Fruit number and weight depend on length, width and thickness of fruiting cladode in *Opuntia albicarpa* Scheinvar variety 'Cristalina'

Número y peso de frutos dependen de largo, ancho y grosor del cladodio de fructificación en *Opuntia albicarpa* Scheinvar variedad 'Cristalina'

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Received: August 11, 2017; Accepted: December 27, 2017

ABSTRACT

Opuntia genus is distributed around the world. It grows in a wide range of environmental conditions, which imply a great variability in fruit yield. Productivity also varies at within-tree levels due to limiting factors like fruiting cladode size. Such a variation can be reduced through horticultural practices. However, there are little evidences on that topic under technical basis. So, we used a database with variables measured on 63 fruiting 1-year-old terminal cladodes and their 532 fruits to characterize the dependence of number of fruits per cladode or fruit weight on cladode maximum length, width and thickness, as well as the relationships between fruit weight or cladode fruit yield and number of fruits per cladode for the case of *Opuntia albicarpa* Sheinvar variety 'Cristalina' using the boundary line approach. Results suggest it may be recommendable not to remove, through pruning practice, fruiting 1-year-old terminal cladodes having ≥28 cm, ≥16 cm, and ≥13 mm in length, width and thickness, respectively, and the convenience of fruit thinning by keeping cladode loads from 7 to 14 fruits.

Keywords**:** Cladode fruit load; Cladode fruit yield; Pruning; Fruit thinning.

RESUMEN

El género *Opuntia* está distribuido en todo el mundo. Las plantas de este género crecen en un rango amplio de condiciones ambientales. Ello implica una gran variabilidad de rendimiento de frutos. La productividad también varía a nivel de planta debido a factores limitantes como tamaño de los cladodios de fructificación. Una base de datos con variables de 63 cladodios (de un año de edad) y sus 532 frutos fue usada para caracterizar las relaciones entre número de frutos por cladodio o peso de fruto por cladodio y largo, ancho o grosor de cladodio, así como las relaciones entre peso de fruto o rendimiento de fruto por cladodio y número de frutos por cladodio para *Opuntia albicarpa* Sheinvar variedad 'Cristalina' con la técnica de curva límite. Los resultados sugieren que es recomendable conservar, cuando se practique la poda, a los cladodios de fructificación de un año de edad que tengan ≥28 cm, ≥16 cm y ≥13 mm de longitud, ancho y grosor, respectivamente, así como la conveniencia de eliminar frutos para que haya de 7 a 14 frutos por cladodio.

Palabras clave**:** Número de frutos por cladodio; Rendimiento de frutos por cladodio; Poda; Aclareo de frutos.

INTRODUCTION

Several *Opuntia* species are important crops due they are widely used in at least 18 countries for fruit production. In Mexico, this crop is developed in 67,000 ha (Riojas-López and Fuentes-Aguilar, 2006). However, the wide range of environmental conditions in which it grows implies a great variability in fruit yield and fruit ripening (Inglese *et al.* 2002). In addition, there is a great diversity of production systems. Then productivity also varies at plant level because of poor management of pruning, plant age, and interactions between developing fruits and flower buds, or vegetative versus productive growth, all of which may account for this behavior.

All of these factors imply *Opuntia* species mean fruit yield variation from seven to 15.4 $t \cdot ha^{-1}$, at national level, as pointed out by Zegbe and Mena-Covarrubias (2008). This variation can be reduced through horticultural management practices. However, there is little evidence on that topic under technical basis (e.g. Riojas-López and Fuentes-Aguilar, 2006) to improve yield and fruit quality. This is of special importance in the Central Region of Mexico for the case of *Opuntia albicarpa* Sheinvar variety 'Cristalina' due it is harvested in 6,000 ha.

It is widely recognized fruit production is complex in *Opuntia* species. Yield and quality depend on tree factors such as plant architecture, fruiting cladode position within the canopy and cladode characteristics. Nonetheless, these factors have been poorly explored (García de Cortázar and Nobel, 1992; Inglese *et al*. 1995). In this work, the aim was to characterize: i) the dependence of fruit weight or number of fruits on fruiting cladode length, width or thickness for *Opuntia albicarpa* Sheinvar variety 'Cristalina', and ii) the relationships between fruit weight or cladode fruit yield and number of fruits per cladode (cladode load) by means of the boundary line approach through quadratic functions. Such knowledge could be useful to define cladode attributes for fruit yield maximization through the pruning and fruit thinning practices.

