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Interaction of agroecosystem intercropped with forage cactus-sorghum in the semi-arid environment: a review

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ABSTRACT

In arid and semi-arid regions, climatic conditions and salinization of soil and water lead to declines in forage production and compromise the yield of herds. Therefore, the use of adapted forage species and of high nutritional value becomes an alternative to maintain the availability of food in seasonal periods. Among these species, forage cactus is a recommended food for ruminants, due to the high-water content in its structures, good acceptability and low production cost. Sorghum cultivation also has high forage potential, high dry matter production, low water demand, and adaptability to intercropping, helping in the improvement of the production in arid and semi-arid environments. The use of intercropped systems added to irrigation is of great relevance for the sustainable management of local livestock, since this type of system maximizes the forage yield of the productive areas. Thus, the aim of this review was to emphasize the importance of studies related to the forage cactus-sorghum intercropping under irrigated conditions in the semi-arid region to subsidize policies for continuous forage production. The information compiled in this review encourages research in agricultural area planning in neglected environments under semi-arid conditions with the forage cactus-sorghum intercropping for the forage production.

Keywords: Intercropping, forage production, grass, cacti.

Introduction

In agricultural production, meteorological conditions are determining factors for decision making, especially in arid and semi-arid areas (Bakali et al., 2016; Pino & Heinrichs, 2017). In these regions, the imbalance between rainfall and potential evapotranspiration generates drought phenomena, which together with climate changes intensify local socioeconomic vulnerability (Eakin et al., 2014; Marengo et al., 2016).

These climatic characteristics reduce the water availability in quantity and quality, due to the salinization of the soil and water. Forage production is compromised, leading to a decline in livestock yield (Bakali et al., 2016; Mora et al., 2017). Under these conditions, the use of adapted forage species, and of high nutritional value, becomes an efficient alternative to maintain the availability of food in seasonal periods (Santos et al., 2017).

Among the crops potentially adapted to arid and semi-arid conditions, the forage cactus (*Opuntia* spp. and *Nopalea* spp.) from the Cactaceae family, originally from Mexico, is an alternative food for ruminants at all times of the year and, mainly in periods of drought, for it has high yield of fresh biomass, high water content in its structures, good acceptability and low production cost (Falcão et al., 2013; Gusha et al., 2015; Marques et al., 2017). It is an essential crop for arid and semi-arid environments, since native vegetation does not meet the continuous demand for food for herds (Queiroz et al., 2015).

As it is a plant with slow vegetative development, as well as low fiber content, the use of intercropped systems such as cactus and sorghum (*Sorghum bicolor* (L.) Moench) helps to increase food production (Bezerra et al., 2007; Cavalcante et al., 2014). Sorghum has high forage potential, high fiber and dry matter production, tolerance to saline-alkaline soils, low water demand, high tolerance to water deficit and adaptability to intercropping (Nxele et al., 2017; Pino & Heinrichs, 2017).

Practices such as intercropped systems are of great relevance for the sustainable management of local livestock. In food crops in the Brazilian Semi-arid, it is a commonly applied practice, and used by producers to improve the efficiency of agronomic attributes, by intensifying land use with more than one species planted in the same area, at the same time. However, the use of intercropping must be followed by an agronomic, ecological and socioeconomic evaluation, to understand its effects on the agricultural system. In this type of evaluation, the co-participation of crops is considered to reduce the risk of losses, due to adverse conditions (i.e., droughts, high air temperatures, pests and diseases) and to increase production and economic return for the success of the crop activity (Souza et al., 2011; Atis et al., 2012; Yilmaz et al., 2015; Diniz et al., 2017).

Furthermore, in order to have good crop yields, and that they do not suffer with the climatic conditions or extreme drought events, the use of irrigation in critical periods is an important practice, which helps in maintaining crop production and enhances the reduction of excessive spending on water, considering its use only in a few months of the year (El-Wahed et al., 2017).

In the literature, there are some studies on the use of irrigation in forage cactus crops (*Opuntia* and *Nopalea*), being an interesting strategy capable of promoting significant increases in its productivity (Flores-Hernández et al., 2004; Pereira et al., 2015; Queiroz et al., 2015; Amorim et al., 2017; Morais et al., 2017; Ferraz et al., 2019). Based on these studies, it is observed that in years with at least 493 mm regularly distributed over seven months in a semi-arid environment, the application of water via irrigation is dispensed under these conditions (Silva et al., 2017).

The use of irrigation in the sorghum crop also shows high biomass yields, due to its high efficiency in water use and competition, being a crop with high potential for the Brazilian Semi-arid (Yimam et al., 2015; Campi et al., 2016). In intercrop with the forage cactus, the productive benefits of the production system are even greater (Farias et al., 2000; Amorim et al., 2017; Diniz et al., 2017), since there is an increase in yield, in quality and in forage intake by animals, reducing spending on concentrated foods (Lopes et al., 2017).

The irrigated and densified forage cactus-sorghum intercropping in biosaline agriculture is an advantageous configuration for the agricultural production system, because of the forage potential of these two species, in quantity and in quality, and the compensatory effect of the use of water due to their different metabolisms photosynthetic. The cactus, a CAM (Crassulasean Acid Metabolism) plant, transpires predominantly at night, and sorghum, a C4 plant that transpires during the day (Taiz et al., 2017). In addition to the mentioned benefits, in this type of intercrop the transference of water to the atmosphere through evaporation in the system is minimized, increasing the efficiency of converting water into dry matter. Therefore, it is important to conduct further studies related to the forage cactus-sorghum intercropping under irrigated conditions to subsidize policies for continuous forage production.

