Forage biomass and water storage of cactus pear under different managements in semi-arid conditions

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ABSTRACT - Forage biomass production and water storage (WS) was evaluated in cactus pear cv. Gigante fertilized with combinations of nitrogen (10, 70, 100, 130, and 190 kg ha^{-1} yr^{-1} N) and phosphorus (10, 70, 100, 130, and 190 kg ha^{-1} yr^{-1} P_2O_5) in annual (AH) and biennial (BH) harvest frequencies, in Quixadá and Tejuçuoca, Brazil. A randomized complete block design was used in a split-plot arrangement with four replications. In Quixadá, the maximum total forage biomass (TFB) recorded in the AH was 3,522.9 kg ha^{-1} yr^{-1} for the N/P_2O_5 combination of 134.6/190.0 kg ha^{-1} yr^{-1}, and in the BH, the maximum TFB of 1,583.2 kg ha^{-1} yr^{-1} was recorded for the N/P_2O_5 combination of 114.6/136.8 kg ha^{-1} yr^{-1}. In Tejuçuoca, the maximum TFB recorded in the AH was 9,783.0 kg ha^{-1} yr^{-1} for the N/P_2O_5 combination of 137.7/190.0 kg ha^{-1} yr^{-1}, and in the BH, the maximum TFB of 12,124.0 kg ha^{-1} yr^{-1} was recorded for the N/P_2O_5 combination of 190.0/56.8 kg ha^{-1} yr^{-1}. In Quixadá, the maximum WS recorded in the AH was 39.1 kg ha^{-1} mm^{-1} for the N/P_2O_5 combination of 161.0/190.0 kg ha^{-1} yr^{-1}, and in the BH, the maximum WS of 11.3 kg ha^{-1} mm^{-1} was recorded for the N/P_2O_5 combination of 113.5/158.7 kg ha^{-1} yr^{-1}. In Tejuçuoca, the maximum WS recorded in the AH was 196.1 kg ha^{-1} mm^{-1} for the N/P_2O_5 combination of 190.0/190.0 kg ha^{-1} yr^{-1}, and in the BH, the maximum WS of 265.5 kg ha^{-1} mm^{-1} was recorded for the N/P_2O_5 combination of 190.0/10.0 kg ha^{-1} yr^{-1}. To achieve the persistence and longevity of the cactus pear cv. Gigante, the management with BH and fertilization with the N/P_2O_5 combination of 114.6/136.8 kg ha^{-1} yr^{-1} (in regions similar to Quixadá) and N/P_2O_5 combination of 190.0/56.8 kg ha^{-1} yr^{-1} (in regions similar to Tejuçuoca) is recommended.

Keywords: harvest frequency, nutrient management, *Opuntia ficus-indica*, water accumulation

1. Introduction

The genus *Opuntia* has approximately 180 of the 1600 species of the Cactaceae family and is represented mostly by platyopuntias (Gibson and Nobel, 1986; Cortázar and Nobel, 1992), highlighting cactus pear (*Opuntia ficus-indica*) as commercially important plant, cultivated in more than 20 countries (Nobel, 1988; Russell and Felker, 1987).

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Cactus pear is a forage resource of great importance for feeding livestock in arid and semi-arid regions, as it presents good productivity in these environments (Nobel et al., 1992; Dubeux Jr. et al., 2006). Also, important characteristics are the tolerance to arid and semi-arid conditions (Fischer and Turner, 1978) and efficiency in the use of water (Kluge and Ting, 1978; Griffith, 2004; Oliveira et al., 2010; Silva et al., 2014), which is a relevant point of crassulacean acid metabolism (CAM) (Ranson and Thomas, 1960; Griffith, 2004).

Many studies carried out with cactus pear in semi-arid regions included only one or few factors (Nobel et al., 1987; Nobel, 1989; Dubeux Jr. et al., 2006; Alves et al., 2007; Cunha et al., 2012), demonstrating the need for more comprehensive research on the effect of multiple factors on the growth and development characteristics of the plants including assessments of water storage (WS) by the shoot biomass. The response of cactus pear cv. Gigante regarding plant density, components of forage biomass, harvest index, and WS in function of environmental and management factors (different conditions of soil and climate, fertilization, and harvest frequency) will be fundamental in defining management practices that can guarantee optimization of the ecophysiological responses of the crop, affording persistence and perenniality to the cactus pear orchard and guaranteeing sustainability of the livestock production system in semi-arid regions.

In view of the above, this study was carried out to evaluate the dynamics of plant density, forage biomass production, and WS of the cactus pear cv. Gigante (*Opuntia ficus-indica*), fertilized with nine combinations of nitrogen (N) and phosphorus (P) under two harvest frequencies in two semi-arid regions, seeking to define the combination of N and P that maximizes the biological response of the forage crop.

2. Material and Methods

2.1. Experimental sites

The experiment was carried out in two semi-arid regions, in the districts of Quixadá (4°59' S, 39°01' W, 190 m a.s.l.; hot semi-arid climate, BSw'h' type) and Tejuçuoca (3°59' S, 39°34' W, 140 m a.s.l.; tropical climate with a dry season, Aw type), in the state of Ceará, Brazil. The climatic classification used was the Koppen classification (Koppen, 1948).

Average temperature and air relative humidity of the experimental period and cumulative annual rainfall were recorded in both regions: in Quixadá, values of 27.0 °C and 58.8% were recorded for temperature and air relative humidity, respectively, over the experimental period; rainfall values of 1,042 and 602 mm were observed in 2011 and 2012, respectively (January 2011 to December 2012). In Tejuçuoca, the values recorded were 26.4 °C and 65.5% for temperature and air relative humidity, respectively; rainfall values recorded were 1,038 and 561 mm in 2011 and 2012, respectively (January 2011 to December 2012). Data were obtained at the Agroclimatological Station of the Universidade Federal do Ceará (Quixadá) and at the Agroclimatological Station of FUNCEME (FUNCEME, 2011, 2012).

A physicochemical characterization of the soil in each region was performed at a depth of 0.0 to 20.0 cm. The soil texture was classified as sandy in Quixadá and sandy loam in Tejuçuoca. In Quixadá, the samples had the following composition: 5 mg dm^{-3} P, 260 mg dm^{-3} K, 20 mg dm^{-3} Na, 3.4 cmol$_c$ dm^{-3} Ca, 3.4 cmol$_c$ dm^{-3} Mg, 0.0 cmol$_c$ dm^{-3} Al, 5.3 g kg^{-1} organic matter (OM), 7.6 cmol$_c$ dm^{-3} sum of bases (SB), 7.6 cmol$_c$ dm^{-3} effective cation exchange capacity (ECEC), 6.1 of pH in water, 513 g kg^{-1} coarse sand, 363 g kg^{-1} fine sand, 89 g kg^{-1} silt, and 35 g kg^{-1} clay. In Tejuçuoca, the following composition was found: 6 mg dm^{-3} P, 243 mg dm^{-3} K, 7 mg dm^{-3} Na, 4.0 cmol$_c$ dm^{-3} Ca, 3.2 cmol$_c$ dm^{-3} Mg, 0.0 cmol$_c$ dm^{-3} Al, 8.2 g kg^{-1} OM, 7.9 cmol$_c$ dm^{-3} SB, 7.9 cmol$_c$ dm^{-3} ECEC, 6.2 pH in water, 164 g kg^{-1} coarse sand, 590 g kg^{-1} fine sand, 153 g kg^{-1} silt, and 93 g kg^{-1} clay. The analyses were performed following Embrapa's method of soil analysis.

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2.2. Orchard establishment and plant material

The soil was prepared for cactus pear (*Opuntia ficus-indica* cv. Gigante) with the planting following the steps: removal of stumps (whenever necessary), removal of vegetation from the area, and harrowing. Subsequently, plots were marked for delimitation of the respective area. Each plot occupied an area of 24.0 m² (4.0×6.0 m), which was composed of 120 plants distributed in three rows of 4.0 m of length – the central row was used for measurements and the sides as borders. After harvesting, cladodes were allowed to rest in the shade for 15 days to heal injuries caused during harvesting and transportation.

Furrows were made by hand using cutter mattock, narrow hoe, and hoe, obeying the average depth of 30 cm and spacing of 2.0 m. Cladodes were inserted up to the depth that provided the coverage of 2/3 of their length, with 2.0×0.10 m of spacing, which is the recommended to obtain the density of 50,000 plants ha⁻¹.

2.3. Mineral fertilization matrix and mineral fertilization program

Nine combinations of nitrogen (N) and phosphorus (P_2O_5) levels, consisting of five levels of N (10, 70, 100, 130, and 190 kg ha⁻¹ yr⁻¹) as urea and five levels of P_2O_5 (10, 70, 100, 130, and 190 kg ha⁻¹ yr⁻¹) as single superphosphate, according to the matrix Plan Puebla II, for two factors ($2^k + 2k + 1$) were assessed (Turrent Fernández and Laird, 1975). We adopted a standard combination (central point) of N (100 kg ha⁻¹ yr⁻¹) and P_2O_5 (100 kg ha⁻¹ yr⁻¹) and from this point, the other combinations were defined according to fixed levels of ±0.3 (30%) and ±0.9 (90%) (Table 1).

