

Morphological characteristics and yield of *Opuntia stricta* and *Nopalea cochenillifera* in integrated crop systems with caatinga trees

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Abstract

The objective was to evaluate the structural and production characteristics of *Opuntia stricta* (Cactus pear Orelha de Elefante Mexicana) and *Nopalea cochenillifera* (Cactus pear Miúda) under different arrangements of caatinga trees. The study was carried out at the Teaching, Research and Extension Unit (UEPE) of the Federal Institute of Education, Science and Technology of Ceará (IFCE), Limoeiro do Norte Campus, state of Ceará. The experimental area consisted of nine systems, arranged in strips of Caatinga trees (woody component), with dimensions of 6.0 x 100.0 m, directed in the north-south direction. Among the tree strips, *Opuntia stricta* and *Nopalea cochenillifera* were implanted in plots, according to the following treatments: cactus pear grown under 46.15% woody cover (ICS46; 1,418 trees per hectare), cactus pear grown under 30.00% woody cover (ICS30; 925 trees per hectare) and cactus pear grown under 17.64% woody cover (ICS18; 524 trees per hectare). The experimental design was completely randomized, in a split-plot arrangement. Mean canopy height (H), number of cladodes per linear meter (NC) and total forage biomass (TFB) were evaluated, considering the east, center and west positions. The lowest H and NC was found for *Nopalea cochenillifera* in the east position. *Nopalea cochenillifera* and *Opuntia stricta* cultivated in system ICS46 had the lowest TFB in the center position. The silvopastoral systems ICS30 and ICS18 can be adopted without negatively affecting the structural and productive characteristics of cactus pears *Opuntia stricta* and *Nopalea cochenillifera*.

Introduction

Hyper-arid, arid, semi-arid and sub-humid regions account for 60.95 million km² or 41% Brazilian territory. They are characterized by low water potential and high evapotranspiration. It is estimated that between 6 and 12 million km² of these areas are under desertification with reduced productive capacity and limited human subsistence resources (Pinheiro and Nair 2018). Therefore, developing sustainable and economically viable production systems is a global challenge, especially for these regions, given the greater climatic and social vulnerability.

Integrated systems enable environmentally, socially and economically sustainable production, becoming an alternative for recovery in degraded areas, improving soil fertility and enabling better animal performance, in addition to promoting additional revenue from the commercialization of the arboreal component (Lima et al. 2019; Paciullo et al. 2011).

Cactus pear has potential to be used in integrated production systems in hot semi-arid regions, given their high survival and production rates in environments with water scarcity and high temperatures, due to morphophysiological adaptation (Hernández et al. 2004). In addition, it is an important ingredient for animal feeding, due to high levels of carbohydrates, being used to substitute other energy feedstuffs, reducing the demand for roughage, such as sorghum and corn silages (Oliveira et al. 2007).

The grating system in savanna makes agricultural mechanization impossible, due to the random positioning of trees in the area, however, thinning in bands enables the use of agricultural mechanization

and also prevents soil erosion when the bands are positioned in the opposite direction to the land slope (Araújo Filho 2013).

However, it is necessary to provide adequate spacing between strips promoting the development of crops present in the understory, since higher tree densities favor reductions in the red/far red ratio of the photosynthetically active radiation, which may cause morphophysiological changes in species present in the lower layer, compromising production, as verified by the authors: Nascimento et al. 2021; Silva et al. 2020; Lima et al. 2019 and Santos et al. 2018, working with grasses in the understory of a silvopastoral system in the Brazilian Cerrado region.

Few studies have been carried out using cactus pear as the crop in the understory of integrated cropping systems. Miranda et al. (2019) evaluated *Nopalea cochenillifera* cultivar IPA-Sertânia intercropped with legume trees in double rows with spacing of nine meters between rows in the Brazilian semi-arid region, and did not find changes in the dry matter yield of that cultivar in different spots in the understory, making it possible to recommend the implementation of this model of integrated system for the Brazilian semi-arid region due to the equality of production when compared to monoculture as well as other additional benefits mentioned in the study.

Therefore, studies on **integrated crop systems** in semi-arid regions that promote the development of species grown in the understory are fundamental for sustainable and economic regional development.

Thus, different spacings between strips of caatinga trees promote changes in the morphological and productive characteristics of the cactus pear in the understory. Thus, the objective of this study was to evaluate the structural and productive characteristics of *Opuntia stricta* (cactus pear Orelha de Elefante Mexicana) and *Nopalea cochenillifera* (cactus pear Miúda) in silvopastoral system with different spacing between strips with caatinga trees.

Material And Methods

The experiment was carried out at the Education, Research and Extension Unit (UEPE) of the Federal Institute of Science and Technology of Ceará (IFCE), Limoeiro do Norte Campus, in Chapada do Apodi, state of Ceará. The experimental area has flat relief and it is characterized by the predominance of Cambisol soils (Santos et al. 2006) at geographic coordinates 05°10'53" S and 38°00'43" W and altitude of 146 m. The climate of the region is hot and semi-arid, classified as BSw'h, according to Köppen (1936).

