UNIVERSIDAD AUTÓNOMA CHAPINGO

UNIDAD REGIONAL UNIVERSITARIA DE ZONAS ÁRIDAS

DEPENDENCIA ENTRE RENDIMIENTO DE FRUTO Y ATRIBUTOS FÍSICOS DE CLADODIOS DE FRUCTIFICACIÓN EN *Opuntia ficus-indica* (L.) Miller VARIEDAD 'ROJO PELÓN'

TESIS

Que como requisito parcial

para obtener el título de

MAESTRO EN CIENCIAS EN RECURSOS NATURALES Y MEDIO AMBIENTE EN ZONAS ÁRIDAS

PRESENTA:

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Bermejillo, Durango; enero del 2016.

El presente trabajo de tesis titulado "DEPENDENCIA ENTRE RENDIMIENTO DE FRUTO Y ATRIBUTOS FÍSICOS DE CLADODIOS DE FRUCTIFICACIÓN EN *Opuntia ficus-indica* (L.) Miller VARIEDAD 'ROJO PELÓN' ", fue realizado por el C. Raúl López García bajo la dirección del Dr. Ricardo David Valdez Cepeda y asesorado por los C. Dr. Arnoldo Flores Hernández, Dr. Fidel Blanco Macías, Dr. Ricardo Mata González y Dr. Ricardo Trejo Calzada. Ha sido revisado y aprobado por el Comité Asesor como requisito parcial para obtener el título de:

MAESTRO EN CIENCIAS EN RECURSOS NATURALES Y MEDIO AMBIENTE EN ZONAS ÁRIDAS

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DEDICATORIAS

A mi familia

A mis amigos

AGRADECIMIENTOS

Al Dr. Ricardo David Valdez Cepeda, por sus enseñanzas, paciencia y tiempo dedicado para desarrollar el presente proyecto.

Al Dr. Fidel Blanco Macías por su orientación y consejos durante la elaboración del trabajo de tesis.

Al Dr. Ricardo Mata González por el apoyo brindado durante la estancia en Oregon State University y por sus aportaciones en la elaboración de los artículos científicos.

Al Dr. Arnoldo Flores Hernández y Dr. Ricardo Trejo Calzada por las observaciones hechas para mejorar el presente trabajo.

Al Consejo Nacional de Ciencia y Tecnología por el financiamiento otorgado durante la maestría.

Al programa de Postgrado en Recursos Naturales y Medio Ambiente en Zonas Áridas de la Universidad Autónoma Chapingo por el apoyo brindado durante la maestría.

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CAPÍTULO I

DEPENDENCIA ENTRE RENDIMIENTO DE FRUTO Y ATRIBUTOS FÍSICOS DE CLADODIOS DE FRUCTIFICACIÓN EN *Opuntia ficus-indica* (L.) Miller VARIEDAD 'ROJO PELÓN'

DEPENDENCE AMONG FRUIT YIELD AND PHYSICAL ATTRIBUTES OF FRUITING CLADODES IN *Opuntia ficus-indica* (L.) Miller VARIETY 'ROJO PELÓN'

López-García Raúl[1], Valdez-Cepeda Ricardo David[2]

Resumen

Opuntia ficus-indica (L.) Miller es un cultivo importante en México y alrededor del mundo. Esta especie crece en un amplio rango de condiciones ambientales; lo cual implica una gran variabilidad en el rendimiento y maduración de los frutos, entre otros aspectos. El objetivo de este estudio de tres años fue analizar la dependencia entre rendimiento de fruto y los atributos físicos de cladodios de fructificación de un año de edad. Los datos de 169 cladodios y sus 1281 frutos de *O. ficus-indica* variedad 'Rojo Pelón' fueron colectados durante 2012, 2013 y 2014 en una huerta experimental en Zacatecas, México. La técnica de la curva límite fue utilizada para identificar la dependencia del número de frutos, peso promedio de frutos y carga por cladodio sobre el peso fresco y seco de cladodio y largo y ancho de cladodios. La fructificación ocurrió cuando los cladodios tienen al menos 16 cm de largo y 11 cm de ancho. Los resultados sugieren que 14.4 a 33 g (dependiendo del año) puede ser el peso seco mínimo de cladodio necesario para producir frutos. Cladodios de fructificación con 1497 g de peso fresco fueron capaces de producir 154 g de peso promedio de fruto. La máxima carga (1602 g) ocurrió sobre cladodios de fructificación con 1629 g de materia fresca, y corresponden a los cladodios que crecieron durante (2013) el año de mayor precipitación (556.2 mm de lluvia). Cladodios con ≈18.5 cm a ≈50 cm de largo están ligados al vértice (X=37.7 cm, Y=154.1 g), y cladodios con ≈12 cm a ≈25 cm de ancho están ligados al vértice (X=17.5 cm, Y=156.8 g). Por lo tanto, la poda basada en estos tamaños y pesos de cladodio pueden reducir la variabilidad en el rendimiento e incrementar la probabilidad de obtener 105.7 g (o más) de peso promedio de fruto por cladodio dejando ocho frutos o más con un tamaño comercial aceptable.

Palabras clave: tuna, número de frutos, peso de frutos, cladodios de fructificación, poda

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; it implies a great variability in fruit yield and fruit ripening, among other aspects. The aim of this three-year study was to analyze the dependence among fruit yield and physical attributes of one-year-old fruiting cladodes. Data from 169 cladodes and their 1281 fruits of *O. ficus-indica* variety 'Rojo Pelón' 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 and load per cladode on one-year fruiting cladode's fresh or dry weight and length or width. Fruiting occurred when cladodes have at least 16 cm of length and 11 cm of width. Results suggest that 14.4 to 33 g (depending on the year) could be the minimum fruiting cladode dry weight required for producing fruits. Cladodes with 1497 g of fresh weight were able to produce mean fruit weight per fruiting cladode of 154 g. The maximum load (1602 g) occurred on 1-year-old fruiting cladodes with 1629 g of fresh matter, and corresponds to cladodes grown during (2013) the wettest year (556.2 mm of rainfall). 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). Therefore, pruning based on these fruiting cladode's sizes and weights 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, fruit number, fruit weight, fruiting cladodes, pruning

[1] Tesista, [2] Director

I. INTRODUCCIÓN GENERAL

En México y otros países, *Opuntia ficus-indica* (L.) Miller es un cultivo de gran importancia, ya que sus brotes tiernos son aprovechados ampliamente como vegetales para consumo humano y los cladodios maduros son usados de manera frecuente como forraje en la alimentación animal (Russell y Felker, 1987; Reyes-Agüero *et al.*, 2005; Blanco-Macías *et al.*, 2010). Inglese *et al.* (2002) mencionan que esta especie es cultivada para producción de fruto en al menos 19 países. Entonces, su cultivo se practica en un rango amplio de condiciones ambientales e implica una gran variabilidad en los rendimientos y maduración del fruto, entre otros aspectos.

Las podas, edad de la planta e interacciones entre desarrollo de frutos, brotes florales y vegetativos contra productividad del cultivo deben ser tomados en cuenta para entender la respuesta o el comportamiento de las plantas (Inglese *et al*., 2002). La calidad y rendimiento de fruto también dependen de factores que han sido escasamente estudiados, tales como arquitectura de la planta, posición del cladodio en fructificación dentro del dosel vegetal y características propias de los cladodios (Inglese *et al*., 1995; García de Cortázar y Nobel, 1992).

En este contexto, Valdez-Cepeda *et al.* (2013) encontraron que la fructificación ocurre cuando el peso seco de cladodio fue mayor a 14.4 g al usar una muestra de 480 frutos procedentes de 60 cladodios en fructificación de un año de edad en *O. ficus–indica* variedad 'Rojo Pelón'. Sin embargo, ellos sugieren que las muestras de cladodios y frutos deben ser incrementadas con observaciones de parcelas asociadas al espectro amplio de entornos y sistemas de producción que involucran a la variedad 'Rojo Pelón'. Este genotipo es particularmente importante en la región central de México porque es un genotipo recomendable para la producción de fruto debido a que ha demostrado ser tolerante a temperaturas congelantes (Valdez-Cepeda *et al*., 2001). Por lo tanto, los siguientes objetivos fueron considerados.

OBJETIVOS

OBJETIVO GENERAL

- Identificar la relación entre rendimiento de fruto y los atributos físicos de cladodios de fructificación en *Opuntia ficus-indica* (L.) Miller variedad 'Rojo Pelón'.