Fertilization was performed during the rainy season. The annual level of P, as single superphosphate, was applied at once, upon planting in the first year and when the rainy season began, in the other years of cultivation. At this time, the micronutrients were applied as 50 kg ha⁻¹ FTE BR-12. Calcium and sulfur balancing was performed for all treatments using agricultural gypsum and calcitic limestone based on the highest level of single superphosphate. The annual level of N, as urea, was applied in three parts, with a 20-day interval between applications. In all applications, the urea was diluted in water and applied as 1 L of solution to each 4-m of length of the cactus pear row, totaling the volume of 3 L per plot. Weed control was performed by cleaning and with herbicide application with directed jet. The control of cochineal (*Diaspis echinocacti*) was carried out using mineral oil.

Table 1 - Treatments studied in the semi-arid conditions of Quixadá and Tejuçuoca, CE, Brazil

Region		N and P_2O_5 (kg ha⁻¹ yr⁻¹)	Harvest frequency	
Quixadá	Tejuçuoca	10 and 70	Annual	Biennial
Quixadá	Tejuçuoca	70 and 10	Annual	Biennial
Quixadá	Tejuçuoca	70 and 70	Annual	Biennial
Quixadá	Tejuçuoca	70 and 130	Annual	Biennial
Quixadá	Tejuçuoca	100 and 100	Annual	Biennial
Quixadá	Tejuçuoca	130 and 70	Annual	Biennial
Quixadá	Tejuçuoca	130 and 130	Annual	Biennial
Quixadá	Tejuçuoca	130 and 190	Annual	Biennial
Quixadá	Tejuçuoca	190 and 130	Annual	Biennial

2.4. Response variables

At the end of every growth cycle, for both annual and biennial harvest frequencies, according to the established management, three plants were collected from each experimental plot (24 m²) to estimate forage biomass production by cladode order. Forage biomass from the sample row above the first-order (primary) cladodes was also collected to estimate harvestable forage biomass (HFB). The primary cladodes were preserved to maintain a post-harvest cladode area (remaining cladode area index) that would ensure good regrowth and perenniality of the orchard over the succeeding years. The biomass

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harvested in the field was sent to the laboratory to separate the cladodes by order (first, second, third, etc.), and identified with a permanent marker at the moment of harvest. After separated by order, cladodes were broken into small pieces and placed in a forced ventilation oven (55 °C, to constant weight), for later estimation of biomass production. Total forage biomass (TFB, kg ha^{-1} yr^{-1}) was determined considering the sum of biomass production of each cladode order, and HFB (kg ha^{-1} yr^{-1}), considering all production above the cutting height, which represents the harvestable biomass with preservation of the primary cladodes.

The harvest index (HI) of cactus pear was determined from the following equation: HI (%) = (HFB/TFB) × 100, in which HFB is the harvestable forage biomass, and TFB is the total forage biomass (55 °C, to constant weight).

Water storage, in kg ha^{-1} mm^{-1}, was estimated from the difference between fresh and pre-dried biomass production, divided by the total rainfall (mm) of the period.

Plant density (plants ha^{-1}) was calculated at the time of harvest for both annual and biennial frequencies. For this recording, the number of plants per linear meter was determined, and the number of plants per hectare was then estimated.

2.5. Experimental design and data analysis

The nine combinations of N and P were studied in association with two harvesting frequencies (annual and biennial) of cactus pear, totaling 18 treatments (Table 1), with four replications, distributed in a split-plot completely randomized block design, with the combinations of N and P levels assigned to the plots and the harvest frequencies, to the subplots.

The following statistical model was used in the experiment:

$$Y_{ijk} = \mu + \alpha_i + \gamma_k + \eta_{ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}, \tag{1}$$

in which Y_{ijk} = value observed in the experimental plot that received the level i of factor α (fertilization) and level j of factor β (harvest frequency) in block k, μ = overall mean, α_i = fixed effect of fertilization, γ_k = fixed effect of block, η_{ik} = whole-plot error (error A), β_j = fixed effect of harvest frequency, $(\alpha\beta)_{ij}$ = interaction between fertilization and harvest frequency, and ε_{ijk} = split-plot error (error B).

Data were subjected to analysis of variance, mean-value comparison test, and multiple regression models analysis, with response surface presentation. The qualitative factors were compared by the Scott-Knott mean-value comparison test (P<0.05), and the mean values were presented graphically together with the standard error of the mean. The quantitative factors were studied in multiple regression models at a significance of P<0.001 (***). The SAEG software (Sistema de Análises Estatísticas e Genética, version 9.1, 2007) was used to perform the analyses.

3. Results

Significant effects of the interaction (P<0.05) between the nitrogen and phosphorus combinations × harvest frequencies were observed in each variable under analysis, under the growing conditions of cactus pear cv. Gigante in Quixadá and Tejuçuoca. The combined effect of nitrogen and phosphorus (P<0.001) on TFB, HFB, HI, WS, and final plant density (FPD) of the cactus pear cv. Gigante was evaluated in the annual and biennial harvest frequencies in the two regions (Figures 1, 2, 5, and 7). The influence of annual and biennial harvest frequencies on the above-mentioned variables was also analyzed (P<0.05) for each combination of nitrogen and phosphorus (Figures 3, 4, 6, and 8).

3.1. Forage biomass and harvest index

In the determination of TFB, HFB, and HI of the cactus pear cv. Gigante grown in Quixadá and Tejuçuoca, we observed effect of the combinations of N and P, fitting the multiple regression model (P<0.001), with response surface presentation (Figures 1 and 2).

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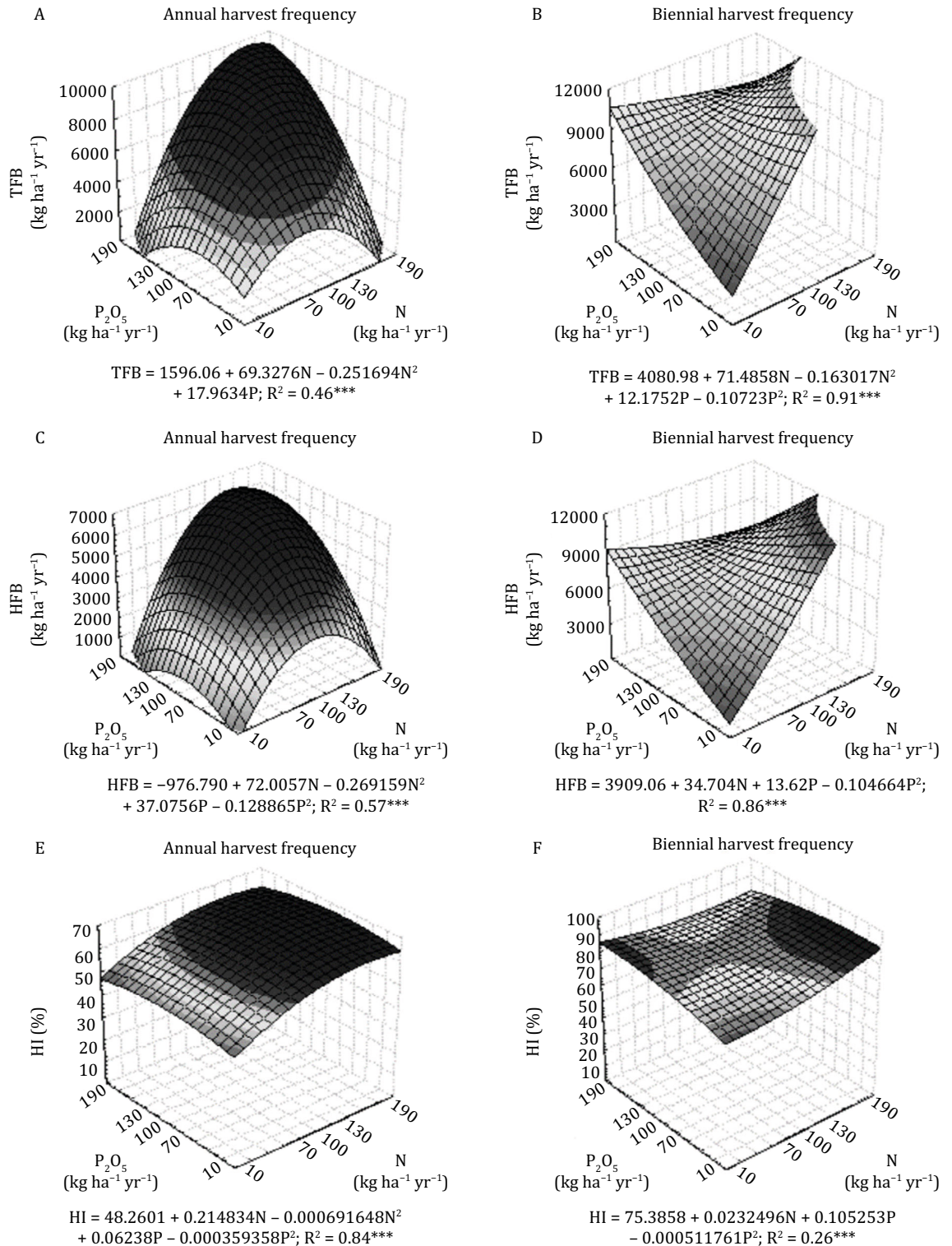Forage biomass and water storage of cactus pear under different managements in semi-arid conditions
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In Quixadá, the maximum TFB in the annual harvest (Figure 1A) was 3,522.9 kg ha^{-1} yr^{-1} for the N/P$_2$O$_5$ combination of 134.6/190.0 kg ha^{-1} yr^{-1} (P<0.001), and in the biennial harvest (Figure 1B), the maximum TFB of 1,583.2 kg ha^{-1} yr^{-1} (P<0.001) was observed for the N/P$_2$O$_5$

