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Forage crops

Accumulation and export of nutrients in cactus pear cladodes (*Opuntia ficus-indica*) under different managements in the Brazilian Semiarid

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ABSTRACT - The present study evaluated the accumulation and export of nutrients in cactus pear (*Opuntia ficus-indica*) cv. Gigante, fertilized with combinations of nitrogen (10, 70, 100, 130, and 190 kg ha^{-1} year^{-1} N) and phosphorus (10, 70, 100, 130, and 190 kg ha^{-1} year^{-1} P_2O_5) under annual and biennial harvests, in Quixadá and Tejuçuoca, using a split-plot randomized block design with four replications. In Quixadá, under annual and biennial harvests, the following orders of accumulation of macronutrients (in kg ha^{-1} year^{-1}) were found, respectively: K (98.8) > Ca (87.2) > N (46.7) > Mg (26.8) > S (18.4) > P (2.04) and Ca (33.5) > K (31.1) > S (18.6) > N (12.9) > Mg (10.5) > P (0.81). In Tejuçuoca, under annual and biennial harvests, the orders of accumulation of macronutrients were, respectively: K (146.5) > Ca (204.6) > N (128.1) > Mg (75.8) > S (50.3) > P (3.7) and K (397.2) > N (191.3) > S (241.2) > Ca (167.8) > Mg (131.0) > P (14.1). The maintenance/production fertilization in cactus pear should be planned according to productive potential, fertilization and harvest managements, and cultivation region, based on nutritional requirement and considering the nutrient recovery efficiency.

Key Words: fertilization, harvest frequency, nutritional demand

Introduction

The knowledge of nutritional requirement of cactus pear from the quantification of nutrient extraction is essential, since its output from the soil system during successive production cycles may reflect in a decrease of crop productivity in the absence of a balanced replenishment of nutrients exported with the harvest (Nobel et al., 1987; Alves et al., 2007; Dubeux Jr. et al., 2010). Evaluating the accumulation and export of nutrients in cactus pear represents a relevant starting point in the definition of levels of fertilizers to be used, constituting a necessary step in the maintenance of adequate nutrition of the crop (Dubeux Jr. et al., 2010; Silva et al., 2012), with monitoring of the balance between the input and output of nutrients in the system, aiming at improvements in soil fertility over the years of cultivation (Nobel et al., 1987).

The high potential for nutrient extraction in cactus pear is evident in studies about the topic, which have shown quantitative changes in response to the different fertilization managements (Dubeux Jr. et al., 2010; Silva et al., 2012), frequency and intensity of harvests (Alves et al., 2007), plant spacing and density (Silva et al., 2012; Cavalcante et al., 2014), cultivated species/cultivar (Cavalcante et al., 2014), and soil and climatic conditions for cultivation (Nobel et al., 1987).

When evaluating the cactus pear clone IPA-20 subjected to four levels of phosphorus (0, 200, 400, and 800 kg ha^{-1} P_2O_5) and four levels of potassium (0, 200, 400, and 800 kg ha^{-1} K_2O), Dubeux Jr. et al. (2010) observed a variation in the accumulation of macro- and micronutrients caused by fertilization. In research with cactus pear cv. Gigante managed under three spacings and different fertilizations (P, NP, and NPK), Silva et al. (2012) observed that, 620 days

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after sowing, the most extracted macronutrient was calcium, with 458.3 kg ha^{-1}, followed by potassium (425.8 kg ha^{-1}), nitrogen (299.3 kg ha^{-1}), magnesium (213.8 kg ha^{-1}), sulfur (63.3 kg ha^{-1}), and phosphorus (20.3 kg ha^{-1}).

In this context, the nutrient accumulation in cactus pear, which reflects the nutritional requirement of this crop, varies according to factors such as species/cultivar, level of biomass production, soil fertility, fertilization management, climate, harvest frequency, and cultural practices. However, the magnitude of the responses is diverse, which justify the demand for research aimed at quantifying the nutritional needs of cactus pear in terms of nutrients accumulated and exported in the harvest.

Therefore, this research was developed from the hypothesis that there is a balanced combination of nitrogen-phosphorus-harvest frequency (N-P-HF) that promotes the maximization of the accumulation and export of macronutrients in cactus pear cv. Gigante under different environmental conditions. In view of the above, this study was conducted to evaluate the nutrient accumulation and export in cactus pear cv. Gigante, fertilized with different combinations of N and P under two harvest frequencies, in the semi-arid regions of Quixadá and Tejuçuoca, state of Ceará, Brazil.

Material and Methods

The experiment was conducted in Quixadá and Tejuçuoca, Ceará, Brazil. The experimental area in Quixadá is located at 190 m altitude, at the geographical coordinates: 4°59' S latitude and 39°01' W longitude, with a BSw’h’ hot semi-arid climate, according to Köppen classification (1948). Tejuçuoca is located at an average altitude of 140 m, at the following geographical coordinates: 3°59'11"S latitude and 39°34'18" W longitude, with Aw climate, tropical with dry season, according to Köppen classification (1948).

The average temperature and relative air humidity of the experimental period and the cumulative annual rainfall were recorded in both regions: in Quixadá, values of 27.0 °C and 58.8% were recorded for temperature and relative air humidity, respectively, in the experimental period; rainfall values of 1,042 and 602 mm were verified in 2011 and 2012, respectively. In Tejuçuoca, the values were 26.4 °C and 65.5% for temperature and relative air humidity, respectively; rainfall values were 1,038 and 561 mm in 2011 and 2012, respectively. Data were obtained at the Agroclimatological Station of the Universidade Federal do Ceará (Quixadá) and at the Agroclimatological Station of FUNCEME (Tejuçuoca). In both regions, the study started in 2011 and was similar regarding treatments.