Review of Literature

Characterization of the Brazilian semi-arid and forage plants production

Climate change is a factor that causes risks to the entire agricultural sector and severe negative impacts unbalancing various regions of the world. Under current conditions, climate change represents a global threat to all crops, impeding the sustainable development of plants, decreasing local biodiversity and high agricultural losses, due to the vulnerability of these regions. Part of these climate changes have profited the increase of territorial bands of arid and semi-arid regions in the world, which are represented by 55% of the land, where part comprises countries in Latin America and the Caribbean, such as Argentina, Brazil, Chile and Mexico, covering about 313 million acres, which corresponds to 80% of tropical and subtropical areas (Cândido et al., 2005; Hussain et al., 2018).

In Brazil, there are different climatic zones, ranging from super humid hot weather in the Northwest to humid temperate in the South. According to Köppen's (1936) climatic classification, there are since the Tropical Climate (Af, Am, Aw, As), Semi-arid (BSh) to the Humid Subtropical (Cfa, Cfb, Cwa, Cwb, Cwc, Csa, Csb) in the country's territorial area (Alvares et al., 2013; Zhang et al., 2016).

The Semi-arid region in Brazil has approximately a territorial extension of 1.03 million km^2, with the state of Pernambuco located between the coordinates 2.5° S and 16.1° S and 34.8° W and 46° W with around 87.60% of its area inserted in this climatic domain. Considered as a region of dry lands and extreme climatic vulnerability, it is one of the most populous semi-arid regions in the world (Pereira Júnior, 2007; Marengo et al., 2016; Ministério da Integração Nacional, 2017).

The semi-arid climate is very characteristic and predominant in the Northeast region, with high air temperatures and low levels of rainfall (≤ 800 mm year^{-1}), long periods of drought in most months of the year, Thornthwaite Aridity Index below 0.50 and frequency of occurrence of drought in six every 10 years (60%), which results in low relative humidity and high atmospheric demand, often causing natural disasters, changes in vegetation and a lot of damage in the agricultural sector (Thornthwaite, 1948; Cunha et al., 2015; Paredes-Trejo et al., 2017).

These regions of great variability in rain events are known as "Polígonos da Seca" (Drought Polygon), which cover 1,189 municipalities in nine states of the country (e.g., Alagoas, Bahia, Ceará, Minas Gerais, Paraíba, Pernambuco, Piauí, Rio Grande do Norte and Sergipe), with critical characteristics in water supply (Ministério da Integração Nacional, 2017; Santos & Farias, 2017).

Due to the climatic variability of the region, studies of the spatio-temporal behavior of rainfall events and potential evapotranspiration become extremely important, since water is a limiting factor in the production of agricultural crops, and its scarcity can compromise the yielding of the production (Marra & Morin, 2017; Silva & Reis, 2017) (Figure 1). Abiotic factors such as drought, air temperature, and edaphic factors such as soil depth and salinity are constant in regions with semi-arid climate, causing negative effects on crops and soil microorganisms, such as ionic intoxication, physiological drought and decreased assimilation of carbon dioxide (CO_2) (Meena et al., 2016; Egamberdieva et al., 2017).

