Agrometeorological research on forage cactus and its advances in Brazil

Thieres G. F. da Silva¹, Gherman G. L. de Araújo², Magna S. B. de Moura² and Luciana S. B. de Souza¹

¹ Federal Rural University of Pernambuco, Academic Unit of Serra Talhada, Street Gregório Ferraz Nogueira, S/N, Neighborhood José Tomé de Souza Ramos, 56909-535, Serra Talhada-PE, Brazil
² Brazilian Agricultural Research Corporation, BR 428, Km 152, Zona Rural, Mailbox 23, 56302-970, Petrolina-PE, Brazil

Received: 14 October, 2017. Accepted: 15 November, 2017
First published on the web November, 2017
Doi: 10.26545/000006x

Abstract

Despite being more resilient than agriculture, the performance of the livestock sector depends greatly on the seasonality of the weather variables, which directly affect the supply and quality of the forage. Many forage species have an accumulation of biomass limited to the rainy season, which restricts the activity. Agrometeorology is the science that studies the effect of meteorological and climatological conditions on the agricultural performance of the species and field activities. The progress of this science to a crop allows the understanding of its interaction with the environment and the measurement of technical data, valuable for the improvement of agricultural resilience, planning, decision making, and expansion of financing and rural insurance policies. As a result, it is important to understand the plant-environment interaction to identify the factors that most influence the performance of crops, to elaborate the climatic risk zoning. Knowledge of phenology improves agricultural management and determines the cutting time. The definition of the crop coefficient helps in water management. The application practices of improving agricultural resilience such as selecting the most suitable cultivars, mulching, intercropping and minimum irrigation use ensure maximization of yield. This knowledge was recently raised for the forage cactus, the most cultivated forage cactus in the world. Hence, the objective of this study was to review the advances of agrometeorology information in Brazil on forage cactus for optimization of irrigation management and maximization productivity of the crop.

Keywords: Agricultural Resilience, Irrigation Management, Meteorological Variables

Introduction

Historically, semi-arid regions are affected by climatic adversities (interannual rainfall oscillations associated with high atmospheric demand) affecting crop production. For this reason, livestock farming acts as an activity that attenuates the socio-economic vulnerability. However, despite being more resilient than agriculture, the performance of this sector depends on the seasonality of the weather, as it conditions the supply and the quality of the forage. In the Brazilian semi-arid region, which includes Agreste and Sertão, the native vegetation is the primary source of animal feed, since livestock farming is often practiced extensively. Moreover, several annual or semi-perennial forage species are grown to diminish the seasonality of forage availability. However, many crops present biomass accumulation limited to the rainy season, which is worrisome in the face of projections of climate change, as the forecast has indicated a reduction in the rainy season and an increase in the intensity of extreme events, such as droughts and heat. In current or future climate scenarios, (agro)meteorological data on forage plants are valuable in planning, decision making of agricultural practices, develop-
ment of agricultural policies and rural insurance of livestock activity.

Agrometeorology is the science that studies the effect of meteorological/climatological conditions on the agricultural performance of the species and the field activities. Concerned about crops, the advancement of this allows the understanding of its interaction with the environment and the measurement of technical data to maximize productivity. Weather/climatological conditions affect growth, development, and yield of the crop, the relationship between plants and pests/diseases, and the selection of the best management practices, ranging from tillage to commercialization of the harvested product (Sentelhas and Monteiro, 2009). As a result, it is also relevant in defining the best practices for improving agricultural resilience.

Regarding agricultural planning, climatic risk zoning is determinant for the selection of the best cultivation site, since it uses climatic data and thermal-water requirements of the species, as well as edaphic information about the growing environment and length of the crop cycle. The latter defines the moment of the harvest, as well as its subdivision in phenological stages, which are essential in the management (Sentelhas and Monteiro, 2009).

Plant phenology presents a narrow relation with the thermal energy available in the growing environment and indicates the moment of fertilization, spraying, pruning, irrigation, that is, the decision of field practices. As for irrigation, evapotranspiration (ET) is important information that, combined with productivity, allows the establishment of indices of evaluation of crop sensitivity to water stress (Kheira et al., 2009; Shrestha et al., 2010).

Evapotranspiration can be measured by applying hydrological (i.e., soil water balance) or micrometeorological (i.e., energy balance based on the Bowen ratio) methods (Silva et al., 2011; Silva et al., 2015a). The hydrological methods allow measuring the destination of the water at the soil-plant-atmosphere interface whereas the micrometeorological methods estimate the available energy partition in the system. In an environment with optimal cultivation condition, the ET is represented as $\text{ET}_c$, crop evapotranspiration, which displays the water requirement of the species. For irrigation, $\text{ET}_c$ is estimated using the crop coefficient ($k_c$), using the expression: $\text{ET}_c = k_c \cdot \text{ET}_0$, where $\text{ET}_0$ is the reference evapotranspiration, that is, it occurs above ground covered in ground plants under full growth and with no water restriction. In this regard, data from meteorological stations set on this type of surface allow the estimation of $\text{ET}_0$, with the application of methods ranging from the simple to the most complex (Sousa et al., 2010; Morais et al., 2015). The Penman-Monteith method parameterized in the bulletin 56 by FAO (Food and Agriculture Organization) is considered the standard in $\text{ET}_0$ estimation.

When cultivation conditions are not the optimal, that is, there are adversities in the environment, one of the first practices of food security is the use of adapted species. As a highlight for the Brazilian semi-arid, the forage cactus (Nopalea sp. and Opuntia sp.) is the most cultivated fodder in the world, indicated for animal feed because of its good acceptability and easy digestibility by the herds, besides being a source of energy and carbohydrates. Also, the cladodes show a great reserve of water, being able to be used for the watering of the animals. In Brazil, its cultivation areas are concentrated in Agreste and Sertão of the northeast region of the country, which have the magnitude and seasonality of very different weather conditions.

Despite being found in several types of environments, the increase in the performance of forage cactus depends on the adoption of better management practices. A very important practice is the selection of the best cultivars per region of cultivation. This species has several cultivars belonging to the genera Nopalea and Opuntia, which exhibit distinct productivities due to their morpho-anatomical peculiarities. Another important practice is the use of mulching, which reduces evapotranspiration and improves crop growth and yield. In irrigated areas, its use reduces the frequency of water application and saves on the operating costs of the irrigation system. Under rainfed farming, mulching allows the maintenance of moisture for longer periods in the soil. Mulching also brings benefits in the supply of nutrients made available during the decomposition process. The minimum and regular use of irrigation is another action that may increase the annual productivity of forage cactus. The largest number of studies on irrigated forage cactus in the world is found in the Brazilian Northeast, where experiments were
extensively conducted with the cultivars ‘IPA Sertânia’ (*Nopalea cochenillífera* (L.) Salm-Dyck), ‘Muída’ (*Nopalea cochenillífera* (L.) Salm-Dyck) and ‘Orelha de Elefante Mexicana’ (*Opuntia stricta* (Haw.) Haw.) (Queiroz et al., 2015; Lima et al., 2016; Barbosa et al., 2017; Carvalho et al., 2017a; Morais et al., 2017; Pereira et al., 2017). When the forage cactus solely is supplied to the herd, the result may be the occurrence of diarrhea, since the plant has a low content of dry matter. Therefore, the insertion of other cultures into the diet may provide fiber as well as a nutritional deficiency (Galvão Júnior et al., 2014). For this reason, the intercropping between cultures is extremely important in the sustainable management of local livestock. It is a practice applied to food crops and used to improve the efficiency of their agronomic attributes (Yilmaz et al., 2015).

Based on what has been exposed so far, the objective of this study was to review the advances of agrometeorology information in Brazil on forage cactus for optimization of irrigation management and maximization productivity of the crop.

**Forage cactus for feed security for the herds in their producing region**

The species that use the crassulacean acid metabolism (CAM) represent around 6% of the global vegetation. Among them, one of greater relevance in several regions of the planet is the forage cactus, which has a wide adaptation in environments with water restriction, due to its structural, anatomical and physiological modifications (Nobel and Bobich, 2002). It is composed of succulent structures (cladodes) covered with waxy cuticle and low stomatal density, which confer them minimal transpiration.

Under different environmental conditions of water availability, temperature, soil salinity, photoperiod, etc., the forage cactus transits its CO$_2$ assimilation process between CAM and C3, which characterizes it as a facultative CAM species with broad plasticity. This physiological response demonstrates that the forage cactus may exhibit stomatal opening during the daytime period, but this occurs only with some structures such as young cladodes and floral bulbs; while mature cladodes open the stomata mostly at night. In this period, CO$_2$ is fixed to the phosphoenolpyruvic acid by the action of the enzyme PEP-case, since it does not require chemical energy (ATP and NADPH), being assimilated in the form of organic acids (aspartic and malic) and accumulated in the vacuoles. In the presence of solar energy, organic acids undergo decarboxylation and CO$_2$ is released into the Benson-Calvin cycle (Lin, 2009).

