Fruit attributes depend on cladode length and width in *Opuntia ficus-indica* variety 'Rojo Pelón' in Zacatecas, Mexico

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ABSTRACT

Opuntia ficus-indica (L.) Miller is an important crop in Mexico and around the world. This species grows in a wide range of environmental conditions. This implies a great variability in fruit yield and fruit ripening. The aims of this three-year study were: i) to compare *O. ficus-indica* fruit and cladode size attributes among years by means of the Tukey test, and ii) to estimate *O. ficus-indica* fruit attributes dependence on length or width of 1-year old fruiting cladode measures for the 'Rojo Pelón' variety through the boundary-line approach. Data from 169 terminal 1-year old fruiting cladodes and their 1,281 fruits were collected during 2012, 2013, and 2014 from an experimental orchard in Zacatecas, Mexico. The boundary-line approach was used to identify the dependence of number of fruits, mean fruit weight or load per cladode on 1-year fruiting cladode's length or width. Influence of rainfall was identified increasing the fruit weight per cladode, but not the number of fruits. Fruiting occurred when cladodes have at least 16 cm length and 11 cm width. Cladodes with ≈ 18.5 cm to ≈ 50 cm of length are linked to the vertex (X= 37.7 cm, Y= 154.1 g) and cladodes with ≈ 12 cm to ≈ 25 cm of width are linked to the vertex (X=17.5 cm, Y= 156.8 g). Pruning based on these cladode sizes may reduce variability of fruit yield and increase the probability of having 105.7 g (or more) of mean fruit weight per cladode leaving eight fruits or more with an acceptable commercial size.

***Keywords*:** cactus pear; fruiting cladodes; "nopal de castilla"; pruning.

INTRODUCTION

Opuntia ficus-indica (L.) Miller (nopal de castilla) is the cacti species with most agronomic interest (Kiesling, 1995). This species is cultivated for its fruit (tuna or prickly or cactus pear) in Mexico and at least in another 19 countries, typically in dry areas around the world (Nobel, 2011). In Mexico, about 70,000 hectares are used for the cactus pear production using various *Opuntia* species. Mexico is the country with more than half of the production of this fruit in the world (Nobel, 2011). In addition, *O. ficus-indica* is also cultivated for its tender shoots ("nopalitos"). Tender shoots are widely used for human consumption as vegetables and mature cladodes are frequently used for animal feed (Rusell and Felker, 1987; Pimienta-Barrios, 1994; Guevara *et al*., 2009). The cultivation of this species is becoming more common in other areas of the world because of its rapid growth rate, undemanding propagation and high water use efficiency (Snyman, 2013; Louhaichi *et al*., 2015).

Technical aspects of *O. ficus-indica* orchard management and its propagation have been relatively well investigated (Barbera, 1984; Wessels, 1988), but the biology and management of flowering and fructification are incomplete or not well known (Barbera *et al*., 1996; Valdez-Cepeda *et al*., 2013). Such information is necessary because of the wide range of environmental conditions in which *O. ficus-indica* grows, which involves a great variability in fruit ripening and fruit yield (Inglese *et al*., 2012).

Incorrect pruning and complex interactions between developing fruits and vegetative growth may determine the high variability of fruit yield that is observed at the orchard, plant and even cladode levels (Valdez-Cepeda *et al*., 2013; Valdez-Cepeda *et al*., 2014). However, fruit yield and fruit quality in relation to within-tree factors such as cladode attributes, fruiting cladode position and plant architecture have been poorly explored (García de Cortázar and Nobel, 1992; Inglese *et al*., 1995). In this context, a prior 1-year study (i.e. Valdez-Cepeda *et al*., 2014) indicates the need for multi-year investigation on the relationship between fruit attributes and cladode characteristics.

