Meteorological variables and morphological characteristics influencing the evapotranspiration of forage cactus[1]

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ABSTRACT

Despite belonging to the same photosynthetic group (CAM - Crassulacean Acid Metabolism), evapotranspiration of distinct species of forage cactus may respond differently to meteorological variables and depends on its growth dynamics. The objective of this work was to analyze the contribution of meteorological variables and morphological characteristics of cladodes and the plants on the evapotranspiration of forage cactus species of the genus *Nopalea* and *Opuntia*. The experiment was conducted in Serra Talhada, State of Pernambuco, where the species 'IPA Sertânia' (*Nopalea* sp.), 'Miúda' (*Nopalea* sp.) and 'Orelha de Elefante Mexicana' (*Opuntia* sp.) were submitted to different irrigation depths (2.5, 5.0 and 7.5 mm) and intervals (7, 14 and 28 days). Actual evapotranspiration and biometric data of forage cactus species and meteorological variables were obtained between March 2012 and August 2013. Pearson correlation matrix and canonical and path analysis were applied to the data. It was verified that the global solar radiation stood out as the variable that most influenced the reduction of the actual evapotranspiration (ET) of the three species, and the wind velocity as the one that affected the response of ET to the atmospheric demand variation (ET/ETo) of the species 'Orelha de Elefante Mexicana' and 'IPA Sertânia'. The increase in the cladode area index implied in the reduction of ET of the latter two species, while the effects of the number of 1st and 2nd order cladodes were the most important for the 'Miúda'. Hence, forage cactus evapotranspiration depends on the seasonality of the meteorological conditions and the morphological characteristics of its species.

Key words: canonical analysis; growth; *Nopalea* sp.; *Opuntia* sp.; path analysis.

RESUMO

Variáveis meteorológicas e características morfológicas influenciando a evapotranspiração da palma forrageira

Embora pertencentes ao mesmo grupo fotossintético (MAC - Metabolismo Ácido das Crassuláceas), a evapotranspiração de distintas espécies de palma forrageira pode responder de maneira diferenciada às variáveis meteorológicas, e depende da sua dinâmica do crescimento. Objetivou-se analisar a contribuição de variáveis meteorológicas e de características morfológicas dos cladódios e da planta sobre a evapotranspiração de espécies de palma forrageira dos gêneros *Nopalea* e *Opuntia*. O experimento foi conduzido em Serra Talhada, Pernambuco, onde as espécies 'IPA Sertânia' (*Nopalea* sp.), 'Miúda' (*Nopalea* sp.) e Orelha de Elefante Mexicana (*Opuntia* sp.) foram submetidos a distintas lâminas (2,5; 5,0; e 7,5 mm) e intervalos e irrigação (7; 14 e 28 dias). A evapotranspiração real e dados biométricos das espécies de palma, e variáveis meteorológicas foram obtidos entre março de 2012 e agosto de

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2013. Matriz de correlação de Pearson e análises canônica e de trilha foram aplicadas aos dados. Verificou-se que a radiação solar global se destacou como a variável que mais influenciou na redução da evapotranspiração real (ET) das três espécies, e a velocidade do vento àquela que afetou a resposta da ET à variação da demanda atmosférica (ET/ETo) das espécies Orelha de Elefante Mexicana e 'IPA Sertânia'. O aumento do índice de área do cladódio implicou na redução da ET dessas duas últimas espécies, enquanto os efeitos do número de cladódios de 1ª e 2ª ordens foram os mais importantes para a 'Miúda'. Logo, a evapotranspiração da palma forrageira depende da sazonalidade das condições meteorológicas e das características morfológicas das suas espécies.

Palavras-chave: análise canônica; análise de trilha; crescimento; *Nopalea* sp.; *Opuntia* sp.

INTRODUCTION

The transfer of water in the plant-atmosphere interface is affected by the meteorological elements (Allen *et al*., 1998). Evapotranspiration (ET) varies among species, as well as with phenology, as a result of changes in resistance to the transpiration process, height, leaf area, among other factors related to plant morphology (Lemos Filho *et al*., 2010). At the same time, ET is affected by crop management and soil water availability, which induces morphophysiological variations in the plant, reflecting in its growth rate (Kiremit & Arslan, 2016; Kresoviæ *et al.*, 2016; Queiroz *et al.*, 2015).

Some reports state that the exchange of water vapor between the surface and the atmosphere in plants C3 and C4 is conditioned by the deficit of water vapor pressure of the air, wind speed and the availability of energy. When control occurs due to the strength of water vapor pressure deficit and wind speed, it said that the vegetation exercises effective control over ET. On the other hand, when there is inhibition of water vapor flow due to air saturation and there is a complete water supply in the soil, ET is more sensitive to the available energy (Silva *et al.*, 2012).

Unlike C3 and C4 plants, plants with photosynthetic mechanisms (CAM) open their stomata at night to capture the CO_2 necessary for their metabolism (Lüttge, 2010). In this period, the water vapor pressure deficit in the air is lower, thus reducing its transpiration losses (Lemos Filho *et al.*, 2010).

