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ORIGINAL PAPER

Boundary-Line Approach Macro-Nutrient Standards for *Opuntia ficus-indica* (L.) Miller Variety "Rojo Pelón" Fruiting

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Abstract

The aim of this research work was to identify the Boundary-Line Approach (B-LA) macro-nutrient optimum concentrations linked to maximum yield and sufficiency ranges at 90% maximum yield per 1-year-old fructification cladode for *Opuntia ficus-indica* (L.) Miller variety "Rojo Pelón". Four years' (2012–2015) data of yield per fructification cladode and macro-nutrient concentration [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), or magnesium (Mg)] were used to elaborate bivariate scatter diagrams ($n = 228$). Selection from 9 to 11 points was performed to estimate quadratic functions as boundary-lines in each bivariate scatter diagram. The vertices allowed estimation of the optimum macro-nutrient concentrations: ln N = 2.32 (10.20 g kg^{-1}), P = 3.04 g kg^{-1}, K = 35.18 g kg^{-1}, Ca = 36.65 g kg^{-1}, Mg = 13.83 g kg^{-1}. The target maximum yield per fructification cladode varies between 1901.13 and 1984.41 g. The estimated sufficiency ranges at 90% of the maximum yield are ln N = 2.07–2.59 (7.86–13.40 g kg^{-1}), P = 2.54–3.54 g kg^{-1}, K = 25.36–45.01 g kg^{-1}, Ca = 27.96–45.35 g kg^{-1}, and Mg = 10.3–17.38 g kg^{-1}. These nutrient standards may be used as a reference for maximizing yield per fructification cladode in *O. ficus-indica*, specifically for the variety "Rojo Pelón".

Keywords Nitrogen · Phosphorus · Potassium · Calcium · Magnesium · Cactus pear

1 Introduction

Tissue analysis can be a useful tool for estimating plant nutrient status, maximizing crop yield, and evaluating fertilizer requirements. Then, the use of tissue analysis as a diagnostic criterion requires knowledge about the relationships between yield and plant nutrient concentrations (Reis Junior and Monnerat 2003). Good relationships between crop performance and plant nutrient status are expected when an involved nutrient is a limiting factor (Dow and Roberts 1982; Blanco-Macías et al. 2010). Improvements in nutrient status should be led by a balanced and adequate supply of macro- and micronutrients for growth and yield focused on nutrient requirements. Thus, it is necessary to know optimum nutrient concentrations (i.e., nutrient requirements) and/or sufficiency ranges of nutrients useful for correct diagnosis and improvements of nutrient status of cultivated plants (Blanco-Macías et al. 2009, 2010).

This contribution is part of Evelyn Hernández-Vidal's Ph. D. thesis

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Commonly, optimum, critical concentrations, and sufficiency ranges are key in plant nutrient diagnosis. Moreover, the determination of nutrient critical values and nutrient balances in plant-diagnostic models (Walworth et al. 1986) has been carried out by using the principle of the Boundary-Line Approach (B-LA). Also, the B-LA has been used to describe the relationship between soil nutrient concentrations and crop yields (e.g., Evanylo 1990). The B-LA considers the upper limits of the scatter of points in a bivariate scatter diagram and would delineate the response of the dependent variable to a particular independent variable when other variables were not limiting. The scatter of points below the boundary line may be due to errors in measurement, variability in biological data, and overall variation caused by other interacting or controlling factors (Webb 1972).

B-LA standards have been developed for several crops, including *Miscanthus sinensis* Andersson (Eulalia grass), *Phalaris arundinacea* L. (Reed canary grass), and *x Triticosecale* Wittm ex *A. Camus* (Triticale) (Lewandowski and Schmidt 2006), *Acer saccharum* Marshall (Sugar maple) (Vizcayno-Soto and Côté 2004), *Picea glauca* (Moench) Voss (White spruce) (Quesnel et al. 2006), *Zea mays* L. (Maize) (Walworth et al. 1986), *Areca catechu* L. (Arecanut) (Bhat and Sujatha 2013), *Vaccinium angustifolium* Aiton (Wild lowbush blueberry) (Lafond 2013), *Mangifera indica* L.(Mango) (Ali 2018), and *Opuntia ficus-indica* (L.) Miller (Nopal) (Blanco-Macías et al. 2009, 2010). However, in the *O. ficus-indica* case, the B-LA nutrient standards were developed under the basis of relationships between 1-year-old cladode macro-nutrient concentrations and produced yearly cladode fresh matter (Blanco-Macías et al. 2009, 2010). Recently, sufficiency ranges have been proposed for *O. ficus-indica* dry matter production by Alves (2017) and Teixeira et al. (2019).

