Opuntia ficus–indica (L.) Mill. yield depends on nutrients and nutrient ratios

Fidel Blanco–Macías[1], Rafael Magallanes–Quintanar[2], Rigoberto E. Vázquez–Alvarado[3], Santiago de J. Méndez–Gallegos[4], Enrique Troyo–Diéguez[5], Clemente Gallegos-Vázquez[1] and Ricardo D. Valdez–Cepeda[1,6*]

[1]Universidad Autónoma Chapingo, Centro Regional Universitario Centro–Norte. Cruz del Sur Núm. 100, Col. Constelación. Apartado Postal 196, El Orito, Zacatecas, Zac., CP 98085, México.
[2]Universidad Autónoma de Zacatecas, Unidad Académica de Ingeniería Eléctrica. Avenida R. López Velarde 801. Zacatecas, Zac., CP 98064, México
[3]Universidad Autónoma de Nuevo León, Facultad de Agronomía. Km 17.5, Carretera Zuazua–Marín. Marín, Nuevo León, CP 66700, México
[4]Colegio de Postgraduados, Campus San Luis Potosí. Iturbide 73. Salinas de Hidalgo, SLP, CP 786000, México
[5]Centro de Investigaciones Biológicas del Noroeste. Mar Bermejo No. 195, Col. Playa Palo de Santa Rita. La Paz, Baja California Sur, México.
[6]Universidad Autónoma de Zacatecas, Unidad Académica de Matemáticas. Paseo Solidaridad s/n. Zacatecas, Zac., CP 98064, México

* Corresponding author: e–mail, vacrida@hotmail.com

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Abstract

Opuntia ficus–indica (L.) Mill. is growing in 25 countries to harvest its fruit (cactus pear), young cladodes (stems or 'nopalitos') and mature cladodes. Mexico is the only country with commercial production of 'nopalitos' of *O. ficus–indica* (L.) Mill. covering 12,041 ha with annual mean yields, at farm level, ranging from 9.03–99.93 t ha^{-1}, and an overall average of 64.33 t ha^{-1}. This great variability of annual mean yields is associated with a wide range of farming systems that differ in terms of crop management practices such as fertilization, a labor closely related to satisfy the nutritional requirements of cultivated species. Nutrient balance in crop science is an indirect effect of nutrient interactions on biotic or commercial yield. In this regard, a database (n = 360) of yield (biomass) and nutrient concentrations of N, P, K, Ca and Mg from an experiment established at El Orito, Zacatecas, Mexico during April 1999 was used to identify yield dependence on nutrients and nutrient ratios through Pearson correlation coefficients. Yield is significantly ($p \leq 0.05$) dependent on N, Mg, Ca and K concentrations in one–year old cladodes. The K:ln P, ln Ca:ln P, and ln Mg:ln P mass ratios have a positive effect on yield; whereas the ln P:ln N, ln Mg:ln N, and ln N:ln Ca ratios negatively affect the production of biomass.

Key words: Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, Stoichiometry.

Introduction

Opuntia ficus–indica (L.) Mill. is growing in 25 countries to harvest its fruit (cactus pear), young cladodes (stems or 'nopalitos') and mature cladodes. The fruits are destined for fresh consumption, processing of tuna cheese, melcocha, honey, and wine, among other products; whereas young cladodes are used as salads and vegetables to prepare special dishes. Mature cladodes are used as forage, especially during dry season (Pimienta, 1990). Mexico is the only country with commercial production of 'nopalitos' of *O. ficus–indica* (L.) Mill. covering 12,041 ha (SAGARPA–SIAP, 2010). The production was 728.94 t in 2009, with annual mean yields ranging from 9.03 to 99.93 t ha^{-1}, and an overall average of 64.33 t ha^{-1} (SAGARPA–SIAP, 2010). This great variability of annual mean yield is associated with a wide range of farming systems that differ in terms of crop management practices such as fertilization, a labor closely related to satisfy the nutritional requirements of cultivated species. However, the amounts of fertilizer applied to improve the availability of nitrogen, phosphorus and potassium in the soil are diverse and do not take into account how they influence the absorption and utilization of nutrients by *O. ficus–indica* (L.) Mill. plants.