Variability of fruiting cladode fresh and dry weight among years have been demonstrated by López-García *et al*. (2016). However, variability fruiting cladode width and length among years remains not documented although those attributes may be easily managed by means pruning (Valdez-Cepeda *et al*., 2014). This is why we suggest that obtaining predictable fruit yields in *O. ficus-indica* require multi-year research on the relationship between fruit production and physical cladode attributes. Thus, in this 3-year study, the main objectives were: i) to compare *O. ficus-indica* fruit and cladode size attributes among years by means of the Tukey test, and ii) to estimate *O. ficus-indica* fruit attributes dependence on length or width of 1-year old fruiting cladode measures for the 'Rojo Pelón' variety through the boundary-line approach. This variety is currently an important genotype for fruit production in central Mexico because of its fruit quality and its freezing tolerance (Blanco-Macías *et al*., 2010). In addition, knowledge on this variety is scarce.

MATERIALS AND METHODS

Experimental site

The study took place at an experimental orchard established in June 2006 at the Centro Regional Universitario Centro Norte, Universidad Autónoma Chapingo (Latitude 22° 44'49.6'' North; Longitude 102° 46'28.2'' West, at 2,296 masl), near the city of Zacatecas, Mexico. The density of the orchard was 625 plants·ha^{-1} [see Valdez-Cepeda *et al.* (2013) for further details of orchard design and establishment]. Climate of the region is semiarid;

the yearly average precipitation is 472 mm and the mean annual temperature varies between 12°C and 18°C. Most of the rainfall (65%) occurs from June to August. The 2009-2014 yearly mean rainfall values were registered at the meteorological station of the Unidad Académica de Agronomía of the Universidad Autónoma de Zacatecas; these values were 461.4 mm (2009), 464.2 mm (2010), 256 mm (2011), 296.8 mm (2012), 556.2 mm (2013) and 435.4 mm (2014). That station is near the experimental orchard. The soil at the experimental orchard is a clay loam of calcareous origin with, and its pH is 7.5; and it has an organic matter content of 3.2% [for more soil details see Blanco-Macías *et al.* (2010)].

Data

For this study, we selected fruiting cladodes during the years 2012, 2013 and 2014 from the uppermost part of the plants to ensure they were 1-year old. The selected cladodes had from one to 15 fruits; so, representative fruit production variability was included (Valdez-Cepeda *et al*., 2013). Four cladodes having each of these numbers of fruits were selected from different plant orientations (north, south, east and west) (Valdez-Cepeda *et al*., 2013). Collected fruiting cladodes and fruits were as follows: 2012, 60 cladodes and 480 fruits; 2013, 52 cladodes and 365 fruits; and 2014, 57 cladodes and 436 fruits. Number of fruits differences among years are due to availability of cladodes having from 1 to 15 fruits was not the same for all three years. In total, 169 terminal fruiting cladodes and 1281 fruits were considered for this study. All Fruits were harvested and weighted when most of them showed peel coloration change indicating the beginning of fruit ripeness. Afterwards, all cladodes were harvested and measured for length and width.

Statistical Analyses

Comparisons among years were performed by taking into account the fruit and cladode attributes through 1-way analyses of variance and Tukey tests at $p \leq 0.05$. We also studied the dependence of number of fruits per cladode (NFC), mean fruit weight per cladode (MFWC) and total fruit weight per cladode (TFWC) on fruiting cladode length (CL) and cladode width (CW); data were recorded in a database. Such a dataset was used for elaboration of scatter diagrams. After this, we applied the boundary-line approach as in Valdez-Cepeda *et al.* (2013) and Valdez-Cepeda *et al.* (2014) to describe the following bivariate relationships:

- Number of fruits per cladode versus cladode length (NFC vs CL)
- Number of fruits per cladode versus cladode width (NFC vs CW)
- Mean fruit weight per cladode versus cladode length (MFWC vs CL)
- Mean fruit weight per cladode versus cladode width (MFWC vs CW)
- Total fruit weight per cladode versus cladode length (TFWC vs CL)
- Total fruit weight per cladode versus cladode width (TFWC vs CW)

The boundary-line is then created when all values for two variables are plotted and a line enclosing these points is defined (Blanco-Macías *et al*., 2010). Such a line represents the limiting effect of the independent variable on the response (Web, 1992; Lark, 1997). It is assumed that all values below the line come from effect of another independent variable or a combination of factors that are limiting the dependent attribute (Web, 1992; Valdez-Cepeda *et al*., 2013).