MATERIAL AND METHODS

Sixty-three detached fructification cladodes from 20 trees and their fruits were used to characterize the dependence of number of fruits and their weight on cladode size measured as maximum length and width, and apical thickness. Thus cladodes having different length, width, thickness and number of fruits were involved. Used methods are described in the following paragraphs.

Experimental plot

An orchard was established in June 2006 in the experimental field of the 'Centro Regional Universitario Centro Norte' of the 'Universidad Autónoma Chapingo' at 22° 44' 49.6'' North Latitude, 102° 46' 28.2'' West Longitude, and 2,296 masl, located near Zacatecas city, Mexico. Climate characterizing the region can be classified as BS1kw(w), which corresponds to the least dry of the dry steppe type, with an annual mean temperature ranging between 8 and 12°C and a yearly average precipitation of 472 mm. Most of the precipitation (65%) occurs from June to August.

The orchard was established in order to propagate *Opuntia albicarpa* Sheinvar variety 'Cristalina'. Twenty mother cladodes were used. The cladodes basic statistics were as follows (mean and standard deviation): 35.5 and 3.4 cm, cladode length; and 20.3 and 1.5 cm, cladode width. There were 20 naturally base-shaped trees. Within the experimental plot, a density of 625 plants ha^{-1} was used. After the orchard establishment, only weeds were removed each year in late spring and summer by low tillage. Fertilization, irrigation and other agronomic practices were not performed. It is worth to be noted that from the orchard establishment to the detaching of experimental cladodes, pruning practice on the trees was nil.

Data

All fruiting cladodes were selected from the uppermost part of the plants ensuring they were 1-year-old. The basis of the selection process consisted on choosing cladodes with 1 to 18 fruits in order to involve four cladodes having each of these numbers of fruits; therefore, we considered 63 cladodes. None of those cladodes had young shoots. Especial care was applied to have one cladode from each part of the plant (North, South, East and West) associated to each number of fruits as well as most of the fruits showed peel color breakage. So, it was possible having 4 cladodes with 1-14 fruits, 3 cladodes with 15 fruits, 2 cladodes with 16 fruits, 1 cladode with 17 fruits and one more with 18 fruits. Thus, we harvested a total of 532 fruits. All these fruits were detached and weighted. Also, all 63 detached cladodes were measured to quantify their maximum length and width. Those actions were performed on nine and 10 August 2013 when all trees were 7-years-old.

Statistical analyses

Data of total fruit weight, fruit number, and cladode maximum length and width were recorded in a database and then used for elaboration of scatter diagrams. Their basic statistics were estimated using Microsoft Office Excel software, version 2010 (Microsoft Corporation, 2010). Later, the Boundary Line Approach (BLA) was applied to describe the relationships between number of fruits or fruit weight and cladode length or width or thickness, and between fruit weight or cladode fruit yield and number of fruits per cladode as pointed out by Evanylo and Sumner (1987) and Evanylo (1990), and described in detail by Valdez-Cepeda *et al*. (2013, 2014).

Generally, the boundary-line is formed when all values for two variables are plotted and a line enclosing these points is established (Michael *et al*. 1985). The line represents the limiting effect of the independent variable on the dependent variable (Webb, 1972; Lark, 1997). Thus, it is assumed that all values below that line it result from the influence of another independent variable or a combination of variables that are limiting the dependent variable (Webb, 1972; Hinckley *et al*. 1978).

RESULTS AND DISCUSSION

In this study, it was characterized the dependence of fruit weight or number of fruits on fruiting cladode length or width for *O. albicarpa* variety 'Cristalina' as well as the relationship between fruit weight or cladode fruit yield and number of fruits per cladode. Those relationships were evidenced by means of the BLA through quadratic functions. The main basic statistics of all these mentioned attributes are shown in Table 1.

At a glance dependent variables showed high variability; coefficients of variation were 50.54, 36.54 and 25.97% for cladode fruit yield, number of fruits per cladode and fruit weight, respectively. Variability is an important aspect to attain the objectives; so, the dataset can be used in that sense. However, cladode size expressed in maximum length (45.5 cm) is lower than that reported by Scheinvar (1999) as maximum (48 cm) for this species; on the other hand, the maximum width (25 cm) result to be almost the maximum (24 cm) pointed out by Scheinvar (1999). The noted difference in cladode size could be linked to involved environments where plants grew were different.