Cactus *Nopalea* sp. and *Opuntia* sp. are the most cultivated forage cactus in the world (over 1 million hectares) (Reyes-Agüero *et al*., 2006), with areas mainly concentrated in the arid and semi-arid regions, where rainfall irregularity and high atmospheric demand are outstanding features. In Brazil, their cultivation predominates in the Northeast (around 500 thousand hectares), where it is used as a food resource for cattle, goats, and sheep. The high content of water, energy, non-fibrous carbohydrates and nutrient digestibility are the main qualities of this crop (Oliveira *et al*., 2010; Silva *et al*., 2015a).

Under optimal conditions of water supply and mild temperatures, forage cactus can reach up to 50,000 kg ha^{-1} $year^{-1}$, depending on the planting density, species and cultural practices adopted (Nobel, 2001). The ideal thermal regime varies between 8.6 ºC and 20.4 ºC (minimum temperature) and from 28.5 ºC to 31.5 ºC (maximum temperature) with annual rainfall ranging from 368.4 mm to 821.4 mm (Souza *et al*., 2008). Felker and Inglese (2003) mention that sites with high atmospheric demand and rainfall below 350 mm $year^{-1}$, the use of irrigation is essential to ensure a good yield. Queiroz *et al*. (2015) report a productive increase of forage cactus up to water depths of 1048 mm.

Different species are grown in the Northeast of Brazil, especially those of the genus *Opuntia* and *Nopalea* (Silva et al., 2015a). Despite exhibiting the same photosynthetic mechanism (CAM), they present specificities that differentiate them, as, in water use efficiency and morphological characteristics (Silva *et al.*, 2015b; Silva *et al.*, 2014a).

In this crop, the leaves fall soon after the emission of modified stem structures, denominated cladodes, responsible for the water storage and the photosynthetic function of the plant, with dimensions that differentiate among species (Pinheiro *et al*., 2014). Silva *et al*. (2014a) point out that cactus species have cladodes with different dimensions, but may have similar cladode area indices (CAI) (CAI equivalent to leaf area index in C3 and C4 plants), which results in distinct interactions with environment, since it affects the density of stomata and the amount of stored water (Lüttge, 2010). Nevertheless, Silva *et al*. (2015b) report that, under the same condition of water availability (rainfed cultivation), cactus species have similar ET.

It is essential to know what factors most affect the regulation of the ET process, whether the plants or the

environmental conditions, since the interaction between the plant and the environment conditions the plant production (Pinheiro *et al*., 2014). The objective of this study was to analyze the contribution of meteorological variables and morphological characteristics of cladodes and the plant in forage cactus evapotranspiration.

MATERIAL AND METHODS

The experiment was carried out in the experimental area of 'Instituto Agronômico de Pernambuco', in the municipality of Serra Talhada, state of Pernambuco (7º59'S, 38º15'W and 431 m above sea level), with a BSh, semi-arid and warm climate, according to the classification of Köppen. Rainfall and historical reference evapotranspiration are 657 mm year^{-1} and 2,232 mm year^{-1}, respectively. The soil of the experimental area was classified as Red Yellow Argissolo, according to the Brazilian Soil Classification System.

Forage cactus species were implanted in February 2010, spaced by 1.60 x 0.20 meter in contour lines, and conducted in rainfed until March 2012. On that date, the first cutting was made, starting the second production cycle, which comprised the present study, which was maintained until August 2013 (532 days). It was used a random block design with factorial arrangement of 3x3x3+3, with one control for each species, and three replicates. Water depths (2.5 mm; 5.0 mm and 7.5 mm, plots) and fixed irrigation frequencies (7 days; 14 days; and 28 days, subplots) were imposed to the species 'IPA-Sertânia' (*Napolea cochenillífera* (L.) Salm-Dick.), 'Miúda' (*Napolea cochenillífera* (L.) Salm-Dick.) and 'Orelha de Elefante Mexicana' (*Opuntia stricta* (Haw.) Haw.), which constituted the sub-subplots with an area of 25.6 m^2 and useful area of 11.52 m^2, each one composed of four rows of 20 plants.

The irrigation events were performed by a drip system, with emitters spaced at 0.40 m, using water from the 'Açu-de Saco' with electrical conductivity between 1.1 and 1.6 dS m^{-1}. At the end of the experiment, water depths equivalent to 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 mm year^{-1} (control) were totalized, regardless of the species. The forage cactus species were submitted to these water regimes, to evaluate the effect of water availability on the actual evapotranspiration of the crop.

Crop management for the elimination of weeds, such as weeding and herbicide application, and disease control were carried out whenever it was necessary. For fertilization, the application of 50 kg ha^{-1} of NPK 14-00-18 formulation was done adjacent to the crop row, as suggested by the 'Instituto Agronômico de Pernambuco'.

Over time, global solar radiation (Rg), average (Tm), maximum (Tx) and minimum (Tn) temperatures, average (URm), maximum (URx) and minimum air relative humidity, wind velocity (u) and rainfall (P) were obtained by means of an automatic station, owned by Instituto Nacional de Meteorologia - INMET, located 1.7 km from the experimental area.