A Annual harvest frequency

$$TFB = 1475.87 + 11.8891N - 0.0441688N^2 - 3.07896P + 0.0507462P^2; R^2 = 0.68^{***}$$

B Biennial harvest frequency

$$TFB = -666.418 + 17.8106N - 0.0777138N^2 + 17.9644P - 0.0656395P^2; R^2 = 0.77^{***}$$

C Annual harvest frequency

$$HFB = 58.234 + 9.10828N - 0.0322415N^2 + 3.1148P; R^2 = 0.84^{***}$$

D Biennial harvest frequency

$$HFB = -178.593 + 7.55034N - 0.0296694N^2 + 2.7439P; R^2 = 0.78^{***}$$

E Annual harvest frequency

$$HI = 20.499 + 0.1779N - 0.00159695N^2 + 0.02728P - 0.0010878P^2 + 0.0020489NP; R^2 = 0.71^{***}$$

F Biennial harvest frequency

$$HI = 25.4752 + 0.241868N - 0.113648P + 0.00166758P^2 - 0.00155611NP; R^2 = 0.69^{***}$$

Significant models at P<0.001 (***).

Figure 1 - Total forage biomass (TFB, A and B), harvestable forage (HFB, C and D), and harvest index (HI, E and F) in response to combinations of nitrogen (N) and phosphorus (P) in cactus pear (*Opuntia ficus-indica* cv. Gigante) in Quixadá, CE, Brazil.

combination of 114.6/136.8 kg ha^{-1} yr^{-1}. In Quixadá, the maximum HFB in the annual harvest (Figure 1C) was 1,293.3 kg ha^{-1} yr^{-1} for the N/P$_2$O$_5$ combination of 141.3/190.0 kg ha^{-1} yr^{-1} (P<0.001), and in the biennial harvest (Figure 1D), the maximum HFB of 823.1 kg ha^{-1} yr^{-1}

A   Annual harvest frequency

$$TFB = 1596.06 + 69.3276N - 0.251694N^2 + 17.9634P; R^2 = 0.46^{***}$$

B   Biennial harvest frequency

$$TFB = 4080.98 + 71.4858N - 0.163017N^2 + 12.1752P - 0.10723P^2; R^2 = 0.91^{***}$$

C   Annual harvest frequency

$$HFB = -976.790 + 72.0057N - 0.269159N^2 + 37.0756P - 0.128865P^2; R^2 = 0.57^{***}$$

D   Biennial harvest frequency

$$HFB = 3909.06 + 34.704N + 13.62P - 0.104664P^2; R^2 = 0.86^{***}$$

E   Annual harvest frequency

$$HI = 48.2601 + 0.214834N - 0.000691648N^2 + 0.06238P - 0.000359358P^2; R^2 = 0.84^{***}$$

F   Biennial harvest frequency

$$HI = 75.3858 + 0.0232496N + 0.105253P - 0.000511761P^2; R^2 = 0.26^{***}$$

Significant models at P<0.001 (***).

Figure 2 - Total forage biomass (TFB, A and B), harvestable forage (HFB, C and D), and harvest index (HI, E and F) in response to combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* cv. Gigante) in Tejuçuoca, CE, Brazil.

was verified for the N/P_2O_5 combination of 127.2/190.0 kg ha^{-1} yr^{-1} (P<0.001). In Quixadá, the maximum HI in the annual harvest (Figure 1E) was 37.06% for the N/P_2O_5 combination of 161.0/164.2 kg ha^{-1} yr^{-1} (P<0.001), while in the biennial harvest (Figure 1F), the maximum HI of 67.50% was observed for the N/P_2O_5 combination of 190.0/10.0 kg ha^{-1} yr^{-1} (P<0.001).

In Tejuçuoca, the maximum TFB in the annual harvest (Figure 2A) was 9783.0 kg ha^{-1} yr^{-1} for the N/P_2O_5 combination of 137.7/190.0 kg ha^{-1} yr^{-1} (P<0.001), and in the biennial harvest (Figure 2B), the maximum TFB of 12,124.0 kg ha^{-1} yr^{-1} was observed for the N/P_2O_5 combination of 190.0/56.8 kg ha^{-1} yr^{-1} (P<0.001). In Tejuçuoca, the maximum HFB in the annual harvest (Figure 2C) was 6,505.7 kg ha^{-1} yr^{-1} for the N/P_2O_5 combination of 133.8/143.9 kg ha^{-1} yr^{-1} (P<0.001), and in the biennial harvest (Figure 2D), the maximum HFB of 10,945.9 kg ha^{-1} yr^{-1} was verified for the N/P_2O_5
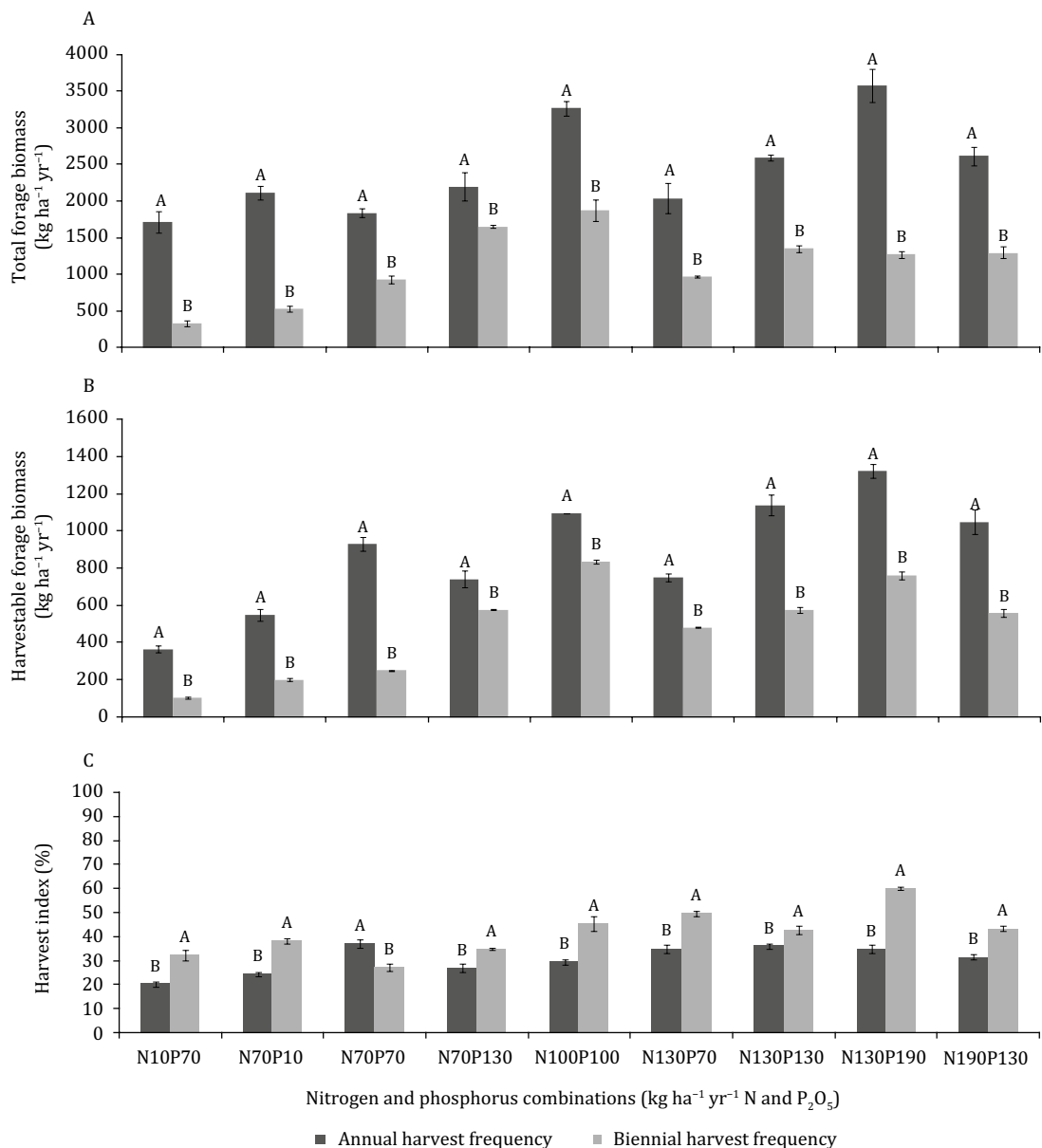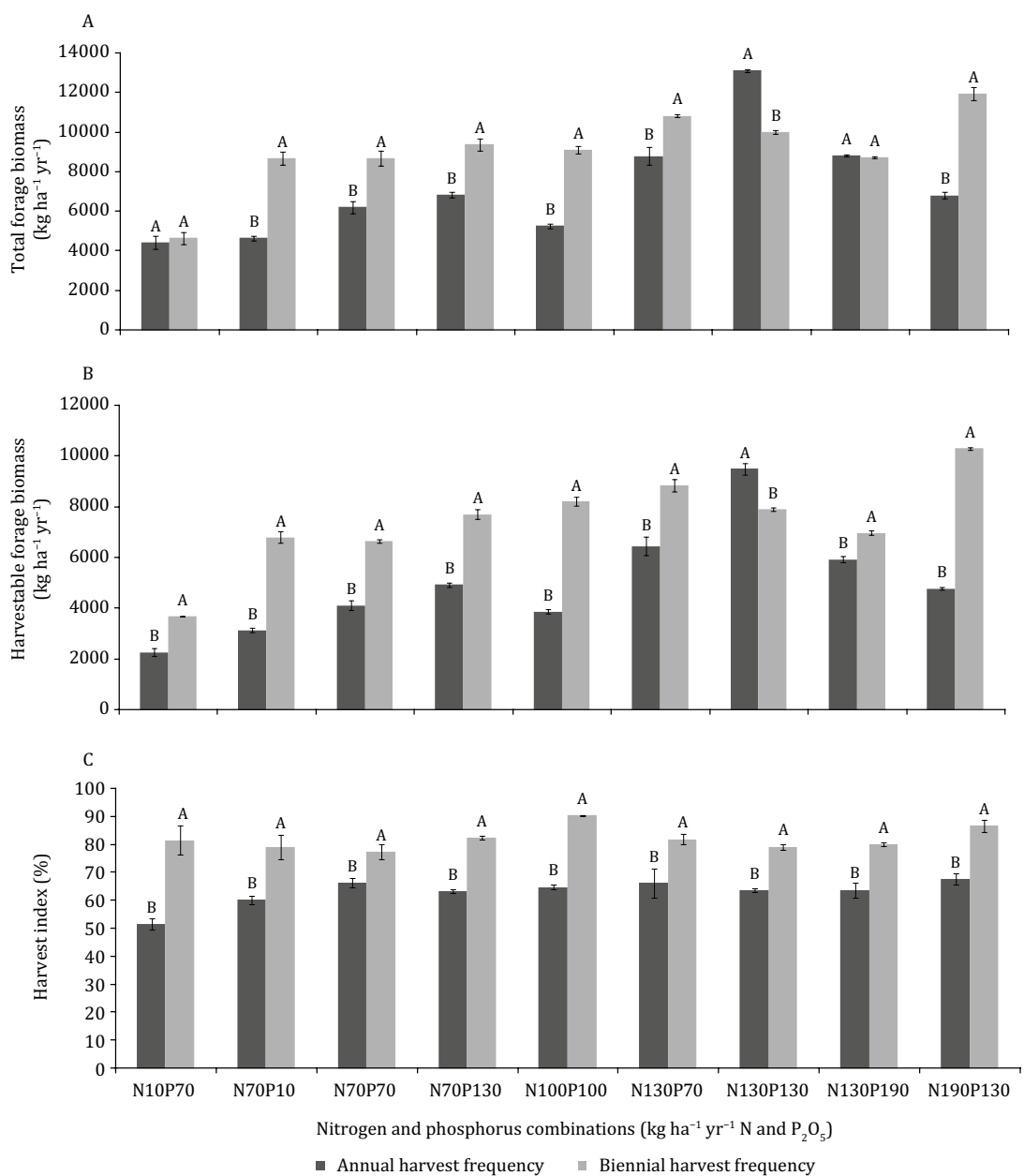