Table 1. Basic statistics of fruiting cladodes and fruit attributes of *Opuntia albicarpa* Sheinvar variety 'Cristalina'.

Variable	Sample (n)	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
Cladode length (cm)	63 cladodes	21.0	45.5	35.87	3.86	10.76
Cladode width (cm)	63 cladodes	14.5	25.0	20.97	1.69	8.06
Cladode thickness (mm)	63 cladodes	13.0	28.3	18.84	3.26	17.30
Number of fruits per cladode	63 cladodes	1.0	18.0	11.00	4.02	36.54
Fruit weight (g)	532 fruits	28.0	220.0	127.55	33.12	25.97
Cladode fruit yield (g)	63 cladodes	139.0	2294.0	1127.49	569.80	50.54

Number of fruits or weight per cladode versus fructification cladode length, width or thickness

It is remarkable minimum fruiting cladode length was 21 cm (Table 1, Figure 1A). In other words, there were not cladodes producing at least 1 fruit if its length was not such a value. In addition, it was strongly noted after the maximum number of fruits of almost 18 as related to 37.38 cm cladode length, the number of fruits per cladode diminished drastically.

The number of fruits per cladode dependence on fruiting cladode length was evidenced (Figure 1A). Most of the data are grouped at the central bottom, that is, at low number of fruits per fruiting cladode. High number of fruits per cladode was only rarely observed across each frequency class considered; thus, selection of representative points for estimation of the quadratic function to define the boundary line was easy. Therefore, we were able to choose points at the upper edge of the data body to identify a maximum relationship between number of fruits and fruiting cladode length for *O. albicarpa* variety 'Cristalina'.

The estimated quadratic functions for number of fruits per cladode against fruiting cladode length indicates cladodes with 33 to 43 cm length correspond to 90% of the maximum number of fruits (i.e. 16 fruits). So, fruiting cladodes having lengths within this range may increase the probability of having 17-18 fruits. Then, such results imply there should be convenient no to detach fruiting 1-year-old terminal cladodes having 33 cm length.

Cladodes with at least 14.5 cm width were able to produce at least 1 fruit and a maximum of 18 fruits (Table 1, Figure 1C). As in the previous case, most of the data are grouped at the central bottom, that is, at low number of fruits per fruiting cladode. Then, high number of fruits per cladode was only rarely observed across each considered frequency class; thus,