Studies on *Opuntia* nutrient requirements are outdated and fragmented (Mayer and Cushman 2019) although *O. ficus-indica* species is becoming an important crop in various countries around the world. It is cultivated due its tender shoots are widely used for human consumption as vegetables, its mature cladodes are frequently used for animal feed, and its fruits are produced and considered of high-value in at least 18 countries (Russell and Felker 1987; Blanco-Macías et al. 2010). Its whole fruit, pulp, flowers, seeds, and peel contain various groups of bioactive compounds including phenolic acids, flavonoids, anthocyanins, carotenoids, betalains, sterols, lignans, saponins, vitamin E, and vitamin C (Tahir et al. 2019). The identified bioactive compounds have demonstrated to be endowed with biologically relative activity such as antioxidant, antimicrobial, anticancer, anti-diabetes mellitus, hypertension, hypercholesterolemic, rheumatic pain, antiulcerogenic activity, gastric mucosa diseases, and asthma (Tahir et al. 2019). For instance, its fruit extract has pH-sensitive, antioxidant, and antimicrobial abilities (Yao et al. 2020).

Information on *O. ficus-indica* nutrition allows for discarding the prevailing common opinion about cactus crop needs low inputs to give high yields. A low number of studies have documented the macro- and micro-element concentrations in cladodes. Several of them have been focused on the mineral contents of cladodes to demonstrate their forage potential. Other studies have been focused on element contents in tender pads and fruits to determine their nutritional contribution to the human diet. A few research works have involved 1-year-old cladode mineral contents and biomass or fruit production relationships.

For instance, macro-nutrient concentrations in 1-year-old fruiting cladodes of *Opuntia dillenii* are as follows (Kalegowda et al. 2015): phosphorus, $P = 0.152$ g kg^{-1}; potassium, $K = 22.43$ g kg^{-1}; calcium, $Ca = 29.38$ g kg^{-1}; and magnesium, $Mg = 9.86$ g kg^{-1}. In addition, estimated macro-element contents in 1-year-old cladodes of *O. ficus-indica* were as follows: nitrogen $(N) = 11.36$ g kg^{-1}, $P = 0.8$ g kg^{-1}, $K = 47.8$ g kg^{-1}, $Ca = 50$ g kg^{-1}, and $Mg = 14.2$ g kg^{-1} when trees were growing under field conditions (Mayer and Cushman 2019), whereas the concentrations were $N = 42.21$ g kg^{-1}, $P = 7.1$ g kg^{-1}, $K = 73.6$ g kg^{-1}, $Ca = 41.6$ g kg^{-1}, and $Mg = 21.2$ g kg^{-1} when plants were growing under greenhouse conditions (Mayer and Cushman 2019).

Other research works have been focused on the effect of soil fertilization on fruit production. For example, nitrogen fertilization (0, 60, 120 kg ha^{-1}) did not affect flower bud formation in *O. ficus-indica* (Nerd and Mizrahi 1994). No *O. ficus-indica* fruit response was obtained in the case of fertilizer application even comparing application rates of 100 kg ha^{-1} N, 50 kg ha^{-1} P, 100 kg ha^{-1} K, and 50 kg ha^{-1} Mg to the control that had never been fertilized (Karim et al. 1997; Galizzi et al. 2004). Nitrogen and phosphorus fertilization (0–0, 0–80, 40–40, 60–0, and 60–80 kg ha^{-1} N-P_2O_5) had no effect on *O. ficus-indica* fruit yielding in the first year; however, the doses 60 kg ha^{-1} N or 80 kg ha^{-1} N-P_2O_5 alone increased the fruit yield by +3 and + 6.1 kg plant^{-1}, respectively, compared with the control (Arba et al. 2017). Those results suggest that fertilizer/response is difficult due to the high moisture content of cladodes and the large mass of *Opuntia*'s buffers nutrient changes (Felker and Bunch 2009).

All these prior research works did not relate cladode nutrient concentrations with yield or quality of yield in terms of fruit (prickly pear or cactus pear) per 1-year-old cladode through statistical trends or functions. This means that nutrient storage at the plant and cladode levels and best fit plant requirements for fruiting remain practically unknown (Inglese et al. 1995). So, we hypothesize that *O. ficus-indica* plants pose macro-nutrient requirements in terms of optimum concentrations and sufficiency ranges for producing fruits. Then, the aim of this research work was to identify the B-LA macro-nutrient optimum concentrations related to maximum yield and sufficiency ranges at 90% maximum yield per 1-year-old fructification cladode for *O. ficus-indica* variety "Rojo Pelón".