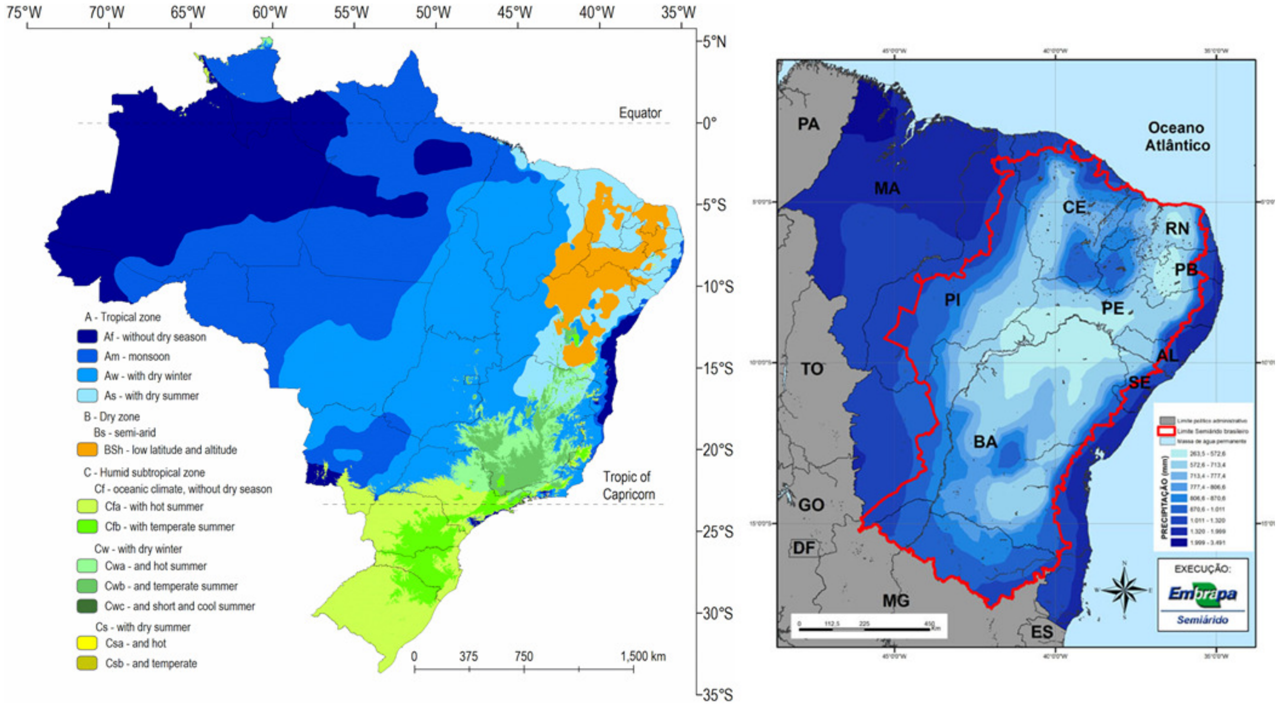

Figure 1. Map of Brazil and the Northeast region with a geographic delimitation of the semi-arid and rainfall indexes. Source: Adapted from Alvares et al. (2013) and Embrapa (2019).

The scarcity of vegetation covering over the soil is quite common for long periods, which maximizes the processes of soil erosion (i.e., water and wind), as well as reducing the water retention capacity and, predominantly dry and deciduous vegetation or typical litterfall of the Caatinga Biome (Rocha & Soares, 2015; Silva et al., 2017; Vaezi et al., 2017; Queiroz et al., 2020).

Use of irrigation in arid and semi-arid environments as a strategy to forage production

One of the ways to mitigate the problems caused by the water deficit is the use of irrigation systems, which allow the availability of water for crops, since drought occurs in great frequency causing problems in pasture ecosystems. However, in arid and semi-arid regions, the availability of good quality water courses and springs is low, due to the high evaporative demand, and groundwater has high levels of salts, requiring rational use and efficient techniques (Makarana et al., 2017; Ergon et al., 2018), thus forcing the use of these waters in production areas.

The use of substandard water for irrigation, such as groundwater from wells is quite common in agriculture for, in many cases; they are the only sources of water available (Mbarki et al., 2017).

In most cases, waters with high salt loads represent a high cost for desalination and release polluting elements (e.g., CO_2 released from equipment and the brine from the desalination process). As the fate of this type of water in agriculture grows more and more, the practice of biosaline agriculture for agricultural production becomes valid (Masters et al., 2007; Díaz et al., 2018), and this type of agriculture is quite common and, it has been gaining prominence in arid and semi-arid environments around the world (Díaz et al., 2018).

It is estimated that, in the future, good quality water will become less accessible in ecosystems, thus requiring efficient systems and the use of lower quality water for irrigation (Glenn et al., 2013; Dar et al., 2017).

In some regions of the world with arid and semi-arid climates, irrigation with brackish water represents the future of agriculture, since the scarcity of good quality water is high, making it a frequent and/or exclusive use. Low-quality waters can promote physiological changes in cultures (Wang et al., 2016), however, studies by Katerji et al. (2003) showed that cultures tolerant to saline waters do not decrease the efficiency of water use, unlike sensitive cultures, which present severe drops in yielding due to the accumulation of salts in the soil (Wang et al., 2016).

When plants are subjected to the conditions of saline environment, they present different physiological, biochemical and morphological responses; this characteristic is related to its degree of tolerance to salinity. The species classified as "halophytes" are characterized by being tolerant to salinity, supporting levels above 500 mM Na^+. The "glycophytes" are sensitive to salinity and tolerate just over 200 mM Na^+. Whether salinity levels are high or low, halophytes and glycophytes have different mechanisms of tolerance to salts by ion exchange of Na^+ influx and efflux (Himabindu et al., 2016; Wu, 2018).

Soils in arid and semi-arid regions are more susceptible to salinization, and, significantly, this is one of the main abiotic factors in the loss of agricultural production. Salinization can be considered primary (i.e., natural processes of soil formation from the type of rock) or secondary (i.e., anthropic intervention, misuse of irrigation systems and chemical fertilizers) (Figure 2).

