NC2	-	-	0.127
	Indirect effect via NC3	-	-	0.284
	Total	-	-	0.714
NC2	Direct effect NC2	-	-	0.149
	Indirect effect via PW	-	-	0.258
	Indirect effect via NC3	-	-	0.298
	Total	-	-	0.705
NC3	Direct effect NC3	-	-	0.393
	Indirect effect via PW	-	-	0.220
	Indirect effect via NC2	-	-	0.113
	Total	-	-	0.725
R ²		-	-	0.607
"Cladode" Group				
CL2	Direct effect CL2	0.324	-	0.455
	Indirect effect via CTB	-0.278	-	0.084
	Indirect effect via CT3	0.138	-	0.293
	Indirect effect via CP2	0.496	-	-0.003
	Total	0.680	-	0.829
CTB	Direct effect CTB	-	-0.746	-
	Indirect effect via CL2	-	0.109	-
	Indirect effect via CT3	-	-0.118	-
	Indirect effect via CP2	-	0.090	-
Total	-	-0.665	-	
CT3	Direct effect CT3	-	-	0.522
	Indirect effect via CL2	-	-	0.256
	Indirect effect via CTB	-	-	0.053
	Indirect effect via CP2	-	-	0.000
Total	-	-	0.830	
CP2	Direct effect CP2	0.625	-	-
	Indirect effect via CL2	0.257	-	-
	Indirect effect via CTB	-0.245	-	-
	Indirect effect via CT3	0.012	-	-
Total	0.650	-	-	
R ²		0.603	0.561	0.891

DMY - Dry matter yield, DMC - Dry matter content, CFB - Cladode fresh biomass; PW - Plant width, NC2, NC3 - Number of second- and third-order cladodes; CL2 - Length of second-order cladode, CTB, CT3 - Thickness of basal and third-order cladodes, CP2 - Perimeter of second-order cladode. "-" Indicates that there was correlation between the variables

responsible for 89.1%. Basal cladodes with greater thickness resulted in plants with lower DMC.

For the clone IPA, the contribution of the number of third-order cladodes to the increment in fresh biomass may be related to the greater capture of CO₂, compared with those of lower orders (Liguori et al., 2013). In turn, plant width has been cited as good variable to be adopted in the selection of more-productive clones (Silva et al., 2010; Pinheiro et al., 2014).

For the clone Miúda, the highest DMY occurred in taller plants and was related to basal cladodes with larger areas (Table 3), either through direct or indirect effect (via CLB, CL2, CPB). These cladodes explained 88.7% of the variation in DMY. Larger basal cladodes are fundamental to guarantee plant support, since MIU has higher number of cladodes in comparison to IPA and OEM (Silva et al., 2015). Nevertheless, Cavalcante et al. (2014) highlight that MIU has lower biomass accumulation compared with the *Opuntia* clones.

The highest yield of OEM (DMY) was observed in plants with higher number and thickness of second-order cladodes (NC2 and CT2) and thicker basal cladodes (CTB) (Tables 4 and 5). Thus, there were increments in DMC and decrease in

Table 3. Partitioning of the correlation coefficient in direct and indirect effects between the variables of the groups "YIELD" and "Cladode" of Miúda (MIU)

Variable	Effect	DMY
CLB	Direct effect CLB	-0.082
	Indirect effect via CL2	0.151
	Indirect effect via CPB	-0.265
	Indirect effect via CAB	0.926
Total	0.730	
CL2	Direct effect CL2	0.193
	Indirect effect via CLB	-0.064
	Indirect effect via CPB	-0.215
	Indirect effect via CAB	0.735
Total	0.648	
CPB	Direct effect CPB	-0.279
	Indirect effect via CLB	-0.078
	Indirect effect via CL2	0.149
	Indirect effect via CAB	0.887
Total	0.678	
CAB	Direct effect CAB	1.092
	Indirect effect via CLB	-0.070
	Indirect effect via CL2	0.130
	Indirect effect via CPB	-0.227
Total	0.926	
Determination coefficient		0.887

DMY - Dry matter yield; CLB, CL2 - Length of basal and second-order cladodes, CPB - Perimeter of basal cladode, CAB - Area of basal cladode

Table 4. Partitioning of the correlation coefficient in direct and indirect effects between the variables of the groups "YIELD" and "Plant" of Orelha de Elefante Mexicana (OEM)

Variable	Effect	DMY	DMC	CFB	CDB
PW	Direct effect PW	0.211	-	-	-
	Indirect effect via NC1	-0.002	-	-	-
	Indirect effect via NC2	0.452	-	-	-
	Total	0.661	-	-	-
NC1	Direct effect NC1	-	-	-	0.726
	Indirect effect via PW	-	-	-	-0.005
	Indirect effect via NC2	-	-	-	-0.037
	Total	-	-	-	0.684
NC2	Direct effect NC2	0.571	-	-	-
	Indirect effect via PW	0.167	-	-	-
	Indirect effect via NC1	0.031	-	-	-
	Total	0.769	-	-	-
Determination coefficient		0.612	-	-	0.500

DMY - Dry matter yield, DMC - Dry matter content, CFB, CDB - Cladode fresh and dry biomass; PW - Plant width, NC1, NC2 - Number of first- and second-order cladodes; "-" Indicates that there was correlation between the variables

CFB, associated with lower first-order cladodes (CW1). Hence, the morphological characteristics of second-order cladodes and vigor of the basal cladode had the highest contributions to the yield of OEM.