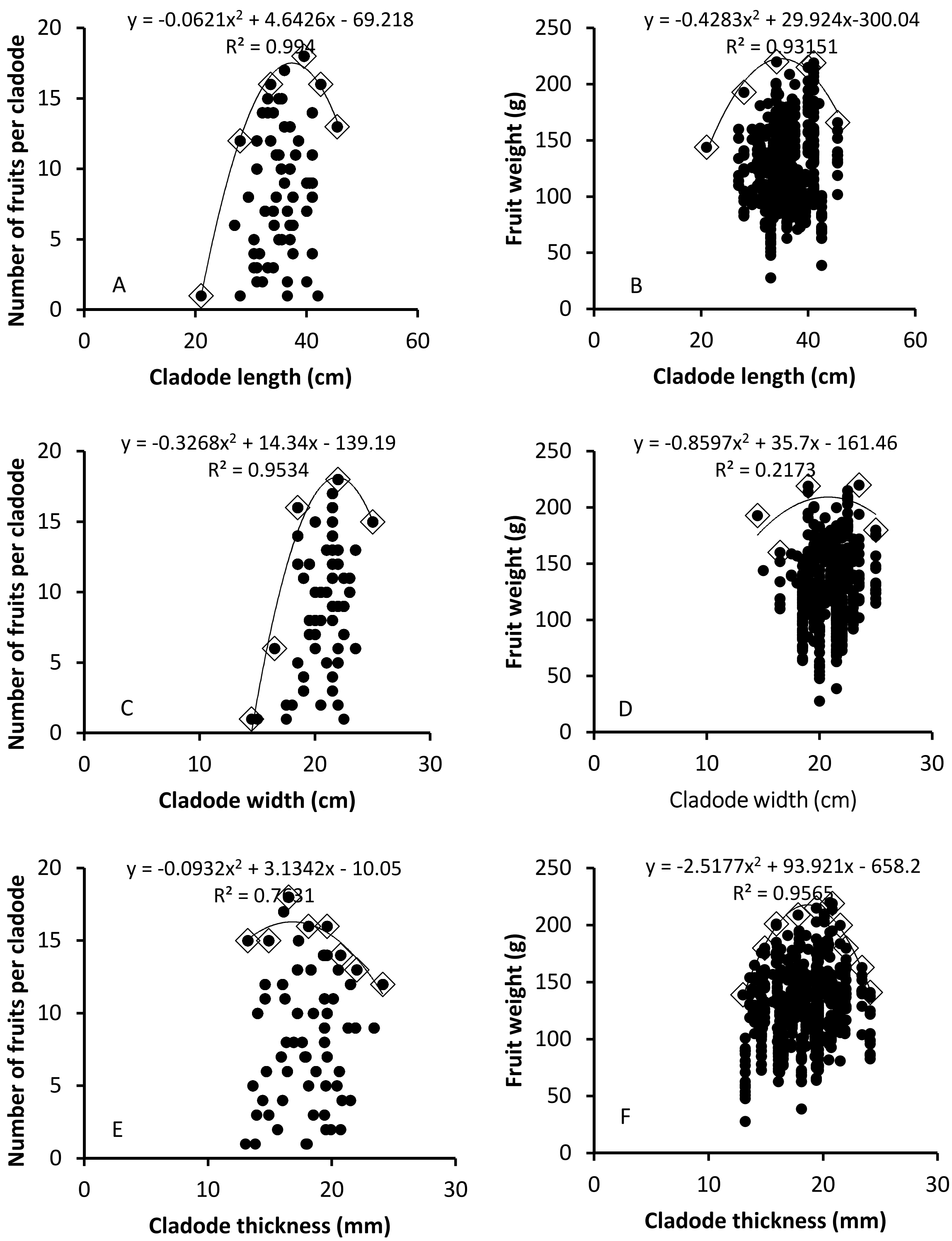


Figure 1. The relationships between number of fruits per cladode and cladode length (A), fruit weight and cladode length (B), number of fruits per cladode and cladode length (C), fruit weight and cladode width (D), number of fruits per cladode and cladode thickness (E) and fruit weight and cladode thickness (F) of *Opuntia albicarpa* variety 'Cristalina' showing boundary lines described by second-degree functions estimated using points marked with diamonds (◊).

selection of representative point for estimation of the quadratic function to define the boundary line was easy.

Notably, the maximum number of fruits (18) per cladode is strongly related to cladodes having 21.94 cm width as suggested by the estimated boundary quadratic line for *O. albicarpa* variety 'Cristalina'. In addition, such a quadratic relationship suggest the range from 20 to 24 cm width could be associated to 90% of the maximum number of fruits (16). That is why fruiting cladodes having widths within such a range may increase the probability of yielding a high number of fruits. These results imply there should be convenient not to detach fruiting 1-year-old terminal cladodes having a width ≥20 cm.

The scatter diagram of fruit weight dependence on fruiting cladode length (Figure 1B) shows most of the data points are grouped at the central bottom, that it, at low fruit weight. Then, fruits with high weights were scarcely observed across each considered frequency class. In addition, the estimated quadratic function suggests fruiting cladodes with 34.93 cm length may be able to produce the heaviest fruits (222.63 g each). It indicates range related to 90% of the maximum fruit weight (222.63 g) can be defined. Such a range for cladode length had 28 and 42 cm as low and high limits for the case of *O. albicarpa* variety 'Cristalina'. Thus, it can be convenient fruiting 1-year-old cladodes have a length of ≥28 cm.

The scatter plot of fruit weight versus fruiting cladode width (Figure 1D) allow to observe most of the data points are also clustered at the central bottom. In other words, many fruits had low weight. However, selected points to define the boundary line were widely dispersed. Nonetheless, the estimated quadratic function indicates maximum fruit weight (209.16 g) is related to fruiting cladodes with 20.76 cm width. Such a line suggests ranges related to 90% of the maximum fruit weight (222.63 g) can be defined. That range for cladode width is defined by 16 cm and 25 cm as limits. Thus, it can be convenient 1-year-old terminal fruiting cladodes having at least 16 cm width.

The number of fruits and fruit weight per cladode dependences on fruiting cladode thickness were evidenced through quadratic functions (Figures 1E, 1F). The maximum number of fruits corresponds to cladodes with thickness of 16.82 mm. On the other hand, the maximum fruit weight belongs to cladodes thickness of 18.65 mm. Those results suggest fruiting cladodes with thickness from 13 to 19.6 mm could yield >16 heavy fruits at the 90% of the maximum number of fruits.