2 Material and Methods

2.1 Study Site

An orchard was established in 2006 at the experimental field of the "Centro Regional Norte Universitario Centro Norte" of the "Universidad Autónoma Chapingo" at 22° 44′ 49.6″ north latitude, 102° 46′ 28.2″ west longitude and 2296 masl, near the city of Zacatecas, Mexico. The regional climate is classified as BS1kw (w), i.e., temperate semiarid climate, with an average annual temperature that varies between 12 and 18 °C, an average annual rainfall of 472 mm, and most of the precipitation (> 65%) occurs from June to August.

The soil at the site had a clay loam texture, a very slightly alkaline pH (7.5), and high content matter (3.23%). Extractable nutrient levels were as follows: availability for inorganic N was low (15 mg kg^{-1}), very high for P (40.5 mg kg^{-1}), medium for K (230 mg kg^{-1}), high for Ca (4371 mg kg^{-1}), moderately high for Mg (569 mg kg^{-1}), moderately low for iron (Fe, 7.85 mg kg^{-1}), very high for copper (Cu, 7.47 mg kg^{-1}), excessive for zinc (Zn, 14.6 mg kg^{-1}), moderately for manganese (Mn, 6.13 mg kg^{-1}), and medium for boron (B, 1.59 mg kg^{-1}). The high content of organic matter can be due to the plot has been used as a fruit orchard during the previous 50 years, involving regular organic soil amendment with cow manure and incorporation of tree's foliage on the ground. The high content of Ca may be associated with the calcareous origin of the soil.

The orchard was established using 20 mother cladodes. Plant density was 625 plants ha^{-1}. Then, 20 trees with a natural vessel-shaped structure were growing. The management of the orchard consisted of removing weeds each year at the end of spring and summer through minimum tillage. Fertilization, irrigation, and other agronomic practices were not performed.

2.2 Sample Collection and Analysis

Two hundred twenty-eight fruiting cladodes and 1744 fruits of *O. ficus-indica* variety "Rojo Pelón" were considered in this research. Fruiting cladodes and their fruits were taken during four consecutive years (2012–2015). The collection was carried out as follows: 2012, 60 cladodes and 474 fruits; 2013, 52 cladodes and 364 fruits; 2014, 56 cladodes and 420 fruits; and 2015, 60 cladodes and 516 fruits. All cladodes were selected from the uppermost part of the trees to ensure they were 1-year-old. We selected cladodes having from 1 to 15 fruits; four cladodes having each of these numbers of fruits were selected from different plant orientations (north, south, east, and west). None of these cladodes had young shoots. All fruits were harvested when most of the fruits showed peel coloration change indicating the beginning of fruit ripeness.

All 1-year-old cladodes and their fruits were identified. Each fruit weight was registered. Besides, all 228 detached fruiting cladodes were cleaned with distilled water and immediately weighed. Afterward, the cladodes were cut into slices and dehydrated to constant weight in an oven at 75 °C for 36 h, and then their dry weights were registered.

Dry tissue of cladode samples was milled and then digested with a mixture of hydrochloric and nitric acids ($HCl:HNO_3$, 3:1). Afterward, these samples were used to determine macro-nutrient concentrations. The N concentration was determined by the Kjeldahl method, whereas the P content was estimated by reduction with the molybdo-vanadate technique using an optical photo spectrometer (Thermo Spectronic, Helios Epsilon model, USA®). The K, Ca, and Mg concentrations were determined with an atomic absorption spectrophotometer (UNICAM Solar model 9626).

2.3 Boundary-Line Approach Standards

A database of N, P, K, Ca, and Mg concentrations (g kg^{-1}) in all 228 fruiting cladodes and their fruit weights (g) was used to develop boundary-line approach standards for *O. ficus-indica* variety "Rojo Pelón" as described by Blanco-Macías et al. (2010) and Ali (2018). The boundary-line is formed when all values for two variables are plotted and a line enclosing most of these points is established (Michael et al. 1985). The boundary-line represents the limiting effect of the independent variable on the dependent one (Webb 1972; Lark 1997); then, it is assumed that all values below such a line result from the effect of another independent variable or a combination of variables that are limiting the dependent variable (Webb 1972). Detailed information regarding B-LA can be obtained from Blanco-Macías et al. (2010) and Ali (2018).