The experiment was conducted in the years 2017, 2018 and 2019. The cumulative rainfall, air relative humidity and average temperature during the evaluation years was 590.4 mm, 68.45% and 27.48°C (2017); 805.75 mm, 74.86% and 27.08°C (2018); and 716.32 mm, 76.56% and 26.96°C (2019), respectively. For climate characterization, data from a meteorological station at approximately 150 m far from the experimental area were used (Fig. 01).

Thinning was carried out in the dry season of 2015, using a tractor with front blade, suppressing 100% vegetation present in the cultivable area, pushing the material to the edges. Before thinning, the area consisted of an arboreal caatinga (Araújo Filho 2013) in secondary succession stage.

The experimental area consisted of nine systems arranged in strips of Caatinga trees (woody component) with dimensions of 6.0 x 100.0 m, in the north-south direction. Enrichment was carried out by planting *Opuntia stricta* and *Nopalea cochenillifera* at a spacing of 1.5 m between rows and 0.20 m between plants, forming the understory, between tree strips during the rainy season of 2016. We decided to use these cultivars due to satisfactory adaptation to soil and climate conditions of the study region, described in several works (Barbosa et al. 2017; Pereira et al. 2015; Silva et al. 2015; Pinheiro et al. 2014).

After a phytosociological survey, the following tree species were identified: *Cordia goeldiana* (Freijó), *Mimosa caesalpiniaefolia* (Sabiá), *Cenostigma pyramidale* (Catingueira), *Commiphora leptophloeos* (Imburana de espinho) and *Mimosa tenuiflora* (Jurema negra). Freijó showed the highest relative density (81.59%) followed by catingueira (7.87%). The mean height of the woody component was 3.98 ± 1.30 m.

Woody covers corresponding to 46.15, 30.00 and 17.64% were obtained considering 6.0 m strips of Caatinga trees, assigning spacings of 07, 14 and 28 m (understory), respectively (Fig. 2). Densities of 1,418 (46.15%), 925 (30.00%) and 524 (17.64%) trees per hectare were obtained, respectively.

The treatments were: cactus pear grown under 46.15% woody cover (ICS46), cactus pear grown under 30.00% woody cover (ICS30) and cactus pear grown under 17.64% woody cover (ICS18) (Fig. 2). The experimental design was completely randomized, in which the ICS18, ICS30 and ICS46 systems were randomly assigned among the three replications, totaling nine plots. Within each plot, the two palm cultivars *Opuntia stricta* and *Nopalea cochenillifera* were randomized, totaling eighteen subplots. In each subplot, the three positions (center, east and west) were considered, totaling fifty-four sub-subplots.

Levels were determined as recommended by Araújo Filho (1992), who established a 30% woody cover in savannah without compromising the growth of the natural herbaceous layer. Thus, it was decided to evaluate woody covers in strips, establishing upper, lower and equivalent levels of 30%.

Before planting the crops, a soil sample was taken from the 0–20 cm layer for further chemical analysis in the soil laboratory of IFCE, Limoeiro do Norte campus. Values of the soil chemical properties for calcium (93.33, mmolc. dm³), magnesium (18.7, mmolc. dm³), potassium (6.32, mg. dm³) and organic matter (31.76, g. kg) were classified as very good, while those of phosphorus (6.03 mg. dm³) were classified as low, according to Ribeiro et al. (1999).

Phosphate fertilization was carried out every year, using the fertilizer single-ammonium-phosphate - MAP (44% P₂O₅ and 10% N), in the level of 200 kg ha⁻¹ year⁻¹, according to the demand for phosphorus found in soil analysis.

The following evaluations were carried out: mean canopy height (H, cm), with a graduated-retractable stick, by sampling six spots per position, number of cladodes per linear meter (NC, cladodes / linear meter), by counting 1st order cladodes within 1.0 linear meter and total forage biomass (TFB, kg ha⁻¹ year⁻¹), estimated from the harvest of two plants per linear meter by cutting right after the 1st order cladode. After harvesting, the material was packed in plastic bags and sent to the laboratory, where it was weighed, then samples were chopped into cubes of approximately 0.05 m² to determine the pre-dry matter, in a forced air oven at 65°C.

Evaluations of H, NC and TFB were made in the end of the rainy season (August). It was considered the positions: center (central region of the plot), east (lateral position with shade in the early morning) and west (lateral position with shade in the early afternoon) of each plot, in order to characterize the effect of the arboreal component in the understory at different spots within the system, because, according to Santos et al. (2016), crops in the understory of integrated systems are subjected to morphological and structural changes, especially in places close to the tree component.

At the end of the growth period of cactus pear *Opuntia stricta* and *Nopalea cochenillifera*, a standardization cut was performed, removing all biomass present after the 1st order cladode, with the aim of standardizing the crops for the next growth period (rainy season).