Means followed by different letters, within the combinations of N and P, are significantly different by the Scott-Knott test at 5% of probability (P<0.05).
Each column represents the mean value of the treatment (n = 4), and bars indicate the standard error of the mean.

Figure 3 - Total forage biomass (A), harvestable forage biomass (B), and harvest index (C) in function of the harvest frequency for different combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* cv. Gigante) in the region of Quixadá, CE, Brazil.

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combination of 190.0/65.1 kg ha^{-1} yr^{-1} (P<0.001). In Tejuçuoca, the maximum HI in the annual harvest (Figure 2E) was 67.65% for the N/P$_2$O$_5$ combination of 155.3/86.8 kg ha^{-1} yr^{-1} (P<0.001), while in the biennial harvest (Figure 2F), the maximum HI of 85.22% was observed for the N/P$_2$O$_5$ combination of 190.0/102.8 kg ha^{-1} yr^{-1} (P<0.001).

In Quixadá, the TFB and HFB were greater (P<0.05) in the annual harvest for all combinations of N and P (Figures 3A and B). The HI was higher (P<0.05) in the biennial harvest for 88.9% of the combinations of N and P (Figure 3C). In Tejuçuoca, TFB and HFB were greater (P<0.05) in the biennial harvest for 66.7 and 88.9% of the combinations of N and P under evaluation, respectively

Means followed by different letters, within the combinations of N and P, are significantly different by the Scott-Knott test at 5% of probability (P<0.05).
Each column represents the mean value of the treatment (n = 4), and bars indicate the standard error of the mean.

Figure 4 - Total forage biomass (A), harvestable forage biomass (B), and harvest index (C) in function of the harvest frequency for different combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* cv. Gigante) in the region of Tejuçuoca, CE, Brazil.
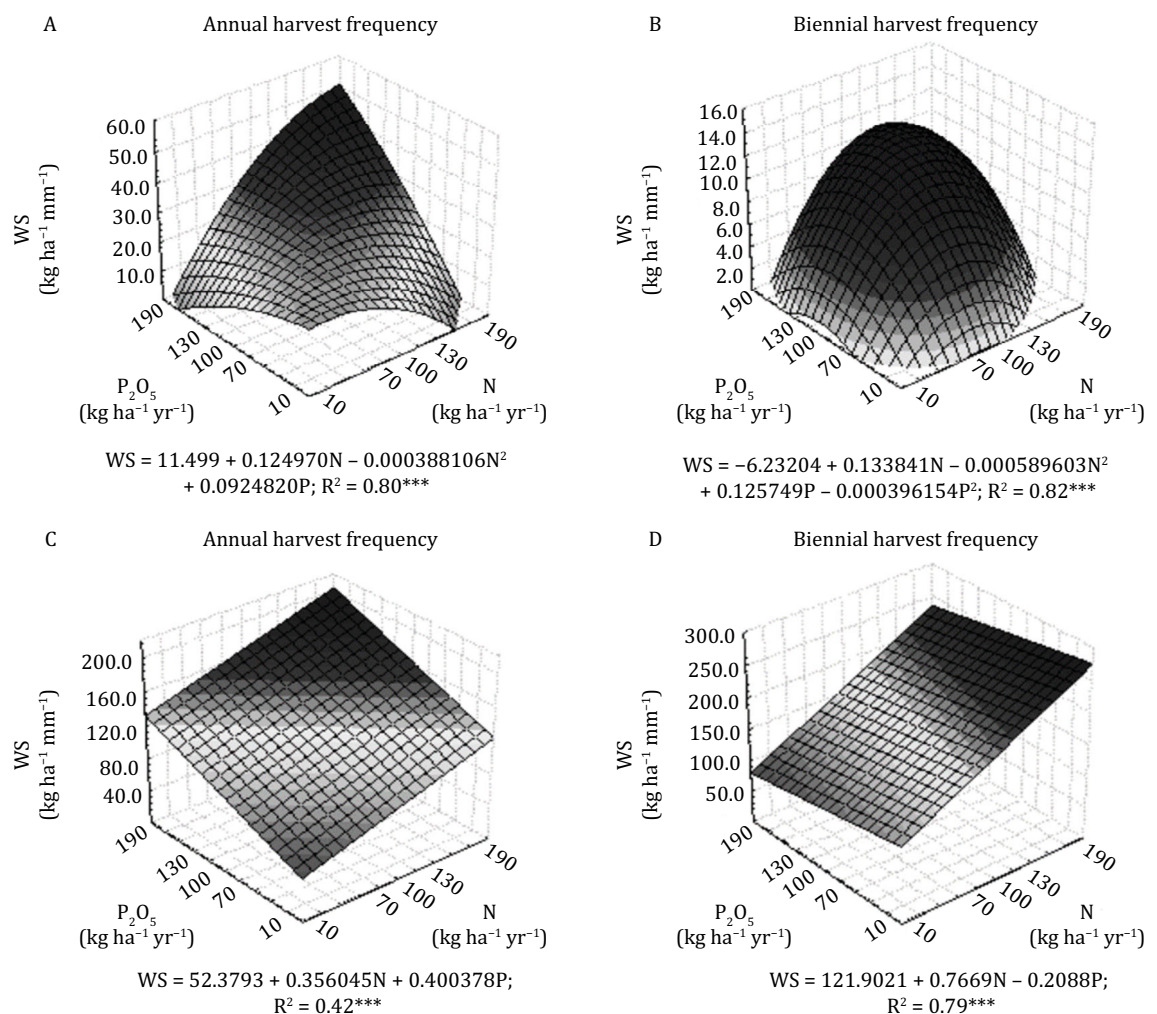
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(Figures 4A and B). The highest HI values were observed in the biennial frequency for all combinations of N and P (Figure 4C).