The physical and chemical characterization of soils, in both regions, was performed at the layer 0.0-20.0 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^{2+}; 3.4 cmol$_c$ dm^{-3} Mg^{2+}; 0.0 cmol$_c$ dm^{-3} Al^{3+}; 5.3 g kg^{-1} organic matter; sum of bases: 7.6 cmol$_c$ dm^{-3}; CTCt: 7.6 cmol$_c$ dm^{-3}; pH of 6.1 in water; coarse sand: 513 g kg^{-1}; fine sand: 363 g kg^{-1}; silt: 89 g kg^{-1}, and clay: 35 g kg^{-1}. 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^{2+}; 3.2 cmol$_c$ dm^{-3} Mg^{2+}; 0.0 cmol$_c$ dm^{-3} Al^{3+}; 8.2 g kg^{-1} organic matter; sum of bases: 7.9 cmol$_c$ dm^{-3}; CTCt: 7.9 cmol$_c$ dm^{-3}; pH of 6.2 in water; coarse sand: 164 g kg^{-1}; fine sand: 590 g kg^{-1}; silt: 153 g kg^{-1}, and clay: 93 g kg^{-1}.

Soil was prepared for cactus pear (*Opuntia ficus-indica* cv. Gigante) planting following these steps: removal of stumps (whenever necessary), removal of vegetation from the area, and harrowing. Subsequently, the plots were marked for delimitation of the respective area. Each plot occupied an area of 24.0 m^2 (4.0 × 6.0 m), which was composed of 120 plants, distributed in three rows of 4.0 m in length – the central row was used for measurements and the others as borders.

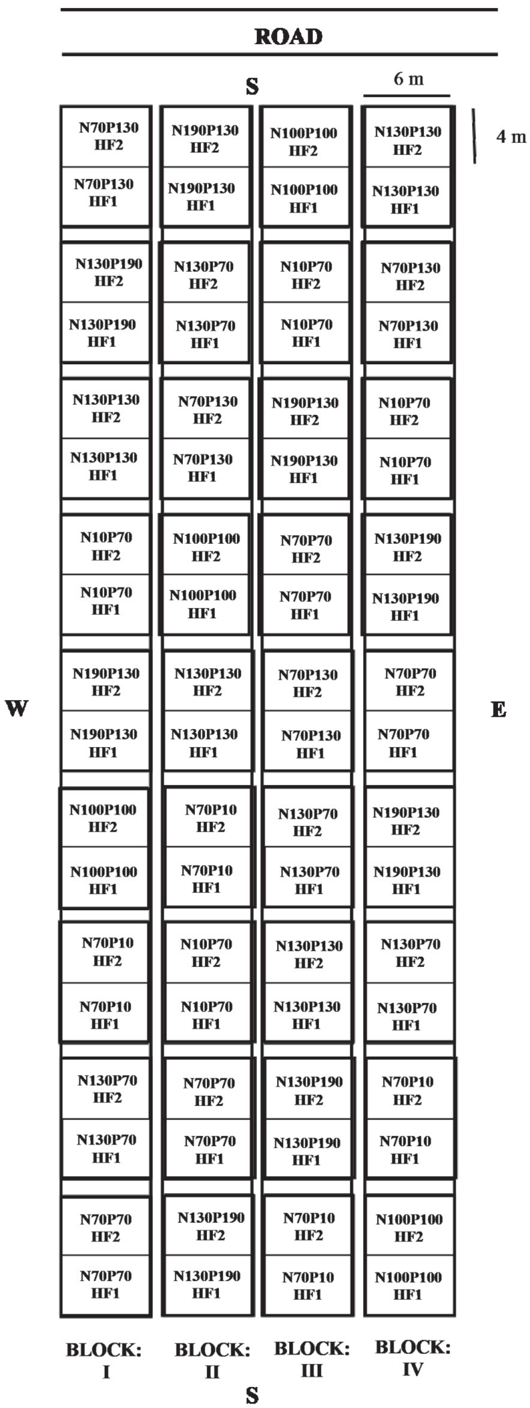
After harvesting, the cladodes were allowed to rest in the shade for 15 days (Lopes et al., 2009) to heal injuries caused during harvesting and transportation.

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, at 2.0 × 0.10 m spacing, recommended to meet the density of 50,000 plants ha^{-1}.

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

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 combinations of N and P_2O_5 levels assigned to the plots and the harvest frequencies, to the subplots (Figures 1 and 2).

Fertilization was performed during the rainy season. The annual level of P, as single superphosphate, was made available at once, upon planting for the first year and when the rainy season began, for the other years of cultivation. At this time, the micronutrients were applied at 50 kg ha^{-1} FTE BR-12. Calcium and S balancing was performed for all treatments using agricultural gypsum and calcitic limestone based on the highest level of single superphosphate.

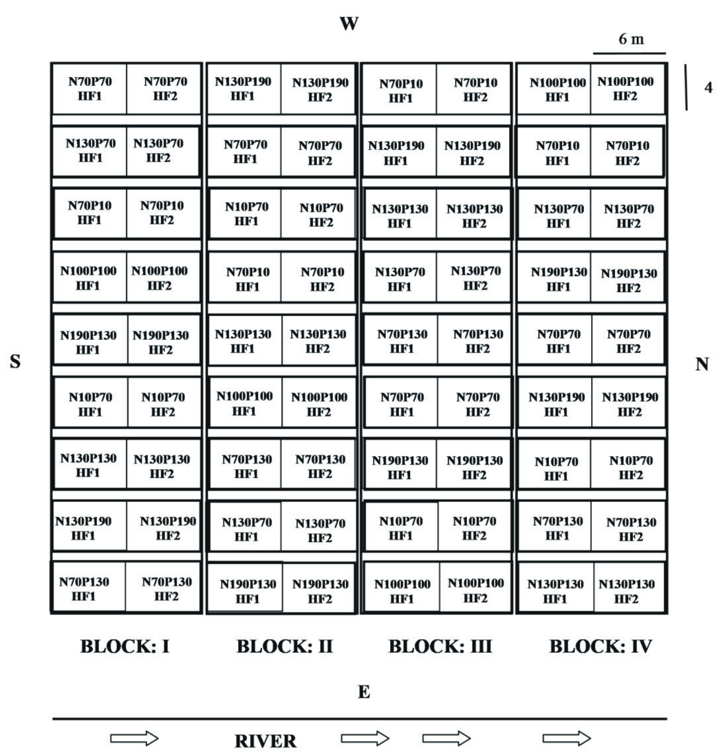


N - Nitrogen; P - phosphorus; HF - harvest frequency

Figure 1 - Experiment layout on semiarid conditions of Quixadá.