Data normality was tested by the Cramer-von Mises test. Data were analyzed using the mixed model procedure, using the following statistical model:

$$Y_{ijklm} = \mu + S_j + \alpha_{ij} + C_k + (SC)_{jk} + \beta_{ijk} + P_l + (SP)_{jl} + (CP)_{kl} + (SCP)_{jkl} + \epsilon_{ijkl}$$

Where:

Y_{ijklm} : value of the ith experimental unit subjected to the jth shading level, in the kth crop, and lth position;

μ : fixed effect of the general mean;

S_j : fixed effect of the shading level;

α_{ij} : random effect of the ith replication in the jth shading level, where α_{ij} assumes $iid N(0, \sigma_A^2)$;

C_k : fixed effect of the crop;

$(SC)_{jk}$: fixed effect of the interaction between shading level and crop;

β_{ijk} : random effect of the kth crop in the ijth shading level, where β_{ijk} assumes $iid N(0, \sigma_B^2)$;

P_l : fixed effect of the position;

$(SP)_{jl}$: fixed effect of the interaction between shading level and position;

$(CP)_{kl}$: fixed effect of the interaction between crop and position;

$(SCP)_{jkl}$: fixed effect of the interaction between shading level, crop and position;

ϵ_{ijkl} : random effect associated to the i^{th} replication, j^{th} shading level, k^{th} crop, and l^{th} position where ϵ_{ijkl} assumes $\sim N(0, \sigma^2)$;

Data were analyzed using the SAS procedure PROC MIXED (SAS Institute. Inc., 2015). The corrected Akaike Information Criterion was used to select the covariance matrix structure for the random effect of year of evaluation. The fixed effects of level of shading, crop, positions and their interactions were considered significant at a p-value < 0.05. When significant differences were detected, mean values were compared by Tukey-Kramer test at a p-value < 0.05.

Results

There was no effect of second order interaction (shading level x culture x position) for the variables evaluated. The variables mean canopy height, number of cladodes and total forage biomass had effect of the interaction between silvopastoral system * position and crop * position.

Cactus pears grown in the ICS18 and ICS30 systems had the lowest mean canopy height in the west position; but there were no differences between the east and center positions (Fig. 3). Cactus pears of the ICS46 system presented no difference in the mean canopy height in the east (68.70 cm), center (80.35 cm) and west (76.41 cm) positions (Fig. 3).

Nopalea cochenillifera presented the lowest mean canopy height in the east and west positions (Fig. 04). There was no difference in the mean canopy height of *Opuntia stricta* between the east, center and west positions (Fig. 4). Comparing *Nopalea cochenillifera* to *Opuntia stricta*, the first had the lowest mean canopy height in the east, center and west positions (Fig. 4).

The highest cladode yield of *N. cochenillifera* and *O. stricta* was found in the center position in systems ICS18 and ICS30 (Fig. 05). System ICS18 showed a lower NC in plants grown in the east and west positions (Fig. 05). System ICS30 had the lowest NC in plants grown in the west position (Fig. 05). Cactus pear grown in system ICS46 showed no difference in NC between the east, center and west positions (Fig. 05).

N. cochenillifera had the lowest NC in the east and west positions (Fig. 06), while *Opuntia stricta* showed no difference in NC between the east, center and west positions (Fig. 06). Comparing *N. cochenillifera* to *O. stricta*, the second had the greatest NC in the west position and similar NC in the east and center positions (Fig. 06).

N. cochenillifera and *O. stricta* grown in system ICS46 had the lowest TFB in the center position (Fig. 07). On the other hand, they did not differ for TFB between the east and west positions in all three systems

(Fig. 07). *N. cochenillifera* and *O. stricta* grown in system ICS46 had similar TFB yields in the east ($5,571.37 \text{ kg ha}^{-1} \text{ year}^{-1}$), center ($6,984.17 \text{ kg ha}^{-1} \text{ year}^{-1}$) and west ($6,057.40 \text{ kg ha}^{-1} \text{ year}^{-1}$) positions.

Higher biomass yield was observed for *N. cochenillifera* ($7,766.51 \text{ kg ha}^{-1} \text{ year}^{-1}$) and *O. stricta* ($11,892 \text{ kg ha}^{-1} \text{ year}^{-1}$) (Fig. 08). Comparing *O. stricta* to *N. cochenillifera*, the greatest TFB was found in the east, center and west positions (Fig. 8).

Discussion

Sampling morphological and production characteristics in various spots in the understory in integrated crop systems, makes a better representation of the estimate of total biomass yield (Santos et al. 2016) and the amount of feed available, helping to achieve greater precision in forage planning. Thus, when evaluating the east and west positions, it was found that *N. cochenillifera* was more vulnerable to positions close to the woody component, due to the lower mean canopy height and the number of cladodes observed in the east and west positions.

Positions of plants close to the woody component in integrated systems cause greater competition for light, becoming critical environments for adequate development of cultivated plants, which can cause heterogeneity in structural characteristics and biomass yield (Pezzopane et al. 2015). Therefore, it is worth emphasizing the importance of solar radiation for the growth of crops, and the existence of a linear relationship between biomass yield and radiant energy absorbed throughout the cycle for several species (Tollenar and Bruulsema 1988).

The present study may have limited the reaching of solar radiation in the canopy of cactus pear in the east and west positions, as well as in the center position of the system with the highest density of trees (ICS46, 1,418 trees per hectare), affecting the assimilation of CO₂ and, consequently, the productivity of crops in the environment close to the woody component.