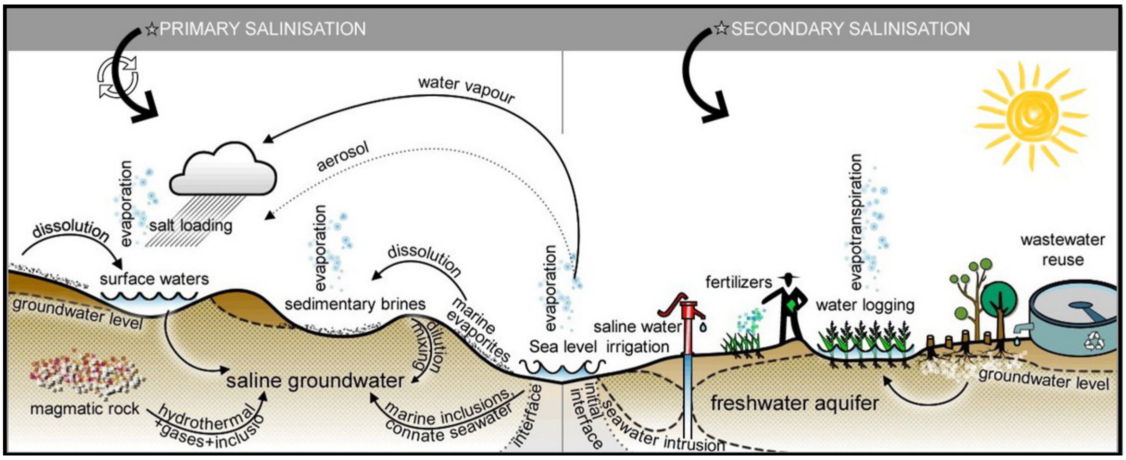

Figure 2. Processes of primary and secondary salinization of soils. Source: Adapted from Daliakopoulos et al. (2016).

The soil, by definition, has the classification of saline, if it has an electrical conductivity of the saturation extract ≥ 4.0 dS m^{-1}. About 20% of irrigated land across the globe (450,000 km^2) is affected by salinization. This process is maximized using inappropriate irrigation methods, associated with the use of water with high salts and erroneous use of chemical fertilizers (Qadir et al., 2014; Daliakopoulos et al., 2016; Negrão et al., 2017; Nikalje et al., 2017; Bertazzini et al., 2018).

Traditional irrigation methods are characterized by low application efficiency, providing only around 30% of the water that is repressed for crops. High-flow surface irrigation methods enhance water losses out of the system and excessive volumes of water are spent, causing damage to nature, unlike localized methods (Mostafa et al., 2017).

Localized irrigation by the drip method is a type of high efficiency practice in the availability of water for crops at low pressure, flow and expenditure on electricity, which can save 65% of the water applied compared to conventional irrigation methods. This type of system causes minimal disturbance to the soil structure, reduces losses due to runoff and evaporation, making the plants to have a better use of the water that is available, since the crop yield is related to the optimal water supply (Gu et al., 2017; Jaafar et al., 2017; Mostafa et al., 2017).

Crops have different water requirements, thus, the precise quantification of this water demand and replacement in the soil, avoids critical events in their phenological phases and, thus, losses in productive yield (Dar et al., 2017; Jaafar et al., 2017; Consoli et al., 2018). In this way, knowledge of irrigation management techniques such as water balance, energy balance, leaf water potential and the requirement of crops are essential to make it more efficient.

Forage cactus

In order to maintain crop yields under stable conditions in the face of climate changes that have occurred over the years, agronomic practices must be adopted. Among them, the choice of forage species adapted to compose the cultivation system of an agricultural area, becomes of great importance, since the seasonality of climatic events, often cause damage to crops (Elias et al., 2016; Teixeira et al., 2018).

One of the crops that presents a high adaptation to the edaphoclimatic conditions of the Brazilian Semi-arid and to the arid and semi-arid regions is the forage cactus (*Opuntia* and *Nopalea*). It is estimated that in Brazil this crop has a planted area of 600,000 ha (Dubeux Júnior et al., 2013; Garcete-Gómez et al., 2017), and worldwide this cactus planted area for the proper purposes (e.g., human consumption or forage) can reach 1,000,000 ha (Cardador-Martínez et al., 2011), which characterizes it as the most important cactus on the planet (Jesus, 2013).

The cactus (*Opuntia* and *Nopalea*) was inserted in Brazil first in the Northeast region in the middle of the 19th century, with the purpose of producing dye (carmine, derived from carminic acid) resulting from the creation of adult female insects that produce this raw material, cochineal (*Dactylopius coccus* Costa, 1829; Hemiptera: Dactylopiidae). However, the action was not successful, because the insect introduced, the cochineal scale bug (*Dactylopius opuntiae* Cockerell, 1929; Hemiptera: Dactylopiidae), did not present high production of dye. This practice made this pest the main devour of crop, especially in the states of Pernambuco and Paraíba, where it decimated several cactus trees (Pessoa, 1967; Ben-Dov, 2006; Santos et al., 2006; Lopes et al., 2009; Vasconcelos et al., 2009).

Despite the great disturbances caused by cochineal scale bug (*D. opuntiae*), clones of forage cactus with resistance to its attack are already widespread in the region for the production of forage, such as Miúda and IPA Sertânia (*N. cochenillifera* (L.) Salm-Dyck) and, the Orelha de Elefante Mexicana (*O. stricta* (Haw.) Haw.) (Vasconcelos et al., 2009; Falcão et al., 2013).

In the case of a plant originating in Mexico, and endemic to the Americas with good development in arid and semi-arid regions of South and Central America, Africa and Mediterranean regions, the forage cactus belongs to the Kingdom: Plantae; Division: *Embryophyta*; Subdivision: *Angiospermea*; Class: *Dicotyledoneae*; Subclass: *Archiclamideae*; Order: *Opuntiales*; Family: Cactaceae. Among the various genera, the most prominent in the Northeast are the genera *Opuntia* and *Nopalea*, which have more than 2,000 species and 178 genera of forage cactus cataloged (Silva & Santos, 2006; Aragona et al., 2017; Garcete-Gómez et al., 2017; Marques et al., 2017).