Usually, supply of one nutrient affects the absorption and utilization of other nutrients, that is, interaction between nutrients in crop plants occurs. Nutrient interactions involve ions whose chemical properties are sufficiently similar that they compete for site of adsorption, absorption, transport, and function on plant root surfaces or within plant tissues (Fageria, 2001). Such interactions are more common between nutrients of similar size, charge, geometry of coordination, and electronic configuration (Robson and Pitman, 1983). Moreover, there is known nutrient interactions are influenced by factors such as concentration of nutrient, temperature, light intensity, soil aeration, soil moisture, soil pH, root morphology, the rate of plant transpiration and respiration, plant age and growth rate, plant species and internal nutrient concentration of plants (i.e. composition of plants). As a result, current understanding of the extent, causes for, and consequences of variation in nutrient composition in *O. ficus–indica* (L.) Mill. plants is limited.

Nutrient effects are typically determined from soil and/or plant nutrient levels and from nutrient addition studies (Drenovsky and Richards, 2004). However, nutrient addition experiments, although often straightforward, are lengthy and labor–intensive (van Duren and Petgel, 2000; Bennet and Adams, 2001). As an alternative to such studies, nutrient ratios could be used to elucidate how flexible they are within a population or species, to predict nutrient limitations and to identify how much the ratios of nutrients to mass and nutrients to each other change. Hence, the aim of this research work was to study the ratio between contents of different nutrients within one–year old cladodes in relation to yield (yearly produced fresh matter per *O. ficus–indica* (L.) Mill. plant).

Materials and methods

Establishment of the experiment

An experiment was established in April 1999 in the experimental field of the 'Centro Regional Universitario Centro Norte' of the 'Universidad Autónoma Chapingo' at 22°44'9.6'' N, 102°46' 28.2'' W, and 2,296 m above sea level, located near Zacatecas city, Mexico. Climate of the region can be classified as BS1kw(w) which corresponds to the least dry of the dry–steppe type, with a mean annual temperature ranging between 12°C and 18°C and a yearly average precipitation of 472 mm. Most of the precipitation (65%) occurs from June to August. The field experiment was carried out in order to study the effects of four fertilization treatments (randomly distributed in three blocks) on yield of *O. ficus–indica* (L.) Mill. Thus, there were 36 experimental units and each experimental unit had 12 plants. However, demonstrating effects of treatments on yield is out of scope of this paper. Within the experimental plot, a density of 10,000 plants ha^{-1} was used.

Soil conditions of the experimental site

A composite sample of the surface soil (0–30 cm) was taken and treated for physical and chemical analyses. Soil at the site had clay–loam texture, very slightly alkaline pH, and high content of organic matter (Table 1). The plot had been used as a fruit orchard during the previous 50 years, involving regular organic soil amendment with cow manure and incorporation of trees' foliage on the ground. Extractable nutrient levels were as follows: Availability was low for inorganic N, very high for P, medium for K, high for Ca, moderately high for Mg, moderately low for Fe, very high for Cu, excessive for Zn, moderately low for Mn, and medium for B (Table 1). High availability for Ca is certainly associated with the calcareous origin of the soil. Soil is classified as Luvic Castañozem according to the FAO soil classification system, modified by the CETENAL (1972).

Data and statistical analyses

Data used in this study were acquired from the mentioned field experiment. Data correspond to an original database (n = 360) of cladode fresh matter as yield and the concentrations of N, P, K, Ca, and Mg in 1–year–old cladodes of *O. ficus–indica* (L.) Mill. Yield data were gathered from 1–year cladodes harvested from plants having the same structure through formation–pruning practice. Each tree structure consisted of three cladodes on the mother cladode, and three cladodes on each of these three. This means that harvested cladodes used for fresh–matter estimation as yield were mainly growing on nine cladodes at the second level from the mother cladode (Magallanes–Quintanar *et al*., 2004). One–year cladodes from each of the 36 experimental plants (one from each experimental unit) were cut from February to March each year from 2001 to 2007 and weighed to obtain fresh matter as yield.

From each plant, a cladode was selected for chemical analyses. Duplicated samples for 2002 to 2004 were considered in order to have an overall sample of 360 cladodes. Those cladodes were cleaned with distilled water, dehydrated to constant dry weight in an oven at 75 °C during 36 h, and then milled. Later, nutrient concentrations (on dry–weight basis) were determined through conventional approaches after acid digestion of the dry tissue samples (Magallanes–Quintanar *et al.*, 2004; Blanco–Macías *et al*., 2010): N with Kjeldahl technique, P by reduction with molybdo–vanadate, and K, Ca, and Mg by means of spectrophotometric techniques.