According to Gommers et al. (2013), the upper tree stratum absorbs part of the incident radiation in the red ($\lambda = 600$ to 700 nm) and blue ($\lambda = 400$ to 500 nm) bands and reflects and transmits part of the far-red wavelengths ($\lambda = 700$ to 800 nm) to lower strata. Thus, there is a decrease in the red / far-red ratio in the lower shaded strata. The low light absorption interferes with the photochemical step of photosynthesis, in the electron transport chain and in part of the necessary production of energy used to transform CO₂ into carbohydrates (Mendes et al. 2013).

The tree densities in systems ICS30 (925 trees per hectare) and ICS18 (524 trees per hectare) did not interfere with biomass yield of *O. stricta* and *N. cochenillifera* in the center position, representing alternatives to be planted in integrated systems with potential for use in the Caatinga biome.

The greater production of *O. stricta* in all positions is related to the larger cladode area compared to *N. cochenillifera* (Pereira et al. 2015). In addition, there was a higher mean canopy height of *O. stricta* in all evaluated positions.

The approach of the woody component can also promote competition for water, due to the higher water demand of trees. Ivanov et al. (2017) compared trees from an agroforestry system with trees from a secondary forest in Caatinga, reported that the higher density of trees results in less water availability in the soil. Thus, in the east and west positions evaluated in this study, greater wilting was observed in the grown cactus pears, mainly in *N. cochenillifera* when subjected to conditions of moderate water stress. Probably, crops in these positions had more intense water competition compared with those in the center position.

Cactus pear *O. stricta* has a greater potential for adaptation to conditions of low water availability in the soil compared to *N. cochenillifera*. This is attributed to the greater capacity to store water in the cladodes, which is important to maintain turgor in situations of water stress (Pereira et al. 2015). In this context, *O. stricta* showed greater homogeneity in the positions, corroborating the maintenance of the mean canopy height and the number of cladodes between the evaluated positions.

In addition to the competition for light and water, *O. stricta* and *N. cochenillifera* suffered attacks from rodents of the species *Cavia aperea* (preá), affecting development in the east and west positions, as these rodents used the area with trees as a shelter, intensifying attacks in positions closer to the trees (east and west). *O. stricta* was less attacked by rodents. There was an intensification in the attack to cactus pear by *Cavia aperea* from August to December, as these months have low rainfall (Fig. 01), causing reductions in the supply of feed and water for these animals. Once cactus pear maintains cladodes with a high-water content (88%) during the dry season, it is a feed reserve for these rodents.

Conclusions

Systems ICS30 and ICS18 can be adopted without negatively affecting the structural and productive characteristics of cactus pears *Opuntia stricta* and *Nopalea cochenillifera*. *N. cochenillifera* is more sensitive to competition imposed by the woody component, presenting difficulties for establishment in places close to the trees in integrated crop systems in the Caatinga. Future research should be carried out in order to verify the nutritive value of the cactus as well as to carry out an economic evaluation of the complete system, considering all the components.

Declarations

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Figures

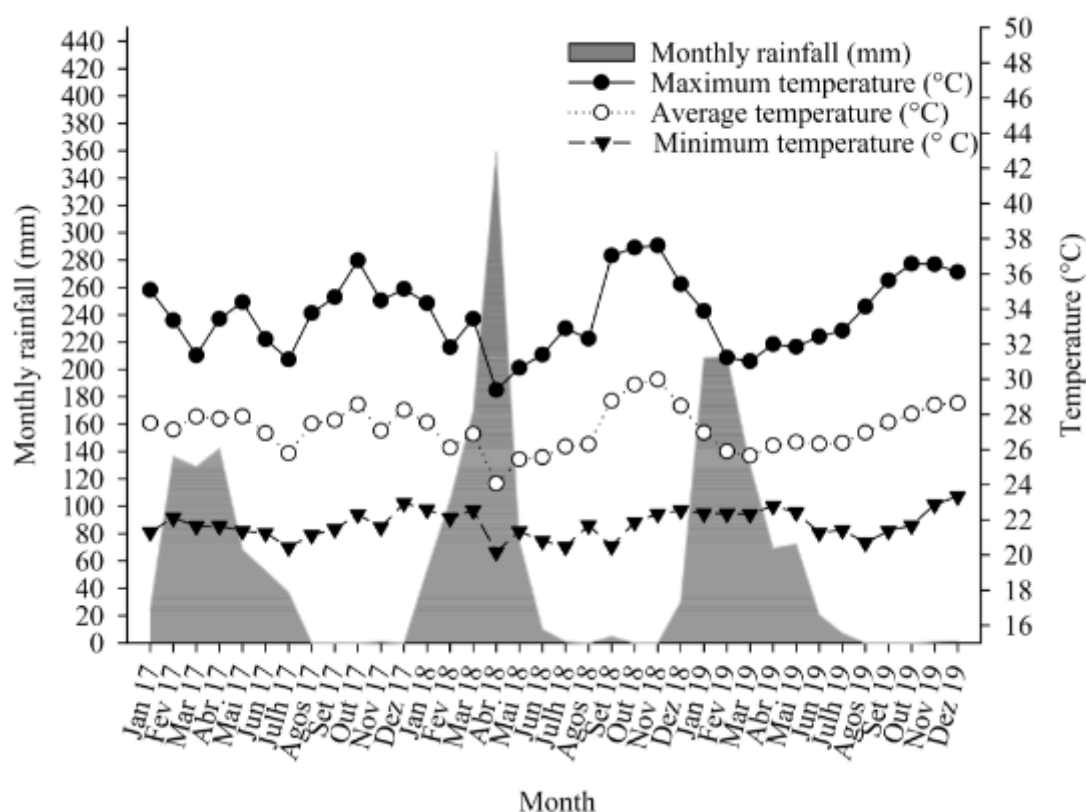


Figure 1

Monthly rainfall (mm), Maximum temperature (°C), Average temperature (°C) and Minimum temperature (°C) during the years 2017, 2018 and 2019.