RESULTS

The variables CL, CW, MFWC and TFWC shown high variability. On the other hand, NFC variability could be considered as moderately high (Table 1). Variability is an important aspect to get our objectives. Remarkably, the mean for 2014 for all the variables (except NFC) was higher than the means for 2013 and 2012 as pointed out by the Tukey test results.

Number of fruits per cladode (NFC) versus cladode length (CL)

According to the estimated quadratic functions, fruiting cladodes produced 12 fruits or more when CL was at least 18 cm for 2012, 20 cm for 2013, and 26 cm for 2014 (Table 2). With the calculated vertices, the highest NFC (15) occurred on cladodes with length of 35.7 cm in 2012 and 2014, whereas cladodes with 27.1 cm of length produced 13 fruits in 2013. The 3-year dataset results suggest that fruiting cladodes with 32.1 cm length were able to yield the maximum number of fruits (15); in addition, most of fruiting cladodes with 18 cm to 32 cm of length produced 12 fruits or more.

Table 1. Basic statistics of 1-year old fruiting cladodes and fruit attributes of *O. ficus-indica* (L.) Miller variety ‘Rojo Pelón’.

Variable	N	Year	Mean*	Standard deviation	Coefficient of variation	Minimum	Maximum
Cladode	60	2012	29.0[b]	5.0	17.4	16.0	40.0
length (CL)	52	2013	28.7[b]	4.3	14.9	17.5	37.0
(cm)	57	2014	35.4[a]	5.6	16.0	22.0	50.0
	169	3 yr	31.1	5.9	19.1	16.0	50.0
Cladode width	60	2012	16.5[c]	1.9	12.0	11.0	21.0
(CW)	52	2013	17.3[b]	1.7	10.3	12.0	21.0
(cm)	57	2014	20.0[a]	3.1	15.9	12.0	26.0
	169	3 yr	17.9	2.8	15.8	11.0	26.0
Number of	60	2012	8.0	4.3	54.4	1.0	15.0
fruits per	52	2013	7.0	3.7	53.9	1.0	13.0
cladode (NFC)	57	2014	8.0	4.1	54.4	1.0	15.0
	169	3 yr	8.0	4.1	54.3	1.0	15.0
Mean fruit	60	2012	76.4[c]	12.2	16.0	52.5	104.5
weight per	52	2013	99.2[b]	13.4	13.5	72.0	129.7
cladode	57	2014	115.6[a]	18.4	15.9	85.0	170.0
(MFWC)(g)	169	3 yr	96.6	22.1	22.9	52.5	170.0
Total Fruit	60	2012	583.6[b]	294.3	50.4	80.0	1186.0
weight per	52	2013	686.7[b]	362.1	52.7	72.0	1356.0
cladode	57	2014	857.1[a]	455.4	53.1	107.0	1780.0
(TFWC)(g)	169	3 yr	707.5	390.6	55.2	72.0	1780.0

*Different letters on the column indicate significant differences according to the Tukey test at $p \leq 0.05$.

Number of fruits per cladode (NFC) versus cladode width (CW)

Fruiting cladodes produced 8 fruits or more when CW was at least 13 cm and 14.5 cm for 2012 and 2013, respectively; and 12 fruit or more when CW was at least 17 cm for 2014. According to the calculated vertices, the highest NFC (15) occurred on cladodes with 18.8 cm and 22.2 cm width for 2012 and 2014, respectively; whereas cladodes with 18.9 cm width produced 13 fruits for 2013. Considering data of the three years, cladodes with 20.7

cm width were able to produce the maximum number of fruits (15). Besides, fruiting cladodes with 12 cm to 20.7 cm width produced six fruits or more (Figure 1).

Table 2. Estimated vertices to explain the relationships among cladode length and cladode width and the number of fruits per cladode, mean fruit weight and total fruit weight per cladode.