Boundary-lines can be described by quadratic functions as maximization curves; therefore, we split each macro-nutrient concentration range into 9 to 11 classes and choose the observation linked to each class's highest yield per fruiting cladode. These datasets were used to fit quadratic functions ($Y = aX^2 + bX + c$). Estimation of the maximum value of the yield per fruiting cladode (dependent variable) and the optimum value of the macro-nutrient concentration (independent variable) was performed by calculating the vertex [vertex $X = -b/2(a)$] in each bivariate case. Besides, macro-nutrient sufficiency ranges and critical concentrations at 90% of maximum yield per fruiting cladode were calculated by solving the estimated quadratic functions ($[-b \pm \sqrt{}b2–4(a)(c)]/2(a)$).

3 Results

In this research work, yield per fructification cladode dependence on macro-nutrient concentrations in 1-year-old cladodes of *O. ficus-indica* variety "Rojo Pelón" was studied to define its macro-nutrient standards. Thus, relationships were evidenced through the B-LA.

Table 1 Basic statistics of *Opuntia ficus-indica* (L.) Miller variety "Rojo Pelón" yield per fructification cladode and N, P, K, Ca, and Mg concentrations in 1-year-old fruiting cladodes (n = 228)

Statistic	Yield (g cladode^{-1})	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})
Mean	795.16	11.67	2.86	32.06	38.45	13.65
Standard deviation	469.79	3.58	0.55	11.69	9.47	2.85
Coefficient of variation	59.08	30.69	19.38	36.48	24.62	20.88
Minimum	60.00	6.00	1.56	13.12	13.00	5.94
Maximum	2186.00	21.70	4.20	65.36	63.50	21.50

Basic statistic estimators of yield per fructification cladode and nutrient concentrations in 1-year-old fruiting cladodes can be appreciated in Table 1. The estimated fruiting cladode mean nutrient concentrations are N = 11.67 g kg^{-1}, P = 2.86 g kg^{-1}, K = 32.06 g kg^{-1}, Ca = 38.45 g kg^{-1}, and Mg = 13.65 g kg^{-1}, whereas the mean yield per fructification cladode is 795.16 g. Also, results suggest that yield shows high variability (CV = 59.08%); P, Mg, and Ca concentrations have moderate variability (CV = 19.38%, CV = 20.88%, and CV = 24.62%, respectively); and K and N show high variability (CV = 36.48% and CV = 30.69%, respectively). Variability is an important issue to get the planned aim. Therefore, our database can be used to identify the dependence of yield per fruiting cladode on cladode nutrient concentrations for the *O. ficus-indica* variety "Rojo Pelón".

It deserves to be noted that concentrations of P, K, Ca, and Mg were normally distributed but those of N did not. Thus, N concentration values were transformed to the natural logarithm (ln); so, ln N values were involved in the analysis.

3.1 Boundary-Line Approach Standards

Bivariate scatter diagrams involving fruit yield and each nutrient expression show that most of the data is grouped at the graph bottom, that is, at lower fruit yields. As a result, it was easy to choose several boundary points, which were used to estimate the boundary-line in each scatter diagram. In fact, from 9 to 11 boundary points (Table 2) were selected to be involved in the estimation of reliable boundary-lines as pointed out by Schmidt et al. (2000). The estimated quadratic boundary-lines were good-adjusted (R^2 values > 0.8) as can be appreciated in Table 2.

The estimated vertexes using parameter values of the quadratic functions indicate optimum concentrations could be as follows: ln N = 2.32 (N = 10.20 g kg^{-1}), P = 3.04 g kg^{-1}, K = 35.18 g kg^{-1}, Ca = 36.65 g kg^{-1}, and Mg = 13.83 g kg^{-1}. The corresponding estimated maximum yields per fructification cladode varies between 1901.13 and 1984.41 g (Fig. 1).

The estimated boundary-line sufficiency ranges at 90% maximum yield are the following: ln N = 2.07–2.59 (N = 7.86–13.40 g kg^{-1}), P = 2.54–3.54 g kg^{-1}, K = 25.36–45.01 g kg^{-1}, Ca = 27.96–45.35 g kg^{-1}, and Mg = 10.3–17.38 g kg^{-1}. The linked 90% maximum yields per fruiting cladode changes between 1711 and 1785.96 g (Fig. 1).