In the state of Pernambuco there is a predominance of the cultivation of two genera of forage cactus, the genus *Opuntia* (e.g., the clones Orelha de Elefante Mexicana (*O. stricta* [Haw.] Haw.), Gigante and Redonda [*O. ficus-indica*]) and the genus *Nopalea* (e.g., the Miúda and IPA Sertânia [*N. cochenillifera*] clone), and the Miúda clone is widespread in the states of Alagoas and Paraíba (Farias et al., 2005; Castro et al., 2011).

As it is a xerophilic plant, with peculiar morphophysiological characteristics, the forage cactus adapts very well to arid and semi-arid conditions in the world. This adaptation is mainly related to its photosynthetic metabolism of the CAM type, causing the plant to assimilate CO_2 at night with the aid of the enzyme Phosphoenolpyruvate carboxylase (PEPcase). During the daytime, stomata are closed, preventing the loss of water to the atmosphere by transpiration, benefitting the maintenance of cell turgor and its full development in conditions of low water regime (Figure 3). In addition, it has a thick and waxy cuticle that covers the entire cladodes (modified stems), reducing the loss of water through transpiration (also helping against the attack of disease vectors); low surface/volume ratio; reduced stomata; large vacuoles; four types of roots (structural, absorbent, spur and those developed from areolas), which absorb water quickly and prevent its loss when the soil dries (Nobel, 2001; Silva & Santos, 2006; Nunes, 2011; Souza Filho et al., 2016; Melgar et al., 2017; Kim et al., 2018).

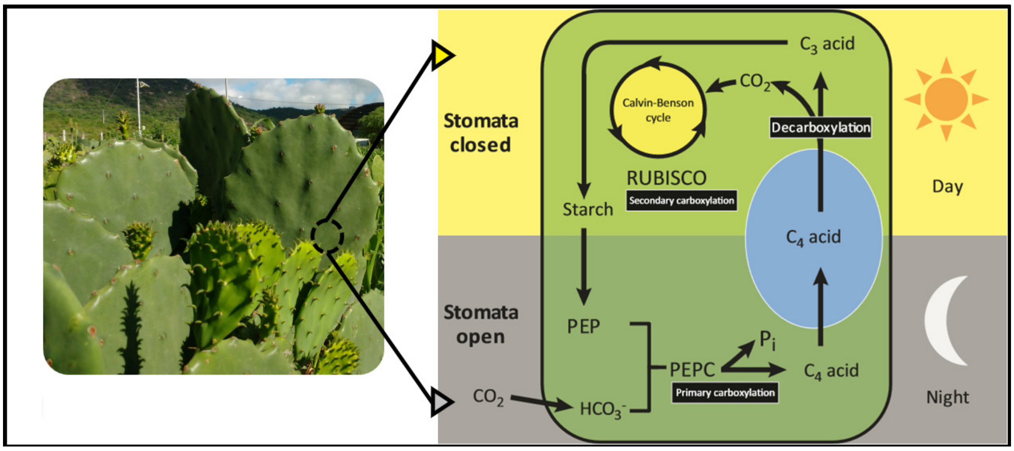

Figure 3. Simplified representation of CAM metabolism (Crassulasean Acid Metabolism) in forage cactus plants. Source: Adapted from Borland et al. (2014).

The genera *Opuntia* and *Nopalea* present cladodes with green to opaque green coloration, flowers mostly hermaphrodite of color scale ranging from yellow, pink, purple, orange, red and white, succulent structures, presence of areolas (which helps in the absorption of atmospheric water) with several spines (i.e., persistent spines and glochids) and the presence of betalaines in their structures that assist in the control of oxidative stress (Anderson, 2001; López et al., 2009; Ju et al., 2012; Chahdoura et al., 2015; Arruda & Melo-de-Pinna, 2016; Melgar et al., 2017).

These morphophysiological features help the crop in the high efficiency in the use of water and nutrients, maximizing with its productive and adaptive yield. By presenting succulent cladodes, these plants are able to remain turgid in periods of water scarcity and maintain their photosynthesis on a normal scale (Liguori et al., 2013). Moreover, they enhance crop survival in regions with rainfall up to 150 mm per year. CAM plants are 3 to 10 times more efficient than the photosynthetic metabolism of C3 and C4 plants, reaching efficiencies in the range from 100 to 150 kg of water per kg of dry matter (Felker et al., 2005; Yang et al., 2015; Bakali et al., 2016).

Regarding nutritional values, forage cactus can be consumed by both humans and animals, from vegetative organs (i.e., cladodes or articles) as reproductive organs (fruits). The fruit of *Opuntia* spp. are beneficial to health and rich in antioxidant properties, betalains, betacyanins and vitamin C, as well as helping to fight some bacteria (Barba et al., 2017; Melgar et al., 2017). It is a culture of great biomass deposition in its structures, increasing its productive performance when supplemented with irrigations in regions that have low water availability (Liguori & Inglese, 2015; Ferraz et al., 2019).

For animal consumption, the largest fraction used is the cladodes, mainly in the Northeast of the country in areas with rainfall varying from 240 to 900 mm. The forage cactus has great benefits in the nutrition of ruminants, as it presents high yield of fresh biomass, high palatability, high digestibility, non-fibrous carbohydrates, rich in water, and can be made available in the form of dehydrated bran and, or, chopped *in natura* (Falcão et al., 2013; Gusha et al., 2015; Marques et al., 2017; Cruz Filho et al., 2019).