Table 1 - Treatments studied under the semiarid conditions of Quixadá and Tejuçuoca

N and P_2O_5 (kg ha^{-1} year^{-1})	Harvest frequency
10 and 70	Annual
10 and 70	Biennial
70 and 10	Annual
70 and 10	Biennial
70 and 70	Annual
70 and 70	Biennial
70 and 130	Annual
70 and 130	Biennial
100 and 100	Annual
100 and 100	Biennial
130 and 70	Annual
130 and 70	Biennial
130 and 130	Annual
130 and 130	Biennial
130 and 190	Annual
130 and 190	Biennial
190 and 130	Annual
190 and 130	Biennial



N - Nitrogen; P - phosphorus; HF - harvest frequency.

Figure 2 - Experiment layout on semiarid conditions of Tejuçuoca.

The annual level of N, as urea, was made available in three plots, with a 20-day interval between applications. In all applications, urea was diluted in water, by applying 1 L solution to each 4-m length of the cactus pear row, totaling the volume of 3 L per plot. Dilution was carried out to obtain a better uniformity of application, due to the small amount of fertilizer per plot in some levels, making it difficult to apply in solid form. Weed control was made with cleaning and herbicide application in directed jet. The control of cochineal (*Diaspis echinocacti*) was carried out using mineral oil.

Samples were subjected to chemical analysis to determine the content of N, P, K, Ca, Mg, and S, according to Silva (2009). The accumulated (total biomass) and exported (harvested biomass) macronutrients (N, P, K, Ca, Mg, and S) in the cactus pear biomass were determined by multiplying the respective nutrient contents in the cladode tissues by the production of the crop expressed in kg ha^{-1} year^{-1}.

In the determination of total forage biomass (TFB, kg ha^{-1} year^{-1}), the sum of biomass production of all cladode orders was considered. In the determination of harvested forage biomass (HFB, kg ha^{-1} year^{-1}), the production above cut height was considered, which represents harvested biomass with preservation of primary cladodes.

The statistical model used in the experiment was the following:

$$y_{ijk} = \mu + \beta_k + \alpha_i + (\alpha\beta)_{ik} + \tau_j + (\alpha\tau)_{ij} + \varepsilon_{ijk},$$

in which y_{ijk} = value observed in experimental plot that received level *i* of factor α (fertilization) and level *j* of factor τ (harvest frequency) in block *k*; μ = general constant; β_k = block effect *k* (*k* = 1, 2, 3, and 4); α_i = effect of level *i* of factor α (*i* = 1, 2, 3, 4, 5, 6, 7, 8, and 9); $(\alpha\beta)_{ik}$ = effect of the interaction between level *i* of factor α and block *k* (error a); τ_j = effect of level *j* of factor τ (*j* = 1 and 2); $(\alpha\tau)_{ij}$ = effect of the interaction between level *i* of factor α and level *j* of factor τ; and ε_{ijk} = experimental error (error b).

Data were tested by analysis of variance, comparison of means, and multiple regression models. Qualitative factors were compared by the Scott-Knott comparison test at 5% probability level. Quantitative factors were studied in multiple regression models (up to the 10% probability level). The software System for Statistical and Genetic Analysis (SAEG 9.1, 2007) was used as a tool to aid analysis.

Results

The combinations of N and P × harvest frequencies had an effect on the accumulation and export of macronutrients in Quixadá and Tejuçuoca. When evaluated, the accumulation and export of N, P, K, Ca, Mg, and S in cactus pear under annual and biennial harvest frequencies in Quixadá and Tejuçuoca showed an effect of N and P combinations (Tables 2, 3, and 4), fitting to a multiple regression model.

In Quixadá, for all combinations of N and P, there was a higher accumulation and export of N under the annual harvest (Table 5). In Tejuçuoca, there was a higher accumulation and export of N under the biennial harvest in most combinations of N and P (Table 6).

In Quixadá, accumulation and export of P under the annual harvest were higher than those of the biennial harvest for all combinations of N and P (Table 5). In Tejuçuoca, P accumulation was higher under the biennial harvest for five combinations of N and P and the export, for six combinations, in relation to the annual harvest (Table 6).

In Quixadá, there was a higher accumulation and export of K under the annual harvest for all combinations of N and P levels (Table 5). In Tejuçuoca, there was a greater K accumulation under the biennial crop in six combinations of N and P. The P export was higher under the biennial harvest in 88.9% of the N and P combinations (Table 6).

In Quixadá, the accumulation and export of Ca for all combinations of N and P (Table 5) was higher under the annual harvest. In Tejuçuoca, Ca accumulation was higher under the annual harvest for six combinations of N and P levels. A higher Ca export under the biennial harvest was verified for five combinations of N and P (Table 6).

In Quixadá, higher accumulation and export of Mg were observed under the annual harvest for all combinations of N and P (Table 5). In Tejuçuoca, there was a superiority in the Mg accumulation under the biennial harvest in almost all combinations of N and P. We observed a higher Mg export under the biennial crop for all combinations of N and P (Table 6).

In Quixadá, S accumulation was higher under the annual harvest for six combinations of N and P. A higher S export was found under the biennial crop for 66.7% of the N and P combinations (Table 5). In Tejuçuoca, higher accumulation and export of S were observed under the biennial harvest for most of the combinations of N and P (Table 6).

Discussion

The effect of N and P fertilization on the accumulation and export of N under the different harvest managements is a result of the activity of these nutrients in the production of forage biomass, since the total extraction is dependent on the biomass yield and nutrient content in plant tissues.

In both harvest frequencies, the addition of N increased the content and availability of this nutrient in the soil solution (Costa et al., 2008), which favored higher uptake of the nutrient, resulting in increased biomass and, consequently, increase in the accumulation and export of this nutrient with the harvest. In Quixadá, under annual harvest, the combination of N and P had a positive effect on the accumulation and export of N. This is a result of the higher N influx, increasing its uptake and, consequently, the accumulation.