Source: data obtained from the meteorological station located at UEPE.

Figure 2

Schematic representation with equipment fixing points (A: east position; B: center position; C: west position) in integrated crop systems in the Caatinga, ICS46 (integrated crop system with 07 m between tree strips, 1418 trees per hectare), ICS30 (integrated crop system with 14 m between tree strips, 925 trees per hectare) and ICS18 (integrated crop system with 28 m between tree strips, 524 trees per hectare).

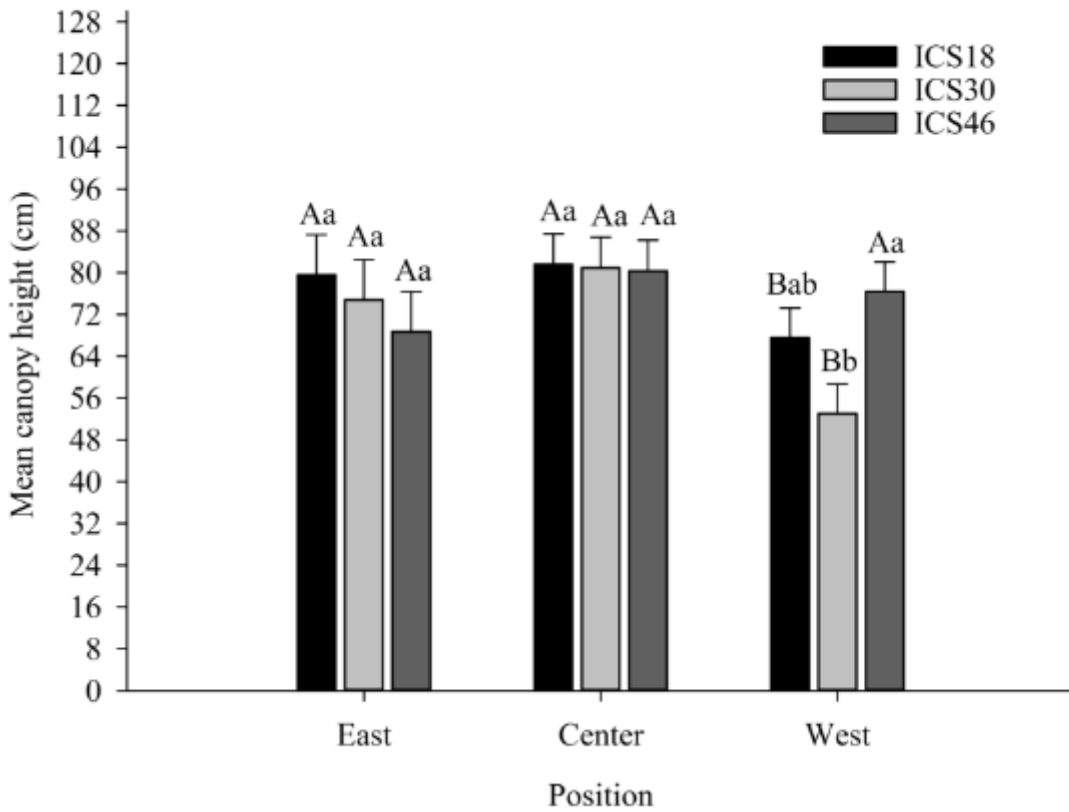


Figure 3

Mean canopy height (cm) of *Nopalea cochenillifera* and *Opuntia stricta* in the east, center and west positions in the ICS18, ICS30 and ICS46 integrated crop systems in the Caatinga.

Different lowercase letters in the same position indicate significant differences by Tukey-Kramer test $p < 0.05$.

Different uppercase letters between positions indicate significant differences by the Tukey-Kramer test $p < 0.05$.