Cladodes can also be used in industry in general, for the production of biofuels, cosmetics, food supplements and recovery of degraded areas preventing desertification processes and soil erosion processes (Cushman et al., 2015; Souza Filho et al., 2016; Rouhou et al., 2018).

Due to its energetic value and the high concentration of non-fibrous carbohydrates, the forage cactus assists in the synthesis of microbial proteins in the animal's rumen and volatile acids, enhancing digestion and providing nutrients for the animals mainly in the dry periods, due to the high concentration of water in its structures, becoming a fundamental food in the diet of ruminants (Costa et al., 2016; Rouhou et al., 2018; Cruz Filho et al., 2019).

Despite the relevant bromatological characteristics that the forage cactus has for animal feeding, due to its high content of constituent water, this type of food cannot be administered exclusively, it can cause ruminal problems, as well as the triggering of diarrhea in animals, and decay in the fat content of milk (Gusha et al., 2015).

As a strategy to overcome this situation, the supply of foods with a higher fiber content and protein supplements, becomes extremely important. The addition of other forage plants, such as leucena (*Leucaena leucocephala* (Lam.) de Wit), corn (*Zea mays* L.), sugarcane (*Saccharum officinarum* L.) and sorghum (*Sorghum bicolor* (L.) Moench) improve the animals' diet (Cushman et al., 2015; Gusha et al., 2015; Pino & Heinrichs, 2017). Other benefits are better functioning of the animals' rumen, absorption of nutrients, greater intake of dry matter, and consequently in feeding conversion (Siqueira et al., 2017), resulting in better production yields in the agricultural sector.

Forage sorghum

Although the vegetation of the Northeast region has approximately 70% of its species with potential for animal feed, this availability of food is seasonal, making it unavailable during dry periods (Nunes et al., 2016), requiring the use of other species. One of these species for cultivation in the semi-arid climatic conditions is the sorghum, which is a crop with high forage potential and promising in fiber production, has high adaptability, high efficiency in water use, low water consumption (i.e., 30 to 50% lower than corn) and tolerant to low soil fertility (Pino & Heinrichs, 2017).

Sorghum is the fifth most cultivated cereal in the world, grass belonging to the order *Poales*, of the family Poaceae, with approximately 793 genera and 10,000 species. In Brazil they are represented by 210 genera, 1,415 species, where 21 genera and 467 species are endemic. Most species have a habit of growing caespitose, perennials, polyploids and feathery inflorescences of whitish color, having as main representative the genus *Sorghum*. This genus has a striking characteristic of its inflorescences, to the panicles (Watson & Dallwitz, 1992; Filgueiras et al., 2012; Liu et al., 2015; Upadhyaya et al., 2017).

The domestication of sorghum of the *bicolor* race, started in Ethiopia and in the Southeast region of the Sahara, after migrating to West and South Africa. It was in these territories that new sorghum breeds emerged, such as: *Caudatum*, *Durra*, *Guinea* and *Kafir*, arising through natural and induced selection mechanisms, introgression, stabilization and recombination (Wet & Huckabay, 1967; Wet, 1978; Upadhyaya et al., 2017).

As it is a culture that is not native to the western hemisphere, the arrival of sorghum in American countries is quite recent. Reports say that this first introduction took place in Caribbean lands from African slaves. In the middle of the 19th century, sorghum cultivation arrived in the United States, via seeds brought by slave ships, where it underwent experiments and adaptation periods to meet new modalities and different cultivation methods, thus reaching the genetic improvement of the Creole varieties cultivars that are now grown (Von Pinho et al., 2007; Roby et al., 2017).

As it is a culture of photosynthetic metabolism of type C4 and of high biomass accumulation, the sorghum culture is widely cultivated in tropical regions, arid and semi-arid areas of the world, with rainfall ranging from 400-750 mm per year. Due to its qualities and agronomic potential, such as low water demand and the ability to regrowth (especially corn), it is grown in 99 countries, totaling an area of 44 million acres. It has a fast growth cycle and high carbon sequestration (Mehmood et al., 2017). Its use in agriculture can be for various purposes, such as the production of green forage, silage, biomass, alcohol, syrup and sugar (Kumari et al., 2014; Campi et al., 2016; Roby et al., 2017).

According to studies by Garofalo & Rinaldi (2013) and Campi et al. (2016), sorghum has greater sustainability, especially in regions with low financial resources. In addition, it is a plant tolerant of high air temperatures, water deficit and salinity (Wakchaure et al., 2016). As food in animal nutrition, sorghum is a rich source of energy and fibers, presenting high values of dry mass, neutral detergent fiber, crude protein, among others (Gomes et al., 2006; Pino & Heinrichs, 2017).

The use of sorghum culture with other forage species in a intercropped and dense system is an alternative that helps food production and increases producer income and cultivation resilience, as it has high efficiency in the use of radiation, water and nutrients (Borghi et al., 2013; Samarappuli & Berti, 2018; Tang et al., 2018).