3.2. Water storage

The WS of cactus pear cv. Gigante in Quixadá and Tejuçuoca had a significant effect of the combinations of N and P, fitting the multiple regression model (P<0.001), with response surface presentation (Figure 5).

In Quixadá, the maximum WS in the annual harvest (Figure 5A) was 39.1 kg ha⁻¹ mm⁻¹ for the N/P$_2$O$_5$ combination of 161.0/190.0 kg ha⁻¹ yr⁻¹ (P<0.001), while in the biennial harvest (Figure 5B), the maximum WS of 11.3 kg ha⁻¹ mm⁻¹ was verified for the N/P$_2$O$_5$ combination of 113.5/158.7 kg ha⁻¹ yr⁻¹ (P<0.001).

In Tejuçuoca, the maximum WS in the annual harvest (Figure 5C) was 196.1 kg ha⁻¹ mm⁻¹ for the N/P$_2$O$_5$ combination of 190.0/190.0 kg ha⁻¹ yr⁻¹ (P<0.001), and in the biennial harvest (Figure 5D), the maximum WS of 265.5 kg ha⁻¹ mm⁻¹ was observed for the N/P$_2$O$_5$ combination of 190.0/10.0 kg ha⁻¹ yr⁻¹ (P<0.001).

A — Annual harvest frequency

$$WS = 11.499 + 0.124970N - 0.000388106N^2 + 0.0924820P; R^2 = 0.80***$$

B — Biennial harvest frequency

$$WS = -6.23204 + 0.133841N - 0.000589603N^2 + 0.125749P - 0.000396154P^2; R^2 = 0.82***$$

C — Annual harvest frequency

$$WS = 52.3793 + 0.356045N + 0.400378P; R^2 = 0.42***$$

D — Biennial harvest frequency

$$WS = 121.9021 + 0.7669N - 0.2088P; R^2 = 0.79***$$

Significant models at P<0.001 (***).

Figure 5 - Water storage (WS) in response to combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* cv. Gigante) in Quixadá (A and B, annual and biennial harvests) and Tejuçuoca (C and D, annual and biennial harvests), CE, Brazil.

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In Quixadá, the highest WS values (P<0.05) were found in the annual harvest frequency for all combinations of N and P (Figure 6A). Whereas is Tejuçuoca, higher values of WS (P<0.05) were found in the biennial harvest for most combinations of N and P (Figure 6B).
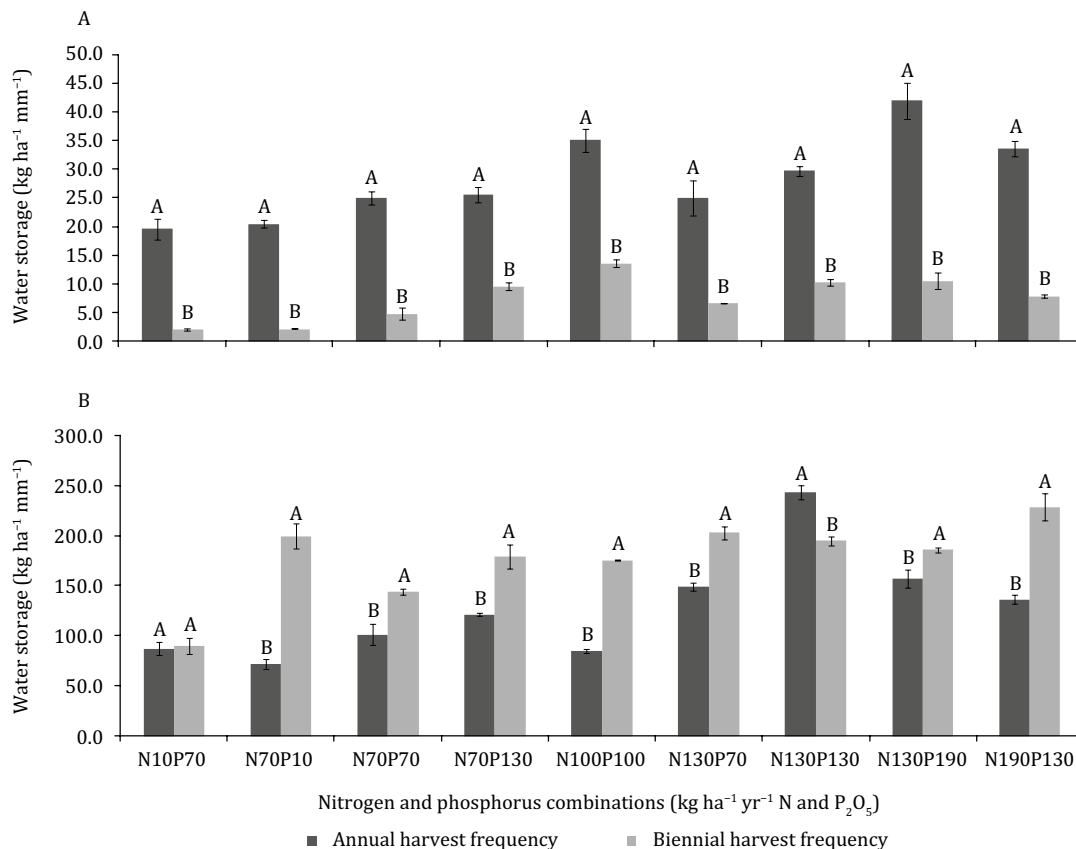
Means followed by different letters, within the combinations of N and P, are significantly different by the Scott-Knott test at 5% of probability (P<0.05).
Each column represents the mean value of the treatment (n = 4), and bars indicate the standard error of the mean.
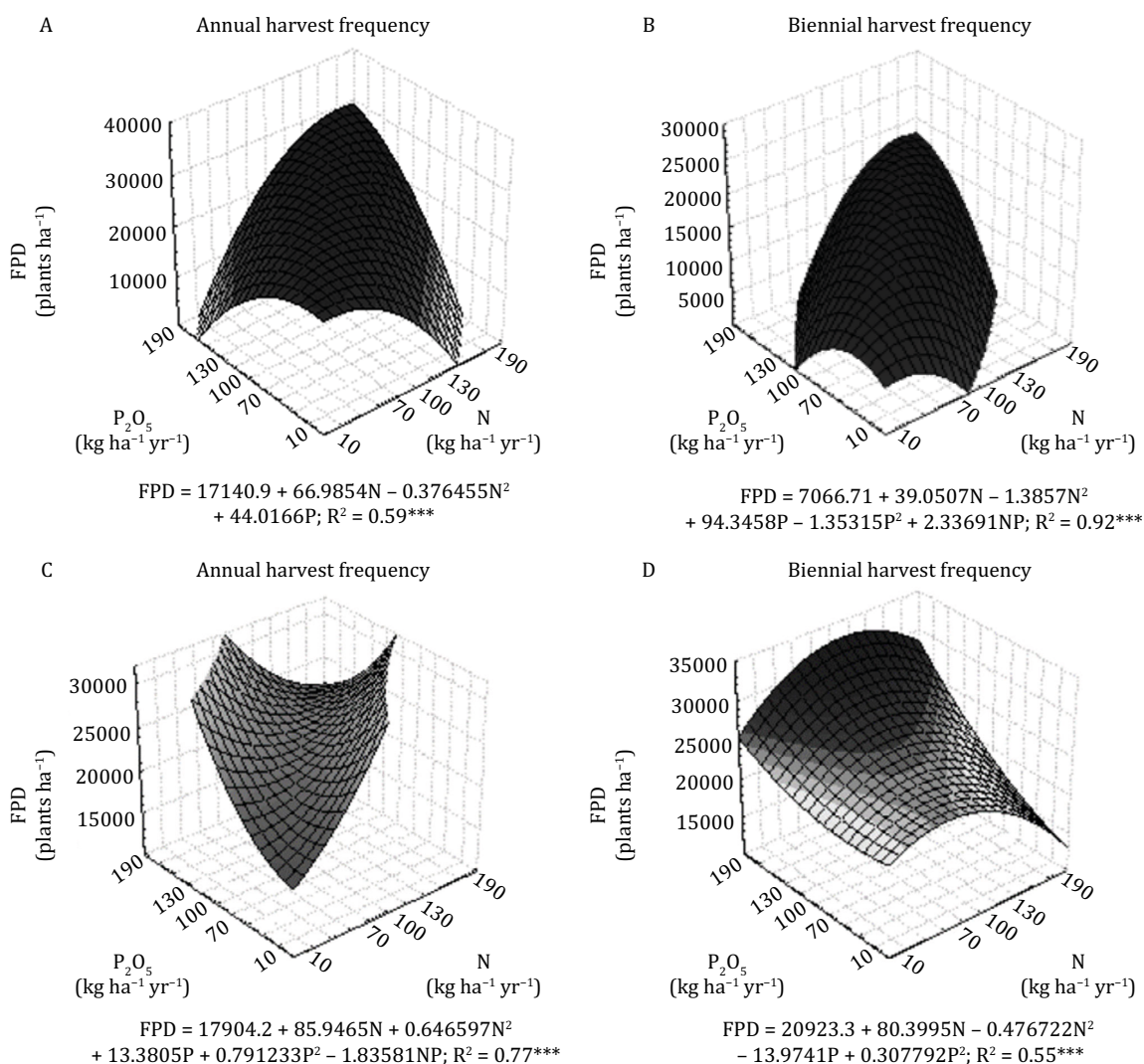
Figure 6 - Water storage (WS) in function of annual and biennial harvest frequencies for differents combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* cv. Gigante) in the regions of Quixadá (A) and Tejuçuoca (B), CE, Brazil.