Variables	Year	Rainfall (mm)	Function	Vertex	
				X	Y
Number of fruits per cladode versus cladode length	2012	296.8	$y = -0.0078x^2 + 0.5574x + 4.9225$ $R^2 = 0.5299$	35.7	15.0
	2013	556.2	$y = -0.0387x^2 + 2.1013x - 15.454$ $R^2 = 0.4861$	27.1	13.0
	2014	435.4	$y = -0.0333x^2 + 2.383x - 27.783$ $R^2 = 0.9319$	35.7	15.0
	3 Yr	$\bar{x}$ = 429.47	$y = -0.0204x^2 + 1.3099x - 5.626$ $R^2 = 0.8418$	32.1	15.0
Number of fruits per cladode versus cladode width	2012	296.8	$y = -0.1778x^2 + 6.7156x - 47.96$ $R^2 = 0.9178$	18.8	15.0
	2013	556.2	$y = -0.2462x^2 + 9.3323x - 75.17$ $R^2 = 0.9417$	18.9	13.0
	2014	435.4	$y = -0.1293x^2 + 5.7466x - 48.305$ $R^2 = 0.8722$	22.2	15.0
	3 Yr	$\bar{x}$ = 429.47	$y = -0.1014x^2 + 4.2031x - 27.891$ $R^2 = 0.7548$	20.7	15.6
Mean fruit weight per cladode versus cladode length	2012	296.8	$y = -0.0625x^2 + 4.3884x + 23.287$ $R^2 = 0.5185$	35.1	100.3
	2013	556.2	$y = -0.1138x^2 + 7.3567x + 6.3903$ $R^2 = 0.8019$	32.3	125.2
	2014	435.47	$y = -0.1318x^2 + 9.5232x - 16.712$ $R^2 = 0.489$	36.1	155.3
	3 Yr	$\bar{x}$ = 429.47	$y = -0.1322x^2 + 9.9729x - 33.929$ $R^2 = 0.6872$	37.7	154.1
Mean fruit weight per cladode versus cladode width	2012	296.8	$y = -0.787x^2 + 25.636x - 106.06$ $R^2 = 0.8036$	16.2	102.7
	2013	556.2	$y = -0.6832x^2 + 23.779x - 78.863$ $R^2 = 0.6328$	17.4	128.0
	2014	435.4	$y = -0.4262x^2 + 13.706x + 48.278$ $R^2 = 0.512$	16.0	158.4
	3 Yr	$\bar{x}$ = 429.47	$y = -0.635x^2 + 22.332x - 39.531$ $R^2 = 0.4651$	17.5	156.8
Total fruit weight per cladode versus cladode length	2012	296.8	$y = -2.5743x^2 + 153.7x - 1250.8$ $R^2 = 0.453$	29.8	1043.3
	2013	556.2	$y = -5.0253x^2 + 302.84x - 3280.9$ $R^2 = 0.5464$	30.1	1281.6
	2014	435.4	$y = -4.655x^2 + 359.39x - 5249.9$ $R^2 = 0.8863$	38.6	1686.7
	3 Yr	$\bar{x}$ = 429.47	$y = -2.3459x^2 + 169.49x - 1461.3$ $R^2 = 0.7382$	36.1	1600.0
Total fruit weight per cladode versus cladode width	2012	296.8	$y = -13.902x^2 + 499.4x - 3466.4$ $R^2 = 0.8265$	17.9	1018.5
	2013	556.2	$y = -23.022x^2 + 880.47x - 7082.2$ $R^2 = 0.9384$	19.1	1336.1
	2014	435.4	$y = -11.681x^2 + 555.94x - 4885.2$ $R^2 = 0.855$	23.7	1729.5
	3 Yr	$\bar{x}$ = 429.47	$y = -6.9823x^2 + 344.99x - 2543.7$ $R^2 = 0.8984$	24.7	1717.7