OBJETIVOS ESPECÍFICOS

- Identificar la dependencia del peso y número de frutos respecto al peso fresco y seco de cladodios de fructificación.

- Identificar la dependencia del peso y número de frutos respecto a la morfometría (largo y ancho) de los cladodios de fructificación.

II. HIPÓTESIS

HIPÓTESIS GENERAL

El rendimiento de fruto depende de los atributos físicos del cladodio de fructificación en *Opuntia ficus-indica* (L.) Miller variedad 'Rojo Pelón'.

HIPÓTESIS ESPECÍFICAS

- El peso y número de frutos dependen del peso fresco y seco de cladodios de fructificación; dichas dependencias pueden ser explicadas mediante una función de maximización.

- El peso y número de frutos dependen de la morfometría (largo y ancho) de los cladodios de fructificación; dichas dependencias pueden ser explicadas mediante una función de maximización.

III. REVISIÓN DE LITERATURA

3.1 Importancia del género *Opuntia*

El género *Opuntia* es nativo del continente americano y se encuentra desde el norte de Canadá hasta el sur de Chile (Bravo-Hollis, 1978). México es el país con mayor diversidad de especies y es considerado centro de origen, domesticación y dispersión (Kiesling, 1995; Griffith, 2004). Actualmente, diversos genotipos han sido introducidos en más de 30 países, donde se aprovechan con diversos fines; así se ha transformado en una planta cosmopolita (Méndez y García, 2006).

Los brotes tiernos comúnmente llamados "nopalitos" son ampliamente aprovechados como vegetales para consumo humano, mientras que los cladodios maduros son usados de manera frecuente como forraje en la alimentación animal (Russell y Felker, 1987; Reyes-Agüero *et al.*, 2005; Guevara *et al*., 2009; Blanco-Macías *et al*., 2010). Además, las plantas de *O. ficus-indica* son utilizadas como hospedero de la "cochinilla" (*Dactylopius coccus*) para la producción de colorantes con importante valor en el mercado (Nobel, 2002).

Recientemente, otros usos de *O. ficus-indica* han sido documentados. Diversos compuestos bioactivos presentes durante el periodo de maduración de los frutos tienen propiedades antioxidantes y anticancerígenas (Zou *et al*., 2005; Magloire *et al*., 2006; Nassar, 2008; Guevara *et al*., 2010; Coria *et al*., 2011; Nazareno y Padrón, 2011; Yahia y Mondragón, 2011). Debido a su contenido nutrimental, diversos productos alimenticios (tortillas, dulces, galletas, jugos, entre otros) son elaborados a partir de los frutos y cladodios de *O. ficus indica* (Cerezal y Duarte, 2005; Touil *et al*., 2010; Guevara *et al*., 2011; Shetty *et al*., 2011).

3.2 Producción de tuna a nivel mundial

Opuntia ficus-indica es, entre las cactáceas, la especie de mayor interés agronómico (Kiesling, 1995). Inglese *et al.* (2002) mencionan que esta especie es cultivada para producción de fruto en al menos 19 países. El cultivo de esta especie para producción de fruto es cada vez más común en varios países alrededor del mundo, principalmente en zonas áridas, debido a su rápida tasa de crecimiento, fácil propagación y a la demanda limitada de agua (Snyman, 2014; Louhaichi *et al*., 2015).

México es el principal productor de tuna a nivel mundial con más del 50% de la producción; sin embargo, Italia es considerada la principal zona exportadora a nivel mundial. En Italia, los rendimientos oscilan entre 25 y 30 t ha^{-1}. En este país, 95% de la producción se concentra en la isla de Sicilia donde se cultivan 8 000 ha de una sola especie y tres variedades (Méndez y García, 2006).

3.3 Producción de tuna en México

En México, la producción de tuna, en la que participan alrededor de 20 000 productores, ocupa una superficie aproximada de 70 000 ha. El rendimiento promedio por hectárea es de 7 t ha^{-1} con oscilaciones entre 5 y 20 t ha^{-1}, debido la diversidad de regiones productoras y sistemas de producción.

La producción se concentra principalmente en tres regiones:

- Acatzingo y Quecholác, Puebla
- Valle de México (Estado de México e Hidalgo)
- Altiplano Potosino-Zacatecano (Aguascalientes, Jalisco, Guanajuato, San Luis Potosí y Zacatecas).

La última región aporta el 50% del volumen total de la producción nacional (Pimienta-Barrios, 1994; Nobel, 2002; Méndez y García, 2006).

3.4 Limitantes de la producción

El rango amplio de condiciones ambientales en el cual crece este cultivo implica una gran variabilidad en los rendimientos y maduración del fruto. Además, la práctica de poda inadecuada, edad de la planta e interacciones entre el desarrollo de los brotes florales o vegetativos contra rendimiento del cultivo son factores que pueden contribuir a este comportamiento (Inglese *et al.,* 2002).

García de Cortázar y Nobel (1992) e Inglese *et al*. (1995) sostienen que la calidad y rendimiento de fruto también dependen de factores propios de las plantas y que han sido escasamente estudiados. Esos factores son, por ejemplo, arquitectura de la planta, posición del cladodio en fructificación dentro del dosel vegetal y características propias de los cladodios.

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CAPÍTULO II

Fruit attributes dependence on fruiting cladode dry or fresh matter in *Opuntia ficus-indica* (L.) Miller variety 'Rojo Pelón'

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Abstract

The wide range of environmental conditions in which *Opuntia ficus-indica* (L.) Miller grows implies a great variability in fruit yield and fruit ripening, among other aspects. There is scarce knowledge about fruit yield and fruit quality dependence on within-tree factors such as plant architecture, fruiting cladode position and cladode characteristics taking into account several growing seasons. In this work, we addressed the dependence of fruit attributes to the weight of fruiting cladodes for the ‘Rojo Pelón’ variety by means of the boundary line approach by considering a 3-year database (2012-2014). Our results suggest that 14.4 to 33 g (depending on the year) could be the minimum fruiting cladode dry weight (CDW) required for producing fruits. In general, above ≈156 g CDW or cladode excess dry weight, the number of fruits per cladode decreased. Considering data from the three years, cladodes with 1497 g of fresh weight were able to produce mean fruit weight per fruiting cladode (MFWC) of 154 g. The maximum load (1602 g) occurred on one-year-old fruiting cladodes with 1629 g of fresh matter, and corresponds to 2014, that is, to fruiting cladodes grown during 2013, the wettest year (rainfall of 556.2 mm). Remarkably, fruiting cladode excess dry and fresh matter required for producing fruit could be important factors in order to avoid high variation between productivity levels in successive years. These attributes may be convenient indexes for predicting which cladodes will produce fruits.

Keywords: cactus pear**,** fruiting cladode, fruit load, fruit number, fruit weight

1. Introduction

Opuntia ficus-indica (L.) Miller is an important crop in Mexico. It is becoming a relatively common crop, especially in dry areas around the world because of its rapid growth rate, undemanding propagation, and high water use efficiency (Griffith, 2004; Snyman, 2013; Louhaichi et al., 2015). This species is cultivated for its fruit in at least 18 countries while its tender shoots are widely used for human consumption as vegetables and its mature cladodes are frequently used for animal feed (Russell and Felker, 1987; Blanco-Macías et al., 2010).

Technical aspects of propagation and general plantation management of *O. ficus-indica* have been investigated (Nobel and Bobich, 2002). These advances should be matched by an adequate enlargement of today's knowledge linked, for instance, with the biology of fructification (Barbera et al., 1992) and qualitative improvement of the fruits (Barbera et al., 1992; Inglese et al., 2002). These aspects are particularly important considering the wide range of environmental conditions in which *O. ficus-indica* grows. Such a range involves a great variability in fruit ripening and fruit yield (Inglese et al., 2002).

Variability of fruit yield could be high at the orchard, plant and even cladode levels (Valdez-Cepeda et al., 2013). Mismanagement of pruning and interactions between developing fruits and vegetative growth may account for this variability (Inglese et al., 2002). Fruit yield and fruit quality dependence on within-tree factors such as plant architecture, fruiting cladode position and cladode characteristics have been poorly explored (García de Cortázar and Nobel, 1992; Inglese, 1995). Recently, single-year studies demonstrated the need for further investigation of longer-term duration about this topic (Valdez-Cepeda et al., 2013; Valdez-Cepeda et al., 2014). In other words, obtaining predictable yields in *O. ficus-indica* would likely require additional, multi-year studies on the relationship between fruit production and physical fruiting cladode characteristics. In this three-year study, we addressed the dependence of fruit attributes to the weight of fruiting cladodes for the 'Rojo Pelón' variety by means of the boundary line approach. *Opuntia ficus-indica* variety 'Rojo Pelón' is becoming an important genotype for fruit production in central Mexico because of its fruit quality and its freezing tolerance (Valdez-Cepeda et al., 2001).