Morphological characteristics of cladodes and the canopy of plants were recorded on 13 dates. Measurements were always made in the same plants, and height (AP) and canopy width (LP) of the plant were monitored using a tape measure. Moreover, the total number of cladodes in each plant (NCT) was recorded, and in order of appearance, ranging from the 1st order (NC1, the first units to appear from the basal cladode) to the 4th order (NC2, NC3, NC4), depending upon the species. The cladode area index (CAI) was determined by the ratio between the sum of the cladode areas and the planting spacing (1.60 x 0.20 m).

Regarding cladodes, their lengths (CCB, CC1, CC2, CC3 e CC4), widths (LCB, LC1, LC2, LC3 and LC4), perimeters (PCB, PC1, PC2, PC3 and PC4) and thickness of basal cladodes up to the fourth order (ECB, EC1, EC2, EC3 and EC4) were included, measured with a tape measure and a plastic pachymeter, in a representative branch of the plant. Additionaly, the values of the area of the cladodes of each order (ACB, AC1, AC2, AC3, and AC4) were calculated. All morphological measurements of cladodes and the canopy of forage cactus follow the procedures detailed by Pinheiro *et al*. (2014), Silva *et al*. (2014a), Silva *et al*. (2015a) and Silva *et al*. (2015b).

The actual evapotranspiration of the species in the different water regimes was calculated by the residue of the water balance in the soil, using data of soil moisture and physical-water properties, according to Silva *et al*. (2014b). The water content was monitored over time, using a capacitive sensor (Diviner 2000®, Sentek Pty Ltda., Australia) and access pipes installed, in each sub-subplot, up to 0.90 m of depth and 0.10 m from the rows of the species. The sensor was calibrated locally according to Araújo Primo *et al*. (2015), and monitoring was done every two days. Soil water balance was accounted at 14-day intervals.

The experimental data were initially submitted to the Lilliefors test, to verify their normality, descriptive statistics and to ANOVA, at a significance level of 5%, to detect the existence of differences between species in the different water depth treatments and frequencies of irrigation treatments. Then, their results were arranged into four groups and responses, or, explanatory, aiming to establish the relationship between their variables. The group denominated "Plant" was constituted by the morphological characteristics of the canopy, that is,

obtained in the 13 measurement dates. The "Cladode" group was composed of the morphological characteristics of the cladodes, which consisted of measurements of the characteristics of the basal cladodes up to the 3rd order of appearance for the 'IPA Sertânia' and 'Orelha de Elefante Mexicana' species, and up to the 4th order for the 'Miúda' species. This procedure was adopted to avoid misinterpretations of the results from orders with a small number of data. The "Environment" group was formed by the meteorological and water supply data, obtained by the integration of rainfall and irrigation values between the 13 measurement dates, dependent upon the treatment of the water depths and frequencies. The meteorological elements and the water supply were considered for the intervals between the sampling dates of the biometric data, using averages (air temperature, air relative humidity, and wind speed) or daily sums (global solar radiation and sum of precipitation data). Finally, the "ET" group was a result of the integrated values of the actual evapotranspiration and the ET/ETo ratio average, between the 13 dates, in which ETo is the reference evapotranspiration, obtained from meteorological data and the Penman-Monteith method modified by the FAO (Allen *et al*., 1998). The "Plant", "Cladode" and "Environment" groups were considered as explanatory variables and the "ET" group as a response.

The data were submitted to Pearson correlation matrix, in which the significance, direction, and intensity of the linear relationship between the groups were evaluated. The significance of the coefficients ($p < 0.01$ and $p < 0.05$) was analyzed by the Student's t-test. The direction was evaluated based on the sign of correlation, positive (+) or negative (-). The Pearson correlation coefficient intensity classification was interpreted according to that used by Thomaz et al. (2012), which comprised the following ranges: 0 to 0.19: "very weak"; 0.20 to 0.39: "weak"; 0.40 to 0.69: "moderate"; 0.70 to 0.89, "strong" and 0.90 to 1.00, "very strong".

The responses and explanatory variables, which presented significant correlations among themselves, were submitted to the multicollinearity test, which was carried out for the data of each group, aiming to identify the existence and the intensity of correlation between their variables. In this analysis, one or more independent variables that were highly correlated were removed (Toebe & Cargnelutti Filho, 2013).

Only the variables that presented weak multicollinearity were used in the analysis of canonical correlation, since, in this analysis, the canonical variables must be orthogonal, that is, linearly independent from each other. Thus, the associations between the groups were evaluated in such a way that the linear correlation was maximal. In this analysis, canonical axes were established, depending on the number of variables of the smallest group. The canonical correlations were tested using the chi-square test at the 1% of probability level.

Path analysis was applied in the unfolding of the correlation coefficients to evaluate the effect of an explanatory variable on the response, using the path coefficient. The significance of the partial correlation was adopted equal to that used in the Pearson correlation. All the analyses were performed in the statistical software "GENES" (Cruz, 2006).