In both regions, for the conditions in which there was an increase in the accumulation and export of N with the addition of P, this increase was due to the effect of this nutrient (P) on growth, development (Malavolta et al., 2006), and increase in root biomass (Souto et al., 2009; Bonfim-Silva et al., 2011; Bonfim-Silva et al., 2014), improving the uptake and consequently the accumulation and export of nitrogen.

In the two regions, the distinct response pattern for the accumulation and export of P, as a function of the combinations of N and P under annual and biennial harvest frequencies, is a result of the structural consolidation of the crop, combined with environmental factors. In this context,

Table 2 - Accumulation and export of nitrogen and phosphorus in response to combinations of N and P levels in cactus pear, in the regions of Quixadá and Tejuçuoca

Region	HF	Model	N and P_2O_5[1] (kg ha^{-1} year^{-1})	Accumulation/export (kg ha^{-1} year^{-1})
Quixadá	Annual	$NA = 29.8113 + 0.00471738N - 0.00097909^{*}N^2 - 0.132988^{\Delta}P + 0.00223828^{*}NP$; $R^2 = 0.51$	134.6 and 190.0	44.7
		$NE = 8.01351 + 0.036463^{\Delta}N - 0.000922934^{***}N^2 - 0.0244868^{\Delta}P - 0.000586568^{**}P^2 + 0.00181879^{**}NP$; $R^2 = 0.84$		16.9
	Biennial	$NA = -7.52882 + 0.158774^{***}N - 0.000680939^{***}N^2 + 0.163461^{***}P - 0.0005956^{***}P^2$; $R^2 = 0.69$	114.6 and 136.8	12.9
		$NE = -3.2121 + 0.072137^{***}N - 0.000291827^{***}N^2 + 0.0502542^{**}P - 0.00012673^{\Delta}P^2$; $R^2 = 0.69$		5.7
Tejuçuoca	Annual	$NA = 18.8241 + 0.813718^{**}N - 0.00234968^{\Delta}N^2 + 0.220002^{*}P$; $R^2 = 0.52$	137.7 and 190.0	128.1
		$NE = -10.4963 + 0.817946^{***}N - 0.00263706^{**}N^2 + 0.417585^{*}P - 0.00138574^{\Delta}P^2$; $R^2 = 0.61$		81.5
	Biennial	$NA = 56.194 + 0.682297^{***}N + 0.0966285^{\Delta}P$; $R^2 = 0.86$	190.0 and 56.8	191.3
		$NE = 42.0385 + 0.603961^{***}N + 0.0738418^{\Delta}P$; $R^2 = 0.90$		161.0
Quixadá	Annual	$PA = 3.3823 + 0.00930029N - 0.0000876597^{*}N^2 - 0.0278706^{**}P + 0.00011877^{**}P^2$; $R^2 = 0.46$	134.6 and 190.0	2.04
		$PE = 0.662775 + 0.00753845^{*}N - 0.0000500049^{**}N^2 - 0.00262998^{\Delta}P + 0.0000110098^{\Delta}P^2$; $R^2 = 0.29$		0.67
	Biennial	$PA = -0.352346 + 0.00888435^{***}N - 0.0000421524^{***}N^2 + 0.00869285^{***}P - 0.0000261226^{**}P^2$; $R^2 = 0.73$	114.6 and 136.8	0.81
		$PE = -0.126986 + 0.0037897^{***}N - 0.000016626^{***}N^2 + 0.00192743^{***}P$; $R^2 = 0.81$		0.35
Tejuçuoca	Annual	$PA = -0.689182 + 0.0553215^{***}N - 0.000210865^{**}N^2 + 0.0499014^{***}P - 0.00024169^{***}P^2$; $R^2 = 0.61$	137.7 and 190.0	3.7
		$PE = -1.19554 + 0.0491068^{***}N - 0.000187009^{***}N^2 + 0.0380175^{***}P - 0.000187927^{***}P^2$; $R^2 = 0.72$		2.5
	Biennial	$PA = 9.09968 - 0.0711668^{**}N + 0.000610042^{***}N^2 - 0.0891463^{***}P + 0.00048548^{***}P^2$; $R^2 = 0.82$	190.0 and 56.8	14.1
		$PE = 7.15466 - 0.0625744^{**}N + 0.000540075^{***}N^2 - 0.067386^{***}P + 0.000368368^{***}P^2$; $R^2 = 0.83$		12.1

HF - harvest frequency; NA - nitrogen accumulation; NE - nitrogen export; PA - phosphorus accumulation; PE - phosphorus export; R^2 - coefficient of determination.
[1] Combined levels of N and P for maximum production of cactus pear biomass [3522.9 and 1583.2 kg ha^{-1} year^{-1} (Quixadá) and 9783.0 and 12124.0 kg ha^{-1} year^{-1} (Tejuçuoca) on annual and biennial harvests, respectively].
*** Significant at 0.1% probability.
** Significant at 1% probability.
* Significant at 5% probability.
Δ Significant at 10% probability.

it is worth emphasizing that, under the annual harvest, the crop was subjected to more stressful management conditions due to frequent cuts. This led to varied responses in P accumulation, reflecting the differentiated potential of the crop in responding to the applied nutrients.

Nitrogen, while governed by mass flow transport, had an influence on the accumulation and export of P from the lowest N levels under annual (Quixadá and Tejuçuoca) and biennial (Quixadá) harvest frequencies until reaching the maximum with higher levels. Under certain conditions, from higher levels, phosphate fertilization increased the accumulation and export of P, which can be ascribed to the effect of the phosphate fertilizer at the highest levels, by increasing the passage of the nutrient to a labile form, favoring the availability to the crop, promoting greater uptake, and, consequently, increasing the extraction.