Intercropping between crops and densed spacing plantation

Due to the growing demand for food with the world population growing exponentially, the use of intercropping systems and densed spacing plantation has been an alternative to improve the use of agricultural areas and available resources and can be adopted in large-scale systems. Among the observed benefits, the most relevant is the productive increase per unit area, favoring the best use and efficiency of the soil and, maintaining diversity (Figure 4) (Bezerra et al., 2007; Cavalcante et al., 2014; Diniz et al., 2017; Samarappuli & Berti, 2018). The ecological diversity of the interaction of species from different habitats, when well-managed, can help to increase the crop resilience and significantly maintain the production of forage under adverse conditions (Mäkinen et al., 2015).

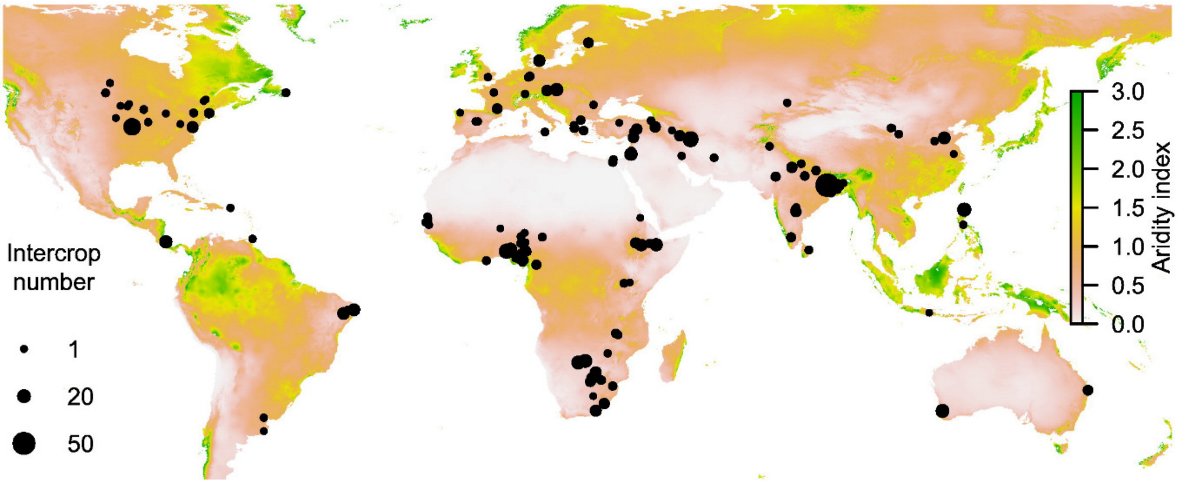

Figure 4. Observations of intercropped crops in different regions of the world, depending on the aridity index. Source: Martin-Guay et al. (2018).

The use of densed crops is in fact a great alternative in the maximization of the productive yielding, as well as to contain the problems caused by climatic adversities, as long as it is managed under favorable conditions for the plants, also helping in the reduction of weeds in the area and lodging resistance (Ren et al., 2016; Hussain et al., 2018; Li et al., 2018).

The intercropping system is characterized by the implantation of crops with two or more species in the same agricultural area. This type of system can prevail in the use of resources (e.g., water, soil nutrients, among others) compared to the exclusive system, being considered as a sustainable cultivation practice (Figure 5). For the choice of the intercropped species, some observations must be made, from the growth habit to the demands of the cultures, since they will compete for essential elements, such as water, nutrients, light and space (Viegas Neto et al., 2012; Ren et al., 2016; Wang et al., 2017). In addition, when it comes to crops in arid and semi-arid environments, water management of the crops is an extremely important observation, so that they make the most of the water offered and reduce the loss through evaporation (Kim et al., 2017).

When it comes to the use of sorghum in densed and intercropped systems, food production becomes more pronounced, due to the efficiency in the use of biophysical resources (water, soil, solar radiation) (Borghi et al., 2013; Samarappuli & Berti , 2018). Throughout the crop cycle, with the entry of light into the system, plants optimize their growth by increasing the number of tillers, leaf area index and biomass yield above the ground, making it sustainable and productive (Diniz et al., 2017; Lima et al., 2018; Tang et al., 2018).

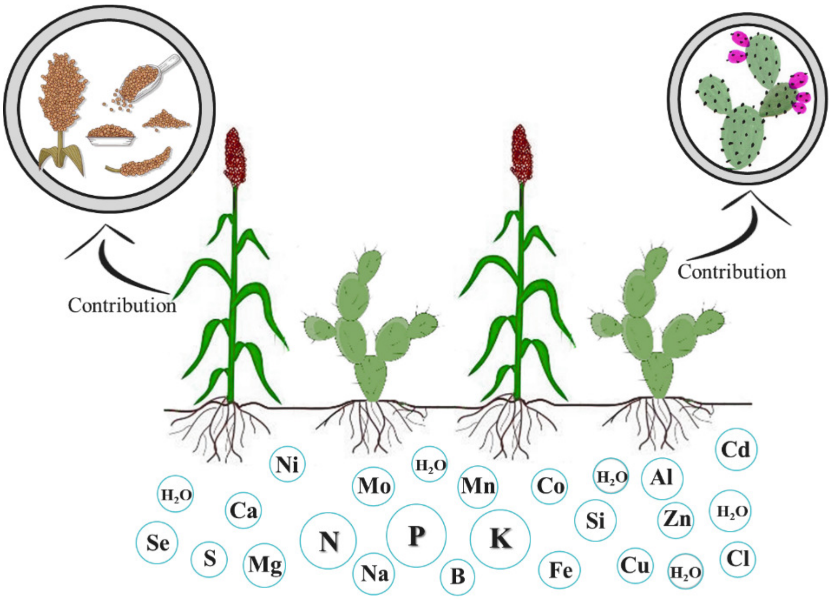

Figure 5. Representation of area with intercropped cultivation system of forage cactus and sorghum. Source: Jardim et al. (2019).