RESULTS

Water depths received by forage cactus species ranged from 493 mm year^{-1} to 756 mm year^{-1} (equivalent annual values), out of which 363 mm year^{-1} corresponded to rainfall, while the reference evapotranspiration was 1,923 mm year^{-1}. Despite that, no effect of the water depths was found on the actual evapotranspiration (ET) and most of the morphological characteristics of the crop ($p > 0.05$). However, ET and most of the morphological variables showed an effect of the species factor ($p < 0.05$), resulting in minimal and maximum ET ranging from 0.79 to 1.82 mm day^{-1}, from 0.77 to 1.81 mm day^{-1} and from 0.82 to 1.79 mm day^{-1}, in that order, for the 'IPA Sertânia', 'Miúda' and 'Orelha de Elefante Mexicana'.

In terms of growth, the cladode area index of the genus *Nopalea* ('IPA Sertânia' and 'Miúda') presented equal magnitudes (0.50 m^2 m^{-2}), but lower than that of the 'Orelha de Elefante Mexicana' (0.94 m^2 m^{-2}), as a reflection of the unit dimensions (329 cm^2, 153 cm^2 and 491 cm^2) and of the total number (8 unit plant^{-1}, 16 unit plant^{-1} and 9 unit plant^{-1}) of their cladodes. Therefore, the analyses of the interrelations between the "Plant", "Cladode", "Environment" and "ET" groups were made over time, individually per species and independent of the distinctions of water regimes (water depth x frequency of irrigation).

Among the meteorological variables, a correlation between solar radiation (Rg) and ET in the three species was observed ('IPA Sertânia': -0.587*; 'Miúda': -0.597*; 'Orelha de Elefante Mexicana': -0.578*). Meanwhile, the wind speed (u) was moderately and positively correlated with the ET/ETo ratio, in the 'IPA Sertânia' species (IPA) (0.620*) as well as in the 'Orelha de Elefante Mexicana' (0.622*). The variation of the water supply over time, among the 13 sampling dates of the biometric data did not affect the ET of the three species ($p > 0.05$).

The morphological characteristics of the plant showed no influence on ET in the species 'IPA Sertânia'. Only the number of 1st order cladodes of 'Miúda' species showed a moderate correlation, according to the classification used by Thomaz et al. (2012) (0.40 to 0.69), and negative with

ET (-0.654*). This fact was not observed in the ET/ETo ratio, which was strongly (between 0.70 to 0.89) and negatively correlated with the cladode area index in the species 'IPA Sertânia' (-0.739**) and 'Orelha de Elefante Mexicana' (-0.709**). Also, a moderate and negative correlation between the ET/ETo ratio and the number of the 1st order (-0.662 *), 2nd order (-0.582*) and 4th order (-0.653*) cladodes were observed, as well as, the cladode area index (-0.646*) of 'Miúda' species. Finally, a correlation was also observed with plant height (-0.662*) in the 'IPA Sertânia' species. Regarding 'Orelha de Elefante Mexicana', the relationship of ET/ETo only with the total number of cladodes (-0.606*) and number of 2nd order cladodes (-0.657*).

No correlation of the characteristics of cladodes was found with ET in the species 'Miúda' and 'Orelha de Elefante Mexicana'. Only the characteristics of the 1st order cladodes presented strong and negative correlation with the ET in the 'IPA Sertânia' species (-0.729**).

In turn, the ET/ETo ratio correlated moderately and negatively with most of the cladodes' characteristics in the three species. The correlation was strong and negative for the 1st and 2nd order cladodes in the 'IPA Sertânia' species, as well as of the 3rd order of the 'Miúda' species and the basal and 1st order cladodes in the 'Orelha de Elefante Mexicana'.

As a result, the associations between the groups "ET" x "Environment" and "ET" x "Plant" were tested by canonical analysis on the species 'IPA Sertânia' and 'Orelha de Elefante Mexicana', while "ET" x "Cladode" for 'IPA Sertânia' and 'Miúda'. These associations showed at least one significant axis by the chi-square test at 1% and 5% of probability so that the groups were not independent of each other. However, they were conditioned by the species, whether 'IPA Sertânia' (Table 1), 'Miúda' (Table 2) or 'Orelha de Elefante Mexicana' (Table 3), and by the variable of the response groups ("Environment," "Plant" or "Cladode").

For the species 'IPA Sertânia' (Table 1) and 'Orelha de Elefante Mexicana' (Table 3), higher intensities of global solar radiation promoted lower values of ET (first canonical axis), while ET/ETo ratio, in the second canonical axis, showed that the higher wind speeds induced higher ET responses to atmospheric demand. In this study, global solar radiation varied between 15 and 25 MJ m^{-2} day^{-1}, while wind velocity is of 2 to 4 m s^{-1}.

The association between the "ET" and "Plant" groups in the species 'IPA Sertânia' (Table 1) showed that higher plants and with higher cladode area index (CAI) had their ET/ETo ratio reduced. However, the higher ET occurred when the plants had lower plant height and cladode area index. A similar trend was observed for the canonical correlation between the Plant and ET group of the 'Orelha de Elefante Mexicana' species (Table 3), in which it was found that in the first canonical axis, the highest magnitudes of the ET and its response to the increase in atmospheric demand occurred when the plants presented lower CAI and cladodes.