In Tejuçuoca, the accumulation and export of P were increased from low combined levels of N and P under annual harvest frequency. This response can be attributed to the lower competition between plants, reflecting the

Table 3 - Accumulation and export of potassium and calcium in response to combinations of levels of N and P in cactus pear, in Quixadá and Tejuçuoca

Region	HF	Model	N and P_2O_5[1] (kg ha^{-1} year^{-1})	Accumulation/export (kg ha^{-1} year^{-1})
Quixadá	Annual	$KA = 131.971 - 0.409659^{*}N - 0.00386564^{*}N^2 - 0.799596^{***}P - 0.00235925^{\Delta}P^2 + 0.012868^{**}NP$; $R^2 = 0.50$	134.6 and 190.0	98.8
		$KE = 39.8292 - 0.049814N - 0.00350438^{***}N^2 - 0.188043^{**}P - 0.0031704^{***}P^2 + 0.00852324^{***}NP$; $R^2 = 0.92$		37.4
	Biennial	$KA = -13.8108 + 0.367852^{***}N - 0.00164839^{***}N^2 + 0.355756^{***}P - 0.00129518^{***}P^2$; $R^2 = 0.81$	114.6 and 136.8	31.1
		$KE = -5.95055 + 0.166732^{***}N - 0.00068787^{***}N^2 + 0.101168^{***}P - 0.000234967^{*}P^2$; $R^2 = 0.83$		13.6
Tejuçuoca	Annual	$KA = -22.4885 + 1.71301^{***}N - 0.00586519^{**}N^2 + 1.6647^{**}P - 0.00753497^{**}P^2$; $R^2 = 0.58$	137.7 and 190.0	146.5
		$KE = -43.8181 + 1.62539^{***}N - 0.0056721^{***}N^2 + 1.31738^{***}P - 0.00620257^{***}P^2$; $R^2 = 0.67$		98.8
	Biennial	$KA = 26.8457 + 1.83532^{***}N + 0.00585605^{**}N^2 + 0.630651^{*}P + 0.0080011^{***}P^2 - 0.0232986^{***}NP$; $R^2 = 0.89$	190.0 and 56.8	397.2
		$KE = 7.94278 + 1.52721^{***}N + 0.0055781^{**}N^2 + 0.724389^{**}P + 0.0061521^{**}P^2 - 0.0203353^{***}NP$; $R^2 = 0.91$		341.0
Quixadá	Annual	$CaA = 59.4371 + 0.087186N - 0.0023297^{**}N^2 - 0.29851^{*}P + 0.00449459^{**}NP$; $R^2 = 0.70$	134.6 and 190.0	87.2
		$CaE = 19.3393 + 0.0690889^{\Delta}N - 0.0024779^{***}N^2 - 0.063069^{\Delta}P - 0.00180038^{***}P^2 + 0.00492826^{***}NP$; $R^2 = 0.94$		32.8
	Biennial	$CaA = -17.2925 + 0.424963^{***}N - 0.0018963^{***}N^2 + 0.429937^{***}P - 0.00170025^{***}P^2$; $R^2 = 0.73$	114.6 and 136.8	33.5
		$CaE = -7.62364 + 0.193269^{***}N - 0.00080081^{***}N^2 + 0.135875^{***}P - 0.000429784^{**}P^2$; $R^2 = 0.73$		14.6
Tejuçuoca	Annual	$CaA = 128.506 + 1.37649^{*}N - 0.0145885^{**}N^2 - 0.0280085P - 0.0090342^{*}P^2 + 0.0189035^{\Delta}NP$; $R^2 = 0.39$	137.7 and 190.0	204.6
		$CaE = 12.4409 + 1.83045^{***}N - 0.00735967^{***}N^2 + 0.555184^{\Delta}P - 0.00273924^{\Delta}P^2$; $R^2 = 0.48$		131.5
	Biennial	$CaA = 83.6595 + 1.26939^{***}N - 0.00472753^{***}N^2 + 0.484615^{*}P - 0.00429745^{***}P^2$; $R^2 = 0.84$	190.0 and 56.8	167.8
		$CaE = 57.5498 + 1.06141^{***}N - 0.0037974^{***}N^2 + 0.573121^{**}P - 0.00431832^{***}P^2$; $R^2 = 0.78$		140.8

HF - harvest frequency; KA - potassium accumulation; KE - potassium export; CaA - calcium accumulation; CaE - calcium export; R^2 - coefficient of determination.
[1] Combined levels of N and P for maximum production of cactus pear biomass [3522.9 and 1583.2 kg ha^{-1} year^{-1} (Quixadá) and 9783.0 and 12124.0 kg ha^{-1} year^{-1} (Tejuçuoca) on annual and biennial harvests, respectively].
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* Significant at 5% probability.
Δ Significant at 10% probability.

reduction of the stand with the cultivation time in the cactus pear under annual cut. In turn, under the biennial management, there was an increase in the accumulation and export of P in the higher combinations of N and P, which reflects the higher nutritional demand of the forage under the said management conditions, in response to the crop with greater density of plants. In the two conditions of the study, but mainly in Quixadá, small amounts of extracted/exported P were observed, indicating the low nutrient recovery applied through fertilization.

In Quixadá, under annual harvest, with lower combinations of N and P, there were declines in the accumulation and export of K. However, the synergistic effect between N and P may have favored the uptake of both (Silva et al., 2012), since they can present transport by symport, in which the two ions of opposite signs (NH_4^+ and $H_2PO_4^-$) are absorbed together.