3.3. Plant density

When evaluating FPD of cactus pear cv. Gigante in Quixadá and Tejuçuoca, we observed effect of the combined levels of N and P, fitting the multiple regression model (P<0.001), with response surface presentation (Figure 7).

In Quixadá, the maximum FPD in the annual harvest (Figure 7A) was 28,484 plants ha^{-1} for the N/P$_2$O$_5$ combination of 89.0/190.0 kg ha^{-1} yr^{-1} (P<0.001), while in the biennial harvest (Figure 7B), the maximum FPD of 18,350 plants ha^{-1} was observed for the N/P$_2$O$_5$ combination of 160.0/173.0 kg ha^{-1} yr^{-1} (P<0.001). In Tejuçuoca, the maximum FPD in the annual harvest (Figure 7C) was 31,946 plants ha^{-1} for the N/P$_2$O$_5$ combination of 190.0/100.0 kg ha^{-1} yr^{-1} (P<0.001), while in the biennial harvest (Figure 7D), the maximum FPD of 32,769 plants ha^{-1} was observed for the N/P$_2$O$_5$ combination of 84.3/190.0 kg ha^{-1} yr^{-1} (P<0.001).

In Quixadá, for 100% of the combinations of N and P under study, the highest FPD values (P<0.05) were found in the annual frequency (Figure 8A). While in Tejuçuoca, the superiority order (P<0.05) of FPD was different in the annual and biennial frequencies and depended on the combination of N and P (Figure 8B).
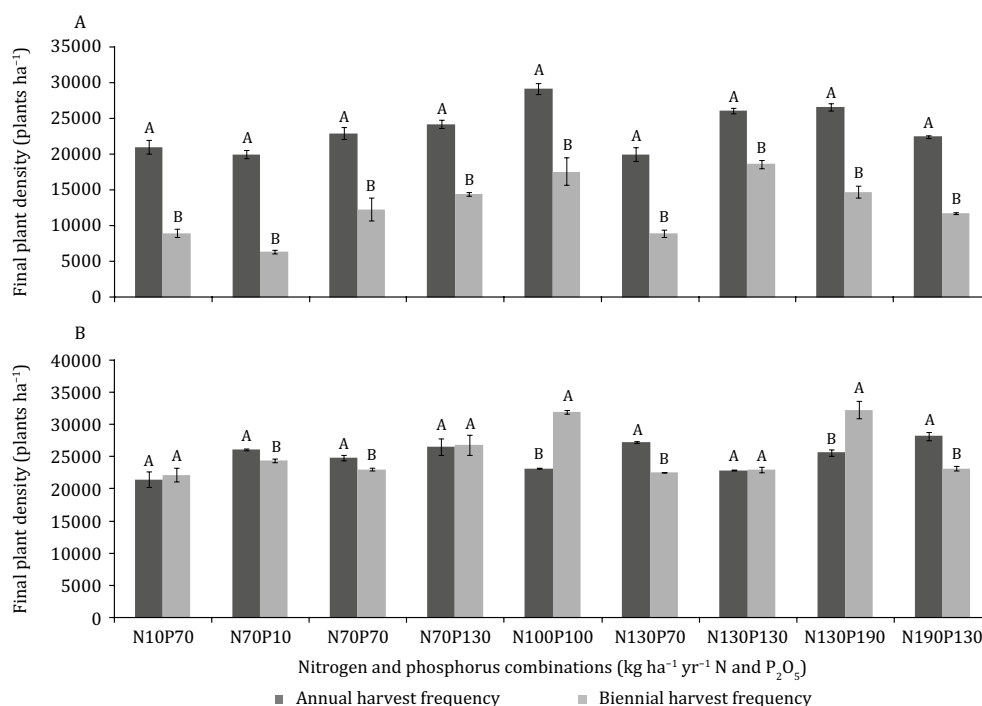
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A   Annual harvest frequency

$$FPD = 17140.9 + 66.9854N - 0.376455N^2 + 44.0166P; R^2 = 0.59***$$

B   Biennial harvest frequency

$$FPD = 7066.71 + 39.0507N - 1.3857N^2 + 94.3458P - 1.35315P^2 + 2.33691NP; R^2 = 0.92***$$

C   Annual harvest frequency

$$FPD = 17904.2 + 85.9465N + 0.646597N^2 + 13.3805P + 0.791233P^2 - 1.83581NP; R^2 = 0.77***$$

D   Biennial harvest frequency

$$FPD = 20923.3 + 80.3995N - 0.476722N^2 - 13.9741P + 0.307792P^2; R^2 = 0.55***$$

Significant models at P<0.001 (***).

Figure 7 - Final plant density (FPD) in response to combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* Gigante) in the regions of Quixadá (A and B) and Tejuçuoca (C and D), CE, Brazil.

4. Discussion

4.1. Forage biomass and harvest index

In cactus pear cv. Gigante (*Opuntia ficus-indica*), the production of forage biomass and WS are optimized by a careful balance of combined levels of N and P. The persistence and perenniality of cactus pear cv. Gigante are severely compromised with the annual harvest frequency under semi-arid conditions and a rainfall regime of consecutive years of low rainfall.

In Quixadá, the higher stress resulting from the annual harvest caused increase in the nutritional demand for phosphorus to optimize the total biomass production (3,522.9 kg ha^{-1} yr^{-1}), with a requirement of 190.0 kg ha^{-1} yr^{-1} P$_2$O$_5$, when compared with the biennial harvest management, which required 136.8 kg ha^{-1} yr^{-1} P$_2$O$_5$ to reach the maximum biological total forage biomass of 1,583.2 kg ha^{-1} yr^{-1}. The higher stress under more frequent harvest was aggravated by the water deficit, since this management compromises the root system more, making the crop more vulnerable to the lower soil moisture, especially in soils of sandy texture, which have low water-retention capacity.

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Means followed by different letters, within the combinations of N and P, are significantly different by the Scott-Knott test at 5% of probability (P<0.05). Each column represents the mean value of the treatment (n = 4), and bars indicate the standard error of the mean.

Figure 8 - Final plant density in function of the harvest frequency for different combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* cv. Gigante) in the regions of Quixadá (A) and Tejuçuoca (B), CE, Brazil.

In Quixadá and Tejuçuoca, the higher values of TFB and HFB, observed as the combined levels of nitrogen and phosphorus increased, can be attributed to the integrated responses of producing different cladode orders from the combined effect of N and P supply on the morphophysiological characteristics of cactus pear. This can be explained by the beneficial action of both nutrients on nutrition and, consequently, on plant growth and development (Marschner, 2012), increasing the productivity of cactus pear (Nobel et al., 1987).

There is the further beneficial effect of fertilization on the ordered production of cladodes, reflecting stimulation of the growing points, increasing production through direct effect together with an increase in cladode area index, which maximizes utilization of the incident photosynthetically active radiation, optimizing the photosynthetic response of the crop. This is corroborated by the positive relationship between cladode area index and biomass production in cactus pear (Garcia de Cortázar and Nobel, 1991).

Furthermore, regarding the increases in production with fertilization, it is worth mentioning the positive effect of the nutrients on root growth in the crop (Zúñiga-Tarango et al., 2009), which favors the greater absorption of nutrients and, consequently, enhances vegetative development. There is also the effect of N on increases in the photosynthetic rate in CAM plants (Nobel and De la Barrera, 2002) through the participation of this nutrient in chlorophyll synthesis, with increase in content per unit of cladode area (Nobel and De la Barrera, 2002), and also for its role in the synthesis of CO_2-fixing enzymes (Taiz and Zeiger, 2013). As for the effect of P, its function should be noted as a regulator of inorganic phosphorus in photosynthesis, metabolism, and assimilate partitioning in the leaves (Marschner, 2012).

The TFB of cactus pear cv. Gigante in the region of Tejuçuoca in comparison with Quixadá showed increases of 177.7 and 628.5% in the annual and biennial harvests, respectively, for the combinations of N and P that maximized production in the two semi-arid regions. The HFB of this crop in Tejuçuoca was increased by 403.0 and 1229.8% in the annual and biennial harvests, respectively, when

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compared with Quixadá, for those combinations of N and P that optimized these responses under the two semi-arid conditions.