The canonical correlations estimated between the "ET" and "Cladode" groups of the 'IPA Sertânia' species (Table 1) allowed the finding that identifies that the highest ET responses to ETo occurred when the dimensions of 1st, 2nd, and 3rd order cladodes were still reduced. In turn, the highest ET values occurred when the dimensions of the 3rd order cladodes were low. The same was observed for 'Miúda' (Table 2), when the 3rd order cladodes were still growing, the ET response to the increase in atmospheric demand had its greatest magnitudes. For the 'Orelha de Elefante Mexicana' species (Table 3), the ET group is independent of the group of structural characteristics of the cladodes, demonstrating that the effects of these variables occur isolatedly.

The variables of the significant canonical axes were submitted to path analysis to evaluate their direct or indirect effects. Thus, at the unfolding of correlation coefficient, it was found that the effect exerted by global solar radiation (Rg) on the real evapotranspiration of the species 'IPA Sertânia' (-0.582) (Table 4) was direct and negative, as well as in the 'Orelha de Elefante Mexicana' species (-0.573) (Table 6), indicating that higher levels of solar radiation reduced ET in these species. The ET response to the ETo increase, that is, the ET/ETo ratio, was positively and directly influenced by the wind velocity in the species 'IPA Sertânia' (0.617) (Table 4) and 'Orelha de Elefante Mexicana' (0.620) (Table 6).

By considering the group of structural characteristics of the plants, it was observed that CAI exerted greater effects, either direct or indirect, on ET/ETo ratio of the species 'IPA Sertânia' (Table 4) and 'Orelha de Elefante Mexicana' (Table 6). Its effect was negative, indicating that the higher response of the ET of the species to the variability of the atmospheric demand occurred when the magnitude of the cladode area index of the plants was smaller.

In relation to 'Miúda' (Table 5), the greater number of second-order cladodes contributed positively using the direct or indirect effects, for the increase in the response of ET to atmospheric demand. However, when the number of 1st order cladodes was still small, ET displayed a greater magnitude.

In the path analysis for growth traits of cladodes and the ET group, it was found that for the 'IPA Sertânia' (0.749) (Table 4), that the presence of younger cladodes (3rd order) regarding thickness (EC3) favored response of the ET to atmospheric demand. However, when the perimeter of the 1st order cladodes was low, ET rates were higher. As for

'Miúda' (Table 5), unlike 'IPA Sertânia', the response of ET to atmospheric demand was reduced with the appearance of 3rd order cladodes (CC3).

DISCUSSION

The lack of a significant effect of the different water regimes (493 mm year $^{-1}$ to 756 mm year^{-1}) on growth and the seasonality of ET of the forage cactus species reinforces the wide range of adaptation that the CAM process confers to this crop. The nocturnal assimilation of CO_2 by the cactus, when the water vapor pressure deficit in the air is lower, reduces the water losses by transpiration and increases the accumulation of water in the cladodes, assuring under water restrictions, their survival for a longer time (Lüttge, 2010; Scalisi *et al*., 2016). Flores-Hernández *et al*. (2004), working with three water regimes (740 mm year^{-1}, 1060 mm year^{-1} and 1380 mm year^{-1}), based on the accumulated evaporation of the Class "A" pan, and four species of the genus *Opuntia*, also did not find the effect of water availability on morphological parameters. The same trend was cited by Queiroz *et al*. (2015), who submitted 'Orelha de Elefante Mexicana' to five water regimes, ranging from 976 mm year^{-1} to 1202 mm year^{-1}.

On the other hand, the seasonality of ET and ET/ETo ratio was related to the environmental variables and the morphology of the plant and cladodes; but it was dependent on the species. Global solar radiation and wind speed were the variables that most affected the ET and ET/ETo of the 'IPA Sertânia' and 'Orelha de Elefante Mexicana', which are species that present a larger cladode area (Silva *et al.*, 2014b; Silva *et al.*, 2015a). For 'Miúda', with a smaller area of the cladode, ET was affected only by radiation.

Radiation had a direct and negative effect on the ET of the three species. Although this variable provides the energy required for evapotranspiration, so the process occurs, it is necessary that there is available water in the soil to the plants. However, the amount of water received

Table 1: Canonical correlations and canonical pairs between the "Evapotranspiration" (ET) group and the "Environment" (environmental variables), "Plant" (structural characteristics of plants) and "Cladode" groups (structural characteristics of cladodes) 'IPA Sertânia', under irrigated conditions, in a semi-arid environment, in the municipality of Serra Talhada, State of Pernambuco, Brazil

Groups	Variables	Canonical factors	
		1st	2nd
I – Evapotranspiration	ET	0.685	0.729
	ET/ETo	0.354	0.935
Environment	u	0.039	0.999
	Rg	-1.000	0.029
Canonical correlation		0.878**	0.650*
χ^2		17	5
Degree of freedom		4	1
I – Evapotranspiration	ET	-0.201	0.980
	ET/ETo	-0.561	0.828
Plant	AP	0.944	-0.330
	IAC	0.845	-0.536
Canonical correlation		0.869**	0.737**
χ^2		19	7
Degree of freedom		4	1
I – Evapotranspiration	ET	0.764	0.645
	ET/ETo	0.953	0.304
Cladode	CC2	-0.877	0.139
	CC3	-0.862	0.404
	EC3	-0.798	0.362
	PC1	-0.864	-0.271
Canonical correlation		0.882**	0.842*
÷^{2}		21	9
Degree of freedom		8	3