Those adaptations allow the forage cactus to assimilate CO$_2$ even during a long drought period and maintain acceptable yield levels under severe stress conditions. Laboratory studies have shown that forage cactus is a plant with high water efficiency, which makes it a very important crop for semi-arid regions (Nefzaoui and Ben Salem, 2002).

In the Brazilian Northeast, the forage cactus is regarded a subsistence crop of the herds, being the main forage, especially in the states of Alagoas and Pernambuco (Lopes et al., 2007). Most of its cultivars belong to the genus *Opuntia* sp. and *Nopalea* sp., which contain carbohydrates, minerals, vitamins, high digestibility, besides being rich in water, supplying the animals’ requirements, especially when added to fibrous and proteinic foods (Peixoto et al., 2006). These characteristics are decisive for the regions of Agreste and Sertão, which usually have predominant cyclical periodicals of rainfall events (Fig 1).

\[
\text{Rainfall} = 619.2484 + 155.9436 \sin(2 \pi \text{Rainfall} / 33.5757 - 4.0323); p = 0.0006
\]

**Fig 1.** Cyclic periods of the rains in Agreste and Sertão of the Brazilian Northeast region (Case study of the municipality of Águas Belas, PE) Source: Personal archive, prepared based on the 88-year annual database of the Water and Climate Agency of the State of Pernambuco (Agência Pernambucana de Águas e Clima, www.apac.pe.gov.br).

In the Brazilian Northeast, the majority of forage cactus crops is located in areas with annual rainfall of 600 mm, on average, for the Sertão, ranging from 400 to 800 mm, and 900 mm in the Agreste, ranging from 800 to 1000 mm, depending on the geographic location in the region. Moreover,
these environments have the characteristic of most years with rainfall levels below their historical average. As shown in Figure 2a, annual rainfall is classified based on the standard deviation (σ) of its historical series of at least 30 years. In regular rainfall variability, half of the standard deviation is used as limits (σ/2), indicating that the rain around the historical average (μ), that is, μ ± σ/2, represents regular years. In cases where these limits are exceeded up to μ ± σ, it is characterized as superior or inferior variability. Under conditions where annual rainfall exceeds the values of μ ± σ, upper or lower climatic anomalies of annual rainfall events are considered.

![Classification of the interannual rainfall variability](image1)

![Case study of the annual rainfall frequency of the municipality of Águas Belas, PE. Note: number above each column of the second figure indicates the number of years in the class. Source: Personal archive, based on the 88-year annual database of Water and Climate Agency of the State of Pernambuco (Agência Pernambucana de Águas e Clima).](image2)

In most sites with forage cactus crops in the Brazilian Northeast, rainfall prevails in the lower variability class (Fig 2b). Moreover, the period of productive accumulation by the forage cactus between these two regions occurs in very different meteorological conditions (Fig 3). In Agreste, the period of greatest rainfall coincides with the months with the lowest air temperature, while in Sertão, it...
occurs in the warmer months, generating, among these environments, different water regimes. These conditions culminate, in Sertão, in meteorological drought most of the year, which may affect the accumulation of biomass by the forage cactus.

It can be seen in Figure 3 that Petrolina and Cabrobó, two municipalities located in Sertão do Estado in the state of Pernambuco, have one to two months with low or zero water deficiency, while in municipalities in Agreste, they vary from five to six months. In this region, the altitude effect promotes milder temperatures than Sertão, although they are located in a low latitude range (between 8º and 9º South).

The persistence of meteorological drought events may promote significant reductions in surface and underground water resources, resulting in hydrological drought. In both types of drought (meteorological and hydrological), the water requirement of many forage crops (grasses and legumes) is not met, inducing to a significant reduction in forage availability. In this situation, the cultivation of forage cactus becomes the main food security for the herds.

The knowledge of the climatology of areas where forage cactus crops occur contributes to the adequacy of management according to the water availability, since its greatest productive increase occurs in the rainy season and its survival in the dry season is due to the amount of water accumulated in the cladodes. Therefore, sites with periods of very prolonged water deficit may not present a good development of the forage cactus, because it reduces the storage of water by the plant. However, the success of forage cactus cultivation also depends on its interaction with other weather elements, which vary from place to place. Thus, the implantation of forage cactus cultivation areas should initially follow the guidelines of climatic risky agricultural zoning.

Forage cactus growing planning (agriculture zoning)

The official Brazilian climatic risk zoning (CRZ) for forage cactus is published annually from ordinances in the website of the Ministry of Agriculture, Livestock and Supply (Ministério da Agricultura, Pecuária e Abastecimento - MAPA) (www.agricultura.gov.br). In this ordinance, the summary of the study and the list of municipalities suitable for cultivation are found, distributed in the following items: "Technical Note", which presents information about the crop and a brief description of the methodology adopted in the elaboration of zoning; “Soil types”, grouped into three categories for water retention capacity (sandy - type 1, medium texture - type 2, and clayey - type 3), according to normative instruction published by MAPA itself; “Planting period”, indicating the time for beginning of the planting; and, the relation of the indicated municipalities for the planting of the culture.

Although the main species and cultivars of forage cactus are mentioned, there is no indication of the most recommended for each State. The CRZ for forage cactus was elaborated only for the states of the Northeast region, except Maranhão. In this CRZ, only annual data of average, maximum and minimum temperature and accumulated rainfall were considered, such that, when no less than 20% of the territory of the municipalities have climatic conditions within these ranges in at least 80% of the evaluated years considered suitable for cultivation.
However, it is understood that other agrometeorological information such as interannual variability of climatic factors, planting time, WRSI (Water Requirement Satisfaction Index), phenological and cycle length, maximum period of days with no rainfall and types of cultivars are essential for the refinement of CRZ.

Besides CRZ, other studies were published with the aim of defining the most suitable areas for forage cactus cultivation in Brazilian Northeast states, such as those suggested by Moura et al. (2011), in Pernambuco, and Bergson et al. (2014), in Paraíba, who recommend cultivation in a wide territorial range (Fig 4). Restrictions due to water deficit and high temperatures are predominant in the Sertão region of the two states, while risks of an excess of water may occur in some Agreste municipalities, in Brejo de Altitude, or in the coastal areas, not recommended for cultivation.

In the zoning of these two states, the thermal-water criteria defined by Souza et al. (2008) (Table 1), who analyzed the regions of origin and producers of forage cactus in the world. According to these authors, the rainfed cultivation of the forage cactus may occur in locations with annual temperatures ranging from 16.1 and 25.4°C, with daily minimums of not less than 8.6°C and maximums not exceeding 31.5°C. The best crops occur in rainfall conditions ranging from 368.4 to 812.4 mm year\(^{-1}\), but they can be encouraged in areas that reach up to 1089.9 mm year\(^{-1}\).

Although grown within these ranges of aptitude, forage cactus presents a great variation of biomass accumulation. For the climatic conditions of the state of Bahia, Carvalho et al. (2017b) simulated that the attainable productivity of the forage cactus (Opuntia sp.) with a density of 15,625 plants ha\(^{-1}\), grown without nutritional restrictions and under rainfed system, can exceed 24 tons of dry matter per ha\(^{-1}\) in two years (Fig 5a).

Compared to crop evapotranspiration, this yield generates an efficiency of water use greater than 4.5 kg of dry matter per cubic meter of water consumed by the cactus (5b). Figure 5a shows that most of the municipalities in the state presents climatology that favors the production of 16 to 24 tons of dry matter per ha\(^{-1}\) every two years, with average efficiency varying from 3.0 to 4.5 kg of dry matter per cubic meter of water consumed by the crop. On the coast, excessive rainfall impairs the yield of forage cactus.

In areas where the agronomic performance of the forage cactus is lower because of water restrictions, it is indispensable to know its interaction with the environment, aiming at choosing the best practices to maximize its productivity.