4 Discussion

Mean macro-nutrient concentrations (Table 1) and the estimated optimum concentrations suggest that the requirement descending order is Ca > K > Mg > N > P. On the other hand, the extreme concentrations (minimum and maximum, Table 1) indicate that the requirement decreasing order is K ≥ Ca > N ≥ Mg > P. Both orders suggest *O. ficus-indica* variety "Rojo Pelón" plants tend to concentrate much more Ca and K than N in their 1-year-old fruiting cladodes, proving that they are calcitrophic organisms (Lüttge 2004). These requirement orders may be explained due to *Opuntia* spp. fruits growing on 1-year-old cladodes concentrate much more K and Ca than Mg, N, and P (e.g., Lamghari El Kossori et al. 1998; Kalegowda et al. 2015); also, these macro-nutrient cations (K, Ca and Mg) are competing nutrients (Marschner 2012); indeed, Ca concentration may decrease as K content increases as driven by K antagonism or luxury consumption (Marschner 2012).

Table 2 Statistics of boundary-lines fitted by second-degree functions: $Y = ax^2 + bx + c$, where Y is *Opuntia ficus-indica* (L.) Miller yield (g) per fructification cladode; x is the nutrient concentration (g kg^{-1}) in 1-year-old fruiting cladode; a, b and c are regression coefficients; R^2 is the coefficient of determination; and n^y is the number of points used to estimate regression equation coefficients

		Regression coefficients			
Nutrient (x)	n^y	a	b	c	R^2
ln N (g kg^{-1})	11	− 2765.600	12,883.00	− 13,092.00	0.83
P (g kg^{-1})	10	− 764.750	4652.00	− 5171.10	0.88
K (g kg^{-1})	9	− 2.052	144.39	− 555.98	0.97
Ca (g kg^{-1})	10	− 2.517	184.51	− 1480.00	0.87
Mg (g kg^{-1})	10	− 15.294	423.32	− 1014.60	0.83