2. Materials and methods

2.1. Experimental plot

The experimental orchard was established in June 2006 at the Centro Regional Universitario Centro Norte, Universidad Autónoma Chapingo (latitude 22° 44'49.6'' N; longitude 102° 46'28.2'' W; 2,296 masl), near the city of Zacatecas, Mexico. The orchard was established in order to propagate *O. ficus-indica* variety 'Rojo Pelón'. Twenty mother cladodes were used. The basic statistics of their attributes were as follows (mean ± standard deviation): 548.6 ± 190 g, fresh matter; 28.5 ± 5.4 cm, cladode length; and 16.3 ± 2.2 cm, cladode width. Thus, there were 20 naturally vase-shaped trees. Within the experimental plot, a density of 625 plants per hectare 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. The climate of the region is semiarid, with a yearly average precipitation of 472 mm and mean annual temperature ranging between 12°C and 18°C. Most of the precipitation (65%) occurs from June to August. The soil at the experimental orchard is a clay loam of calcareous origin with a pH of 7.5 and organic matter content of 3.2% (for more details on soil characteristics see Blanco-Macías et al., 2010).

2.2. Data

One hundred sixty nine terminal fruiting cladodes and 1281 fruits of *O. ficus-indica* variety 'Rojo Pelón' were considered for this study. Cladodes and fruits were collected during the years 2012, 2013 and 2014 on six- seven- and eight-year-old trees, respectively, as follows: 2012, 60 cladodes and 480 fruits; 2013, 52 cladodes and 365 fruits; and 2014, 57 cladodes and 436 fruits. All cladodes were selected from the uppermost part of the plants to ensure they were one-year-old. We selected cladodes having from one to 15 fruits in order to include representative variability in fruit production (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). All fruits were harvested when most of the fruits showed peel coloration change indicating the beginning of fruit ripeness. All fruits were harvested and weighted. All fruiting cladodes were cleaned with distilled water and immediately weighted. Afterwards, all cladodes were cut in slices and dehydrated to constant dry weight in an oven at 75°C during 36 h and then their dry weights were registered.

2.3. Statistical analyses

Data of number of fruits per cladode (NFC), mean fruit weight per cladode (MFWC), total fruit weight per cladode (TFWC), and cladode fresh (CFW) and cladode dry weights (CDW) were recorded in a database and used for elaboration of scatter diagrams. Later, the boundary line approach was applied as in Valdez-Cepeda et al. (2013) to describe the following relationships:

- Number of fruits per cladode versus cladode dry weight (NFC vs. CDW)
- Number of fruits per cladode versus cladode fresh weight (NFC vs. CFW)
- Mean fruit weight per cladode versus cladode dry weight (MFWC vs. CDW)
- Mean fruit weight per cladode versus cladode fresh weight (MFWC vs. CFW)
- Total fruit weight per cladode versus cladode dry weight (TFWC vs. CDW)
- Total fruit weight per cladode versus cladode fresh weight (TFWC vs. CFW)

The boundary-line is created when all values for two variables are plotted and a line enclosing these points is established (Blanco-Macias et al., 2010). The line represents the limiting effect of the independent variable on the dependent variable (Lark, 1997). Thus, it is assumed that all values below the line result from the influence of another independent variable or a combination of variables that are limiting the dependent variable (Webb, 1972).

3. Results and discussion

The basic statistics of the cladode and fruit attributes are shown in Table 1. The variables CDW, MFWC, and TFWC showed high variability, whereas CFW and NFC variability could be considered as moderately high. Variability is an important aspect to get our objectives. Thus, this database was used to our purposes.

3.1. Differences among years

The estimated CFW mean for 2014 (1400 g) was higher than the means for 2013 (682 g) and 2012 (566 g) (Table 1). This pattern can be observed in the remaining measured variables with the exception of CDW. Thus, we looked for an explanation on this phenomenon by studying relationships between CFW and CDW. These results can be seen in Fig. 1. Yearly and overall strong linear relationships were evidenced when CFW was considered dependent on CDW. Results suggest each g of dry matter stored 11.65 g of water in 2012, as previously pointed out by Valdez-Cepeda et al. (2013). This quantity was lower than 15.44 g and 16.52 g of water linked to 2013 and 2014, respectively. In addition, most registered values of CFW and CDW corresponding to 2014 were higher than those related to 2012 and 2013.

This interesting result could be attributable to the high precipitation observed in 2013, the year when 2014's fruiting cladodes grown. In fact, 2013 was the wettest year throughout the three years when involved fruiting cladodes were growing (256 mm in 2011, 296.8 mm in 2012 and 556.2 mm in 2013).

3.2. Number of fruits per cladode (NFC) versus cladode dry weight (CDW)

In general, most of the data points are grouped at the bottom of plot, that is, at low NFC. Clearly, CDW was much higher in 2014 than in 2012 and 2013 (Fig. 2). In addition, needed CDW's or cladode excess dry weights for fruit production were 14.4, 22 and 33 g for 2012, 2013 and 2014, respectively. Notably, most of the fruiting cladodes with 14.4 to 156 g dry weight produced 5 fruits or more. Overall, an abrupt shift from no fruit to up to 14.4 g CDW suggests this value could be the minimum CDW required for producing fruits. On the other hand, no fruits occurred above ≈156 g CDW (Fig. 2). Such a value was ≈100 g for the case of *O. ficus-indica* as reported by García de Cortázar and Nobel (1992). Thus, the value for the current case is higher than the estimated by these authors.

Table 1

Basic statistics of 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
Number of fruits per cladode (NFC)	60	2012	8	4.35	54.46	1	15
	52	2013	7	3.77	53.97	1	13
	57	2014	7.63	4.15	54.40	1	15
	169	3 yr	7.56	4.11	54.34	1	15
Cladode dry weight (g) (CDW)	60	2012	48.74	12.52	25.69	14.40	78.52
	52	2013	44.45	10.75	24.19	22.00	65.00
	57	2014	84.45	23.40	27.70	33.00	156.00
	169	3 yr	59.67	24.44	40.96	14.40	156.00
Cladode fresh weight (g) (CFW)	60	2012	566.08	162.51	28.71	144.00	964.00
	52	2013	681.70	196.20	28.78	288.00	1073.00
	57	2014	1399.90	387.90	27.71	464.00	2518.00
	169	3 yr	882.60	460.60	52.18	144.00	2518.00
Mean fruit weight per cladode (g) (MFWC)	60	2012	76.43	12.23	16.00	52.50	104.50
	52	2013	99.25	13.46	13.56	72.00	129.75
	57	2014	115.65	18.41	15.92	85.09	170.00
	169	3 yr	96.68	22.16	22.92	52.50	170.00
Total fruit weight per cladode(g) (TFWC)	60	2012	583.60	294.30	50.42	80.00	1186.00
	52	2013	686.70	362.10	52.73	72.00	1356.00
	57	2014	857.10	455.40	53.13	107.00	1780.00
	169	3 yr	707.50	390.60	55.20	72.00	1780.00