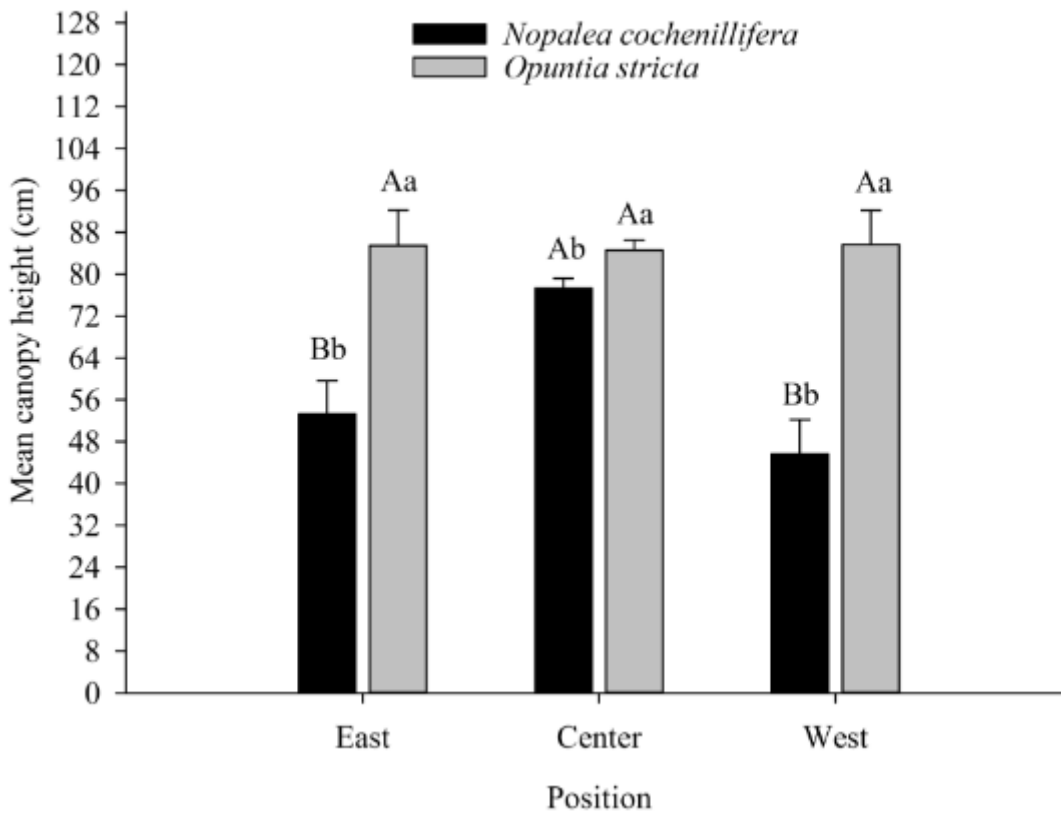


Figure 4

Mean canopy height (cm) of *Nopalea cochenillifera* and *Opuntia stricta* in the east, center and west positions in the ICS18, ICS30 and ICS46 integrated crop systems in the Caatinga.

Different lowercase letters in the same position indicate significant differences by Tukey-Kramer test $p < 0.05$.

Different uppercase letters between positions indicate significant differences by the Tukey-Kramer test $p < 0.05$.

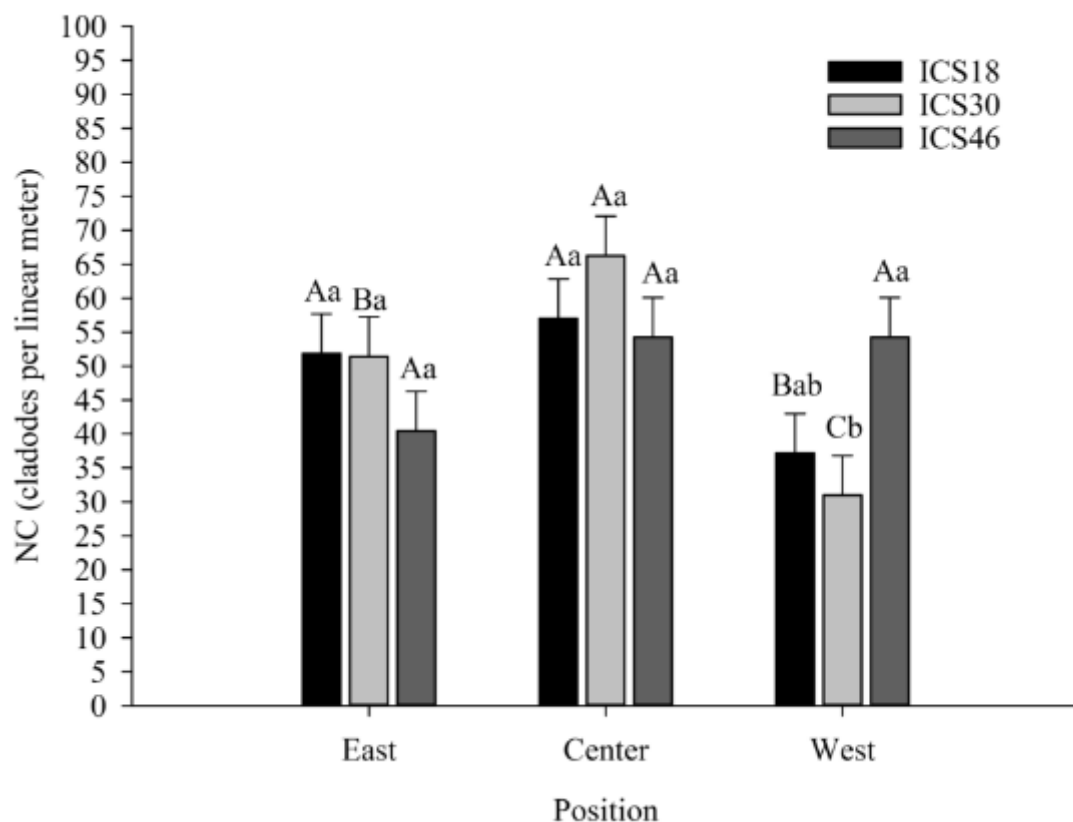


Figure 5

Number of cladodes (NC, cladodes per linear meter) of *Nopalea cochenillifera* and *Opuntia stricta* in the east, center and west positions in the ICS18, ICS30 and ICS46 integrated crop systems in the Caatinga.