**Understanding the interaction cactus-environment (agriculture environment measures)**

The understanding of the response of the forage cactus to the conditions of the cultivation environment can be evaluated by means of micrometeorological measurements and vegetation of the soil-plant-atmosphere system, which allow to identify the primary factors that rule energy and mass changes (Qin et al., 2010). Some studies with CAM plants (eg, cactus and pineapple) (Consoli et al., 2013; San José et al., 2007) have used micrometeorological techniques to evaluate changes in energy fluxes and their partitions in sensible and latent heat, as well as water vapor, in terms of evapotranspiration of these species. In other cases, the water dynamics between the soil-plant-atmosphere interface has been studied (Silva et al., 2015a; Morais et al., 2017). In spite of their importance, there are few published studies containing micrometeorological information of the forage cactus and its interrelations with the conditions of the crop environment in the international literature. In Brazil, the only experimental farms have been implemented since 2014 in the study area of the System CAAM-DESAT (Study System of Caatinga, CAM Plants and desertification areas in interaction with the Atmosphere) located between the municipalities of Serra Talhada, Floresta and Mirandiba, in Pernambuco, and in the International Reference Center for Agrometeorological Studies of Cactus and Other Forage Plants (Centro de Referência Internacional de Estudos Agrometeorológicos de Palma e Outras Plantas Forrageiras) (Fig 6), in Serra Talhada, both linked to the Serra Talhada Academic Unit of the Federal Rural University of Pernambuco.

In these farms, micrometeorological measures provide the ability of the forage cactus to control water transfer, analyze the influence of environmental factors on the evapotranspiration process, and define a pattern of plant growth response to varying environmental conditions.
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Fig 4. Climate zoning of the states of Pernambuco (a, Source: Moura et al. 2011) and Paraíba (b, Source: Bergson et al. 2014) for the cultivation of forage cactus.

Fig 5. (a) Achievable yield, in ton ha\(^{-1}\), (b) water use efficiency, in kg dry matter m\(^{-3}\), by forage cactus in climate conditions in the State of Bahia. Source: Extracted from Carvalho et al. (2017b).

Table 1. Climate aptitude criteria of forage cactus according to Souza et al. (2008).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ideal</th>
<th>With restrictions</th>
<th>Inadequate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average temperature (ºC)</td>
<td>16.1 to 25.4</td>
<td>Lower than 16.1 or greater than 25.4</td>
<td>-</td>
</tr>
<tr>
<td>Maximum temperature (ºC)</td>
<td>28.5 to 31.5</td>
<td>Lower than 28.5 or greater than 31.5</td>
<td>-</td>
</tr>
<tr>
<td>Minimum temperature (ºC)</td>
<td>8.6 to 20.4</td>
<td>Lower than 8.6 or greater than 20.4</td>
<td>-</td>
</tr>
<tr>
<td>Temperature range (ºC)</td>
<td>10.0 to 17.2</td>
<td>Lower than 10.0 or greater than 17.2</td>
<td>-</td>
</tr>
<tr>
<td>Rainfall (mm year(^{-1}))</td>
<td>368.4 to 812.4</td>
<td>Between 812.4 and 1089.9 or less than 368.4</td>
<td>Greater than 1089.9</td>
</tr>
<tr>
<td>Humidity index (-)</td>
<td>-65.6 to -31.8</td>
<td>Between -31.8 and -7.7 or lower than -65.6</td>
<td>Greater than 7.7</td>
</tr>
</tbody>
</table>
Such premise is consolidated when the biosphere and climate are considered to be a coupled system, where the meteorological scales (temperature and relative humidity, rainfall, insolation, among others) and biological processes (photosynthesis, respiration, heat exchanges and water vapour) affect water balance, carbon fluxes and plant growth, and can modify the partitioning of the radiation balance in latent and sensitive heat fluxes, soil heat and surface storage, as well as water in the soil-plant-atmosphere system. In this interaction, the type of species and their respective physiological and morphological processes are relevant factors (Krishnan et al., 2012).

In the Central Sertão experimental farms (Fig 6a), micrometeorological measurements are obtained from high- and low-frequency systems composed of electronic sensors coupled to a galvanized iron tower or installed along the soil profile. In the high-frequency system (Eddy Covariance), measurements are made with an infrared gas analyzer (that is, IRGA Li-7500, LI-COR, Lincoln, USA) and a three-dimensional sonic anemometer (that is, CSAT3, Campbell Scientific, Logan, USA). High-frequency measurements are performed at 10 Hz with stored mean values, for example, every 30 minutes, using data acquisition systems (i.e., CR5000, Campbell Scientific, Logan, USA). In turn, the low-frequency system is composed of two temperature and air relative humidity sensors (i.e., HMP155A, Vaisala, Helsinki, Finland) in the form of a profile at equidistant heights above the soil surface: an anemometer (i.e., 034A-L, R. M. Young Co., Traverse, MI, USA); a radiometer balance (i.e., NR-Lite, Campbell Scientific, Inc., Logan, Utah); two pyranometers, one inverted for measuring surface-reflected solar radiation (i.e. CM3, Kipp and Zonen, Delft, The Netherlands) and another for incident solar radiation (i.e. LI200X, LI-COR, Lincoln, USA); a quantum (i.e. PAR Lite, Kipp and Zonen, Delft, Netherlands); an infrared thermometer (i.e., Apogee SQ-321, NE, USA) and a rain gauge (i.e. 10116 rain gauge, TOSS, Potsdam, Germany), all installed in the towers; a linear quantum sensor under the canopy of the plants (PAR line, Kipp and Zonen, Delft, Netherlands) was installed nearby; two flowmeters (i.e. HFP01, Hukseflux, Delft, The Netherlands) and two soil temperature sensors at 0.15 and 0.30 m (i.e. TB107, Markasub, Olten, Switzerland). The low-frequency measurements are performed every 60 seconds with mean values stored every 30 minutes, using data acquisition system (i.e., CR1000, Campbell Scientific, Logan, USA). Access tubes were installed to measure soil moisture up to 0.8 m depth (that is, Diviner 2000, Sentek Ltd., Australia) and load cell weighing mini-lime meters to measure the evaporation of soil water (Campbell Scientific, Inc., Logan, Utah) at weekly intervals (Fig 6b). From these measurements, it was found that the incidence of radiation above the forage cactus is strongly affected by solar declination, the maximum length of the daytime period and local cloud conditions for the Brazilian semi-arid region. The cactus-soil system reflected twenty percent of the incident global solar radiation, and the crop absorbed 19%. Most of the energy available in the system is intended for air heating (H, 64%); while less energy is spent in the evapotranspiration process (LE, 32%), even in the rainy season (unpublished data). This information is essential for the management of water for the crop and the
understanding the factors that influence its performance.

Based on the emission of cladodes in order of appearance, Amorim et al. (2017) established the phenology and cutting time of forage cactus, and the effects of water availability and the adoption of cropping systems over their durations. According to these authors, the transition of vegetative phenological phases of the forage cactus occurs when the rate of emission of cladodes of a certain order is exceeded by the rate of emission of cladodes of the subsequent order, it is characterizing the beginning of a new phase.

It is observed in this example that the rate of emission of cladodes was related to the thermal time (TT), which expresses the amount of thermal energy for the advancement of the phenological phases of the crop. For its estimation, Silva et al. (2015b) suggest the lower base temperature (t\(_b\)) of 20°C, i.e., that the development of forage cactus effectively occurs only when the environment temperature exceeds this value. Thus, TT is calculated from daily average air temperature data (t\(_a\)\(\text{verage}\), °C), throughout the crop cycle, and the expression \(TT = \sum_{i=1}^{n} (t_{a\text{verage}} - t_b)\), (i = 1) until harvest, after n days.

In addition to the effect of air temperature on the length of the phenological stages of forage cactus, Amorim et al. (2017) state that, in one-year interval, the increase of water depth from 976 mm year\(^{-1}\) to 1202 mm year\(^{-1}\) in the cultivation of \(O.\) stricta increases the emission of 2\(^{nd}\) order cladodes (Fig 7a), but to the detriment of the appearance of 3\(^{rd}\) order cladodes (Fig 7b).

However, this result depends on the species and the management adopted. By using mulch and intercropping with sorghum, these same authors verified that forage cactus had a reduction in the length of its third phenological phase (Fig 8) when third-order cladodes predominate. In the mulch system, this result is justified by the microclimatic modification of the growing environment that promoted the highest emission of second order cladodes.

On the other hand, in the intercropping, the reduction in the incidence of radiation higher than the forage cactus and competition for water and nutrients, inhibited the emission of cladodes. In the study by Amorim et al. (2017), the authors found no effect of water availability and cropping system on the length of the first phenological phase, since the imposition of treatments was established after the emission of first-order cladodes.
Although cutting, that is, the harvesting of the forage cactus depends on the farmer’s need to provide it to the animals, its morphogenesis must be observed to guarantee greater productivity and longevity. For forage cactus, harvesting time can be defined by the rate of dry mass accumulation, according to the methodology proposed by Amorim et al. (2017) who took over the crop at the instant this rate is decreasing and become less than half the rate of the cycle. An example can be seen in Figure 9.