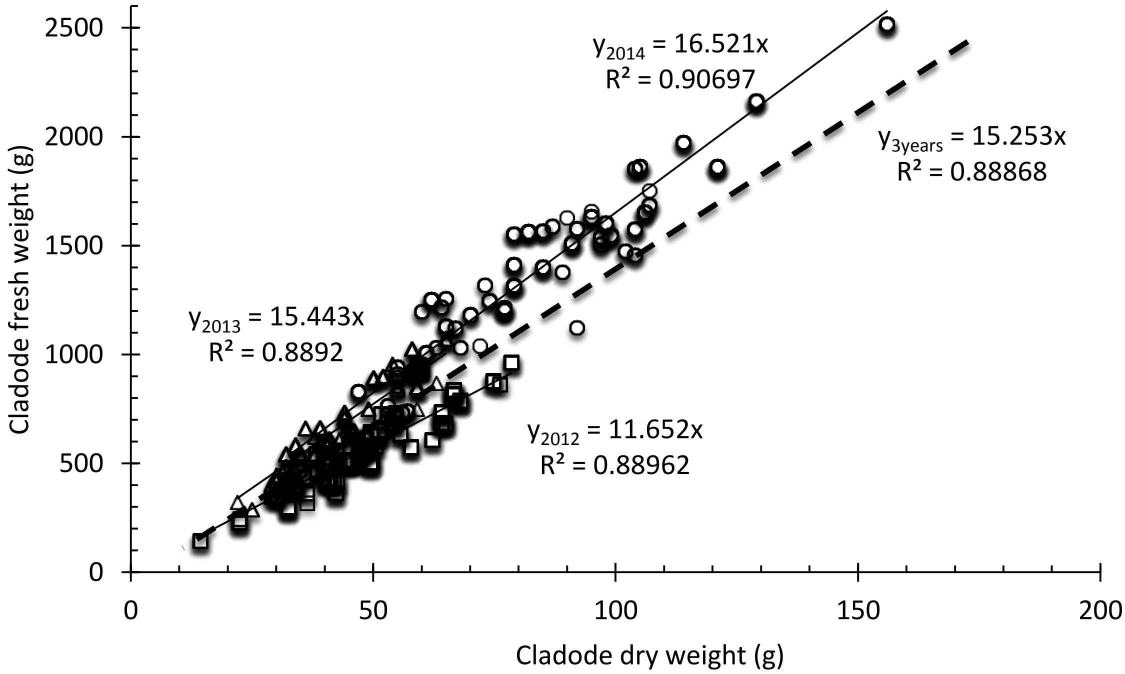

Fig. 1. The linear relationships between dry weight and fresh weight of 1-year-old cladodes of *Opuntia ficus-indica* (L.) Miller variety 'Rojo Pelón' for the years 2012, 2013 and 2014, and the three years.

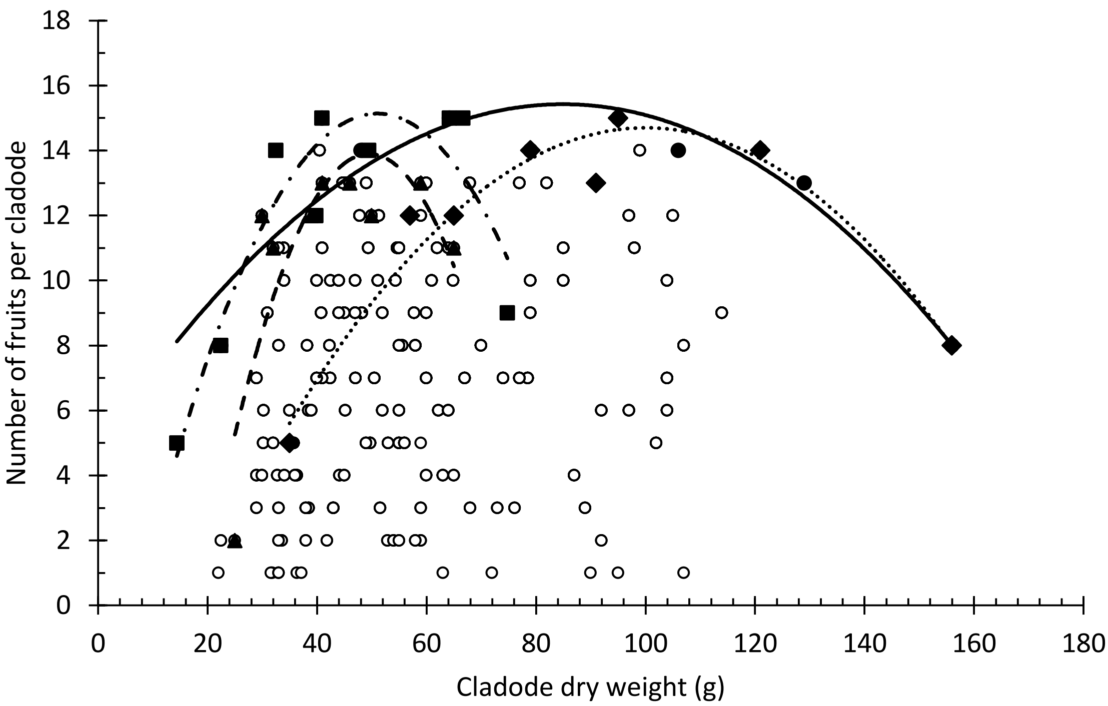

Fig. 2. The relationships between cladode dry weight (g) and number of fruits per 1-year-old cladodes of *Opuntia ficus-indica* (L.) Miller Variety 'Rojo Pelón' for the years 2012, 2013 and 2014. The lines represent quadratic function boundary-lines for each year and the three years: - · - 2012, - - - 2013, ···2014, and — the 3 years. The estimated quadratic functions are: $y = -0.0079x^2 + 0.8029x - 5.3348$, $R^2 = 0.843$, and vertex defined by 50.81 g and 15 fruits for 2012; $y = -0.0144x^2 + 1.4242x - 21.351$, $R^2 = 0.683$, and vertex defined by 49.45 g and 14 fruits for 2013; $y = -0.0022x^2 + 0.4304x - 6.8272$, $R^2 = 0.944$, and vertex defined by 97.81 and 14 fruits for 2014; and $y = -0.0015x^2 + 0.2494x + 4.8386$, $R^2 = 0.817$, and vertex defined by 83.13 and 15 fruits for the 3 years.

Prior works have identified different critical CDW's, referred as 'cladode dry weight' by García de Cortázar and Nobel (1992) that were necessary for fruit production. García de Cortázar and Nobel (1992) mentioned that fruiting occurred when CDW exceeded 33 g for *O. ficus-indica*, and Inglese et al. (2010) found fruiting occurs when CDW surpassed 50 g for *O. ficus-indica* cv. 'Gialla'. Our results suggest that 14.4 to 33 g could be the critical CDW that was necessary for *O. ficus-indica* variety 'Rojo Pelón' fruit production. Thus the critical CDW's differences may be linked to genetic material involved in the three cases; and our results suggest these differences could also be related to the biomass of fruiting cladodes which strongly depend on factors influencing their growing, that is, depending on the year.

In addition to the critical values of CDW, we performed other statistical analyses to estimate maximum number of fruits in relation to CDW. We estimated enveloping curves that suggest the maximum number of fruits for each year and the three years altogether was notably dependent on CDW. This result can be appreciated by considering the distribution of the observations, and the estimated quadratic functions and vertices (Fig. 2, Table 2). The estimated quadratic function indicates that the cladodes with 51 g of dry weight may be able to yield the highest number of fruits (15) for 2012; whereas cladodes with 49 and 98 g were able to produce the highest number of fruits, i.e. 14, for both 2013 and 2014. Considering data from the three years, cladodes with 83 g of dry matter were able to yield the highest number of fruits (15).

The estimated enveloping curves suggest maximum number of fruits for each year and the three years were strongly dependent on CDW. By considering data from the three years, cladodes with 83 g of dry matter were able to yield the highest number of fruits (15) in *O. ficus-indica* variety 'Rojo Pelón'. The number of fruits difference among years is modest. This result may be linked to sink demand to support the growth of fruit while the current season cladodes require a substantial flow of stored carbohydrates from basal cladodes (Luo and Nobel, 1993). That is, it does not depend exclusively on one-year-old fruiting cladodes.

Table 2

Estimated vertices to explain the relationships among CFW and CDW and the NFC, MFWC and TFWC through the boundary-line approach.