Different lowercase letters in the same position indicate significant differences by Tukey-Kramer test $p < 0.05$.

Different uppercase letters between positions indicate significant differences by the Tukey-Kramer test $p < 0.05$.

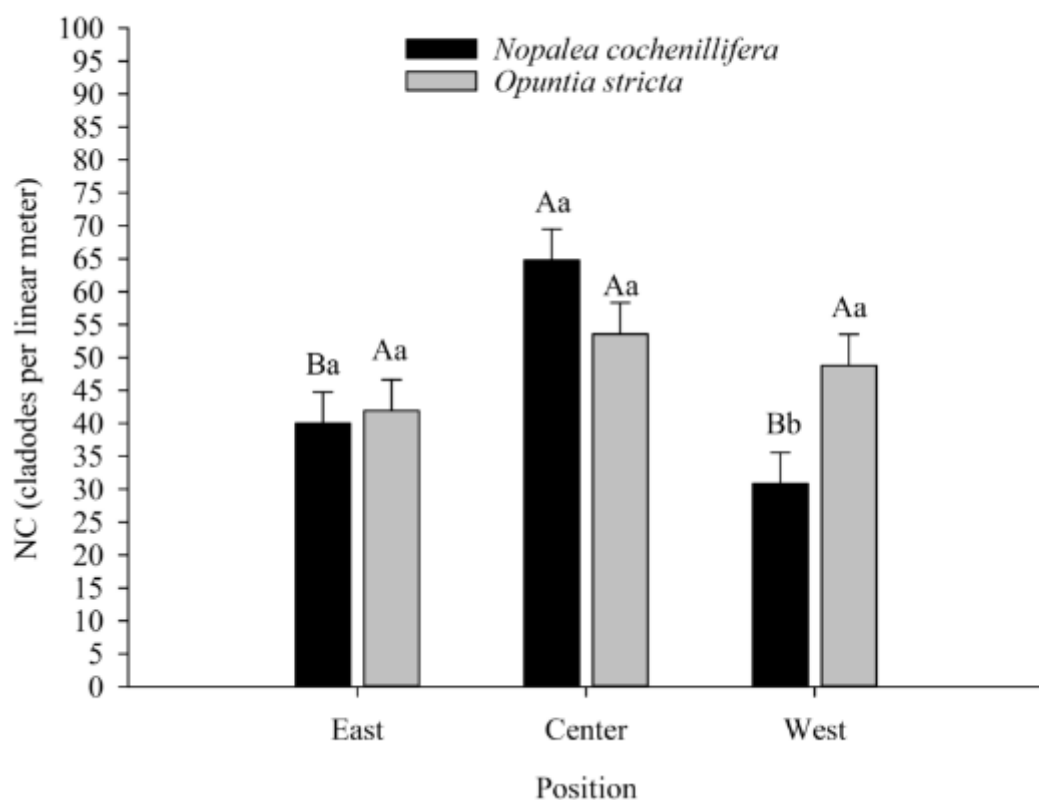


Figure 6

Number of cladodes (NC, cladodes per linear meter) of *Nopalea cochenillifera* and *Opuntia stricta* in the east, center and west positions in integrated crop systems in the Caatinga.

Different lowercase letters in the same position indicate significant differences by Tukey-Kramer test $p < 0.05$.

Different uppercase letters between positions indicate significant differences by the Tukey-Kramer test $p < 0.05$.