Where: Evapotranspiration group: ET - actual crop evapotranspiration, ET/ETo - ratio between actual crop evapotranspiration and reference evapotranspiration; Environment group: Rg - global solar radiation, u - wind speed; Plant Group: AP - plant height, CAI - cladode area index; Cladode group: CC2 - 2nd order cladode length, CC3 - 3rd order cladode length, EC3 - 3rd order cladode thickness, PC1 - 1st order cladode perimeter. **, * Significant at 1 and 5%, respectively, by the chi-square test.

by the species during the experiment, at the best condition (7.5 mm water depth every 7 days, 756 mm year^{-1}), was much lower (only 32% of the ETo) than it was necessary for the crop demand (1,900 mm equivalent year^{-1}) which according to Queiroz et al. (2016), the adequate water supply is around 52% of the ETo. This fact means that in the present study, over time, the imposed water regimes and the seasonality of the rainfall gave low water supply to the crop, especially at times when the radiation intensity was high.

On the other hand, high intensity of radiation may also affect the stomatal activity, even when it occurs more in the nocturnal period. Nobel & Hartsock (1983) conducted a study with *Opuntia ficus-indica* (L.) Mill. under controlled environment conditions, submitting it to different regimes of photosynthetically active radiation and temperatures during day and night. The authors observed that in cladodes exposed to excessive radiation for more than 6 hours, a decrease in acid accumulation and nocturnal CO_2 uptake occurred, indicating a reduction in the stomatal opening, even at night, and a consequent drop in the transpiration of crop.

Wind speed was determinant in the variation of the ET/ETo values with a direct and positive effect for the

Table 2: Canonical correlation and canonical pairs between "Evapotranspiration" group (ET) and the "Cladode" group (structural characteristics of the cladodes), of 'Miúda' species, under irrigated conditions, in a semi-arid environment, in Serra Talhada, State of Pernambuco, Brazil

Groups	Variables	Canonical factors	
		1st	2nd
I – Evapotranspiration	ET	0.635	0.773
	ET/ETo	0.887	0.461
Cladode	CC3	-0.983	-0.184
	PC3	-0.919	-0.395
Canonic correlation		0.842*	0.024
χ^2		10	0
Degree of freedom		4	1

Where: Evapotranspiration Group: ET - actual crop evapotranspiration, ET/ETo - ratio between actual crop evapotranspiration and reference evapotranspiration; Cladode group: CC3 - 3rd order cladode length, PC3 - 3rd order cladode perimeter.
* Significant at 5% by Chi-square test.

Table 3: Canonical correlations and canonical pairs between the "Evapotranspiration" (ET) group and the "Environment" (environmental variables) and "Plant" (structural characteristics of plants) groups of the 'Orelha de Elefante Mexicana' species under irrigated conditions in the semi-arid in the municipality of Serra Talhada, State of Pernambuco, Brazil

Groups	Variables	Canonical factors	
		1st	2nd
I - Evapotranspiration	ET	0.623	0.782
	ET/ETo	0.256	0.967
Environment	u	-0.076	0.997
	Rg	-0.996	-0.086
Canonical correlation		0.859**	0.663*
χ^2		16	5
Degree of freedom		4	1
I – Evapotranspiration	ET	0.558	0.830
	ET/ETo	0.845	0.535
Plant	NCT	-0.586	-0.660
	NC2	-0.872	-0.035
	CAI	-0.984	0.093
Canonical correlation		0.881*	0.479
χ^2		14	2
Degree of freedom		6	2

Where: Evapotranspiration group: ET - actual crop evapotranspiration, ET/ETo - ratio between actual crop evapotranspiration and reference evapotranspiration; Environment Group: Rg - global solar radiation, u - wind speed; Plant Group: NTC - total number of cladodes of the plant, NC2 - number of 2nd order cladodes, CAI - cladode area index.
**, * Significant at 1 and 5%, respectively, by the chi-square test.

'IPA Sertânia' (Tables 1 and 4) and 'Orelha de Elefante Mexicana' (Tables 2 and 6), that is, this variable affected the response of ET of the species to the atmospheric demand. The ET/ETo depends on the water supply in the soil in such a manner that, for example, under low water availability, the increase in ETo results in a decrease in ET, reducing ET/ETo values, while under full water conditions in the soil, the increase in ETo favors ET (Silva *et al.*, 2015b).

Wind is responsible for the renewal of the air in the vicinity of the vegetative canopy, contributing to the increase in the pressure deficit of water vapor in the air. Consequently, it can be inferred that the ET of the species responded more to the water vapor pressure deficit than to the energy provided by the solar radiation, indicating that the species were coupled with the atmosphere, exerting greater control to the ET process. This fact was also reported in the literature for other crops (Silva *et al.*, 2012).