Variables	Year	Function	Vertex X	Vertex Y
NFC versus CFW	2012	$y = -5E\text{-}05x^2 + 0.0565x - 1.027$ $R^2 = 0.7897$	565 g	15
	2013	$y = -4E\text{-}05x^2 + 0.0592x - 9.5641$ $R^2 = 0.7006$	759 g	13
	2014	$y = -7E\text{-}06x^2 + 0.0224x - 2.9747$ $R^2 = 0.9061$	1600 g	15
	3 years	$y = -2E\text{-}06x^2 + 0.0045x + 12.728$ $R^2 = 0.7123$	1125 g	15
MFWC versus CDW	2012	$y = -0.0107x^2 + 1.2205x + 64.047$ $R^2 = 0.4005$	57 g	99 g
	2013	$y = -0.0591x^2 + 5.2901x + 11.562$ $R^2 = 0.6946$	45 g	130 g
	2014	$y = -0.0083x^2 + 1.5756x + 85.107$ $R^2 = 0.7123$	95 g	160 g
	3 years	$y = -0.0088x^2 + 1.6409x + 83.45$ $R^2 = 0.7368$	93 g	160 g
MFWC versus CFW	2012	$y = -0.0002x^2 + 0.1392x + 68.292$ $R^2 = 0.9188$	348 g	93 g
	2013	$y = -9E\text{-}05x^2 + 0.123x + 83.206$ $R^2 = 0.4738$	683 g	125 g
	2014	$y = -3E\text{-}05x^2 + 0.0795x + 101.22$ $R^2 = 0.6507$	1325 g	154 g
	3 years	$y = -3E\text{-}05x^2 + 0.0898x + 91.641$ $R^2 = 0.766$	1497 g	159 g
TFWC versus CDW	2012	$y = -0.4077x^2 + 43.733x - 168.44$ $R^2 = 0.7604$	54 g	1004 g
	2013	$y = -1.2261x^2 + 126.09x - 1881.6$ $R^2 = 0.6134$	51 g	1360 g
	2014	$y = -0.2495x^2 + 52.4x - 1037.5$ $R^2 = 0.941$	105 g	1714 g
	3 years	$y = -0.1666x^2 + 31.94x + 138.19$ $R^2 = 0.7808$	96 g	1669 g
TFWC versus CFW	2012	$y = -0.0038x^2 + 4.375x - 146.6$ $R^2 = 0.8265$	576 g	1113 g
	2013	$y = -0.0037x^2 + 5.7888x - 869.39$ $R^2 = 0.6572$	782 g	1395 g
	2014	$y = -0.0008x^2 + 2.6066x - 520.98$ $R^2 = 0.8823$	1629 g	1602 g
	3 years	$y = -0.0006x^2 + 1.7705x + 418.67$ $R^2 = 0.8886$	1475 g	1725 g

3.3. Number of fruits per cladode (NFC) versus cladode fresh weight (CFW)

The dependence of number of NFC on CFW for each and all the three years is shown in Table 2. Most of the data points were clustered at the bottom of the plot (data not shown), that is, at low number of fruits. The maximum number of fruits was notably dependent on fruiting cladodes with higher CFW in 2014 than in 2013 and 2012. This result can be appreciated by considering the estimated vertices (Table 2).

Cladodes produced 5 fruits or more when CFW was at least 144 g. The estimated quadratic functions suggest cladodes having 759 g of fresh weight may be able to yield the maximum NFC (13) for 2013; whereas cladodes with 1600 and 565 g were able to produce the maximum number of fruits (15) for 2014 and 2012. Considering data from the three years, cladodes with 1125 g were able to yield the maximum number of fruits (15).

Remarkably, one-year-old cladodes were able to support fruits when they had at least 144 g of CFW. Thus, this value could be recognized as the cladode excess fresh weight for *O. ficus-indica* variety 'Rojo Pelón'. Maximum NFC was 13 for 2013, and 15 for both 2014 and 2012. These differences could be related to plant age and to the fact one-year-old fruiting cladodes grown during 2013 (the wettest year) yielding fruits during 2014, i.e., on most of the heaviest fruiting cladodes.

3.4. Mean fruit weight per cladode (MFWC) versus cladode dry weight (CDW)

The highest maximum mean fruit weight occurred on cladodes with the higher dry matter, that is, on fruiting cladodes corresponding to 2014 (Table 2). Considering the calculated vertices, cladodes having 57, 45 and 95 g of dry weight produced MFWC of 99, 130 and 160 g for 2012, 2013 and 2014, respectively. Data of the three years suggest cladodes with 93 g of dry weight were able to yield a MFWC of 160 g.

Remarkably, the higher accumulation of dry and fresh matter of fruiting cladodes are linked to 2014 fruiting cladodes. It may be due to the higher precipitation in 2013 (the wettest year). In addition, it could be meaning cladodes with higher excess dry weight may be yielding heavier fruits.

3.5. Mean fruit weight per cladode (MFWC) versus cladode fresh weight (CFW)

Considering data from the three years, cladodes with 1497 g of fresh weight were able to produce MFWC of 154 g (Table 2). The maximum MFWC (154 g) was notably higher for 2014 than for 2013 (125 g) and 2012 (93 g). The corresponding values of CFW were 1325, 683 and 348 g for 2014, 2013 and 2012, respectively. Then, the MFWC increased clearly when the CFW was higher. This trend suggest flow of carbohydrates strongly depend on one-year fruiting cladodes; there is widely recognized they 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 at al., 1994).

3.6. Total fruit weight per cladode (TFWC or load) versus cladode dry weight (CDW)

Considering data from the three years, cladodes with 96 g of dry matter were able to produce 1669 g of load (Table 2). In addition, cladodes with 105 g of dry matter had a load of 1714 g, for 2014; whereas cladodes with 51 and 54 g of dry matter were able to have loads of 1360 and 1004 g for 2013 and 2012, respectively. Thus, the highest maximum TFWC occurred on one-year-old cladodes grown during 2013 (the wettest year), that is, it corresponds to 2014 fruiting cladodes (the heaviest fruiting cladodes).

3.7. Total fruit weight per cladode (TFWC or load) versus cladode fresh weight (CFW)

Data from the three years suggest cladodes with 1475 g of fresh matter yielded 1725 g of fruit weight per cladode (Table 2). The maximum load (1602 g) occurred on one-year-old cladodes with 1629 g of fresh matter, and corresponds to 2014. Loads of 1395 and 1113 g were produced on cladodes with 782 and 576 g of fresh matter for 2013 and 2012, respectively. Therefore, the highest maximum load occurred on one-year-old cladodes grown during 2013 (the wettest year), that is, it corresponds to 2014 fruiting cladodes (the heaviest fruiting cladodes).

In general, our findings extend those of García de Cortázar and Nobel (1992), Inglese et al. (2010) and Valdez-Cepeda et al. (2013). In the current report, we describe the relationship yielded by NFC, MFWC and TFWC as dependent variables and CDW or CFW as independent variables for the case of *O. ficus-indica* variety 'Rojo Pelón'. Remarkably, a pattern was evidenced for most of the measured variables. We found the highest values of CFW, MFWC and TFWC correspond to 2014 and the lowest to 2012. This could be attributable to the high precipitation observed in 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 our study, most of the cladodes grown during the wettest year (2013) were more heavier than cladodes grown during the previous two years. There appears that former cladodes were able to support fruit sink demand in a better way than those grown in 2011 and 2012. Such results provide evidence that *O. ficus-indica* variety 'Rojo Pelón' trees could be able to support growing plant structures (i.e. fruiting cladodes) that will serve as intermediate sinks for assimilates (García de Cortázar and Nobel, 1992).

4. Conclusions

Interesting, our findings extend those of García de Cortázar and Nobel (1992), Inglese et al. (2010) and Valdez-Cepeda et al. (2013). There may be maximum values for number of fruits, mean fruit weights and load per cladode as a function of cladode dry or fresh weight. For example, the maximum mean fruit weight of ≈160 g may be related to ≈93 g of cladode dry weight taking into account data of the three years (Table 2). In addition, our data are compelling evidence to estimate minimum and maximum fruiting cladode excess dry and fresh matter. These measures can be expressed in terms of critical values or ranges at which fruiting occurs on one-year old cladodes for the *O. ficus-indica* variety 'Rojo Pelón'. For instance, in our three-year case of study most of one-year-old fruiting cladodes with ≈14.4 g to ≈156 g of dry weight produced 5 fruits or even more (Fig. 2). Fruiting cladode excess dry and fresh matters required for producing fruit could be important factors in order to avoid high variation between productivity levels in successive years. They provide convenient indexes for predicting which cladodes will produce fruits. Both indexes can be manipulated through pruning, that is, they should be considered to attain the proper balance between fruiting cladodes and those for vegetative growth to replace the terminal cladodes with the aim of reducing year-to-year variability in fruit production by means of pruning.

Pruning based on these principles is justified because there is known that flowers and cladodes appear simultaneously in spring, the flowers occurring mostly of the crown edge of terminal one-year-old cladodes, with the new cladodes usually developing on two-year-old or even older cladodes (Inglese et al; 1994). However, to estimate fruiting cladodes dry or fresh matter under field conditions and during pruning is not a simple task. Thus, there remains to involve cladode size measurements to generate recommendations about which one-year old cladodes must be detached or not, through the pruning practice, in order to minimize variability of cladode load and plant and orchard yields. In other words, it is advisable to provide information on length and width measurements to ensure profitable yields involving other varieties of *O. ficus-indica* or *Opuntia* species and different production systems and environments.