Under the biennial harvest in Quixadá, with the lowest combinations of N and P levels, there were increases in the accumulation and export of K. At 730 days after planting,

Table 4 - Accumulation and export of magnesium and sulfur in response to combinations of levels of N and P in cactus pear, in the regions of Quixadá and Tejuçuoca

Region	HF	Model	N and P_2O_5[1] (kg ha^{-1} year^{-1})	Accumulation/export (kg ha^{-1} year^{-1})
Quixadá	Annual	$MgA = 21.5382 + 0.012918N - 0.00103342^{*}N^2 - 0.0884679^{\Delta}P - 0.000410102P^2 + 0.00210454^{*}NP$; $R^2 = 0.53$	134.6 and 190.0	26.8
		$MgE = 6.11599 + 0.0281236^{*}N - 0.000848389^{***}N^2 - 0.0152323P - 0.000638702^{***}P^2 + 0.00162313^{***}NP$; $R^2 = 0.98$		10.1
	Biennial	$MgA = -5.1748 + 0.125591^{***}N - 0.00058386^{***}N^2 + 0.134231^{***}P - 0.000504897^{***}P^2$; $R^2 = 0.79$	114.6 and 136.8	10.5
		$MgE = -2.21726 + 0.0563913^{***}N - 0.000241162^{***}N^2 + 0.0403414^{***}P - 0.00011154^{**}P^2$; $R^2 = 0.82$		4.5
Tejuçuoca	Annual	$MgA = 39.6197 + 0.295091^{\Delta}N - 0.00455016^{*}N^2 + 0.0506423P - 0.00309888^{*}P^2 + 0.00703465^{\Delta}NP$; $R^2 = 0.42$	137.7 and 190.0	75.8
		$MgE = 14.7694 + 0.376568^{*}N - 0.0034911^{**}N^2 + 0.10887P - 0.00227677^{*}P^2 + 0.0042321^{\Delta}NP$; $R^2 = 0.53$		49.7
	Biennial	$MgA = 49.7547 + 0.402591^{***}N + 0.0842316^{\Delta}P$; $R^2 = 0.82$	190.0 and 56.8	131.0
		$MgE = 37.1674 + 0.367973^{***}N + 0.0665201^{\Delta}P$; $R^2 = 0.82$		110.9
Quixadá	Annual	$SA = 2.70814 + 0.118644^{**}N - 0.000852559^{**}N^2 + 0.0519692^{\Delta}P - 0.000524042^{*}P^2 + 0.000944808NP$; $R^2 = 0.84$	134.6 and 190.0	18.4
		$SE = 0.7353 + 0.0395735^{***}N - 0.000337834^{***}N^2 + 0.0154844^{\Delta}P - 0.000234318^{**}P^2 + 0.00047502^{**}NP$; $R^2 = 0.99$		6.6
	Biennial	$SA = -11.8805 + 0.222936^{***}N - 0.00082827^{**}N^2 + 0.255796^{***}P - 0.00102656^{***}P^2$; $R^2 = 0.68$	114.6 and 136.8	18.6
		$SE = -5.04958 + 0.10181^{***}N - 0.000354526^{**}N^2 + 0.0843578^{**}P - 0.000285159^{*}P^2$; $R^2 = 0.69$		8.2
Tejuçuoca	Annual	$SA = 6.73909 + 1.01193^{***}N - 0.0045823^{***}N^2 + 1.08073^{***}P - 0.00593578^{***}P^2$; $R^2 = 0.75$	137.7 and 190.0	50.3
		$SE = -37.8436 + 1.20345^{***}N - 0.0015622^{\Delta}N^2 + 1.06195^{***}P - 0.00197452^{*}P^2 - 0.00762355^{**}NP$; $R^2 = 0.85$		29.3
	Biennial	$SA = 26.994 + 0.997894^{***}N + 0.00326167^{*}N^2 + 0.385718^{\Delta}P + 0.00383419^{*}P^2 - 0.0118057^{**}NP$; $R^2 = 0.79$	190.0 and 56.8	241.2
		$SE = 12.4198 + 0.842409^{***}N + 0.00306102^{*}N^2 + 0.461556^{*}P + 0.00273087^{\Delta}P^2 - 0.0102914^{*}NP$; $R^2 = 0.75$		206.9

HF - harvest frequency; MgA - magnesium accumulation; MgE - magnesium export; SA - sulfur accumulation; SE - sulfur export; R^2 - coefficient of determination.
[1] Combined levels of N and P for maximum production of cactus pear biomass [3522.9 and 1583.2 kg ha^{-1} year^{-1} (Quixadá) and 9783.0 and 12124.0 kg ha^{-1} year^{-1} (Tejuçuoca) on annual and biennial harvests, respectively].
*** Significant at 0.1% probability.
** Significant at 1% probability.
* Significant at 5% probability.
Δ Significant at 10% probability.

plants probably showed a greater growth of the root system and, consequently, a smaller distance between ion and root, favoring the contact by diffusion, potentiating K^+ uptake and its accumulation/export in response to fertilization. In the two regions, the increases observed in the accumulation and export of K according to the N and P combinations are a result of the effect of nutrients on the morphological and physiological characteristics of the cactus pear, which resulted in a greater total biomass accumulation.

In Quixadá and Tejuçuoca, the accumulation and export of Ca as a function of the N and P combinations under the two harvest frequencies reflected the effect of nutrition on productivity. The performance of N in the accumulation and export of Ca under the annual and biennial harvest management can be attributed to the increased biomass, associated with the increase in nitrate content in the plant tissue, which increases the uptake of cations, such as Ca^{2+}, to maintain the cation-anion balance in the plant (Mengel and Kirkby, 2001).

In both study regions, in the management with annual harvest, the combination of N and P favored Ca extraction at the highest levels of fertilization. The decreasing effect

Table 5 - Accumulation and export of macronutrients by cactus pear according to harvest frequencies, for different combinations of nitrogen and phosphorus, in the region of Quixadá