The whole database (n = 360) allowed us to know that yield showed high variability with a coefficient of variation of 44.3%. Also, high variability in concentration of N, Ca, and Mg (coefficient of variation of 46.5 %, 36.5 %, and 27.6 %, respectively) was clearly evident; whereas variability for K and P could be considered as moderately high with coefficient of variation values of 22.4% and 21.0%, respectively (see Blanco–Macías *et al*., 2010). Variability is an important aspect when identifying nutrient composition and its consequences on yield and other processes. Yield and nutrient concentrations can be considered as plant responses to biotic and abiotic factors, especially those associated with changes in year–to–year climatic conditions and to different fertilization treatments. Thus, this database can be used to identify yield dependence on nutrients and/or nutrient ratios.

Concentration values of N, P, Ca, and Mg were transformed to natural logarithm (ln) because they were not normally distributed. Later, each bivariate relationship was used in order to analyze the distribution pattern, to determine its suitability and potential use, and to remove obvious outliers. Observations positioned within tails defined by $\alpha = 0.025$ in each distribution were considered as outliers. Thus, original database (n = 360) was reduced to n = 250. So reduced database was used to identify important relationships between nutrients, and between each nutrient expression with yield through Pearson correlation coefficients.

Table 1. Soil properties of the experimental plot (Blanco–Macías *et al*., 2010).

Nutrient/Factor	Quantity	Interpretation of nutrient availability or factor condition	Method
pH	7.5	Very slightly Alkaline	pH Meter (Soil:water, 1:2)
Organic Matter (%)	3.2	High	Walkley and Black
N–Inorganic (mg kg^{-1})	15.0	Low	Extracted with KCl 2 M, determined with Kjeldahl approach
P (mg kg^{-1})	40.5	Very high	Olsen
K (mg kg^{-1})	230.0	Medium	Extracted using ammonium acetate and determined by spectrophotometry
Ca (mg kg^{-1})	4371.0	High	Extracted using ammonium acetate and determined by spectrophotometry
Mg (mg kg^{-1})	569.0	Moderately high	Extracted using ammonium acetate and determined by spectrophotometry
Fe (mg kg^{-1})	7.9	Moderately low	Extracted with DTPA, ratio 1:4, determined by atomic spectrophotometry
Cu (mg kg^{-1})	7.5	Very high	Extracted with DTPA, ratio 1:4, determined by atomic spectrophotometry
Zn (mg kg^{-1})	14.6	Excessive	Extracted with DTPA, ratio 1:4, determined by atomic spectrophotometry
Mn (mg kg^{-1})	6.1	Moderately low	Extracted with DTPA, ratio 1:4, determined by atomic spectrophotometry
B (mg kg^{-1})	1.6	Medium	Extracted with $CaCl_2$ 1.0 M, determined by means of photocolorimetry
Sand (%)	32.2		Bouyoucos hydrometer
Silt (%)	41.6	Clay loam texture	Bouyoucos hydrometer
Clay (%)	26.2		Bouyoucos hydrometer

Results

Previous studies have demonstrated that Ca and K cladode mean or optimum concentrations are respectively from 2.9 to 4.5 and from 3.4 to 4 times greater than the N concentrations (see Galizzi *et al*., 2004; Magallanes–Quintanar *et al*., 2004, 2006; Blanco–Macías *et al*., 2006, 2010), and that vegetative and reproductive growth are often influenced by P:N ratio and K availability (Galizzi *et al*., 2004). Most of them were nutrient addition experiments and did not report basic statistics except nutrient concentration means associated to fertilizer treatments. In our study, yield showed high variability with a coefficient of variation of 40.1%; and low variability was clearly evident for N, P, and K concentrations (coefficient of variation of 17.4, 16.7 and 17.8%, respectively); whereas variability for Ca and Mg could be considered as moderately low with coefficient of variation values of 8.3 and 7.4%, respectively (Table 2). Variability of nutrients and yield is an important aspect when developing knowledge on plant nutrition, as previously pointed out. Thus, our reduced database can be used for such purpose mainly because of the evidenced high variability of yield expressed as cladodes fresh matter.