5. Acknowledgements

RLG acknowledges financial support from *Consejo Nacional de Ciencia y Tecnología* during his Master in Science studies. This research work was partially supported by the *Programa de Investigación en Fruticultura* of the *Universidad Autónoma Chapingo*.

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CAPÍTULO III

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

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Abstract

Introduction. *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, which implies a great variability in fruit yield and fruit ripening. The aim of this three-year study was to analyze the dependence of fruit yield on fruiting cladode length or width by means of the boundary-line approach. **Material and methods.** Data from 169 terminal one-year-old fruiting cladodes and their 1281 fruits of *O. ficus-indica* variety Rojo Pelón 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 one-year fruiting cladode's length or width. **Results and discussion.** Influence of rainfall was identified increasing the fruit weight per cladode, but not the number of fruits. Fruiting occured when cladodes have at least 16 cm of length and 11 cm of 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). **Conclusion.** 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; tuna

1. Introduction

Opuntia ficus-indica (L.) Miller (nopal de castilla) is the cacti species with most agronomic interest [1]. This species is cultivated for its fruit (tuna) in Mexico and at least in another 19 countries, typically in dry areas around the world [2]. In Mexico, about 70,000 hectares are used in the production of *O. ficus-indica* cactus pear, being the country with more than half of the production of this fruit in the world [2]. In addition, *O. ficus-indica* is also cultivated for its tender shoots (nopalitos), which are widely used for human consumption as vegetables and for its mature cladodes, which are frequently used for animal feed [3, 4, 5]. Because of its rapid growth rate, undemanding propagation, and high water use efficiency the cultivation of this species is becoming more common in other areas of the world [6, 7].

Technical aspects of orchard management and propagation of *O. ficus-indica* have been relatively well investigated [8, 9], but the biology and management of flowering and fructification are incomplete or not well known [10, 11]. 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 [12].

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 [11, 13]. In addition, fruit yield and fruit quality in relation to within-tree factors such as plant architecture, fruiting cladode position and cladode characteristics have been poorly explored [14, 15]. Recently, single-year studies, demonstrate the need for multi-year investigation of the relationship between fruit attributes and cladode characteristics, especially those characteristics that are easily managed by the orchard manager such as fruiting cladode width or length [13]. This is the reason 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 characteristics. In this three-year study we evaluated fruit attributes of *O. ficus-indica* as affected by the length and width of 1-year old fruiting cladodes for the ‘Rojo Pelón’ variety by means of the boundary line approach. The ‘Rojo Pelón’ variety is becoming an important genotype for fruit production in central Mexico due to its fruit quality and its freezing tolerance [16] and information on this variety is scarce.

2. Materials and methods

2.1. Experimental site

The study took place at an experimental orchard that was established in June 2006 at the Centro Regional Universitario Centro Norte, Universidad Autónoma Chapingo (latitude 22° 44´49.6´´ N; longitude 102° 46´28.2´´ W, 2,296 masl), near the city of Zacatecas, Mexico. The density of the orchard was 625 plants·ha^{-1} [see 11 for further details of orchard design and establishment]. The climate of the region is semiarid, with a yearly average precipitation of 472 mm and mean annual temperature ranging between 12°C and 18°C. Most of the precipitation (65%) occurs from June to August. The soil at the experimental orchard is a clay loam of calcareous origin with a pH of 7.5 and organic matter content of 3.2% [for more soil details see 17].

2.2. Data

Cladodes and fruits for this study were collected during the years 2012, 2013 and 2014 as follows: 2012, 60 cladodes and 480 fruits; 2013, 52 cladodes and 365 fruits; and 2014, 57 cladodes and 436 fruits. In total, 169 terminal fruiting cladodes and 1281 fruits were considered for this study. All cladodes were selected from the uppermost part of the plants to ensure they were one-year old. We selected cladodes having from one to 15 fruits in order to include representative variability in fruit production [11]. Four cladodes having each of these numbers of fruits were selected from different plant orientations (north, south, east and west) [11]. 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.

2.3. Statistical analyses

We 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 and used for elaboration of scatter diagrams. Later, the boundary line approach was applied as in [11] and [13] 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 created when all values for two variables are plotted and a line enclosing these points is established [17]. The line represents the limiting effect of the independent variable on the dependent variable [18, 19]. It is assumed that all values below the line result from the influence of another independent variable or a combination of variables that are limiting the dependent variable [11, 19].

3. Results

The variables CL, CW, MFWC and TFWC showed high variability, whereas NFC variability could be considered as moderately high (Table 1). Variability is an important aspect to get our objectives. Thus, this database was used to our aims. Remarkably, the mean for 2014 for all the variables (except NFC) was higher than the means for 2013 and 2012.

3.1. 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 for 2012 and 2014, whereas cladodes with

27.1 cm of length produced 13 fruits in 2013. By considering data of the three years, cladodes with 32.1 cm of 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.

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

From the estimated quadratic functions, 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 width of 18.8 cm and 22.2 cm for 2012 and 2014, respectively; whereas cladodes with 18.9 cm of width produced 13 fruits for 2013. Considering data of the three years, cladodes with 20.7 cm of width were able to produce the maximum number of fruits (15). Besides, fruiting cladodes with 12 cm to 20.7 cm of width produced six fruits or more (Figure 1).

3.3. 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 length of 36.1 cm for 2014, whereas cladodes with 32.3 cm produced 125.2 g of MFWC for 2013, and cladodes with 35.1 cm of length produced 100.3 g of MFWC for 2012. By considering data from the three years, cladodes with 37.7 cm of 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 of length produced MFWC of 105.7 g or more.

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

The estimated quadratic functions suggests 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. By considering data from the three years, 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.

3.5. 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 of 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. By considering data from the three years, cladodes with 36.1 cm of 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 of length produced a load of 769 g or more.

3.6. 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. By considering data from the three years, cladodes with 24.7 cm of 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 of width produced a load of 409 g or more.

4. Discussion

Only a few studies have documented the dependence of fruit yield on cladode length and width. Valdez-Cepeda et al. [13] found that fruiting cladode lengths from ≈ 21.8 cm to ≈ 38.4 cm, and fruiting cladodes widths from ≈15.2 cm to ≈20.8 cm are linked to the estimated highest fruit yield per cladode for the same variety of *O. ficus-indica*. However, [13] is a report of only one year. Our three-year results extend those of Valdez-Cepeda et al. [13]. This confirms that fruiting occurs when cladodes have at least 16 cm and 11 cm of length and width, respectively. This can be the minimum size required to produce fruits in *O. ficus-indica* (L.) Miller variety 'Rojo Pelón'.

A pattern can be observed for the measured variables. We found the highest fruit yields in 2014 than in 2013 and 2012. This could be due to the high precipitation observed in 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 our study, most of the cladodes grown during 2013 (the wettest year) were larger than cladodes grown during the previous two years. In this context, Nobel and Bobich [20] 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 predicting productivity under any environmental condition and serves as a model for assessing the net CO_2 uptake and hence the potential biomass productivity.

Water availability impacted the size of cladodes for 2014 and then were able to support fruit sink demand in a better way than those in 2013 and 2012. Our findings strengthen those of Luo and Nobel [21] and Inglese [22], who indicated that fruits obtain most of their assimilates from their mother cladode, but 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.

Cladodes collected in 2014 were the largest. However, the influence of rainfall on the cladodes size during 2013 and 2012 appears to be minimum. On the other hand, with regard to the fruits, rainfall clearly had an influence on the weight of fruits (MFWC and TFWC), but not in the number of fruits per cladode. Apparently, this variable is less related to water availability.

Considering data of the three years, 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). 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 is carried out with the sizes suggested, it should be possible to obtain high yields per cladode and fruits with acceptable commercial size. This would also help to reduce variability of fruit productivity at least at cladode, plant and orchard levels of *O. ficus-indica* (L.) Miller variety 'Rojo Pelón'.

We suggest more multi-year research on this topic must be performed with other varieties of *O. ficus-indica* (L.) Miller, including the wide range of environmental conditions in which this species is grown, as well as involving other factors such as temperatures.

5. Remarks

Our findings complement those of Valdez-Cepeda *et al*. [13], confirming that for this variety, fruiting occurs when 1-year-old fruiting cladodes have at least 16 cm and 11 cm of length and width, respectively. In *O. ficus-indica* (L.) Miller variety 'Rojo Pelón' 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 in this sizes could reduce variability of fruit yield and increase the probability of have 105.7 g (or more) of mean fruit weight per cladode leaving eight fruits or more with an acceptable commercial size.