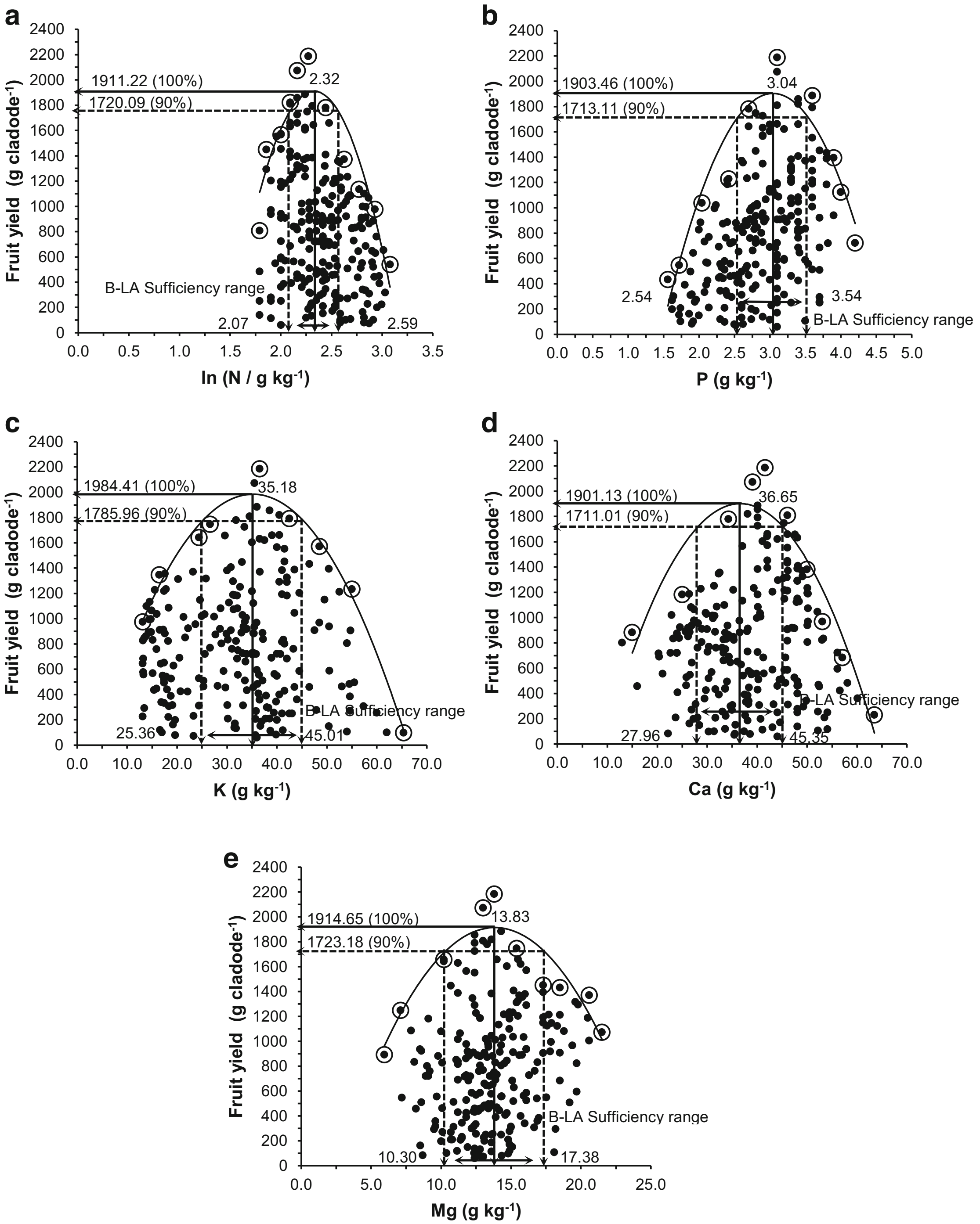

Fig. 1 Relationships between nutrient concentrations (g kg^{-1}) in 1-year-old fruiting cladodes and *Opuntia ficus-indica* (L.) Miller variety "Rojo Pelón" fruit yield (g cladode^{-1}) ($n = 228$) showing boundary-lines described by second-degree functions using the independent variables ln nitrogen (**a**), phosphorus (**b**), potassium (**c**), calcium (**d**), and magnesium (**e**). See Table 2 for fitted quadratic functions

There is noticeable that fruiting occurred on cladodes with concentrations surpassing the following minimum values: N = 6 g kg^{-1}, P = 1.56 g kg^{-1}, K = 13.12 g kg^{-1}, Ca = 13, and Mg = 5.94 g kg^{-1}. The mentioned fruiting cladode N minimum concentration (i.e., 6 g kg^{-1}) is strongly higher than the N concentration (1.8 g kg^{-1}) reported by Blanco-Macías et al. (2010) as the minimum required for the production of vegetative buds in *O. ficus-indica*. On the other hand, the Mg minimum concentration (5.94 g kg^{-1}) is lower than the Mg concentration (7.8 g kg^{-1}) reported by Blanco-Macías et al. (2010) as the minimum required for *O. ficus-indica* vegetative growth. However, minimum concentrations of P, K, and Mg appear to be similar for both purposes, that is, for the production of fruits and new cladodes. The noted discrepancies could be due to differences in plant age, type of sampled cladode (with new cladodes or fruits), plant density, and the genotype, among other factors. It is widely known flowers and cladodes appear simultaneously in spring; the flowers occur mostly at the crown edge of 1-year-old cladodes whereas new cladodes usually develop on 2-year-old or even older cladodes (Inglese et al. 1994).

The minimum macro-nutrient concentrations required for producing fruits might be an important issue to avoid variation between productivity levels in successive years. It can provide a convenient index for predicting which 1-year-old cladodes will produce fruits. They should be used together with the proposed boundary-line standards to perform reliable nutrient diagnosis, and then, adequate fertilization practice can be recommended having in mind the management of nutrient balance for fruit production.

Notably, this is the first study to our knowledge proposing boundary-line approach macro-nutrient standards for *O. ficus-indica* fruiting. It was possible because normal distributions were found for macro-nutrient concentrations in fructification cladodes (N content was ln distributed) and bivariate observations (yield per 1-year-old fructification cladode against macro-nutrient concentrations, Fig. 1).

Prior works were mainly focused on the estimation of *O. ficus-indica* nutrient requirements for biomass production (cladode's dry matter or fresh matter) as can be appreciated in Table 3. There are interesting differences between the Brazilian (Alves 2017; Teixeira et al. 2019) and the Mexican cases (Blanco-Macías et al. 2010; Valdez-Cepeda et al. 2013b; and the current work). The Brazilian P sufficiency ranges are notably lower than the Mexican ones. Brazilian K sufficiency ranges lie within that of the present case but their extreme limits are lower than those pointed out by Blanco-Macías et al. (2010) and Valdez-Cepeda et al. (2013b), and the lower value of the K sufficiency range of the present case is markedly lower than the others. The extreme values of the Brazilian Ca and Mg sufficiency ranges are lower than those of the Mexican ranges. In general, the upper limits of the Brazilian N sufficiency ranges tend to be higher than the Mexican ranges, and the N sufficiency range of the current case is strongly lower than the others.