From a practical point of view, results for *O. albicarpa* variety 'Cristalina' allow to hypothesize it may be recommendable not to remove, through pruning practice, fruiting 1-year-old terminal cladodes having ≥28 cm, ≥16 cm and ≥19.6 mm of length, width and thickness, respectively. Pruning practice may allow the proper balance between cladodes for fruit production and those for vegetative growth to replace terminal cladodes. Pruning might be an important issue with the aim of reducing year-to-year variability in fruit production. In the current case of study, none of the involved 63 cladodes had young shoots, so undoubtedly competition between fruits and vegetative growth for assimilates was nil. In other words, this circumstance implies the twenty *O. albicarpa* variety 'Cristalina' experimental trees possessed mainly fruiting 1-year-old terminal cladodes. It could be due 2013 was the first year they produced fruits. However, such a circumstance may be not the same in the next years, and pruning to replace old terminal fruiting cladodes will be a need.

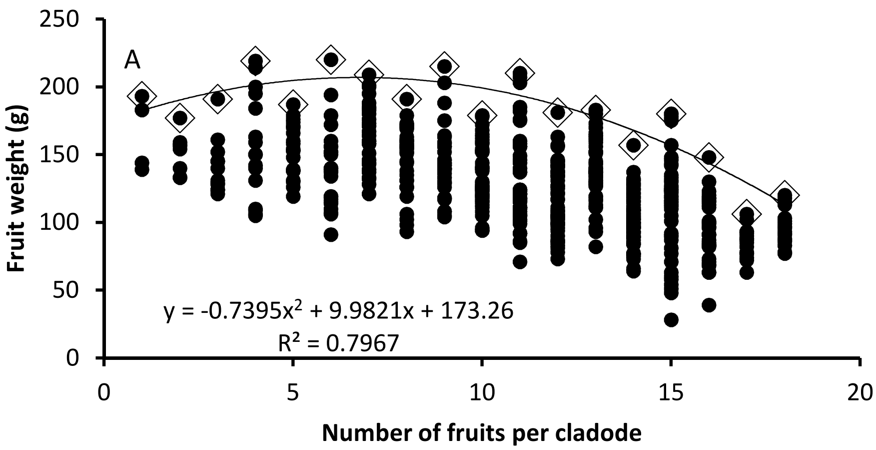
This circumstance could be due there is also known flowers and cladodes appear simultaneously in spring, the flowers occurring mostly at the crown edge of terminal 1-year-old cladodes, with the new cladodes usually developing on 2-year-old or even older cladodes (Inglese *et al*. 1994a). One-year-old fruiting cladodes are strong sinks during the fruit sigmoidal growth period that occurs during the first 4–5 weeks (Inglese *et al*. 1999). At this stage, they switch to linear growth in terms of dry-weight accumulation, and change from being sinks to sources of carbohydrates (Luo and Nobel, 1993). That is why the sink demand to support growth of fruits and newly initiated daughter cladodes involves a substantial flow of stored carbohydrates from basal cladodes (Luo and Nobel, 1993; Inglese *et al*. 1994b). As a result, a strong competition between fruits and new cladodes for assimilates can occur. Then, pruning to promote the terminal fruiting to non-fruiting cladodes proper balance is an important issue. As a matter of fact, information on such a balance is scarce having in mind trees should be trained through pruning at yearly and long-term levels to improve their fruiting potential.

Fruit weight or cladode fruit yield versus cladode fruiting load

There is widely known fruit size in cactus pear depends on cladode fruiting load (Brutsch, 1992); thus, a scatter diagram was performed using fruit weight versus number of fruits per cladode (Figure 2A) for *O. albicarpa* variety 'Cristalina'. Data distribution suggests there could be an optimum cladode load as estimated through a quadratic function as an enveloping curve. This optimum was of 7 fruits per cladode. As a possible consequence, cladodes having such fruiting load could be yielding fruits with weights of 209 g. This result may be useful to increase fruit weight practicing fruit thinning. Thinning must be carried out mainly during the most appropriate time, i.e. 10 to 20 days after bloom when differences in fruit size are clear enough to remove the smallest fruits and flesh development is still negligible (Barbera *et al*. 1992).