A fruit weight per cladode dependence on cladode length and width was identified. In addition, rainfall increases 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. Our study provides convenient information for predicting which cladodes will produce the highest yield under their size basis. Thus, it can be manipulated through pruning in productive orchards when environmental and management conditions are similar to those reported in this study.

6. Acknowledgements

RLG acknowledges financial support from *Consejo Nacional de Ciencia y Tecnología* during his Master in science studies. This research work was partially supported by the *Programa de Investigación en Fruticultura* of the Universidad Autónoma Chapingo.

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

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	256	$y = -0.0078x^2 + 0.5574x + 4.9225$ $R^2 = 0.5299$	35.7	15.0
	2013	296.8	$y = -0.0387x^2 + 2.1013x - 15.454$ $R^2 = 0.4861$	27.1	13.0
	2014	556.2	$y = -0.0333x^2 + 2.383x - 27.783$ $R^2 = 0.9319$	35.7	15.0
	3 Yr	$\bar{x}$ = 369.6	$y = -0.0204x^2 + 1.3099x - 5.626$ $R^2 = 0.8418$	32.1	15.0
Number of fruits per cladode versus cladode width	2012	256	$y = -0.1778x^2 + 6.7156x - 47.96$ $R^2 = 0.9178$	18.8	15.0
	2013	296.8	$y = -0.2462x^2 + 9.3323x - 75.17$ $R^2 = 0.9417$	18.9	13.0
	2014	556.2	$y = -0.1293x^2 + 5.7466x - 48.305$ $R^2 = 0.8722$	22.2	15.0
	3 Yr	$\bar{x}$ = 369.6	$y = -0.1014x^2 + 4.2031x - 27.891$ $R^2 = 0.7548$	20.7	15.6
Mean fruit weight per cladode versus cladode length	2012	256	$y = -0.0625x^2 + 4.3884x + 23.287$ $R^2 = 0.5185$	35.1	100.3
	2013	296.8	$y = -0.1138x^2 + 7.3567x + 6.3903$ $R^2 = 0.8019$	32.3	125.2
	2014	556.2	$y = -0.1318x^2 + 9.5232x - 16.712$ $R^2 = 0.489$	36.1	155.3
	3 Yr	$\bar{x}$ = 369.6	$y = -0.1322x^2 + 9.9729x - 33.929$ $R^2 = 0.6872$	37.7	154.1
Mean fruit weight per cladode versus cladode width	2012	256	$y = -0.787x^2 + 25.636x - 106.06$ $R^2 = 0.8036$	16.2	102.7
	2013	296.8	$y = -0.6832x^2 + 23.779x - 78.863$ $R^2 = 0.6328$	17.4	128.0
	2014	556.2	$y = -0.4262x^2 + 13.706x + 48.278$ $R^2 = 0.512$	16.0	158.4
	3 Yr	$\bar{x}$ = 369.6	$y = -0.635x^2 + 22.332x - 39.531$ $R^2 = 0.4651$	17.5	156.8
Total fruit weight per cladode versus cladode length	2012	256	$y = -2.5743x^2 + 153.7x - 1250.8$ $R^2 = 0.453$	29.8	1043.3
	2013	296.8	$y = -5.0253x^2 + 302.84x - 3280.9$ $R^2 = 0.5464$	30.1	1281.6
	2014	556.2	$y = -4.655x^2 + 359.39x - 5249.9$ $R^2 = 0.8863$	38.6	1686.7
	3 Yr	$\bar{x}$ = 369.6	$y = -2.3459x^2 + 169.49x - 1461.3$ $R^2 = 0.7382$	36.1	1600.0
Total fruit weight per cladode versus cladode width	2012	256	$y = -13.902x^2 + 499.4x - 3466.4$ $R^2 = 0.8265$	17.9	1018.5
	2013	296.8	$y = -23.022x^2 + 880.47x - 7082.2$ $R^2 = 0.9384$	19.1	1336.1
	2014	556.2	$y = -11.681x^2 + 555.94x - 4885.2$ $R^2 = 0.855$	23.7	1729.5
	3 Yr	$\bar{x}$ = 369.6	$y = -6.9823x^2 + 344.99x - 2543.7$ $R^2 = 0.8984$	24.7	1717.7

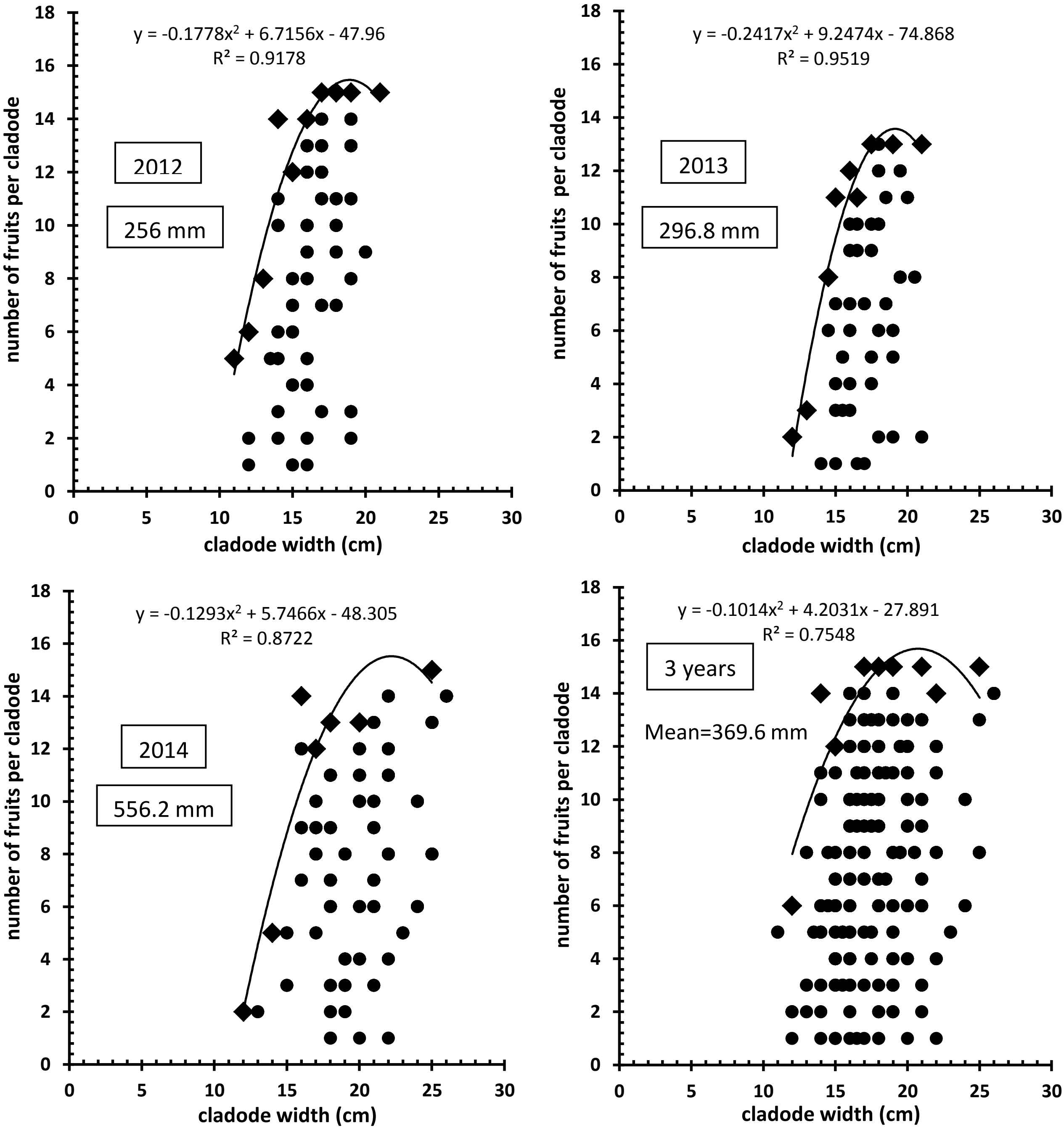

Figure 1. The relationships between cladode width (cm) and number of fruits per 1-year-old fruiting cladodes of *Opuntia ficus-indica* (L.) Miller variety 'Rojo Pelón' for the years 2012, 2013 and 2014 and the three years. Rainfall in the charts for each year, corresponds to the year in which cladodes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

CAPÍTULO IV

DIFERENCIAS DE ATRIBUTOS FÍSICOS DE CLADODIO DE FRUCTIFICACIÓN ENTRE AÑOS: CASO: *Opuntia ficus-indica* (L.) MILLER VARIEDAD 'ROJO PELÓN'

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Resumen

Opuntia ficus–indica (L.) Miller es usada en al menos 18 países para producir fruto. Debido a que crece en un rango amplio de condiciones ambientales y de manejo, la producción de fruto varía mucho entre países, sistemas de producción, plantas y cladodios de fructificación. Sin embargo, la información sobre las relaciones entre rendimiento (producción de frutos) y factores ambientales es escasa. Por lo tanto, el objetivo fue identificar las relaciones posibles entre precipitación, pesos fresco y seco de los cladodios de fructificación, y el peso de frutos por cladodio de fructificación (carga) en el caso de *O. ficus-indica* (L.) Miller variedad „Rojo Pelón‟ al considerar información de tres años. Los resultados sugieren que la materia fresca de los cladodios de fructificación de un año de edad depende de la precipitación y que la carga también depende de la materia fresca de los cladodios de fructificación.