![Graph showing dry matter accumulation rate](image)

**Fig 9.** Example of the monthly accumulation rate of the forage cactus (*O. stricta*) as an indicator of the cutting moment. The dashed line refers to the mean value (μ), with the cut being defined as the half of μ, that is, μ/2. The arrow is indicating the harvest time for this example.

Amorim et al. (2017) mention that this harvesting time is sensitive to crop management. In irrigated conditions, these authors show that *O. stricta* should be harvested, on average, at 19 months old, but it depends on the growing system imposed on the crop. Under single cropping systems with and without mulch, the harvesting time is on average 21 and 19 months, respectively. On the other hand, in the intercropping with the sorghum, the cutting time should be even more anticipated, at 17 months on average.

The knowledge of forage development is essential for the improvement of its management since it affects the number of cladodes emitted. According to Pinheiro et al. (2014), the productivity of forage cactus cultivars is directly associated with the number of cladodes, cladode area index and the morphology of the higher cladodes of the plant. Therefore, the magnitude and seasonality of the meteorological factors that influence the emission of cladodes define the performance of the crop.

According to Barbosa (2015), forage cactus cultivars have different meteorological requirements, because of their different morphologies. According to this author, in general, the nocturnal temperature, the relative humidity of the diurnal and nocturnal air, wind speed and incident solar radiation affect the growth of the forage cactus. *O. stricta* is more sensitive to variations in air temperature than *N. cochenillifera* cultivars, while they are more affected by incident solar radiation.

Because of its high water storage capacity, low water demand and reduced conversion to dry matter as a consequence of CAM photosynthetic metabolism, forage cactus does not always respond to the regular increase of water. This behavior was investigated in a study conducted by Flores-Hernandez et al. (2004), under the climatic conditions of Mexico, with four forage cactus cultivars, which did not present significant increases in production even after the rise in the water depths (760 to 1380 mm year⁻¹). A similar result was found by Queiroz et al. (2015), working with the regular application of water to *O. stricta* under Brazilian semi-arid conditions, which ranged from 976 to 1202 mm year⁻¹.

More recently, Barbosa et al. (2017), in the Brazilian semi-arid region, verified that the regular application of water in *N. cochenillifera* (cv. Sertânia and ‘Miúda’) and *O. stricta* (cv. ‘Orelha de Elefante Mexicana’), which resulted in annual water depths of 493 mm year⁻¹ (rainfed condition and seven months with at least 55 mm) at 756 mm year⁻¹ did not have an effect on the productivity of these species. Scalisi et al. (2016) suggest that controlled reductions in irrigation depths may not affect forage cactus productivity since this species regulates growth rate and can rehydrate the cladodes even after a long period of drought. These authors, studying the *O. ficus-indica* in pot, found that this species maintains some growth and gas exchanges in relative water content above 45%, which is value is well below the critical limit of C3 and C4 plants.

In a study carried out in Serra Talhada, Pernambuco, during the fourth productive year of *O. stricta* (November 2014 to October 2015), with successive annual cuttings and maintenance of only the basal cladode, it was observed that 355 mm year⁻¹ plus 208 mm of irrigation, totaling 563 mm year⁻¹, were sufficient to maintain productivity similar to
treatments irrigated with water depths of to 1011 mm year\(^{-1}\) (unpublished data). According to Felker and Inglese (2003), for locals with high atmospheric demand and rainfall below 350 mm year\(^{-1}\), the use of irrigation is essential to ensure a good yield.

On the other hand, the drop in crop yield due to excess of water is as marked as under water restriction conditions, suggesting that forage cactus is more sensitive to excess of water than to deficit. Queiroz et al. (2015) experimentally observed that the complementary and regular application of water through irrigation during the forage cactus cycle promoted a productive increase up to 1048 mm year\(^{-1}\), with monthly values above 70 mm; from this value (1048 mm year\(^{-1}\)), the yield is significantly reduced.

The combined effect of meteorological elements on the productive performance of forage cactus was modeled by Silva et al. (2015c):

\[
\text{Increment-cladode} = f(\Delta T).f(\Delta RH).f(\Delta(P+I)).0.6479 +0.4801,
\]

where: \(f(\Delta T) = 4.2893 \cdot \exp(-0.5 \cdot ((\Delta T - 1.1643)/1.1115)^2)\); \(f(\Delta RH) = 1.5768 \cdot \exp(-0.5 \cdot ((\Delta RH + 2.0681)/6.1652)^2)\) and \(f(\Delta(P+I)) = 7.0 \cdot 10^{-5} \cdot \Delta(P+I)^2 - 0.0152 \cdot \Delta(P+I) + 1.4223\), and, \(\Delta T, \Delta RH\) and \(\Delta(P+I)\) are the monthly increments of air temperature (\(^\circ\)C), air relative humidity (%) and water availability by precipitation and irrigation (mm), respectively.

Based on the displayed information, it is recommended that the use of irrigation is used when the rainfall level of the site is less than 493 mm year\(^{-1}\) or even higher than this quantity, but irregular throughout the crop cycle. In the months when precipitation is less than 70 mm, irrigation depths should be applied based on the water requirement of the cactus (crop evapotranspiration).

The evapotranspiration represents the water depth transferred by the soil-plant system to the atmosphere, through the simultaneous processes: evaporation and transpiration. Under full conditions of water regime and management, maximum crop evapotranspiration (ETc) is referred, which must be returned to the soil to ensure potential productivity. When these conditions are not met, it is denominated actual evapotranspiration (ETr).

Under the conditions of the Brazilian semi-arid, Silva et al. (2015a) found ETr values for the forage cactus conducted in rainfed varying between 0.73 and 5.41 mm day\(^{-1}\). In this study, the authors did not find differences between the ETr of the cultivars ‘IPA Sertânia’, ‘Miúda’ and ‘Orelha de Elefante Mexicana’, resulting in an average of 2.35 mm day\(^{-1}\). However, the variability of evapotranspiration depends on the cultivar. According to these authors, ‘Miúda’ responds rapidly to fluctuations in atmospheric demand, suggesting a lower plasticity.

On the other hand, the actual evapotranspiration of the ‘Orelha de Elefante Mexicana’ decreases as the cladode area index increases, showing a drop in the magnitude of the evaporation component due to shading of the soil surface or a fall in the water consumption by the plant as a function of greater storage of water in cladodes. Similar results were obtained by Barbosa (2015), studying these cultivars conducted on complementary and regular irrigation depths, that is, the increase of the cladode area index of the ‘Orelha de Elefante Mexicana’ reduced its evapotranspiration. For ‘Miúda’, the increase in the number of first- and second-order cladodes is determinant for the increment of the evapotranspiration of this cultivar.

The capacity of water accumulation by the forage cactus was measured by Morais et al. (2017). These authors report that, when conducted under complementary irrigation with regular 2.5 mm, 5.0 mm and 7.5 mm water depths every 7, 14 or 28 days, only 5.4% of the water at the soil-cactus-atmosphere, equivalent to 27.8 mm for 18 months, is retained in the cladodes, in order to guarantee its continuous growth. These data highlight the high efficiency in the use of water by the forage cactus, indicating that the minimum and regular use of irrigation events is sufficient for the proper development of the crop. On the other hand, Han and Felker (1997) showed that, on average, 45% of the ETr of \(O. ellisiana\) is a result of soil water evaporation. In studies conducted in Serra Talhada, estimates of the partitioning of the evaporation component in ETr based on the cladode area index and the extinction coefficient (Leite et al., 2017) have suggested values of up to 84% on average for the cultivar ‘IPA Sertânia’ at two years of age under complementary irrigation conditions (unpublished information).

Barbosa (2015) mentions that, in addition to the growth dynamics, the evapotranspiration of the forage cactus depends on the seasonality of the meteorological conditions. The increase in solar radiation in the soil-forage cactus system implied a reduction in the evapotranspiration of the cultivars ‘IPA Sertânia’ and ‘Orelha de Elefante Mexicana’,...
while the decrease in wind speed reduced the response of these cultivars to the rise in the atmospheric demand. Global solar radiation and wind velocity combined with water vapor pressure deficit in the atmosphere push the evapotranspiration process in C3 and C4 plants. Regardless of the photosynthetic process (C3, C4, and CAM), the low wind speed diminishes the interaction of the plant with the environment, which justifies its effect on the forage cactus. Or, the reduction of the evapotranspiration of a crop as the incident radiation is increased may happen if the availability of water in the soil is not sufficient for the crop. In the case of the forage cactus, the high incidence of radiation may also affect the stomatal activity and so, plant transpiration, as suggested by Barbosa (2015) based on information in the literature.