Nutrient means reported in Table 2 for P, K, Ca and Mg are greater than the optimum nutrient concentrations for *O. ficus–indica* (L.) Mill. fruit production as reported by Claaessens and Wessels (1997), probably due to different purpose, environment and genotype. However, all these means lie within optimum ranges previously reported for biomass production (Magallanes–Quintanar *et al*., 2004, 2006; Blanco–Macías *et al*., 2006, 2010). In addition, these values agree with nutrient concentrations in cladodes from fruit high yielding plants (see Galizzi *et al*., 2004).

According to the basic statistics (Table 2), the order of nutrient requirements is as follows: K > Ca > Mg > N > P. This result is in agreement with previous studies (e.g. Blanco–Macías *et al*., 2010) Therefore, it appears reasonable that K, Ca and Mg could be limiting biomass production in *O. ficus–indica* (L.) Mill., then it is remarkable that this species mineral nutrition is not similar to other fruit, vegetable or forage crop. In other words, N and P could be not so important macronutrients for this species as they are for other crops when nutrient concentrations are taken into account.

Table 2. Basic statistics for yield (cladodes fresh matter in kg Plant^{-1}) and N, P, K, Ca, and Mg concentrations (g kg^{-1}) in 1–year old cladodes of *Opuntia ficus–indica* L. (n = 250).

Statistic	Yield	ln N¶	ln P¶	K	ln Ca¶	ln Mg¶
Mean	30.9	2.3 (10.0)	1.2 (3.4)	40.4	3.6 (36.7)	2.7 (14.6)
Std. Deviation	12.4	0.4 (1.5)	0.2 (1.2)	7.2	0.3 (1.4)	0.2 (1.2)
Coefficient of Variation (%)	40.1	17.4	16.7	17.8	8.3	7.4
Minimum	6.4	1.4 (4.1)	0.8 (2.3)	26.0	2.9 (18.9)	2.2 (9.3)
Maximum	59.0	3.2 (23.3)	1.6 (5.0)	56.5	4.3 (74.3)	3.2 (24.2)

¶Retransformed values are in parenthesis.

Bivariate relationships between nutrients and each of them and yield

Magallanes–Quintanar *et al*. (2006) reported significant positive correlations between N and P, N and Ca, P and Ca, K and Mg, Ca and Mg, and yield and each of the nutrients K, Ca and Mg. On the other hand, Blanco–Macías et al. (2006) have reported a significant negative correlation between Mg and N. In the present case, Pearson correlations (Table 3) provide an overview of relationships between nutrients, and between each of them and yield.

Significant positive correlations between K and Mg, Ca and Mg, N and K, and Ca and P were identified. They could be interpreted as synergism, i.e. both nutrients in each case increase their concentrations within referred ranges. Magallanes–Quintanar et al. (2006) have reported all these relationships previously. On the other hand, a significant negative correlation between Ca and N was evidenced suggesting that when concentration of one increases while the other decreases.

Moreover, yield is significantly dependent ($p \leq 0.05$) on N, Mg, Ca and K concentrations in cladodes one–year old. In other words, significant positive correlations between each of these nutrients with yield imply that yield increases while their concentration increases. Although correlation between P and yield was not significant, is important to maintain adequate levels of all nutrients in cladodes to ensure that photosynthesis or regulatory processes work optimally.

To gain more knowledge on *O. ficus-indica* (L.) Mill. nutrition, we estimated Pearson correlations between yield and each identified significant nutrient relation treated as mass nutrient ratio (Table 4).

Table 3. Pearson correlations (r) between nutrients and yield in *Opuntia ficus–indica* (L.) Mill. (n = 250).

Nutrient expression	K ($g\ kg^{-1}$)	ln Ca [ln ($g\ kg^{-1}$)]	ln Mg [ln ($g\ kg^{-1}$)]	ln P [ln ($g\ kg^{-1}$)]	ln N [ln ($g\ kg^{-1}$)]
ln Ca [ln ($g\ kg^{-1}$)]	0.092 p=0.147				
ln Mg [ln ($g\ kg^{-1}$)]	**0.416** **p=0.0001**	**0.304** **p=0.0001**			
ln P [ln ($g\ kg^{-1}$)]	0.078 p=0.219	**0.139** **p=0.028**	0.060 p=0.344		
ln N [ln ($g\ kg^{-1}$)]	**0.160** **p=0.011**	**–0.237** **p=0.0001**	–0.075 p=0.239	0.037 p=0.565	
Yield (kg $Plant^{-1}$)	**0.201** **p=0.001**	**0.253** **p=0.0001**	**0.272** **p=0.0001**	–0.088 p=0.165	**0.292** **p=0.0001**

Pearson correlation coefficients (r) significant at $p \leq 0.05$ in bold.