HF	Combinations of N and P_2O_5 (kg ha^{-1} year^{-1})								
	10/70	70/10	70/70	70/130	100/100	130/70	130/130	130/190	190/130
	Nitrogen accumulation (kg ha^{-1} year^{-1}; CV = 16.8%)								
Annual	22.9A	26.7A	19.4A	26.8A	44.0A	23.4A	26.7A	45.1A	34.2A
Biennial	2.1B	3.3B	6.1B	11.6B	17.7B	6.6B	11.7B	10.4B	10.3B
	Nitrogen export (kg ha^{-1} year^{-1}; CV = 10.9%)								
Annual	4.9A	6.9A	9.9A	9.1A	15.6A	8.7A	12.0A	16.8A	13.9A
Biennial	0.67B	1.3B	1.7B	4.0B	7.9B	3.3B	5.0B	6.2B	4.4B
	Phosphorus accumulation (kg ha^{-1} year^{-1}; CV = 19.1%)								
Annual	1.3A	3.9A	2.8A	3.5A	1.4A	0.73A	1.2A	1.5A	1.1A
Biennial	0.13B	0.25B	0.49B	0.88B	0.94B	0.32B	0.69B	0.72B	0.62B
	Phosphorus export (kg ha^{-1} year^{-1}; CV = 20.8%)								
Annual	0.29A	1.0A	1.3A	1.2A	0.46A	0.27A	0.47A	0.56A	0.41A
Biennial	0.04B	0.10B	0.13B	0.31B	0.42B	0.16B	0.29B	0.44B	0.27B
	Potassium accumulation (kg ha^{-1} year^{-1}; CV = 15.7%)								
Annual	68.7A	88.7A	66.2A	57.9A	105.8A	55.6A	72.4A	94.1A	92.4A
Biennial	6.4B	10.5B	17.7B	33.1B	35.0B	19.5B	28.3B	24.5B	23.5B
	Potassium export (kg ha^{-1} year^{-1}; CV = 14.8%)								
Annual	14.8A	23.1A	33.9A	19.8A	38.1A	21.0A	34.9A	34.8A	38.2A
Biennial	2.0B	4.0B	4.8B	11.5B	15.6B	9.7B	12.1B	14.7B	10.1B
	Calcium accumulation (kg ha^{-1} year^{-1}; CV = 17.3%)								
Annual	42.3A	54.6A	49.9A	54.3A	78.7A	46.9A	58.6A	86.0A	66.5A
Biennial	6.9B	11.5B	17.8B	34.4B	42.5B	20.1B	30.8B	23.3B	25.1B
	Calcium export (kg ha^{-1} year^{-1}; CV = 13.1%)								
Annual	9.0A	14.2A	25.5A	18.6A	27.7A	17.4A	27.2A	31.8A	27.3A
Biennial	2.2B	4.3B	4.9B	12.0B	19.0B	10.0B	13.2B	14.0B	10.8B
	Magnesium accumulation (kg ha^{-1} year^{-1}; CV = 14.8%)								
Annual	16.1A	18.3A	14.6A	16.4A	27.6A	16.7A	20.8A	26.6A	19.9A
Biennial	2.1B	3.2B	6.5B	11.5B	11.9B	6.0B	9.2B	7.7B	7.6B
	Magnesium export (kg ha^{-1} year^{-1}; CV = 13.3%)								
Annual	3.4A	4.7A	7.5A	5.5A	9.5A	6.2A	9.6A	9.8A	8.1A
Biennial	0.66B	1.2B	1.8B	4.0B	5.4B	3.0B	3.9B	4.6B	3.3B
	Sulfur accumulation (kg ha^{-1} year^{-1}; CV = 17.1%)								
Annual	6.4A	8.6A	8.9A	12.7B	18.7B	13.2A	18.0A	17.8A	15.3B
Biennial	2.3B	4.7B	6.7B	18.5A	25.4A	12.0B	16.0B	13.1B	18.3A
	Sulfur export (kg ha^{-1} year^{-1}; CV = 17.9%)								
Annual	1.4A	2.2A	4.3A	4.1B	5.2B	4.5B	6.1B	6.5B	5.8B
Biennial	0.73A	1.8A	1.8B	6.4A	11.4A	6.0A	6.8A	7.8A	7.9A

HF - harvest frequency; CV - coefficient of variation.
Means followed by different letters, within the combinations of nitrogen and phosphorus, in the same column, are significantly different by Scott-Knott test at 5% probability.

of P alone at the lower levels under annual harvest may be an indirect result of fertilization in response to the direct effect of harvest management with annual cut, which greatly compromised the root system of cactus pear, especially the young roots under conditions of high water stress, in such a way that it influenced the accumulation and export of Ca because, as discussed by Mengel and Kirkby (2001), the uptake of this nutrient is done only by young roots. Under biennial harvest, in well-structured and stabilized plants, with a better consolidated root system and higher nutrient reserve in the tissues, P levels promoted an increase in Ca extraction by the cactus pear. It is worth mentioning that the higher P levels that caused a reduction in the accumulation and export of Ca may have precipitated Ca in the soil when reacting with the phosphates present in the higher levels of P, influencing the availability of Ca^{2+} for the crop, resulting in lower absorption, with reduced accumulation and export of the nutrient.

By providing positive responses on the productive pattern of cactus pear, N fertilization promoted, to a certain extent, a point of maximum accumulation and export of Mg. Nevertheless, N fertilization increased aerial biomass and possibly favored root development (Zúñiga-Tarango et al., 2009) and potentiated the photosynthetic and respiratory area

Table 6 - Accumulation and export of macronutrients by cactus pear according to harvest frequencies, for different combinations of nitrogen and phosphorus, in the region of Tejuçuoca