Under full water regime conditions, few fluctuations in the amount of water in the soil are sufficient to modify the evapotranspiration of the forage cactus, regardless the cultivar (Silva et al., 2015a). Under conditions of water restriction, the increase in atmospheric demand reduces the actual evapotranspiration of the three cultivars. Under cultivation irrigated with regular water depths throughout the cycle and well managed, Queiroz et al. (2016) found values of maximum evapotranspiration of the forage cactus varying between 2 and 4 mm day\(^{-1}\) on average, with a mean of 2.59 mm day\(^{-1}\) (Fig 10).

In the study by Queiroz et al. (2016), during the second productive cycle of *O. stricta*, after conduction in rainfed system in the first fifteen months followed by a cut of uniformity maintaining only the basal cladodes, these authors showed that the crop coefficient (kc) did not vary much during a year, with an average value of 0.52. Although the work of Queiroz et al. (2016) was conducted only during a cycle year, this result was the first published in Brazil, to assist in the management of water from the crop. Studies conducted with forage cactus cultivars for two years in Serra Talhada indicate the variation of the crop coefficient according to the rate of cladodes emission by the plant (unpublished information).

Methods for measuring evapotranspiration in forage cactus

Measurement of evapotranspiration in forage cactus has been determined mainly by the application of hydrological (that is, soil water balance) and micrometeorological (that is, energy balance based on the Bowen ratio) methods. The first method was applied by Silva et al. (2015a), Queiroz et al. (2016), Pereira et al. (2017) and Morais et al. (2017), assuming a control volume of 0.60 m, but which may vary according to the yield of the crop root system. In all of these studies, because of the low declivity of the cropped areas and the adoption of level curves in the plantation, the gains and losses of water by subsurface runoff were considered negligible or that they were annulled. Hence, actual evapotranspiration of the forage cactus can be estimated using the following simplified equation:

\[
P - ET \pm Q - R = \Delta A
\]

where, \(P\) = rainfall (mm), \(ET\) = evapotranspiration (mm), \(Q\) = soil water flow where it may be \(D = \) deep drainage (mm) (negative sign) or \(AC = \) capillary rise (mm) (positive sign); \(R\) = superficial draining (mm), \(\Delta A = \) variation in soil water storage (mm).

Components of the soil water balance should be determined for time intervals of more than five days. Rainfall is collected using a rain gauge installed near the crop area. The deep drainage or capillary rise is calculated by measurements of soil moisture and physical-water properties of the layer right above and below the lower base of the control volume and using the Buckingham-Darcy equation expressed by:
Q = - K(θ) \frac{Δψt}{Δz}

where, Q = soil water flow by deep drainage or capillary rise (mm day⁻¹), K(θ) = hydraulic conductivity of the unsaturated soil (mm day⁻¹), obtained by the ratio K(θ) = Ko e^(-αθ-βθ) and Δψt/Δz = gradient of the total soil water potential, between the layers above and below the lower limit of the control volume.

The ψt can be estimated, for both layers, using the following adjusted equation, using tensiometric and soil moisture measurements:

ψt = α e^{-βθ}

where, α and β are adimensional parameters.

Surface runoff (R) can be obtained by direct measurements, using runoff or estimated runners using, for example, the "Curve Number" method proposed by SCS-USDA (Department of Soil Conservation of the United States Department of Agriculture United). This method considers the soil-vegetation complex, the soil type, the use, the initial moisture and the hydrological properties of the site, where the flow is estimated by the equation:

R = \left( \frac{P - 0.2 \left( \frac{25400}{CN} - 254 \right)}{P + 0.8 \left( \frac{25400}{CN} - 254 \right)} \right)^2

where, CN is the curve number, equal to 75 for the cultivation conditions cited by Silva et al. (2015a), which represents a soil condition with moderate infiltration rate, planting in rows with level curves and an area of a suitable hydrological condition.

Soil water storage (A) can be obtained by integrating the water depth values of the control volume. Thus, the variation in water storage in the soil profile (ΔA) is determined by the difference between the values of A of the initial and final times of each period considered, being expressed by:

ΔA = A_f - A_i

where, A_f and A_i represent the water stores accumulated in the soil at the final and initial time, respectively.

Using the values of the other components of the water balance in the soil, the actual accumulated evapotranspiration of the forage cactus is obtained by residue:

\[ \int_0^t \text{ET} \, dt = -\text{ET} \]

where, n is the time expected for the achievement of ET.

The micrometeorological method, one of the most used in different vegetation types to estimate the evapotranspiration is the energy balance based on the Bowen - BERB ratio (Silva et al., 2011). By this method, latent heat flux (LE) values are estimated using micrometeorological measurements of the soil-plant interface with homogeneous characteristics, low slope, and wide border.

Values of the latent heat flux are estimated using the following equation:

\[ \text{LE} = \frac{R_n - G}{1 + β} \]

where, R_n = surface radiation balance (W m⁻²); G = heat flux in the soil (W m⁻²); L = latent heat of vaporization (kJ kg⁻¹); β = Bowen ratio (dimensionless).

This method is based on the energy balance, R_n = LE + H + G, forcing its closure by using the relationship between the fluxes of LE and H (sensible heat flux), called Bowen's ratio (β), where β is calculated from the equation:

\[ β = \frac{H}{\text{LE}} = γ \left( \frac{ΔT}{Δe} \right) = γ \left( \frac{t_1 - t_2}{e_1 - e_2} \right) \]

where Δ = slope of the water vapor pressure curve (kPa °C⁻¹); γ = psychrometric constant (kPa °C⁻¹); t_1 and t_2 = air temperature measured at two measurement levels above the crop canopy (°C); and, e_1 and e_2 = actual pressure of water vapor in the atmosphere measured at two levels of measurement above the crop canopy (°C), calculated by the equations: e = es UR/100, where RH = air relative humidity and es is the saturation pressure of the water vapor in the atmosphere estimated by the equation: es=0.61078.10^((7.5 t)/(2373.3+t)), where t is the air temperature at the corresponding level.

For its application, electronic sensors must be installed above the crop within the adjusted boundary layer or constant flow layer (Perez et al., 1999). The reading interval by the BERB method can be every 60 seconds with averages of not less than 5 minutes, as suggested by Steduto and Hsiao (1998).

As described previously in the item “Understanding forage cactus- environment
interaction (Measures of the Agricultural Environment)”, measurements of the balance of radiation and soil heat flux are obtained by the radiometer balance and flow meter sensors, while the temperature and air relative humidity by two thermohygrometers installed at 0.5 and 2.0 m above the crop, for example.

The minimum border distance to ensure the consistency of the estimate of the above-surface flux values, as shown in Figure 6a, can be calculated by the equation:

$$\delta = 0.1 z_{om}^{0.2} X^{0.8}$$

where, $z_{om}$ = surface roughness parameter for momentum (m); X = distance between the transition point of the new surface and the installation site of the equipment, that is, “fetch” (m).

According to Rosenberg et al. (1983), the BERB method presents good results for flow estimation when there is a fetch:height of the sensors ratio greater than 100:1. Within this range, measurements of temperature and water vapor pressure gradients tend to come into equilibrium with the canopy of the crop. However, when $\beta$ values are small and positive, Heilman et al. (1989) state that a fetch:height ratio of 20:1 is sufficient.

Some problems resulting from the BERB method are related to the precision of the sensors and approximation of the values from $\beta$ to -1. Moreover, it is necessary to reverse the thermogravimetry to reduce measurement errors and, therefore, the inconsistency of LE results (Silva et al., 2011). Errors of LE estimation usually occur at dawn and dusk or even during rainfall or irrigation events, which promote the inversion of temperature and water vapor pressure gradients. Therefore, to reject $\beta$ values close to -1, some authors consider a rejection interval based on the accuracy of water vapor pressure and temperature measurements (Perez et al., 1999). The LE data that meets the quality analysis criteria is considered to be physically consistent.