Bivariate relationships between nutrient ratios and yield

It was noted that K:ln P, ln Ca:lnP and ln Mg:ln P ratios have a positive effect on yield. In addition, ln P:ln N, ln Mg:ln N and ln Ca:ln N ratios have a negative effect on biomass production. Thus, our results remark the complexity of *O. ficus–indica* plant regarding its nutrition status. For instance, it is interesting to point out that N and P participate in the other five mass nutrient ratios influencing yield in a significant way. This suggest that among those evidenced ratios in the present work, P:N ratio is very important and nutrient disorder could be due to an N deficiency. This late asseveration is confirmed by significant correlation coefficients in each of Tables 3 and 4 (0.292 for yield *vs.* ln N and –0.278 for yield *vs.* ln P: ln N, respectively).

Discussion

Of those evidenced five significant ($p \leq 0.05$) nutrient correlations (Table 3), only two mass nutrient ratios (ln Ca: ln N and ln Ca: ln P, Table 4) were correlated with yield in a significant way ($p \leq 0.05$). It calls our attention that Ca:N ratio negatively affected the yield and the Ca/P ratio influenced positively the yield. Indubitably, such results are associated to a Ca excess or to a N deficiency; but it is possible a P deficiency with respect to Ca. Blanco–Macías *et al*. (2006) reported an antagonism between N and Ca; however, it cannot be associated to dilution effect of Ca with respect to N because its dilution possibilities are minimum due to *O. ficus–indica* plants tends to accumulate more Ca in its tissues when getting old (Magallanes–Quintanar *et al*., 2004.

Commonly, interaction between Ca and P is negative, but in the present case was positive (Table 3) and had a positive influence over yield (Table 4), this could be associated with the fact that *O. ficus–indica* (L.) Mill. plants are calcitrophic (Lütge, 2004) and that probably taken up more Ca than P because their high soil availability in the experimental site. Knetch and Göranson (2004) pointed out that plants might take up nutrients in excess of their requirements for growth, and sometimes concentrate them at high levels, then nutrients become toxic and the growth decrease. This was not the case regarding Ca and P because plant growth depended on their accessibility and most of their concentration values were within the known sufficiency ranges.

It deserves be noted that the evidenced order of nutrient requirements taking into account estimated means implies the following general proportion (N:P:K:Ca:Mg, with nitrogen, set to 100, as reference) on a mass basis: 100:34:404:36:146. Then, these general ratios disagree with those reported for phytoplankton and most of the terrestrial plants. For instance, Knetch and Göranson (2004) reported the following nutrient ratios (N:P:K:Ca:Mg) for herbaceous plants: 100:14.3:68.3:8.3:8.7. These differences could be associated to organs or tissues used for measurements (leaves and cladodes). However, both leaves and cladodes are photosynthetic. Future work should therefore include nutritional standards, growth, yield and nutrient stoichiometry.

Table 4. Pearson correlations (r) between nutrient ratios and yield in *Opuntia ficus–indica* (L.) Mill. (n = 250).

Nutrient ratio	Yield (kg Plant^{-1})
K/lnCa	0.084
	p=0.187
K/ln Mg	0.094
	p=0.139
K/lnP	**0.236**
	p=0.0001
K/lnN	–0.052
	p=0.417
lnCa/lnMg	0.014
	p=0.820
lnCa/lnP	**0.236**
	p=0.0001
lnCa/lnN	**–0.132**
	p=0.038
lnMg/lnP	**0.232**
	p=0.0001
lnMg/lnN	**–0.152**
	p=0.016
LnP/lnN	**–0.278**
	p=0.0001

Pearson correlation coefficients (r) significant at p<0.05 are in bold.

Conclusions

Yield of *O. ficus–indica* plants was related ($p \leq 0.05$) to N, Mg, Ca and K concentrations in one–year old cladodes.

It was noted that K:ln P, ln Ca:lnP and ln Mg:ln P ratios had a positive effect on yield. In addition, ln P:ln N, ln Mg:ln N and ln Ca:ln N ratios had a negative effect on biomass production.

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