The great increases in TFB and HFB in Tejuçuoca are a result of the better availability of part of the growth factors. In cactus pear, the better response in growth and development through optimization of the photosynthetic process and, consequently, greater biomass, is a function of the adequate balance of factors such as photosynthetically active radiation (photosynthetic photon flux density), mean night-time temperature (temperature index), water availability (water index), and nutritional supply (nutrient indices) (Nobel and Hartsock, 1986; Nobel, 1989; Nobel and Israel, 1994; Israel and Nobel, 1995). It can, therefore, be inferred that the differences in production, with superiority in Tejuçuoca, can be explained by the better balance of soil and climate factors, especially more favorable water availability together with the better conditions of natural soil fertility at that site. It should be noted that even under similar levels of accumulated rainfall, the soil of Tejuçuoca, characterized by a higher organic matter content, higher total porosity, lower density, and higher water retention capacity, resulted in superior growth of cactus pear. It is also worth noting that rainfall frequency is an important factor in water index dynamics throughout the crop growth cycle.

The response pattern observed for HI is a result of the effects of N and P on the balance between TFB and HFB. Thus, as fertilization favored greater biomass for the cladode orders above the remaining order, resulting in an increase in HFB in relation to TFB, it promoted increase in the HI of cactus pear.

In Quixadá, the higher values of TFB and HFB in annual harvest frequency is the result of the biomass response of the different cladode orders in the annual harvest. The highest HI in biennial frequency can be explained by the greater participation of HFB in TFB in biennial harvest in comparison with annual harvest. Under the crop growing conditions of Tejuçuoca, the better structure of the forage, with a more developed and consolidated root system, besides the larger reserves accumulated during the longer growth period, acted towards better crop development, showing persistence and minimizing the negative effect of water stress. As such, a combination of the positive effects of the factors above determined the higher values of TFB and HFB in biennial harvest. In Tejuçuoca, the higher HI in biennial harvest frequency for all combinations of N and P is the result of the greater contribution of the HFB component in TFB, a fact that reflected in a higher HI under biennial harvest management in comparison with annual harvest frequency.

4.2. Water storage

In both studied regions, the response of cactus pear cv. Gigante in regards to WS confirmed the importance of the fertilizer when cultivating the crop under semi-arid conditions, in such a way that the greater nutrient availability of the soil increased water accumulation in the cladodes. This is an important characteristic when cultivating the forage, since it affords greater persistence and perenniality under conditions of prolonged water deficit, besides favoring physiological processes under such conditions.

The greater increase in WS promoted by fertilization is directly related to the production of fresh biomass, and in cactus pear, it can be explained by the greater growth of the root system (Zúñiga-Tarango et al., 2009) together with the increase in plant density and total number of cladodes found in the fertilized plants. Despite the low dry matter content of cactus pear, its significant water content is an important factor during periods of drought in semi-arid regions, when the crop also functions as a reserve of this "nutrient" for ruminants (Cavalcante et al., 2014).

It should be mentioned, regarding WS in Quixadá, that the highest mean plant densities that contributed to the greater production of fresh and dry biomass recorded in annual harvest under the growing conditions in Quixadá support the higher WS rates found under such conditions. In Tejuçuoca, the highest WS value in biennial harvest frequency is based on the highest values found for this index corresponding to the pattern of responses shown by the biomass under the biennial harvest

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management. It is also worth pointing out the better plant structure, with a more consolidated root system, that more efficiently exploits environmental resources, such as water and nutrients.

The improvement in WS in fertilized cactus pear under semi-arid conditions is a relevant response because it reflects the ability of the crop to tolerate low rainfall and its irregular distribution. In view of the great importance of the water factor in animal production systems of semi-arid regions, its high accumulation in the cladode tissue of the cactus pear represents a valuable contribution to the conservation of this nutrient in these regions.

4.3. Plant density

In Quixadá and Tejuçuoca, the response of cactus pear in terms of FPD to the combined use of N and P is a result of the indirect action of the fertilizers. As the crop does not form new plants from the main (basal) cladode, nutrient action was related to the effect on crop development and resulted in better plant structure, providing a more consolidated root system, with greater accumulation of reserves (Zúñiga-Tarango et al., 2009) that act as a supply under stress conditions, thereby conferring a reduction in plant mortality throughout the growth cycle, a fact that contributed to a greater FPD by the end of the growth period.

For both regions (Quixadá and Tejuçuoca), it is worth stressing an important point regarding the FPD; in the annual harvest frequency, the mean value of density in the two cycles (Figures 8A and B) masked the low persistence of the crop under that management, revealed by the high loss in the stand by the end of the second cycle (Figures 9A and B). In both regions, the greater FPD during the first cycle (Figures 9A and B) can be attributed to better rainfall and soil moisture, which increased the mean
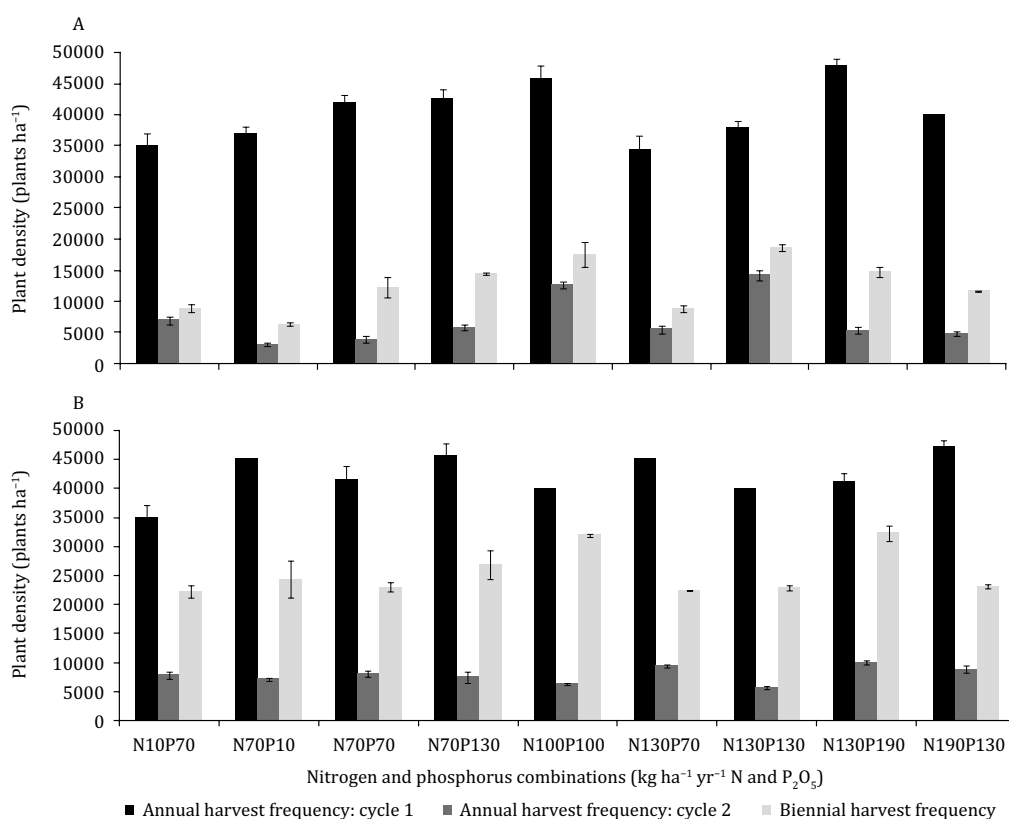
Each column represents the mean value of the treatment (n = 4), and bars indicate the standard error of the mean.

Figure 9 - Plant density of different cycles at annual and biennial harvest frequencies for different combinations of nitrogen and phosphorus in cactus pear (*Opuntia ficus-indica* cv. Gigante) in the regions of Quixadá (A) and Tejuçuoca (B), CE, Brazil.

value (Figures 8A and B) during each cycle and did not clearly express the real plant population at the end of the evaluation period.

As such, the greater mean plant density during the cycles, which was superior under all fertilizer managements in Quixadá (Figure 8A) and almost half of the N and P combinations in Tejuçuoca (Figure 8B), should not be used as a reference in defining the type of crop management that would guarantee persistence and perenniality to cactus pear. The actual survival situation of the crop can only be visualized from data of plant density that represent each growth cycle (Figures 9A and B).

Therefore, the dynamics of plant density during each growth cycle, which defines the final stand conditions of the cactus pear, can be better studied by monitoring the number of plants for each harvest frequency throughout crop development (Figures 9A and B). In Quixadá, the mean FPD in the annual harvest frequency (cycles 1 and 2) represented 47.1% of the initial plant density (when planting), while FPD by the end of the second cycle (actual conditions of cactus pear orchard) represented 13.9% of the density at the beginning of the study (50,000 plants ha^{-1}). In the biennial harvest frequency, the FPD represented 25.2% relative to the density when planting. In Tejuçuoca, the mean FPD in the annual harvest (cycles 1 and 2) represented 50.2% of the plant density at the beginning of cultivation, while the FPD at the end of the second cycle, which represents the actual situation of the stand, showed 15.8% of the plant density at the beginning of the study. In the biennial harvest frequency, the FPD represented 50.9% of the total of 50,000 plants ha^{-1} when the crop was first planted.