From the data measured for the average intervals of not less than 5 minutes (t), the evapotranspiration values are calculated by the equation:

$$ET(t) = \frac{LE \times t \times f_{tempo}}{L}$$

where, $LE$ = latent heat flux (W m$^{-2}$); t = storage interval of average values ($\geq$ 5 minutes); $f_{time}$ = time scale adjustment factor (i.e. 60 s); $L$ = latent heat of vaporization (kJ kg$^{-1}$)

Daily values of ET (t) are calculated by considering the values in the period in which the available energy ($Rn - G$) is positive

$$ETc = \sum_{Rn-G>0} ETc(t)$$

### Estimating evapotranspiration for optimization of irrigation management

For irrigation purposes, the meteorological method by the product between the crop coefficient (kc) and the reference evapotranspiration ($ETo$) is globally accepted for the estimation of crop evapotranspiration ($ETc$) (Allen et al., 1998):

$$ETc = kc \cdot ETo$$

Regarding the application of this method, it is recommended to carry out the first irrigation event based on available water capacity (AWC), which considers the field capacity (FC), permanent wilting point (PWP), soil density (SD) and the depth of the root system (pf). The FC, PWP, and SD are determined from dispatching soil samples to a laboratory. In turn, it is suggested that the pf is equal to the depth of planting of the basal cladode. When the first irrigation based on the AWC cannot be carried out, it is recommended the first event to last to ensure that the soil moisture is in the field capacity.

For further events of irrigation based on the meteorological conditions, one must first know the water requirement throughout the cycle. This information is represented by kc. As previously mentioned, Queiroz et al. (2016) found the kc equal to 0.52 for the forage cactus with crop already established and with an annual cut interval. In the bulletin 56 by FAO (Allen et al., 1998), three values of kc are indicated over the crop cycle (Fig 11): initial kc, intermediate kc, and final kc, with the objective of facilitating their estimation over four stages of development: initial, development, intermediate and final. The length of these stages for the forage cactus depends on the climatic conditions in the local, the cultivar and the adopted management.

For most crops, half of the average of these three kc values suggested by FAO is close to the initial kc value.
Based on this information, the kc value of 0.26, during the planting and establishment period of the forage cactus, can be used. Silva et al. (2015a) and Barbosa (2015) cite that the evapotranspiration of this species tends to reduce with as cladode area index increases. Thus, it is recommended that the final kc is also 0.26. Table 2 shows a summary of the kc values to be adopted in forage cactus water management.

In the initial phase, the most appropriate management of irrigation frequency should be considered, since water stress in this period is important to stimulate the rooting of the basal cladode. The excess of water in this phase promotes the decay of the cladode in the field. In the development and intermediate stages, it is important to know the number of orders emitted by each cultivar to identify the most representative one. For example, if this is the second order, the predominance of first-order cladodes emission is considered to occur during the development phase and the second order falls within the intermediate phase; in turn, if the third order is the most representative, it fits in the intermediate phase, and the highest emission of 1st and 2nd order cladodes occurs in the development phase. In the final phase, when there is a significant reduction in the emission of cladodes, it is more subject to the need of cutting by the farmer to supply food to the animals. The important thing to note is that the harvest delay must accompany the reduction of the crop coefficient, up to the kc value of 0.26.

As crop coefficient is defined over the cycle, the next step is linked to the estimation of reference evapotranspiration (ET0). Conceptually, the ET0 is the evapotranspiration rate of a hypothetical, low surface, with height around 0.12 m, albedo of 0.23, stomatal resistance of 70 m s\(^{-1}\), soil completely covered (it may be grass) and without water restrictions, which was created with the objective of studying the evaporative power of the atmosphere regardless of the species, the development of the crop and the adopted management. In ET0, the transfer of water to the atmosphere depends only on the seasonality of the weather conditions. For this reason, in its estimation, it is considered the use of meteorological data conventionally or automatically collected in data collection platforms.

Several methods are used to estimate ET0 (Sousa et al., 2010; Morais et al., 2015). However, the Penman-Monteith method parameterized in the Bulletin 56 by FAO is currently the most widely used. It is a biophysical method that assumes the energy and aerodynamic factors, and the resistance to the transfer of water vapor, that rule the process of evapotranspiration. Mathematically, this method is expressed by the equation (Allen et al., 1998):

\[
\text{ET0}_{\text{PM-FAO56}} = \frac{0.408 \Delta (Rn - G) + \gamma \left( \frac{900}{t_{\text{average}} + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}
\]

where ET0 = reference evapotranspiration (mm day\(^{-1}\)); \(\Delta\) = slope of the water vapor pressure curve (kPa\(^\circ\)C\(^{-1}\)); \(Rn\) = radiation balance (MJ m\(^{-2}\) d\(^{-1}\)); \(G\) = heat flux in the soil (being equal to 0 for daily estimates); \(\gamma\) = psychrometric constant (kPa\(^\circ\)C\(^{-1}\)); \(t_{\text{average}}\) = average daily air temperature (°C); \(u_2\) = wind velocity at 2 m of height (ms\(^{-1}\)); and \(a\) = the partial pressure of water vapor; \(e_s\) = saturation pressure of water vapor; and, \((e_s - e_a)\) = water vapor pressure deficit (kPa).

In this equation, Rn is estimated using the following equations:

\[
Rn = Rns - Rnl
\]

\[
Rns = (1 - \alpha)Rsl
\]

\[
Rnl = \left[ \left( \frac{1}{2} \left( \frac{1}{t_{\text{min}} + 273.16} + \frac{1}{t_{\text{max}} + 273.16} \right) \right) 0.34 - 0.14 \left( \frac{Rn}{Rso} \right) 0.35 \right]
\]

\[
Rso = 0.75 Rsl
\]

\[
Rsl = 37.6 d_c (\alpha \cdot \text{sen} \phi \cdot \text{sen} \delta + \cos \phi \cdot \cos \delta \cdot \text{sen} \omega_c)
\]

\[
d_c = 1 + 0.033 \cos \left( \frac{2\pi \varepsilon}{365} \right)
\]
Table 2. Crop coefficient values recommended for forage cactus.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Length (days)*</th>
<th>Description</th>
<th>kc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>60</td>
<td>Crop planting and establishment</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Canopy formation with emission of lower order cladodes (1st) and 2nd order-cladodes</td>
<td></td>
</tr>
<tr>
<td>Growth</td>
<td>210</td>
<td>Significant emission of cladodes of representative order(s) (2nd)</td>
<td>0.26 to 0.52</td>
</tr>
<tr>
<td>Intermediate</td>
<td>240</td>
<td>Significant reduction of cladode emission</td>
<td>0.52</td>
</tr>
<tr>
<td>Final</td>
<td>60</td>
<td></td>
<td>0.52 to 0.26</td>
</tr>
</tbody>
</table>

* Values dependent on local climate conditions, on the cultivar and the management adopted by the farmer.

\[
\delta = 0.409 \cdot \text{sen}\left(\frac{2\pi}{365} J - 1.39\right)
\]

\[
\omega_s = \arccos(-\tan \varphi \cdot \tan \delta)
\]

where, \(Rns\) = short-wave net radiation (MJ m\(^2\) d\(^{-1}\)); \(Rln\) = long-wave net radiation (MJ m\(^2\) d\(^{-1}\)); \(\sigma\) = hypothetical surface albedo (0.23 for gram); \(Rn\) = radiation balance (MJ m\(^2\) d\(^{-1}\)); \(\sigma\) = Stefan-Boltzmann constant \((4.903 \times 10^{-8}\) MJ m\(^2\)d\(^{-1}\)\)); \(t_{\text{max}}\) = maximum air temperature (°C); \(t_{\text{min}}\) = minimum air temperature (°C); \(R_s\) = exaterrestrial solar radiation (MJ m\(^2\) d\(^{-1}\)); \(d_s\) = inverse of the square of the Earth-Sun distance; \(J\) = day of the year (1 to 365 or 366); \(\delta\) = solar declination; \(\omega_s\) = solar angle of the sunset; and, \(\varphi\) = local latitude.

The other parameters used for estimating \(ET_0\) are, as follows:

\[
\Delta = 4098 \left( \frac{6.108 \exp\left(\frac{17.27 \cdot t_{\text{average}}}{t_{\text{average}} + 237.3}\right)}{\left(t_{\text{average}} + 237.3\right)^2} \right)
\]

\[
\gamma = 0.665 \cdot 10^{-3} \cdot \text{Pa}
\]

\[
e_s = \frac{0.6108 \exp\left(17.27 t_{\text{max}}\right)}{t_{\text{max}} + 237.3} + \frac{0.6108 \exp\left(17.27 t_{\text{min}}\right)}{t_{\text{min}} + 237.3}
\]

\[
e_e = \frac{R \cdot H_{\text{average}}}{100} \cdot e_s
\]

where, \(t_{\text{max}}\) = maximum air temperature (°C); \(t_{\text{min}}\) = minimum air temperature (°C); \(R \cdot H_{\text{average}}\) = average relative humidity of the air (calculated by daily maximum and minimum values); and, \(P_a\) = atmospheric pressure (kPa).

When wind speed measurement is not made at 2 m of height, its conversion can be established by the following equation:

\[
u_2 = \frac{4.87}{\ln\left(67.8z - 5.42\right)}
\]

where, \(u_2\) = speed obtained in the automatic weather station (m s\(^{-1}\)) ; \(z\) = wind speed measurement height.