Usage of biophysical resources in forage cactus-sorghum intercropping

Despite the use of irrigation in systems of cultivation of forage species, priority should be given to crops tolerant to water deficit. Even crops irrigated with water available in the soil, the crops are subject to vapor pressure deficit or atmospheric drought, which substantially decreases the relative humidity of the air causing the culture to transpire excessively (Hainaut et al., 2016). Irrigated cultivation environments, with well-managed soil fertilization and well-distributed spacing between plants, favor high biomass yields due to the efficient use of photosynthetically active radiation (Chakwizira et al., 2018).

The cultures present different indexes of leaf area, consequently their efficiency in the use of radiation is varied. This efficiency expresses the culture's ability to fix atmospheric carbon and transform it into biomass, being able to alternate according to the photosynthetic system and the variation of environmental conditions in diurnal and seasonal scales (Gitelson et al., 2015). Studies show that this efficiency can be altered depending on environmental variations, phenological phases of cultures, morphology, architectural arrangement of leaves and canopy (Xu & Baldocchi, 2003; Pearcy et al., 2004; Houborg et al., 2011).

The study of radiation efficiency can also be used to determine the planting density of crops, since biomass production is closely linked to photosynthesis (Purcell et al., 2002; Jia et al., 2018). The efficiency of the use of radiation aggregates factors of physiological processes of the cultures (e.g., photosynthesis and respiration) and may vary depending on the period of growth of the cultures and photosynthetic metabolism. Type C4 cultures are normally more efficient at using radiation when compared to C3 cultures (Gou et al., 2017).

In the forage cactus, daily photosynthetically active radiation is close to that of most CAM plants (Nobel, 1982). Due to the allometric variation of the canopy, thickness of the cladodes, height of the plant and branches, the radiation interception models are complex to estimate (Cortazar et al., 1985; Delgado-Fernández et al., 2017; Drezner, 2017), and when radiation is not captured efficiently it compromises the plant's CO_2 absorption (Ponce-Bautista et al., 2017).

The canopy of the plants has a three-dimensional structure, being the largest area of capture of solar radiation from the crops, which can be determined by direct and indirect measurements. The direct methods consist of biometric measurements of the leaf area, while the indirect methods are more complex and start from a theoretical foundation of the direct methods, which allow the use of portable sensors such as ceptometer or quantum (e.g., LAI-2200, LAI-2000 (PCA), TRAC and AccuPAR) to estimate the leaf area index through the fractions of gaps in the canopy of plants. The measurement above and below the canopy of the plants allows quantifying the fraction of photosynthetically active radiation intercepted (*f*PAR) by the plants, with a view to use in modeling the growth of species (López-Lozano et al., 2009; Campos et al., 2017). These biophysical parameters help to understand the phenotypic characteristics of cultures, making possible more accurate decision-making applications (Roosjen et al., 2018).

Therefore, variables such as leaf area index, plant growth rate, biological efficiency and competitive ability of crops within an intercropped system are extremely important. The understanding of these production parameters can be carried out in monitoring the rate of growth and productivity, which subsidize information on their development and income (Benjamin, 2016). This information is of utmost relevance, since the adequate production and yield of forage plants are the pillars of the agricultural sector (Hanna et al., 2018).

The quality and development of forage plants can be changed chemically and phenologically as a result of local climate changes. This occurs due to the influence of the variation of maximum and minimum temperatures, increase of CH_4, N_2O and atmospheric CO_2, and prolonged water deficit, making them lose digestibility and palatability for the animals, and variations in the vegetative and reproductive cycle (Fangueiro et al., 2017; Ergon et al., 2018).

Biometric analysis of plants is a simple and low-cost tool, capable of understanding and comparing the devaluation (e.g., morphological, physiological and phenological) of the crops in different cultivation systems. Environmental and biological factors can exert changes in the characteristics of crops, such as expansion of part of its organs and distribution of photoassimilates to the constituent parts of the plant (Di Benedetto & Tognetti, 2016; Impagliazzo et al., 2017).

However, when the biometric variables of the crops are combined and/or together with the productive yields, the applications of biological indexes (e.g., indexes of biological efficiency and competitive ability) in intercropped systems are used to assist in the understanding of the complex responses of the cultures, due their competitive effects, which is of greater importance in the development of species, economic benefits and ideal planting configurations (Sadeghpour et al., 2013; Lin & Hülsbergen, 2017; Chimonyo et al., 2018). Through this knowledge, it becomes possible to determine the best configuration of the forage cactus-sorghum planting system.

Conclusions

The information compiled in this review shows that resilience strategies such as the use of intercropping systems of forage plants such as forage cactus-sorghum can increase forage production in neglected environments under semi-arid conditions.

However, more research conducted in the field is needed to understand the role of intercropped forage cactus-sorghum systems to identify optimal crop combinations and their benefits in the agricultural sector.

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