The noted differences between the Brazilian and Mexican sufficiency ranges could be mainly linked with the involved genotype, environmental conditions, and management practices. For instance, Brazilian experimental sites are much more humid and warmer than the Mexican sites. Besides, the appreciated discrepancies between the results of the current case and the others could also be associated with the type of sampled cladodes (vegetative cladodes or fruiting cladodes). The lower N sufficiency range and the lower limit of the K sufficiency range in mature fruiting cladodes may be explained because these organs serve as a source of N and K for flowering and fruit development. This means that 1-year-old fruiting cladodes may support reductions in dry weight (García de Cortázar and Nobel 1992) between flowering and fruit growth. Fruiting occurs when the cladode dry weight surpasses 14.4 g referred to as "cladode excess dry weight" in *O. ficus-indica* variety Rojo Pelón (Valdez-Cepeda et al. 2013a), and of course, all involved 1-year-old fruiting cladodes in our work had dry weights higher than that cladode excess dry weight.

We propose standards that involve optimum concentrations (N = 10.20 g kg^{-1}, P = 3.04 g kg^{-1}, K = 35.18 g kg^{-1}, Ca = 36.65 g kg^{-1}, Mg = 13.83 g kg^{-1}); the target maximum yield per fructification cladode varies between 1901.13 and 1984.41 g. In addition, the norms involve macro-nutrient sufficiency ranges at 90% maximum yield (N = 7.86–13.40 g kg^{-1}, P = 2.54–3.54 g kg^{-1}, K = 25.36–45.01 g kg^{-1}, Ca = 27.96–45.35 g kg^{-1}, and Mg = 10.3–17.38 g kg^{-1}. All these optimum contents and sufficiency ranges indicate that *O. ficus-indica* plants require macro-nutrients in the following descending order Ca > K > Mg > N > P. Both nutrient standard types may be used as a reference for maximizing yield per fructification cladode in *O. ficus-indica*, specifically for the variety "Rojo Pelón". Uses of nutrient standards can be found in the scientific literature. For instance, in a surprising experience, Arba et al. (2017) pointed out that they successfully used the Compositional Nutrient Diagnosis approach nutrient standards for *O. ficus-indica* fresh matter production as developed by Valdez-Cepeda et al. (2013b) to identify the best soil fertilization dosage for *O. ficus-indica* cv. "Moussa" fruit yield and fruit size improvements. Nonetheless, future works should dedicate efforts to increase the database by involving more *O. ficus-indica* fruit production sites and to a refinement of target values for soil available nutrient concentrations by using other varieties and species; in fact, plants take up

Table 3 Macro-nutrient sufficiency ranges in 1-year-old cladodes for *Opuntia ficus-indica* (L.) Miller with different purpose as proposed by several authors

Source	Response	Target yield	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})
Blanco-Macías et al. (2010)	Fresh matter	> 27.01 kg Plant^{-1}	8.40–20.30	2.40–4.20	38.20–50.80	31.80–45.20	14.30–20.90
Valdez-Cepeda et al. (2013b)	Fresh matter	> 27.01 kg Plant^{-1}	6.20–16.60	2.70–4.10	33.70–50.90	28.50–56.50	11.80–20.60
Alves (2017)	Dry matter	> 21.80 t ha^{-1} cycle^{-1}	12.70–18.50	1.00–1.80	31.60–44.10	23.20–32.80	9.50–14.30
Teixeira et al. (2019)	Dry matter	> 18.12 t ha^{-1} cycle^{-1}	13.03–18.21	0.80–2.12	30.74–45.04	23.3–32.76	9.07–14.69
This work	Fruit yield	> 1901 g cladode^{-1}	7.86–13.40	2.54–3.54	25.35–45.02	27.96–45.34	10.30–17.38

most of the mineral nutrients that they require from the soil; then, information on soil fertility should also be collected.

Variation of macro-nutrient concentrations in 1-year-old fructification cladodes may be explained because old cladodes function as stems and branches. So, these organs play a key role in the reallocation of nutrients toward vegetative and floral buds (new cladodes and fruits). It is known differences in nutrient conservation from one growing season to the next can cause changes in growth responses of perennial plants to dual nutrient (e.g., N/P) supply ratios (Güsewell et al. 2003). Some species show the same patterns in nutrient concentrations and dual nutrient ratios, whereas others have high nutrient contents and low dual ratios even at nutrient-poor soils (Güsewell et al. 2003). Then, an evidenced variation of macro-nutrient contents may be linked to atmospheric conditions; so, future research work should be considering environmental (or weather) variables and fruit yield relationships.