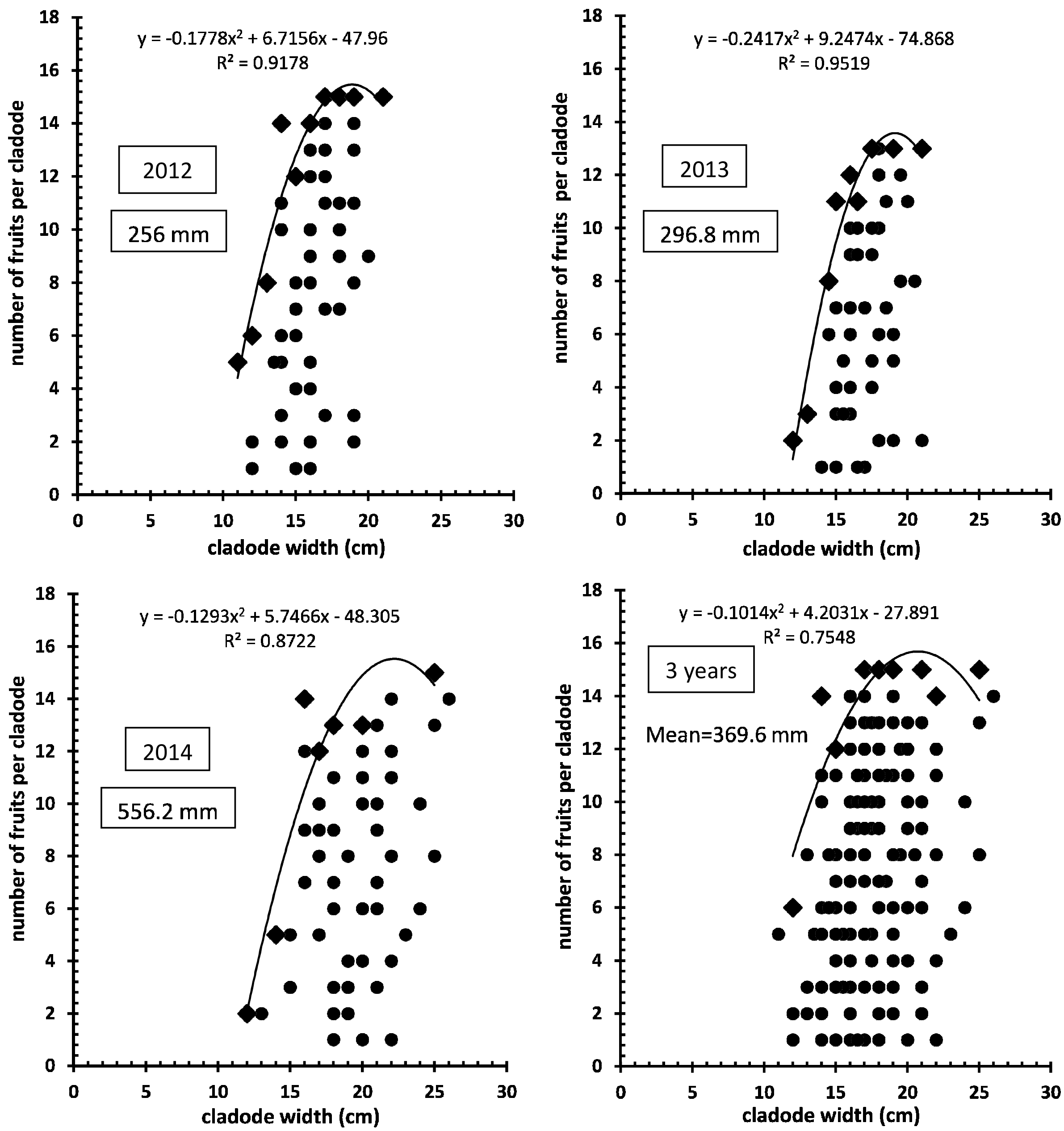

Figure 1. The relationships between cladode width (cm) and number of fruits per 1-year old fruiting cladodes of *Opuntia ficus-indica* (L.) Miller variety 'Rojo Pelón' for the years 2012, 2013 and 2014 and the three years. Rainfall in the charts for each year corresponds to the year in which fruiting cladodes were growing (one year before).