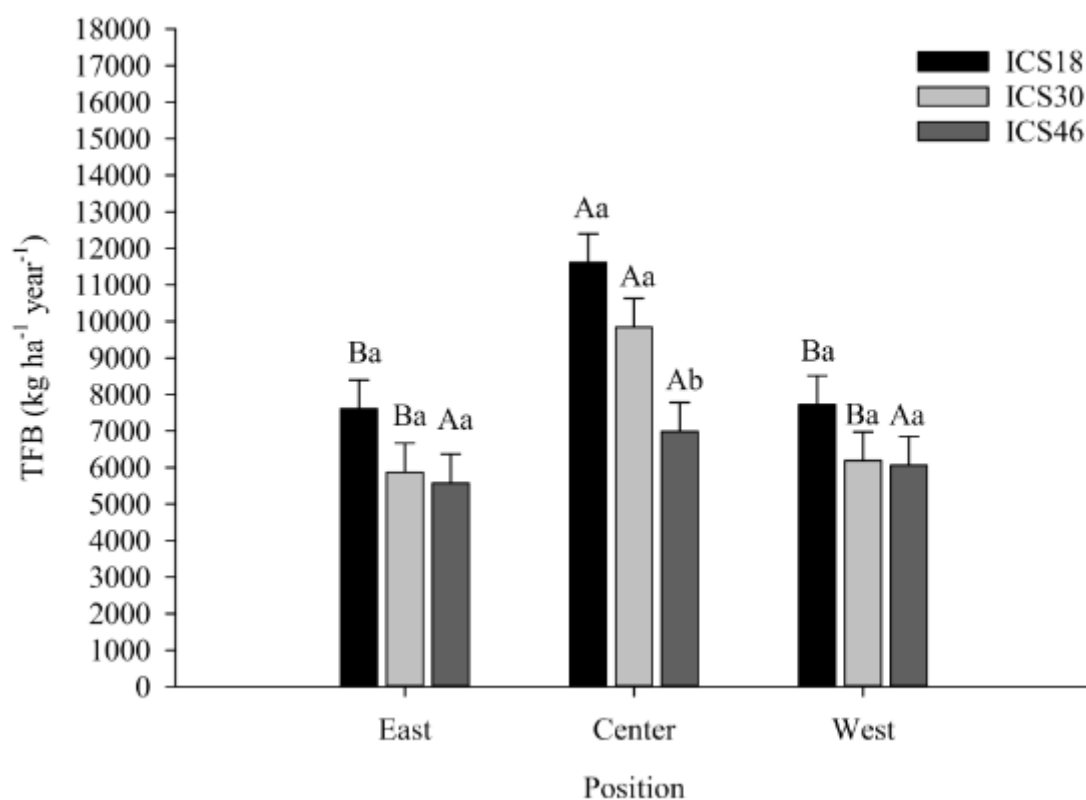


Figure 7

Total forage biomass (TFB, kg ha⁻¹ year⁻¹) of *Nopalea cochenillifera* and *Opuntia stricta* in the east, center and west positions in the ICS18, ICS30 and ICS46 integrated crop systems in the Caatinga.

Different lowercase letters in the same position indicate significant differences by Tukey-Kramer test $p < 0.05$.

Different uppercase letters between positions indicate significant differences by the Tukey-Kramer test $p < 0.05$.

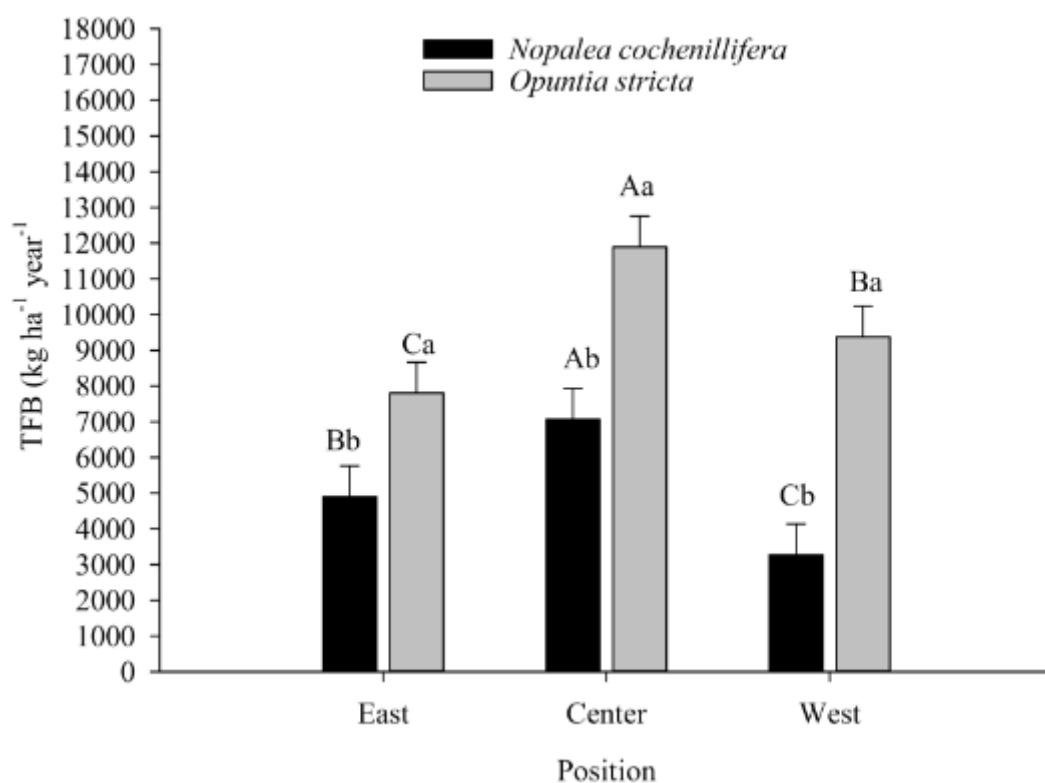


Figure 8

Total forage biomass (TFB, kg ha⁻¹ year⁻¹) of *Nopalea cochenillifera* and *Opuntia stricta* in the east, center and west positions in integrated crop systems in the Caatinga.

Different lowercase letters in the same position indicate significant differences by Tukey-Kramer test $p < 0.05$.

Different uppercase letters between positions indicate significant differences by the Tukey-Kramer test $p < 0.05$.