In general, our results provide compelling pieces of evidence about yield increasing and decaying trends departing from macro-nutrient optimum concentrations or extreme values of their sufficiency ranges at 90% maximum fruit yield in *O. ficus-indica* variety “Rojo Pelón” (Fig. 1). Strongly, our results appear to confirm the validity of several scientific laws and principles; for instance, Sprengel’s “Law of the Minimum” (van der Ploeg et al. 1999), Mitscherlisch’s “Law of Diminishing Returns”, and Wallace’s “Law of the Maximum” (Velayutham 2017), and “Critical Levels of Deficiency and Toxicity”. Our results may also be supported on the “Response Model” of the “Diagnosis-Recommendation Integrated System” as pointed out by Sumner and Farina (1986) and Walworth and Sumner (1987). All the reliable five boundary functions were estimated because each bivariate dataset contained several instances in which the involved nutrient (N, P, K, Ca, or Mg) was limiting the fruit yield as crop response. In other words, each estimated boundary-line might be representing the response of fruit yield to the corresponding macro-nutrient in a model expressing the “Law of the Minimum” (Lark et al. 2020). Besides, the decaying trend after the upper concentration (Critical Level of Toxicity) of each macro-nutrient sufficiency range might be expressing the “Law of the Diminishing Returns”.

The proposed optimum macro-nutrient concentrations and sufficiency ranges for *O. ficus-indica* variety “Rojo Pelón” fruiting have limitations due to nutrients are treated separately. For instance, these standards do not account for nutrient interactions and nutrient balances. Nutrient concentrations (as compositional data) are parts of a whole (Parent et al. 2013)—really a complex system—bounded between zero and the unit of measurement, i.e., 1, 100%, 1000 g kg^{-1}, or 1,000,000 mg kg^{-1}. Thus, several properties of compositional data were not considered because these nutrient norms do not involve the corresponding compositional space. As a consequence, future works should develop nutrient norms useful to perform diagnosis and recommendations focused on nutrient concentrations in plant tissue or organ of reference as compositional space (e.g., Parent et al. 2013). From this point of view, the compositional or ionomic profile of plants can reflect effects or adaptations to the local environment, especially to levels of soil factors (e.g., salinity and pH) and atmospheric conditions (i.e., weather). In some cases, local adaptations could be driven by ionomic loci (Huang and Salt 2016).

5 Conclusions

There can be no doubt knowing macro-nutrient requirements for *Opuntia ficus-indica* (L.) Miller fruit production and quality improvements is an important horticultural issue. These requirements can be used as references to improve yields. In this context, the yield per fructification cladode dependence on each macro-nutrient concentration in 1-year-old fruiting cladodes of *O. ficus-indica* variety “Rojo Pelón” was evidenced through the boundary-line approach. The estimated optimum contents are N = 10.20 g kg^{-1}, P = 3.04 g kg^{-1}, K = 35.18 g kg^{-1}, Ca = 36.65 g kg^{-1}, and Mg = 13.83 g kg^{-1}; the corresponding estimated maximum yields per fructification cladode vary between 1901.13 and 1984.41 g. In addition, the calculated macro-nutrient sufficiency ranges at 90% maximum yield (between 1711 and 1785.96 g) are N = 7.86–13.40 g kg^{-1}, P = 2.54–3.54 g kg^{-1}, K = 25.36–45.01 g kg^{-1}, Ca = 27.96–45.35 g kg^{-1}, and Mg = 10.3–17.38 g kg^{-1}. These nutrient standards may be used as a reference for maximizing yield per fructification cladode in *O. ficus-indica*, specifically for the variety “Rojo Pelón” through the application of chemical and/or organic fertilizers.

Notable differences were evidenced when these results were compared with *O. ficus-indica* requirements for fresh and dry matter production under different environments. Nonetheless, these standards do not account for nutrient interactions and nutrient balances. Then, future works should develop nutrient norms and diagnosis focused on macro- and micro-nutrient concentrations in 1-year-old fruiting cladodes as compositional spaces. So, researchers should consider the ionomic profile of specific genotype plants that can reflect effects or adaptations to a local environment, especially to levels of soil factors and atmospheric conditions, mainly weather.

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Data Availability Data will be available through request.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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