Table 4: Unfolding of Pearson correlation in direct and indirect effects between the response group "Evapotranspiration", with the explanatory groups "Environment", "Plant" (structural characteristics of plants) and "Cladode" (structural characteristics of cladodes) of the species 'IPA Sertânia', under irrigated conditions, in semi-arid environment, in the municipality of Serra Talhada, State of Pernambuco, Brazil

	Variable	Effect	ET	ET/ETo
Environment group	u	Direct effect u	-	0.617
		Indirect effect via Rg	-	0.003
		Total	-	0.620
	Rg	Direct effect Rg	-0.582	-
		Indirect effect via u	-0.005	-
		Total	-0.587	-
	Coefficient of determination		0.586	0.466
Plant group	AP	Direct effect AP	-	1.124
		Indirect effect via IAC	-	-1.786
		Total	-	-0.662
	IAC	Direct effect IAC	-	-1.834
		Indirect effect via AP	-	1.095
		Total	-	-0.739
	Coefficient of determination		-	0.610
Cladode group	CC2	Direct effect CC2	-	-0.193
		Indirect effect via CC3	-	-0.764
		Indirect effect via EC3	-	1.054
		Indirect effect via PC1	-	-0.798
		Total	-	-0.701
	CC3	Direct effect CC3	-	-1.001
		Indirect effect via CC2	-	-0.147
		Indirect effect via EC3	-	1.131
		Indirect effect via PC1	-	-0.604
		Total	-	-0.621
	EC3	Direct effect EC3	-	1.220
		Indirect effect via CC2	-	-0.167
		Indirect effect via CC3	-	-0.928
		Indirect effect via PC1	-	-0.703
		Total	-	-0.579
	PC1	Direct effect PC1	-1.347	-0.905
		Indirect effect via CC2	0.114	-0.170
		Indirect effect via CC3	-0.532	-0.668
		Indirect effect via EC3	1.036	0.948
		Total	-0.729	-0.796
	Coefficient of determination		0.749	0.772

Where: Evapotranspiration group: ET - actual crop evapotranspiration, ET/ETo - ratio between actual crop evapotranspiration and reference evapotranspiration; Group Environment: Rg - global solar radiation, u - wind speed; Plant Group: AP - plant height, CAI - cladode area index; Cladode group: CC2 - 2nd order cladode length, CC3 - 3rd order cladode length, EC3 - 3rd order cladode thickness, PC1 - 1st order cladode perimeter. "-" indicates that the variable did not present correlation with any of the variables of the evapotranspiration group.

In contrast to the C3 and C4 plants, in which evapotranspiration increases as leaf area index increases (Pivetta et al., 2011), canopy expansion does not necessarily result in an in increase in the ET of forage cactus species, as its loss of water via transpiration is lower, since the opening of its stomata occurs predominantly at night. So, the larger canopy dimensions, in this case, represented greater shading at the soil surface. Also, low soil water supply and increased crop growth induce less transpiration as the crop intensifies the storage of water in the cladode.

This trend was verified for 'Orelha de Elefante Mexicana', in which the characteristics of the canopy (NTC, NC2, and CAI) presented a negative correlation with ET

Table 5: Pearson correlation analysis of direct and indirect effects among the variables of the response group "Evapotranspiration" (ET), with the variables of the explanatory group "Cladode" (structural characteristics of cladodes), of the 'Miúda' species, under irrigated conditions, in semi-arid environment, in the municipality of Serra Talhada, State of Pernambuco, Brazil

	Variable	Effect	ET	ET/ETo
Cladode group	CC3	Direct effect CC3	-	-1.297
		Indirect effect via PC3	-0.561	
		Total	-	-0.736
	PC3	Direct effect PC3	-	0.575
		Indirect effect via CC3	-	-1.265
		Total	-	-0.690
	Coefficient of determination		-	0.558

Where: Evapotranspiration group: ET - actual crop evapotranspiration, ET/ETo - the ratio between actual crop evapotranspiration and reference evapotranspiration; Cladode group: CC3 - 3rd order cladode length, PC3 - 3rd order cladode perimeter. **"-"** indicates that the variable did not present any correlation with one of the variables of the evapotranspiration group.

Table 6: Pearson correlation analysis on direct and indirect effects among the variables of the response group "Evapotranspiration" (ET), with the variables of the explanatory groups "Environment" (environmental variables) and "Plant" (structural characteristics of plants) of 'Orelha de Elefante Mexicana', under irrigated conditions, in semi-arid environment, in the municipality of Serra Talhada, State of Pernambuco, Brazil

	Variable	Effect	ET	ET/ETo
Environment group	u	Direct effect u	-	0.620
		Indirect effect via Rg	-	0.003
		Total	-	0.622
	Rg	Direct effect Rg	-0.573	-
		Indirect effect via u	-0.005	-
		Total	-0.578	-
	Coefficient of determination		0.555	0.459
Plant group	NCT	Direct effect NCT	-	-0.618
		Indirect effect via NC2	-	0.749
		Indirect effect via IAC	-	-0.737
		Total	-	-0.606
	NC2	Indirect effect NC2	-	0.980
		Indirect effect via NCT	-	-0.472
		Indirect effect via IAC	-	-1.166
		Total	-	-0.657
	CAI	Direct effect via IAC	-	-1.256
		Indirect effect via NCT	-	-0.362
		Indirect effect via NC2	-	0.910
		Total	-	-0.709
	Coefficient of determination		-	0.620