There is widely known fruit thinning could be a good complementary management practice. For instance, fruit and flesh fresh weight increased by 35% when cladode load was reduced from 15 to six fruits in *O. ficus-indica* Mill. cultivar 'Gialla' under irrigated conditions (Inglese *et al*. 1995). In this sense, results for *O. albicarpa* variety 'Cristalina' strongly suggest fruit weight may be maximized if the number of fruits per cladode is seven (Figure 2A). Surprisingly, the difference between both genotypes is minimum. However, it deserves be noted a low fruit load does not result in any further increase of fruit weight, but it strongly reduces yield (Inglese *et al*. 1995); in fact, our result is compelling evidence of this behavior, that is, cladode fruit yield appears to diminish when its load is 14 fruits or more (Figure 2B) as estimated taking into account the maximum cladode fruit yield for each number of fruits per cladode (n=18) to calculate a quadratic equation. The associated maximum cladode fruit yield corresponds to 1,869 g. Thus, it is also advisable to perform fruit thinning by keeping cladode loads from 7 to 14 fruits.

It deserves to be mentioned that mean of number of fruiting 1-year old cladodes per plant was 29, and the corresponding coefficient of variation was 36.8% (data not shown). By this way, taking into account 29 fruiting cladodes per plant, the estimated maximum cladode fruit yield of 1,869 g, cladode loads from 7 to 14 fruits and 625 trees per hectare, it is expected having a fruit yield of 33.87 t·ha^{-1}. This value is much higher than the *Opuntia* sp. mean yield range from 7 to 15.4 t·ha^{-1}, at national level, reported by Zegbe and Mena-Covarrubias (2008).



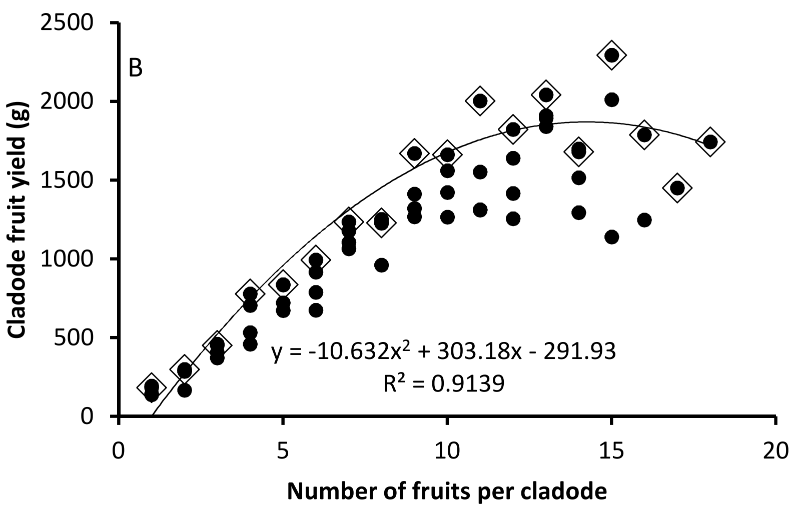


Figure 2. The relationships between fruit weight (A) or cladode fruit yield (B) and number of fruits per cladode of *Opuntia albicarpa* (L.) Sheinvar variety 'Cristalina' showing boundary lines described by second-degree functions estimated using points marked with diamonds (◊).

CONCLUSIONS

These results provide compelling evidence about dependence of number of fruits per cladode (cladode fruiting load) and fruit weight on fruiting cladode size measured as length, width or thickness for the case of *O. albicarpa* variety 'Cristalina'. In this context, it may be recommendable not to remove, through pruning practice, fruiting 1-year-old terminal cladodes having ≥28 cm length and ≥16 cm width. It is also advisable to perform fruit thinning by keeping cladode loads from 7 to 14 fruits. However, such management strategies need to be evaluated in relation to number of fruiting and non-fruiting terminal cladodes per tree, and orchard efficiency, especially involving older plants and at least three growth seasons, that is, taking into account knowledge about ability of cladodes to store higher volumes of water and carbohydrates as soil water availability increases.

Acknowledgements

All authors thank the partial financial support from 'Instituto de Horticultura' of the Universidad Autónoma Chapingo. When this research was performed, RDVC was on sabbatical at the 'Facultad de Zootecnia y Ecología' of the Universidad Autónoma de Chihuahua. Authors gratefully acknowledge two anonymous reviewers for suggestions to improve the manuscript.

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