Second-order cladodes are those in higher number in the clone OEM; thus, they contribute more to the final crop yield. On the other hand, the growth of these cladodes is expected to result in reduction of the dimensions of lower cladodes. Silva et al. (2010), in study conducted with 50 clones, observed that the basal and first-order cladodes showed the largest morphological dimensions since they support the plant; however, proportional reductions of these dimensions were observed with the appearance of cladodes of higher orders.

Regardless of the clone, the vigor of the basal cladode was determinant for crop yield. Pimienta-Barrios et al. (2005) observed decrease in the daily gain of CO₂ and reduction in the relative water content of these cladodes in dry periods, indicating water

Table 5. Partitioning of the correlation coefficient in direct and indirect effects between the variables of the groups "YIELD" and "Cladode" of Orelha de Elefante Mexicana (OEM)

Variable	Effect	DMY	DMC	CFB	CDB
CLB	Direct effect CLB	-	-	-	-0.383
	Indirect effect via CL1	-	-	-	-0.554
	Indirect effect via CW1	-	-	-	0.064
	Indirect effect via CTB	-	-	-	-0.023
	Indirect effect via CT2	-	-	-	0.040
	Indirect effect via CAB	-	-	-	0.051
	Total	-	-	-	-0.805
CL1	Direct effect CL1	-	-	-	-0.757
	Indirect effect via CLB	-	-	-	-0.281
	Indirect effect via CW1	-	-	-	0.044
	Indirect effect via CTB	-	-	-	-0.016
	Indirect effect via CT2	-	-	-	0.035
	Indirect effect via CAB	-	-	-	0.049
	Total	-	-	-	-0.926
CW1	Direct effect CW1	-	-0.765	0.884	-
	Indirect effect via CLB	-	0.014	0.004	-
	Indirect effect via CL1	-	-0.133	0.003	-
	Indirect effect via CTB	-	0.005	-0.129	-
	Indirect effect via CT2	-	-0.018	0.101	-
	Indirect effect via CAB	-	0.083	-0.065	-
	Total	-	-0.815	0.799	-
CTB	Direct effect CTB	0.452	-	-	-
	Indirect effect via CLB	-0.009	-	-	-
	Indirect effect via CL1	-0.148	-	-	-
	Indirect effect via CW1	0.025	-	-	-
	Indirect effect via CT2	0.267	-	-	-
	Indirect effect via CAB	0.048	-	-	-
	Total	0.635	-	-	-
CT2	Direct effect CT2	0.456	-	-	-
	Indirect effect via CLB	-0.012	-	-	-
	Indirect effect via CL1	-0.247	-	-	-
	Indirect effect via CW1	0.044	-	-	-
	Indirect effect via CTB	0.265	-	-	-
	Indirect effect via CAB	0.125	-	-	-
	Total	0.630	-	-	-
CAB	Direct effect CAB	-	-	-	0.066
	Indirect effect via CLB	-	-	-	-0.298
	Indirect effect via CL1	-	-	-	-0.559
	Indirect effect via CW1	-	-	-	0.026
	Indirect effect via CTB	-	-	-	-0.008
	Indirect effect via CT2	-	-	-	0.028
	Total	-	-	-	-0.746
Determination coefficient		0.840	0.873	0.924	0.956

DMY - Dry matter yield, DMC - Dry matter content, CFB, CDB - Cladode fresh and dry biomass; CLB, CL1 - Length of basal and first-order cladodes, CW1 - Width of first-order cladode, CTB, CT2 - Thickness of basal and second-order cladodes, CAB - Area of basal cladode. "-" Indicates that there was correlation between the variables

movement to the cladodes above. Thus, besides the function of support, basal cladodes become source of water and maintenance of the plant photosynthetic activity in drought periods.

CONCLUSIONS

1. The yield of forage cactus cultivated under water regimes from 493 to 756 mm year⁻¹ was more associated with the peculiarities of the morphological characteristics of its clones than with different water supplies or actual evapotranspiration.

2. The increase in water supply from 493 to 756 mm year⁻¹ did not promote significant increment of production for the forage cactus.

3. Regardless of water regime and clone, the vigor of the basal cladode was highly decisive for the expression of the productive capacity of irrigated forage cactus.

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