When atmospheric pressure data are not available, it is estimated from the following expression:

\[
P_a = 101.3 \cdot \left(\frac{293 - 0.0065z}{293}\right)^{5.26}
\]

where, \(z\) = elevation over the sea level (altitude, m).

In Brazil, the advance of the networks of automatic meteorological stations favored the applicability of the Penman-Monteith method. The National Institute of Meteorology (INMET - Instituto Nacional de Meteorologia) provides meteorological data of automatic stations in an hourly interval on its website (www.inmet.gov.br): “Station and Data”/menu/submenu “Meteorological Data” and “Automatic Stations.” Currently, INMET has 539 automatic stations, out of which 535 are distributed throughout the national territory and four in Uruguay (Fig 12).

These stations are composed of a datalogger, which is connected to electronic sensors to measure the variables: atmospheric pressure (barometer), temperature (thermometer) and air relative humidity of the air (hygrometer), rainfall (rain gauge), incident solar radiation (pyranometer), and direction and wind speed (anemometer), in one-minute intervals and automatically available on the site.
In the Northeast of Brazil, where forage cactus crops predominate, with the exception of the state of Maranhão, the number of meteorological stations owned by INMET is 112 units, of which are distributed according to the territorial dimension of the state. Table 3 shows the municipalities that have an INMET station, demonstrating the availability of meteorological data for the calculation of \( ET_0 \) and, consequently, \( ET_c \) of forage cactus for water management.

Overall, these automatic stations are installed along the territory of the State in municipalities representative of climatically homogeneous regions or that contemplate some specific topoclimatic condition. As a consequence, it is reasonable for the technician or farmer interested in using the meteorological data to consider the distance from the automatic station of his or her property. When the farm is located in the same climatically homogeneous region of the automatic station, and the distance between them does not exceed 50 km in a straight line, it is wise to use all meteorological data, with the exception of rainfall. Because of the wide spatial variation of this variable, it is suggested the installation of a rain gauge on the farm for a better precision of the water management, following the density of a rain gauge every 20 hectares depending on the slope of the terrain.

Figure 13 shows the output of meteorological data from INMET automatic stations. For its use in estimating \( ET_0 \) by the Penman-Monteith equation presented above, it is necessary to convert the hourly data into a daily scale.

One should note that data output occurs in UCT (Universal Coordinated Time, also known as Greenwich Mean Time, GMT, Greenwich Mean Time), which refers to the reference time, three hours more than local time in Brasília, for example, which is in the 45° spindle. Data processing can be done in any spreadsheet. The instantaneous data of the temperature and relative humidity of the air, atmospheric pressure and wind speed, necessary in the estimation of \( ET_0 \), should be converted into daily scale using the arithmetic mean of the 24 hourly values. The highest value between the maximums and the lowest value between the minimums of each variable must be selected to represent the daily data.

The incident solar radiation is expressed cumulatively every hour, in kJ m\(^{-2}\). Therefore, its positive values throughout the day must be summed and, subsequently, the result obtained, divided by 1000 to convert it to MJ m\(^{-2}\) day\(^{-1}\). To complement the water management of forage cactus, the daily rainfall data must be obtained by the sum of the 24 hourly values.

With the data of \( ET_c \) and rainfall precipitation (Prec.), water management of the forage cactus can be accomplished, using the following condition:

\[
\text{whether } ET_c > 0.75 \times \text{Rainfall}, \text{ so } LL = ET_c - 0.75 \times \text{Prec.}
\]

\[
\text{whether } ET_c < 0.75 \times \text{Rainfall}, \text{ so } LL = 0, \text{ that is, no irrigation.}
\]

where, \( LL \) = net irrigation depth; 0.75. Rainfall = rainfall precipitation, assuming that 75% of the rainfall is available for the crop and 25% was lost by drainage or deep drainage.

**Practices for improving the agricultural resilience of forage cactus**

Practices to improve agricultural resilience are those used to enhance the capacity and ability of agricultural production systems to deal with and to overcome adversities, especially climatic ones. According to Sentelhas and Monteiro (2009), this resilience depends on the adoption of practices that reduce the adverse effects of climate on crops, such as drought events, high temperatures, strong winds and among other factors. Despite being a cactus with a wide range of environmental adaptation, forage cactus may have its agronomic performance significantly improved. The increase in the productivity of this crop allows that at least in years with climatic adversities, when the production of...
Table 3. Municipalities in the States of the northeast producers of forage cactus with automatic meteorological stations owned by National Institute of Meteorology - INMET

<table>
<thead>
<tr>
<th>Alagoas</th>
<th>Bahia</th>
<th>Ceará</th>
<th>Paraíba</th>
<th>Pernambuco</th>
<th>Piauí</th>
<th>Rio</th>
</tr>
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<tbody>
<tr>
<td>Arapiraca;</td>
<td>Abrolhos;</td>
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<td>Areia;</td>
<td>Arcoverde;</td>
<td>Alvorada do</td>
<td>Caicó;</td>
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<td>Amargosa Barra;</td>
<td>Barbalha;</td>
<td>Cabaceiras;</td>
<td>Cabrobó;</td>
<td>Gurguéia;</td>
<td>Calcanhar;</td>
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<td>Brumado;</td>
<td>Campos Sales;</td>
<td>Camaratuba;</td>
<td>Caruarú;</td>
<td>Bom Jesus do</td>
<td>Macau;</td>
</tr>
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Fig 13. Output of meteorological data collected by INMET (Instituto Nacional de Meteorologia) automatic station and available on www.inmet.gov.br

Forage by other species is very compromised, food supply is not interrupted, to guarantee the survival of the herd.

It is plausible to say that farms where forage cactus crops are well managed, they are stable, well-productive and profitable enterprises. Historically, this species and in most farms has been treated with the minimum use of management practices, which culminates in low productive levels and plants with reduced longevity. The adoption of the most recommended management practices for forage cactus in accordance with its (agro)meteorological information should be encouraged to maximize its productivity.

Figure 14 illustrates the main practices of improving forage cactus agriculture resilience, in
Agrometeorological research on forage cactus and its advances in Brazil

Fig 14. Management practices recommended for improving the agricultural resilience of forage cactus. Source: Personal file. Experiments conducted at the Instituto Agronômico de Pernambuco (Agronomic Institute of Pernambuco), in Serra Talhada, PE. (A) forage cactus cultivars, (B) minimum and regular use of irrigation, (C) use of mulch and (D) forage cactus intercropping and other forage plants.

relation to the selection of forage cactus cultivars more adequate per region, minimum and regular use of irrigation, use of mulch and forage cactus intercropping and other forage plants.

Forage cactus has a diversity of cultivars belonging to the genus *Nopalea* and *Opuntia*. However, their morphological and anatomical differences give them different adaptations. Many studies have proved that the species *Opuntia* sp. Exceeds *Nopalea* sp. in relation to agronomic performance. When studying the cultivars ‘IPA Sertânia’ and ‘Miúda’, species of the genus *Nopalea*, and ‘Orelha de Elefante Mexicana’, *Opuntia* species, under rainfall conditions for two years, Silva et al. (2015d) verified that the latter cultivar was 35% more productive. Morais (2016) mentions that even under conditions of regular water supply (via irrigation), this productive disparity tended to be even higher, reaching 45%. Barbosa et al. (2012) observed that the cultivar ‘Orelha de Elefante Mexicana’ presents lower pH values than the cultivars ‘IPA Sertânia’ and ‘Miúda’, suggesting the greater assimilation of CO$_2$ at night and accumulation in organic acids to be used in the photosynthesis during the daytime period.

In addition, Morais et al. (2017) showed that the Mexican Elephant Ear has lower retention of water per cladode area unit than cultivars ‘IPA Sertânia’ and ‘Miúda’, justifying the greater efficiency in water use. Of these three cultivars, ‘Miúda’ showed the least adaptability to drier environments. In terms of the transfer of water to the atmosphere, Silva et al. (2015a) cites that this cultivar responds quickly to small climate variations in the growing environment. On that account, in environments with greater water deficiency, such as the Northeastern Sertão, species of the genus *Opuntia* sp. Should be cultivated, while cultivars of the genus *Nopalea* sp. should be encouraged in regions where water deficiency is lower, such as Agreste.