Mean fruit weight per cladode (MFWC) versus cladode length (CL)

Fruiting cladodes produced MFWC's of 81.8 g, 105.7 g, and 128 g (or more) when CL was at least 16 cm, 18.5 cm, and 22 cm for 2012, 2013 and 2014, respectively (Table 2). The calculated vertices suggest that the highest MFWC (155.3 g) occurred on cladodes with 36.1 cm length for 2014, whereas cladodes with 32.3 cm length produced 125.2 g of MFWC for 2013, and cladodes with 35.1 cm length produced 100.3 g of MFWC for 2012. Data results from the three years suggest that cladodes with 37.7 cm length were able to yield maximum MFWC (155.3 g). In addition, there is notably most of 1-year old fruiting cladodes with 18.5-37.7 cm length produced MFWC of 105.7 g or more.

Mean fruit weight per cladode (MFWC) versus cladode width (CW)

The estimated quadratic functions suggest that fruiting cladodes produced MFWC's of 81.8 g, 113.5 g, and 157 g (or more) when CW was at least 11 cm, 12 cm, and 13 cm for 2012, 2013 and 2014, respectively (Table 2). Taking in account the calculated vertices, the highest MFWC (158.4 g) occurred on cladodes with width of 16 cm for 2014, whereas cladodes with 17.4 cm produced 128 g of MFWC for 2013, and cladodes with 16.2 cm of length produced 102.7 g of MFWC for 2012. Data results from the three years indicate that cladodes with 17.5 cm of width were able to yield maximum MFWC (156.8 g). Furthermore, there is notably most of 1-year old fruiting cladodes with 12-17.5 cm of width produced MFWC of 128 g or more.

Total fruit weight per cladode (TFWC) (load) versus cladode length (CL)

Fruiting cladodes produced TFWC's of 555 g, 317 g, and 484 g (or more) when CL was at least 19 cm, 18.5 cm, and 23 cm for 2012, 2013 and 2014, respectively (Table 2). The calculated vertices suggest that the highest load (1686.7 g) occurred on cladodes with length of 38.6 cm for 2014, whereas cladodes with 30.1 cm length produced 1281.6 g of load for 2013, and cladodes with 29.8 cm of length produced 1043.3 g of load for 2012. Data results from the three years suggest that cladodes with 36.1 cm length were able to yield maximum load (1600 g). Besides, there is notably most of 1-year old fruiting cladodes with 18-36.1 cm length produced a load of 769 g or more.

Total fruit weight per cladode (TFWC) (load) versus cladode width (CW)

Fruiting cladodes produced TFWC's of 409 g, 227 g, and 314 g (or more) when CW was at least 11 cm, 12 cm, and 13 cm for 2012, 2013 and 2014, respectively (Table 2). According to the calculated vertices, the highest load (1729.5 g) occurred on cladodes with width of 23.7 cm for 2014, whereas cladodes with 19.1 cm of width produced 1336.1 g of load for 2013, and cladodes with 17.9 cm of width produced 1018.5 g of load for 2012. The 3-year dataset results indicate that cladodes with 24.7 cm width were able to produce maximum load (1717.7 g). Besides, there is notably most of 1-year old fruiting cladodes with 11-24.7 cm width produced a load of 409 g or more.

DISCUSSION

Few studies have documented the dependence of fruit yield on fruiting cladode length and width. For instance, Valdez-Cepeda *et al.* (2014) pointed out that fruit yield depends on fruiting cladode length and width; however, such a research contribution involved just a 1-year database. Thus, our three-year results extend those of Valdez-Cepeda *et al.* (2014). In fact, our results confirm that fruiting occurs when cladodes have at least 16 cm and 11 cm length and width, respectively. This can be the fruiting cladode minimum sizes required to produce fruits in *O. ficus-indica* (L.) Miller variety 'Rojo Pelón'.

A pattern can be observed for the cladode size variables and fruit yield relationships. Valdez-Cepeda *et al.* (2014) found that fruiting cladode having from ≈ 21.8 cm to ≈ 38.4 cm length, and fruiting cladodes having from ≈15.2 cm to ≈20.8 cm width are linked to the estimated highest fruit yield per cladode for *O. ficus-indica* variety Rojo Pelón when a 1-year dataset was involved. Our results clearly indicate that fruit yield changes among years. We found that 2014 fruit yields per cladode were higher than those of 2013 and 2012. This could be linked to the high precipitation occurred during 2013. In fact, 2013 was the wettest year throughout the last 6-year period in the study area (461.4 mm in 2009, 464.2 mm in 2010, 256 mm in 2011, 296.8 mm in 2012, 556.2 mm in 2013 and 435.4 mm in 2014).