Where: Evapotranspiration group: ET - actual crop evapotranspiration, ET/ETo - ratio between actual crop evapotranspiration and reference evapotranspiration; Environment group: Rg - global solar radiation, u - wind speed; Plant group: NTC - total number of cladodes of the plant, NC2 - number of second order cladodes, CAI - cladode area index, ;"-" indicates that the variable had no correlation with one of the variables in the evapotranspiration group.

and ET/ETo (Table 3). On the other hand, a positive relationship with the ET of the 'IPA Sertânia' was found, but with the occurrence of a negative relation with the ET/ETo. In both cases, this result was more associated to the direct and indirect effects of the cladode area index (Tables 4 and 6), in which the lower values associated with the growth habit of IPA reduced the contact surface with the environment and exposed the soil more, when compared to 'Orelha de Elefante Mexicana' in such a way that it influenced differently the components perspiration and evaporation.

Among the three species evaluated, 'IPA Sertânia' and 'Miúda' are those with the smallest cladode area index. Besides presenting a higher cladode area index, 'Orelha de Elefante Mexicana' has presented the highest lateral canopy growth (Silva *et al*., 2014b), which reduces the soil exposure and the response of the evaporation component to the atmospheric demand. Moreover, Nobel (2001) points out that plants with higher cladode area indices and more densified crops reflect a lower incidence of photosynthetic photon flux and a reduction in CO_2 uptake. Hence, in these conditions, the opening of the stomata will be smaller, reducing the transpiration and the evapotranspiration process, consequently.

For 'Miúda', even with the occurrence of a significant correlation between ET and ET/ETo ratio with more than one characteristic of the plant, the lack of significant canonical axes (Table 2) indicates that this set of variables was independent of the "ET" group, and its effects occurred in isolation, rather than in association. In this case, the negative correlation of the number of first order cladodes with ET, and positive of the number of second order cladodes with the ET/ETo ratio shows that the emission of second order cladodes, to the detriment of the ratio of the first order cladodes, reflected on the response of the ET to the atmospheric demand. Silva *et al.* (2015a) report that the number of second order cladodes is the one with the highest expression in 'Miúda'.

'IPA Sertânia' and 'Orelha de Elefante Mexicana' showed some similarities in relation to the effects of cladodes in ET and ET/ETo. When the size of the 1st order cladodes was larger, the ET and, or, the ET/ETo ratio was reduced. Older cladodes, such as first-order cladodes, besides being shaded by higher order cladodes display a higher proportion of water storage tissues (parenchyma) than the younger ones (Liguori *et al*., 2013). Thus, with the growth of the plant and these cladodes, more water is retained in the plant through storage, to the detriment of the release into the atmosphere in the form of water vapor (Han & Felker, 1997). In addition, first order cladodes with larger dimensions imply the emergence of new orders, which, under condition of water availability and the increase in the atmospheric demand, increase the consumption of water of the crop; but, under water limitation, there is an induction of water accumulation in the cladodes, a reduction of soil evaporation and decrease of ET (Silva *et al*., 2015a).

For genus *Nopalea* species, 'IPA Sertânia' and 'Miúda', when the 3rd order cladodes were still small, the ET response to the variation of the atmospheric demand was higher (ET/ETo). However, as growth increased, values of ET/ETo values decreased. Liguori et al. (2013) report that young cladodes have higher CO_2 uptake when compared to older cladodes, contributing to ET. With cladodes of higher orders and smaller dimensions, the response of the crop to atmospheric demand may increase due to the consumption of water by lower orders cladodes or due to the contribution of the evaporation component. In conditions of water restriction and the growth of cladodes of higher orders, ET is reduced, diminishing its response to atmospheric demand.

CONCLUSION

The meteorological variables and the morphological characteristics of the plant and cladodes of forage cactus affected the variation of the actual evapotranspiration (ET) and its response to the atmospheric demand.

The high intensity of global solar radiation reduced the actual evapotranspiration of the forage cactus species, while the low wind speed decreased the ET response of the 'IPA Sertânia' and 'Orelha de Elefante Mexicana' to the increase of the atmospheric demand.

The increase in canopy characteristics of forage cactus species (cladode area index for 'IPA Sertânia' and 'Orelha de Elefante Mexicana' and number of 1st and 2nd cladodes for 'Miúda') implied the reduction of the ET of the species due to the conditions of water restriction, increase of water storage in cladodes and reduction of the contribution of the evaporation component in the ET process.

Regarding characteristics of the cladodes, this effect was shown by the expansion of the lower orders (1st order) in the 'IPA Sertânia' and 'Orelha de Elefante Mexicana' and by the younger cladodes (3rd order), but these were exclusive of the species of *Nopalea* genus ('IPA Sertânia' and 'Miúda'), which had their ET/ETo ratio reduced.

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