Another important practice for the maximization of forage cactus productivity is the minimum and regular use of irrigation. However, studies on that subject should be deepened to identify the best water management to be adopted, considering the peculiar morpho-anatomical-physiological of this cactus. As already reported in this document, the application of this practice should be carried out based on the local climatology and the requirement of the crop. In studies revised in this work shows that the increase of regular depths from 493 mm year$^{-1}$ to 1380 mm year$^{-1}$ (Flores-Hernandez et al., 2004, Queiroz et al., 2015, Barbosa et al., 2017) did not generate any effect on yield of forage cactus. Yet, it has also been pointed out that the evaporation component is quite significant in the evapotranspiration of the forage cactus (Han and Felker, 1997) and that the water depth retained by the crop favors the reduction of the depth to be applied and the increase in the frequency of application (Scalisi et al., 2016; Morais et al., 2017). Such information was ratified by Morais (2016), who did not verify any effect of the depths (2.5 mm, 5.0 mm and 7.5 mm) and irrigation frequency (7 days, 14 days and 28 days) on the yield of the cultivars ‘IPA Sertânia’, ‘Miúda’ and ‘Orelha de Elefante Mexicana’. Henriques (2016), studying the cultivars ‘IPA Sertânia’, ‘Miúda’ and ‘Orelha de Elefante Mexicana’, verified that the use of irrigation (above 493 mm year$^{-1}$) promoted productive increments to forage cactus only when associated with the use of mulch. In this condition, an increase of 73% was observed regarding fresh matter and 81% regarding dry matter, when compared to the system of cultivation in the rainfed or only with the use of irrigation.

The application of mulch is widely applied in C3 and C4 cropping systems. In addition to the expected benefits in terms of longer maintenance of soil moisture and nutrient supply, the improvement in the soil thermal regime seems to be a decisive factor for forage cactus. As reviewed earlier in this
paper, Barbosa (2015) mentions that the temperature of the agricultural environment has significant effects on the dynamics of cladodes emission by forage cactus. In the semi-arid environment, the use of mulch reduces the high thermal load produced in the growing area, diminishing the implications on the performance of this cactus, as a consequence. More recent studies conducted in Serra Talhada have shown that the use of mulch is the most important agricultural resilience improvement practice for the forage cactus production system, especially when the production of cladodes units or fresh mass yield is desired.

When the production of dry matter is the objective, no practice is better than the intercropping of forage cactus irrigated with other forages, especially grasses. In a semi-arid forage production system with the minimal and regular use of irrigation, it is understood that the autonomy of the water resources is low, and the use of this practice should be carried out in small units of the farm. In this context, intercropping of forage cactus with other forage plants gains importance. Lima (2015) and Diniz (2016) mention that the irrigated forage cactus-sorghum intercropping for one year of this cactus cycle and two cycles of sorghum (planting and regrowth) increased the yield of dry matter in relation to the single (> 120% regarding dry matter) cropping system. Also, the implantation and successive conduction of sorghum cycles do not require the increase of the irrigation depths, and the kc of the forage cactus can be used in water management. This result is due to the compensatory effect of the use of water promoted by the intercropping of C3 or C4 with CAM plants. As the latter preferentially open the stomata at night, during the daytime when “water loss” by evaporation is significant, the use of a second crop increases the efficiency of using this natural resource in the production system. These two authors verified the drop of productivity of the two crops (forage cactus and sorghum), but when the yields of the cultivation system are added, the productivity of their single crops is exceeded.

Although studies with improvement practices of forage cactus resilience have advanced in recent years, there are many knowledge gaps, which strengthens the need to implement new experiments, mainly those related to the use of irrigation in the production system of this cactus.

Recent studies on forage cactus at UFRPE/UAST

Studies with forage cactus conducted between 2010 and 2015, in Serra Talhada, Pernambuco, were carried out at the Instituto Agronômico de Pernambuco - IPA, with financial support from this institution and resources approved in the proposal of CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and FACEPE (Fundação de Amparo à Ciência e Tecnologia de Pernambuco) for the acquisition of equipment and scholarships. Starting in 2016, with the support of local management, IPA and Embrapa Semiárid, it was created within the experimental field of the Academic Unit of Serra Talhada - UAST, at the Federal Rural University of Pernambuco - UFRPE, the International Reference Center for Agrometeorological Studies of Cactus and Other Forage Plants (Centro de Referência Internacional de Estudos Agrometeorológicos de Palma e Outras Plantas Forrageiras). This center, coordinated by Professor Thieres George Freire da Silva, develops studies with the use of agricultural resilience improvement practices for the forage production system in the semi-arid environment. Some experiments conducted at the Center are illustrated in Figure 15.

Fig 15. Experiments conducted with practices to improve agriculture resilience of forage cactus at the International Reference Center for Agrometeorological Studies of Forage Cactus and Other Forage Plants, located in the Academic Unit of Serra Talhada of the Federal Rural University of Pernambuco. Source: Personal archive

In total, six field experiments and seven pot experiments are conducted. A summary of these experiments is reported here. Field experiments of forage cactus are conducted in nineteen-month cycles, as suggested by Amorim et al. (2017), with the maximum number of cycles of intercropped crops in the same period. Three forage cactus cultivars are intercropped with three sorghum...
cultivars (plant and regrowth cycles), with the objective of identifying the most suitable forage production with the minimal and regular use of irrigation based on water requirement of forage cactus (Table 2).

Forage cactus cultivars are also submitted to four water regimes for determination of technical data to subsidize the updating of the Brazilian climatic risk zoning (CRZ) for forage cactus of the Ministry of Agriculture, Livestock and Supply. The use of mulch has been evaluated in the three forage cactus cultivars under rainfed and irrigated conditions. The use of mulch is also studied in the single forage cactus cropping system, forage cactus intercropped with millet and millet in a single crop, all with minimal and regular use of irrigation. Competition between cultivars of forage cactus is conducted under irrigation. Other intercropping between forage cactus and irrigated forage plants with mulch are evaluated: forage cactus + millet, forage cactus + pigeon pea and forage cactus + forage sunflower. On the other hand, experiments carried out in pots; three forage cactus cultivars are used in the evaluation of the management of planting, harvesting, use of biofertilizers, pest and disease management, root system dynamics and day/night irrigation.

Final considerations

A survey on the state of the art and studies conducted in Brazil on agrometeorology of forage cactus were carried out. The climatic diversity of the growing regions, regarding intra/interannual seasonality of the water regime, show the wide range of adaptation of this species. However, its cultivation should be encouraged in those areas which are most indicated by agricultural zoning, where the magnitude and seasonality of thermal-water factors indicate areas with greater productive potential, such as those identified in the state of Bahia. Although forage cactus is grown in favorable areas, the understanding of its response to the environment is essential for the selection of the best management practices. This analysis can be done through micrometeorological measurements and vegetation of the soil-plant-atmosphere system, which allow identifying the factors that rule the energy and water vapor exchanges and, therefore, its agronomic performance. The creation of criteria for delimitation of the phenological phases and definition of the harvest period of the forage cactus were important information recently obtained for the crop. Also, it was pointed out that forage cactus cultivars have different meteorological requirements, so they should be recommended in different ways. Because of its high water storage capacity, low water demand and low conversion to dry matter, forage cactus does not always respond to the regular increase of water. Based on the information gathered here, it is recommended that the use of irrigation is adopted when the local rainfall level is less than 493 mm year\(^{-1}\) or even higher than this quantity, but without regularity in most of the months of the cycle of the crop. In the months when precipitation is less than 70 mm, irrigation depths should be applied based on the water requirement of the forage cactus (crop evapotranspiration). Measurement of forage cactus evapotranspiration has been done mainly by the application of hydrological methods (that is, water balance in the soil) and micrometeorological methods (that is, energy balance based on the Bowen’s ratio). In practice, for irrigation, the meteorological method by the product between the crop coefficient (\(k_c\)) and the reference evapotranspiration (\(E_{To}\)) is globally accepted for the estimation of crop evapotranspiration (\(E_{Tc}\)): \(E_{Tc} = k_c \times E_{To}\). The \(k_c\) of the forage cactus per phenological phase is exposed in this study. On the other hand, the advance of the networks of automatic meteorological stations in Brazil favored the applicability of the Penman-Monteith method parameterized in bulletin number 56 by FAO, considered the standard for estimation of \(E_{To}\) through meteorological data. The procedures for acquiring and processing meteorological data provided on the website of the National Meteorological Institute (Instituto Nacional de Meteorologia) are presented in this paper. Despite being a cactus with a wide range of adaptation, the performance of forage cactus can be enhanced through the adoption of agricultural resilience practices. Among them, the selection of the most suitable cultivars per region, minimum and regular use of irrigation, use of mulch and intercropping with other forage plants. The success of the advancement of these studies in the next years will be possible due to the implantation of the Center of International Reference of Agrometeorological Studies of Cactus and other Forage Plants (“Centro
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