In this study, most of the cladodes grown during 2013 (the wettest year) were larger than cladodes grown during the previous two years. Our results extend those of López-García *et al*. (2016) who pointed out that 2014 fruiting cladodes had the highest fresh and dry weights. In this context, Nobel and Bobich (2002) mentioned that the greater availability of water increases CO_2 capture, which implies a higher biomass that is necessary to support the growth of a higher number of fruits; then, the response of net CO_2 uptake is important to predict productivity under any environmental condition; such a behavior may serve as a model for assessing the net CO_2 uptake and hence the potential biomass productivity (Nobel and Bobich, 2002).

Water availability could have had impacted the size of cladodes growing during 2013, then 2014 fruiting cladodes were able to support fruit sink demand in a better way than those of 2013 and 2012. Thus, our findings strengthen those of Luo and Nobel (1993) and Inglese *et al.* (1994). These authors indicated that fruits obtain assimilates from their mother cladode; moreover, they pointed out that the sink demand to support the growth of fruit and the current season's cladodes involves a substantial flow of stored carbohydrates from basal cladodes.

Certainly, fruiting cladodes collected during 2014 were the largest. However, the influence of rainfall on the cladodes size during 2013 and 2012 appears to be low. On the other hand, with regard to the fruits, rainfall could have had a delayed or indirect influence on the weight of fruits (MFWC and TFWC) but not on the number of fruits per cladode. Apparently, this late variable is less related to water availability.

Three-years data results suggest that cladodes with ≈ 18.5 cm to ≈ 50 cm length are linked to the vertex (X= 37.7 cm, Y= 154.1 g), and cladodes with ≈ 12 cm to ≈ 25 cm width are linked to the vertex (X=17.5 cm, Y= 156.8 g). Thus, fruiting cladodes having sizes within the estimated range could increase the probability of having 105.7 g (or more) of mean fruit weight per cladode leaving 8 fruits or more. In other words, when pruning be carried out taking into account these suggested sizes, it should be possible to obtain fruits with acceptable commercial size and high fruit yields per cladode. This would also help to reduce fruit yield variability at least at cladode, plant and orchard levels in the case of *O. ficus-indica* (L.) Miller variety 'Rojo Pelón'.

It is suggested a more multi-year research on this topic must be performed with other varieties of *O. ficus-indica* (L.) Miller. Then, future works may be performed taking into account the wide range of environmental conditions in which this species is growing, as well as involving other factors such as temperatures and irrigation schedules.

CONCLUSIONS

This findings extend those of Valdez-Cepeda *et al*. (2014) and confirm that fruiting occurs when *O. ficus-indica* (L.) Miller variety 'Rojo Pelón' 1-year old fruiting cladodes have at least 16 cm length and 11 cm width. On the other hand, fruiting cladodes with ≈18.5 cm to ≈50 cm length are linked to the vertex (X=37.7 cm, Y=154.1 g) and cladodes with ≈12 cm to ≈25 cm width are linked to the vertex (X=17.5 cm, Y=156.8 g). Pruning based on those compelling sizes may reduce variability of fruit yield and increase the probability to have 105.7 g (or more) of mean fruit weight per cladode leaving 8 fruits or more with an acceptable commercial size.

Fruit weight per cladode dependences on cladode length and width were identified. In addition, yearly rainfall may be increasing the mean fruit weight per cladode (MFWC) and total fruit weight per cladode (TFWC) but not the number of fruits per cladode (NFC), which appears to be less related to water availability. This results provide convenient information for predicting which cladodes will produce the highest yield under their size basis. Thus, fruiting cladodes can be manipulated taking into account their size through pruning in productive orchards when environmental and management conditions are similar to those reported in this study.

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