Regarding plant density, it can be inferred that the most frequent harvest (annual), added to the water stress caused by the years followed by drought (which also aggravated the loss of the stand under the biennial frequency) and a crop with low reserves (annual frequency), correspond to the factors that determined the loss in the stand, which resulted in a low FPD, especially in the annual harvest at the end of the second cycle. In general, plant mortality was high under both harvest managements in both crop-growing regions, but in the annual harvest, the persistence and perenniality of cactus pear were seriously compromised, a situation that led to degradation of the crop by the end of the second cycle. This fact is relevant to the rainfed management of cactus pear in the semi-arid region, since, despite being a crop adapted to severe drought, the succeeding years of low rainfall plus the stress of frequent harvesting, with the plant having low reserves in addition to their high mobilization for the production of new cladodes after harvest, can lead to high mortality in the long term, making it unviable for commercial exploitation.

5. Conclusions

The combination of nitrogen and phosphorus that provides the maximum biological efficiency of forage biomass production and water storage in cactus pear cv. Gigante varies according to the crop management and growing region. In Quixadá, the most recommended management for growing cactus pear cv. Gigante in the medium/long term is under biennial harvest, adopting fertilization of 114.6 kg ha^{-1} yr^{-1} N combined with a level of 136.8 kg ha^{-1} yr^{-1} P$_2$O$_5$. Under the growing conditions of Tejuçuoca, the level of 190.0 kg ha^{-1} yr^{-1} N combined with 56.8 kg ha^{-1} yr^{-1} P$_2$O$_5$ in the biennial harvest frequency is recommended for the maximum biological response in terms of total forage biomass.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

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Silva. Project administration: M.N. Lopes and M.J.D. Cândido. Supervision: M.J.D. Cândido. Visualization: M.N. Lopes, M.J.D. Cândido, T.D. Maranhão, I. Soares, R.C.F.F. Pompeu and R.G. Silva. Writing-original draft: M.N. Lopes, M.J.D. Cândido, I. Soares, R.C.F.F. Pompeu and R.G. Silva. Writing-review & editing: M.N. Lopes, M.J.D. Cândido, I. Soares, R.C.F.F. Pompeu and R.G. Silva.

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References

Alves, R. N.; Farias, I.; Menezes, R. S. C.; Lira, M. A. and Santos, D. C. 2007. Produção de forragem pela palma após 19 anos sob diferentes intensidades de corte e espaçamentos. Revista Caatinga 20:38-44.

Cavalcante, L. A. D.; Santos, G. R. A.; Silva, L. M.; Fagundes, J. L. and Silva, M. A. 2014. Respostas de genótipos de palma forrageira a diferentes densidades de cultivo. Pesquisa Agropecuária Tropical 44:424-433. https://doi.org/10.1590/S1983-40632014000400010

Cortázar, G. V. and Nobel, P. S. 1992. Biomass and fruit production for the prickly pear cactus, *Opuntia ficus-indica*. Journal of the American Society for Horticultural Science 117:558-562. https://doi.org/10.21273/JASHS.117.4.558

Cunha, D. N. F. V.; Gomes, E. S.; Martuscello, J. A.; Amorim, P. L.; Silva, R. C. and Ferreira, P. S. 2012. Morfometria e acúmulo de biomassa em palma forrageira sob doses de nitrogênio. Revista Brasileira de Saúde e Produção Animal 13:1156-1165. https://doi.org/10.1590/S1519-99402012000400005

Dubeux Jr., J. C. B.; Santos, M. V. F.; Lira, M. A.; Santos, D. C.; Farias, I.; Lima, L. E. and Ferreira, R. L. C. 2006. Productivity of *Opuntia fícus-indica* (L.) Miller under different N and P fertilization and plant population in north-east Brazil. Journal of Arid Enviroments 67:357-372. https://doi.org/10.1016/j.jaridenv.2006.02.015

Fischer, R. A. and Turner, N. C. 1978. Plant productivity in the arid and semiarid zones. Annual Review of Plant Physiology 29:277-317. https://doi.org/10.1146/annurev.pp.29.060178.001425

FUNCEME - Fundação Cearense Meteorologia e Recursos Hídricos. 2011, 2012. Variáveis meteorológicas (PCDs). Available at: <http://www.funceme.br/>. Accessed on: Jan. 20, 2016.

Garcia de Cortázar, V. and Nobel, P. S. 1991. Prediction and measurement of high annual productivity for *Opuntia ficus-indica*. Agricultural and Forest Meteorology 56:261-272. https://doi.org/10.1016/0168-1923(91)90095-8

Gibson, A. C. and Nobel, P. S. 1986. The cactus primer. Harvard University Press, Cambridge, MA.

Griffith, M. P. 2004. The origins of an important cactus crop, *Opuntia ficus-indica* (Cactaceae): new molecular evidence. American Journal of Botany 91:1915-1921. https://doi.org/10.3732/ajb.91.11.1915

Israel, A. A. and Nobel, P. S. 1995. Growth temperature versus CO_2 uptake, Rubisco and PEPCase activities, and enzyme high-temperature sensitivities for a CAM plant. Plant Physiology and Biochemistry 33:345-351.

Kluge, M. and Ting, I. P. 1978. Crassulacean acid metabolism: analysis of an ecological adaptation. Ecological studies series. Springer-Verlag, Berlin, Germany.

Koppen, W. 1948. Climatologia: con un estudio de los climas de la tierra. Fondo de Cultura Econômica, Mexico. 478p.

Marschner, P. (ed.) 2012. Marschner's mineral nutrition of higher plants. 3rd ed. Academic Press, London. 651p.

Nobel, P. S. 1988. Environmental biology of agaves and cacti. Cambridge University Press, New York.

Nobel, P. S. 1989. A nutrient index quantifying productivity of agaves and cacti. Journal of Applied Ecology 26:635-645. https://doi.org/10.2307/2404088

Nobel, P. S. and De la Barrera, E. 2002. Nitrogen relations for net CO_2 uptake by the cultivated hemiepiphytic cactus, *Hylocereus undatus*. Scientia Horticulturae 96:281-292. https://doi.org/10.1016/S0304-4238(02)00060-2

Nobel, P. S. and Hartsock, T. L. 1986. Environmental influences on the productivity of three desert succulents in the south-western United States. Plant, Cell and Environment 9:741-749. https://doi.org/10.1111/j.1365-3040.1986.tb02107.x

Nobel, P. S. and Israel, A. A. 1994. Cladode development, environmental responses of CO_2 uptake, and productivity for *Opuntia ficus-indica* under elevated CO_2. Journal of Experimental Botany 45:295-303. https://doi.org/10.1093/jxb/45.3.295

Nobel, P. S.; García-Moya, E. and Quero, E. 1992. High annual productivities of certain agaves and cacti under cultivation. Plant, Cell & Environment 15:329-335. https://doi.org/10.1111/j.1365-3040.1992.tb00981.x

Nobel, P. S.; Russell, C. E.; Felker, P.; Medina, J. G. and Acuñã, E. 1987. Nutrient relations and productivity of prickly pear cacti. Agronomy Journal 79:550-555. https://doi.org/10.2134/agronj1987.00021962007900030030x

Oliveira, F. T.; Souto, J. S.; Silva, R. P.; Andrade Filho, F. C. and Pereira Júnior, E. B. 2010. Palma forrageira: adaptação e importância para os ecossistemas áridos e semiáridos. Revista Verde 5:27-37.

Ranson, S. L. and Thomas, M. 1960. Crassulacean acid metabolism. Annual Review of Plant Physiology 11:81-110. https://doi.org/10.1146/annurev.pp.11.060160.000501

Russell, C. and Felker, P. 1987. The prickly-pears (*Opuntia* spp., Cactaceae): A source of human and animal food in semiarid regions. Economic Botany 41:433-445. https://doi.org/10.1007/BF02859062

Silva, L. M.; Fagundes, J. L.; Viegas, P. A. A.; Muniz, E. N.; Rangel, J. H. A.; Moreira, A. L. and Backes, A. A. 2014. Produtividade da palma forrageira cultivada em diferentes densidades de plantio. Ciência Rural 44:2064-2071. https://doi.org/10.1590/0103-8478cr20131305

Taiz, L. and Zeiger, E. 2013. Fisiologia vegetal. 5.ed. Editora Artmed, Porto Alegre. 918p.

Turrent Fernández, A. and Laird, R. J. 1975. La matriz experimental Plan Puebla, para ensayos sobre prácticas de producción de cultivos. Agrociencia 19:117-143.

Zúñiga-Tarango, R.; Orona-Castillo, I.; Vázquez-Vázquez, C.; Murillo-Amador, B.; Salazar-Sosa, E.; López-Martínez, J. D.; García-Hernández, J. L. and Rueda-Puente, E. 2009. Desarrollo radical, rendimiento y concentración mineral en nopal *Opuntia ficus-indica* (L.) Mill. en diferentes tratamientos de fertilización. Journal of the Professional Association for Cactus Development 11:53-68.