HF	Combinations of N and P_2O_5 (kg ha^{-1} year^{-1})								
	10/70	70/10	70/70	70/130	100/100	130/70	130/130	130/190	190/130
	Nitrogen accumulation (kg ha^{-1} year^{-1}; CV = 8.5%)								
Annual	54.1A	57.0B	80.4B	78.1B	65.3B	114.7B	168.8A	118.1B	101.0B
Biennial	49.7A	104.3A	133.2A	136.2A	119.7A	161.5A	142.5B	167.1A	192.6A
	Nitrogen export (kg ha^{-1} year^{-1}; CV = 9.3%)								
Annual	27.3B	37.5B	53.4B	55.5B	47.0B	80.1B	120.2A	77.7B	69.9B
Biennial	39.7A	82.1A	102.3A	111.8A	108.0A	132.3A	112.5B	133.6A	166.1A
	Phosphorus accumulation (kg ha^{-1} year^{-1}; CV = 16.1%)								
Annual	2.7B	2.2B	4.5B	3.9B	3.8A	6.4A	6.6A	3.9B	3.9B
Biennial	3.3A	6.0A	6.5A	5.1A	2.9B	5.6B	4.3B	10.9A	15.4A
	Phosphorus export (kg ha^{-1} year^{-1}; CV = 15.8%)								
Annual	1.3B	1.5B	3.0B	2.8B	2.7A	4.5A	4.7A	2.5B	2.7B
Biennial	2.5A	4.7A	4.9A	4.2A	2.6A	4.5A	3.3B	8.7A	13.3A
	Potassium accumulation (kg ha^{-1} year^{-1}; CV = 12.1%)								
Annual	90.2A	78.3B	150.6A	134.2B	122.1B	202.9B	263.1A	144.3B	156.4B
Biennial	105.0A	184.4A	153.2A	208.4A	165.1A	220.0A	201.8B	186.3A	234.8A
	Potassium export (kg ha^{-1} year^{-1}; CV = 12.7%)								
Annual	45.3B	52.0B	99.6B	96.2B	90.5B	149.7B	190.1A	95.5B	109.9B
Biennial	83.7A	145.3A	117.4A	171.2A	149.0A	180.1A	159.3B	148.9A	202.3A
	Calcium accumulation (kg ha^{-1} year^{-1}; CV = 8.3%)								
Annual	124.7A	166.3A	182.0A	161.9A	145.3B	211.5A	312.7A	186.6A	148.3A
Biennial	101.4B	154.2B	166.3B	157.4A	168.8A	183.7B	135.4B	105.3B	151.9A
	Calcium export (kg ha^{-1} year^{-1}; CV = 7.6%)								
Annual	67.0B	113.8A	120.3B	117.4B	107.7B	153.8A	225.3A	123.4A	103.6B
Biennial	81.2A	120.3A	127.8A	129.3A	152.3A	150.4A	107.1B	84.2B	130.7A
	Magnesium accumulation (kg ha^{-1} year^{-1}; CV = 11.9%)								
Annual	44.1A	40.5B	54.2B	47.7B	45.6B	67.6B	103.3B	72.4B	47.8B
Biennial	53.9A	81.0A	92.9A	106.8A	88.6A	96.2A	107.7A	109.1A	149.8A
	Magnesium export (kg ha^{-1} year^{-1}; CV = 10.1%)								
Annual	22.9B	27.1B	35.8B	34.1B	33.1B	47.6B	72.3B	46.6B	33.3B
Biennial	42.6A	63.5A	71.3A	87.7A	80.0A	78.9A	85.1A	87.2A	129.3A
	Sulfur accumulation (kg ha^{-1} year^{-1}; CV = 11.1%)								
Annual	67.0A	64.1B	94.7B	100.9B	85.8B	123.4B	117.8A	50.0B	66.6B
Biennial	66.0A	110.2A	112.3A	128.9A	131.4A	138.3A	102.6B	132.2A	168.1A
	Sulfur export (kg ha^{-1} year^{-1}; CV = 11.4%)								
Annual	36.1B	44.5B	62.4B	73.6B	63.8B	91.2B	84.9A	32.0B	46.4B
Biennial	52.5A	86.6A	85.6A	106.0A	118.6A	113.4A	81.2B	105.8A	144.7A

HF - harvest frequency; CV - coefficient of variation.
Means followed by different letters, within the combinations of nitrogen and phosphorus, in the same column, are significantly different by Scott-Knott test at 5% probability.

of the crop, which, associated with the evaporative demand of the atmosphere (vapor pressure deficit), optimized the nutrient uptake capacity by increasing the flow of the soil solution to the root zone and by the expansion of the root system, favoring the ion-root contact.

Moreover, the N and P combination favored the productive performance of the cactus pear and, consequently, reflected an increase in the accumulation and export of Mg. The beneficial effect of P fertilization on Mg uptake is related to the fact that Mg plays a key role in the transport of P in the biochemical processes of the plant, mainly in phosphorylated reactions (Oliveira et al., 2001).

The dynamics of accumulation and export of S, as well as the other nutrients, demonstrated the direct relationship with the productive capacity of the cactus pear. Thus, the factors that promoted a positive effect on the yield of the crop also potentiated the extraction of nutrients, including S, in which the results indicated the influence of fertilization associated with annual and biennial harvest frequencies.

Furthermore, regarding the accumulation and export of S, it is important to emphasize the action of urea (nitrogen fertilizer used herein) as a source of NH_4^+, which favors the absorption and consequent accumulation of S because, according to Tisdale et al. (1985), the uptake of N in the ammoniacal form (NH_4^+) can stimulate the absorption of S (SO_4^{2-}).

The pattern of accumulation and export of N in the two harvest frequencies in both regions resulted from the dynamics of biomass production in the two regions, altering the order of superiority between the harvest managements.

With respect to the differences found for the accumulation and export of P under the two harvest frequencies, for Quixadá and Tejuçuoca conditions, as mentioned for the accumulation and export of N, these are results of the differentiated pattern of biomass accumulation in each cultivation condition in the two harvesting frequencies. This is a reflection of fluctuations in crop growth throughout the development cycle, which is closely related to the environment and management conditions.

The distinct accumulation and export of K and Ca between the harvesting frequencies, in Quixadá and Tejuçuoca, with higher values either for annual or biennial harvest, were due to the variations in the production of forage biomass, associated with the contents of these nutrients in the tissues of cactus pear cladodes.

The dynamics of cactus pear response in terms of accumulation and export of Mg and S under annual and biennial harvest frequencies, in Quixadá and Tejuçuoca regions, can be attributed to the same reasons previously described in the scope of this study for the other macronutrients.

Conclusions

In Quixadá, under management of annual harvest frequency and fertilization with combined levels of N and P for maximum biological response in terms of biomass production, the cactus pear exhibits the following decreasing order of accumulation of macronutrients: K > Ca > N > Mg > S > P. Under biennial harvest, the decreasing order of accumulation is Ca > K > S > N > Mg > P.

In Tejuçuoca, with annual harvest frequency and fertilization with combined levels of N and P for maximum biomass production, the cactus pear shows the following decreasing order of accumulation of macronutrients: K > Ca > N > Mg > S > P. Under biennial harvest, it presents the following decreasing order of accumulation: K > N > S > Ca > Mg > P.

The maintenance/production fertilization in cactus pear should be planned according to productive potential, fertilization and harvest managements, and cultivation region, based on nutritional requirement and considering the nutrient recovery efficiency.

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