Palabras clave: Precipitación, Cladodio de Fructificación, Peso fresco de Cladodio.

Abstract

Opuntia ficus–indica (L.) Miller is used at least in 18 countries around the world for fruit production. Due it grows under a wide range of environmental and management conditions, fruit yield shows high variability among countries, production systems, plants and fruiting cladodes. However, information on relationships between yield and environmental factors is really scarce. By this way, the objective was to identify possible relationships between precipitation, fruiting cladodes fresh and dry weight and weight of fruits per cladode (load) taking into account data of three years for the case of *O. ficus-indica* (L) Miller variety „Rojo Pelón‟. Results suggest one-year old fruiting cladode fresh weight could depend on yearly precipitation, and the load also could be dependent on fruiting cladode fresh weight.

Key words: Precipitation, Fruiting Cladode, Cladode fresh weight.

Introducción

La especie *Opuntia ficus–indica* (L.) Miller es usada en al menos 18 países para producir fruto. Sin embargo, dicha especie crece en un rango amplio de condiciones ambientales, lo cual implica una gran variabilidad de rendimiento de fruto y maduración (Inglese *et al*., 2002), entre otros aspectos. También, su productividad es extremadamente variable de país a país (Inglese *et al*., 2002).

Además, la productividad varía a nivel de planta. Una poda inadecuada, edad de la planta e interacciones entre los frutos en desarrollo y los brotes vegetativos o florales *versus* el crecimiento productivo pueden contribuir para que esa variación ocurra. Estos aspectos pueden ser importantes en la Región Centro Norte de México, donde *O. ficus–indica* variedad 'Rojo Pelón' se está convirtiendo en un cultivo importante dada su tolerancia a temperaturas de congelación (Valdez–Cepeda *et al*., 2001) del agua en sus tejidos.

El rendimiento de fruto y su calidad pueden depender de los factores del árbol como arquitectura de planta, posición del cladodio de fructificación en la copa del árbol y características de cladodio de fructificación. Además, los atributos de los cladodios de fructificación pueden depender de las condiciones de manejo y de factores ambientales. Sin embargo, tales relaciones han sido exploradas pobremente (Inglese *et al*., 1995; García de Cortázar y Nobel, 1992). En especial, la dependencia de los atributos de los cladodios de factores ambientales como temperatura y precipitación ha sido evidenciada en pocas ocasiones. Por lo tanto, el objetivo del presente trabajo fue identificar las relaciones posibles entre precipitación, pesos fresco y seco de los cladodios de fructificación, así como el peso de frutos por cladodio de fructificación (carga), al considerar datos de tres años.

Materiales y Métodos

Parcela experimental

Una huerta se estableció durante junio de 2006 en el Campo Experimental del 'Centro Regional Universitario Centro Norte' de la 'Universidad Autónoma Chapingo' a 22° 44' 49.6'' Latitud Norte, 102° 46' 28.2'' Longitud Oeste, y 2,296 msnm, localizada cerca de la Ciudad de Zacatecas, México. El clima de la región es BS1kw(w) y corresponde al menos seco de los del tipo estepario seco, con temperatura media anual de entre 12 y 18 °C, y lluvia media anual de 472 mm; la mayor parte de la lluvia (65 %) ocurre de Junio a Agosto (Blanco-Macías *et al*., 2010).

La huerta se estableció con el propósito de propagar *O. ficus–indica* variedad 'Rojo Pelón'. Para ello se consideraron 20 árboles. La densidad fue de 625 plantas·ha^{-1}. Después del establecimiento de los cladodios madre, sólo las malezas fueron eliminadas cada año durante primavera y verano con el mínimo posible de labores culturales. Las prácticas fertilización, irrigación y podas, entre otras, no se realizaron.

Datos

Los datos de precipitación de los años 2011, 2012 y 2013 fueron proporcionados por el personal de la Comisión Nacional del Agua. Por su parte, los cladodios terminales de fructificación y sus frutos fueron cosechados durante los años 2012, 2013 y 2014.

Todos los cladodios considerados tenían un año de edad, fueron seleccionados de la parte superior de la copa de los árboles y sólo presentaron brotes florales. El proceso de selección consistió en que tuvieran de 1 a 15 frutos con el propósito de involucrar cuatro cladodios que tuvieran cada uno de esos números de fruto. Un cuidado especial se consideró para tener, en cada caso de número de frutos, un cladodio de cada parte de la planta con respecto a su posición (norte, sur, este y oeste). Todos los frutos fueron cosechados y pesados. Después, los cladodios fueron limpiados con agua destilada y pesados. Los datos de todas las variables se presentan en el Cuadro 1.

Análisis

Los datos de precipitación anual, así como de los promedios de longitud, peso fresco y seco de cladodios de fructificación y peso de frutos por cladodio (carga) se capturaron en Excel para elaborar diagramas de dispersión al considerar pares de variables. Cuando se consideró a la precipitación anual como variable independiente, se contempló que los cladodios de un año de edad produjeron frutos al año siguiente pues crecieron durante el año que ocurrió esa cantidad de lluvia.

Tabla 1. Información de precipitación pluvial y de atributos de cladodios de fructificación de *Opuntia ficus-indica* (L.) Miller variedad 'Rojo Pelón'.

Año	Número de Cladodios de Fructificación	Número de Frutos	Precipitación Anual (mm)	Promedio de Peso Fresco de Cladodios de Fructificación (g)	Promedio de Peso seco de Cladodios de Fructificación (g)	Promedio de Peso de Frutos por Cladodios de Fructificación (g)
2011	-	-	256.0	-	-	-
2012	60	480	296.8	566.1	48.74	583.6
2013	52	364	556.2	681.7	44.45	686.7
2014	57	456	-	1399.9	84.45	857.1

Resultados y Discusión

Peso de materia fresca de cladodio de fructificación versus precipitación

Los promedios anuales del peso de materia fresca de cladodios de fructificación y su posible dependencia de la precipitación durante el año que crecieron se aprecia en la Figura 1A. La dependencia parece ser lineal pero solo sería válida para los rangos de precipitación anual (256 a 556 mm) y de materia fresca de cladodios de fructificación (566 a 1,400 g) evidenciados. Resultaría interesante contar con al menos otro año de información.

Así entonces, el peso de frutos por cladodio de fructificación se incrementó conforme el peso fresco de los cladodios, lo cual se demuestra también al graficar dicha variable sobre el año de cosecha (Figuras 1BC). Estos resultados implican que en cladodios con peso fresco dentro del rango de 566 a 1,400 g de materia fresca pueden presentarse cargas de 583 a 857 g de frutos. También, la tendencia puede ser lineal al considerar esos rangos. Sin embargo, al considerar que la carga pudiera depender del peso seco de los cladodios de fructificación la evidencia quizás sea no lineal (Figura 1D). Por lo tanto, sería importante contar al menos otro año de información con la finalidad de evidenciar con mayor certidumbre el tipo posible de relación al considerar a la materia seca como variable independiente.

Lo que si queda claro es que, al considerar la materia fresca de los cladodios de fructificación como variable independiente y a la carga como dependiente, fue posible evidenciar que mientras más agua oferten los cladodios se produjo una carga mayor. En otras palabras, la carga fue dependiente de la disponibilidad de agua para la planta en *Opuntia ficus-indica* (L.) Miller variedad 'Rojo Pelón'.

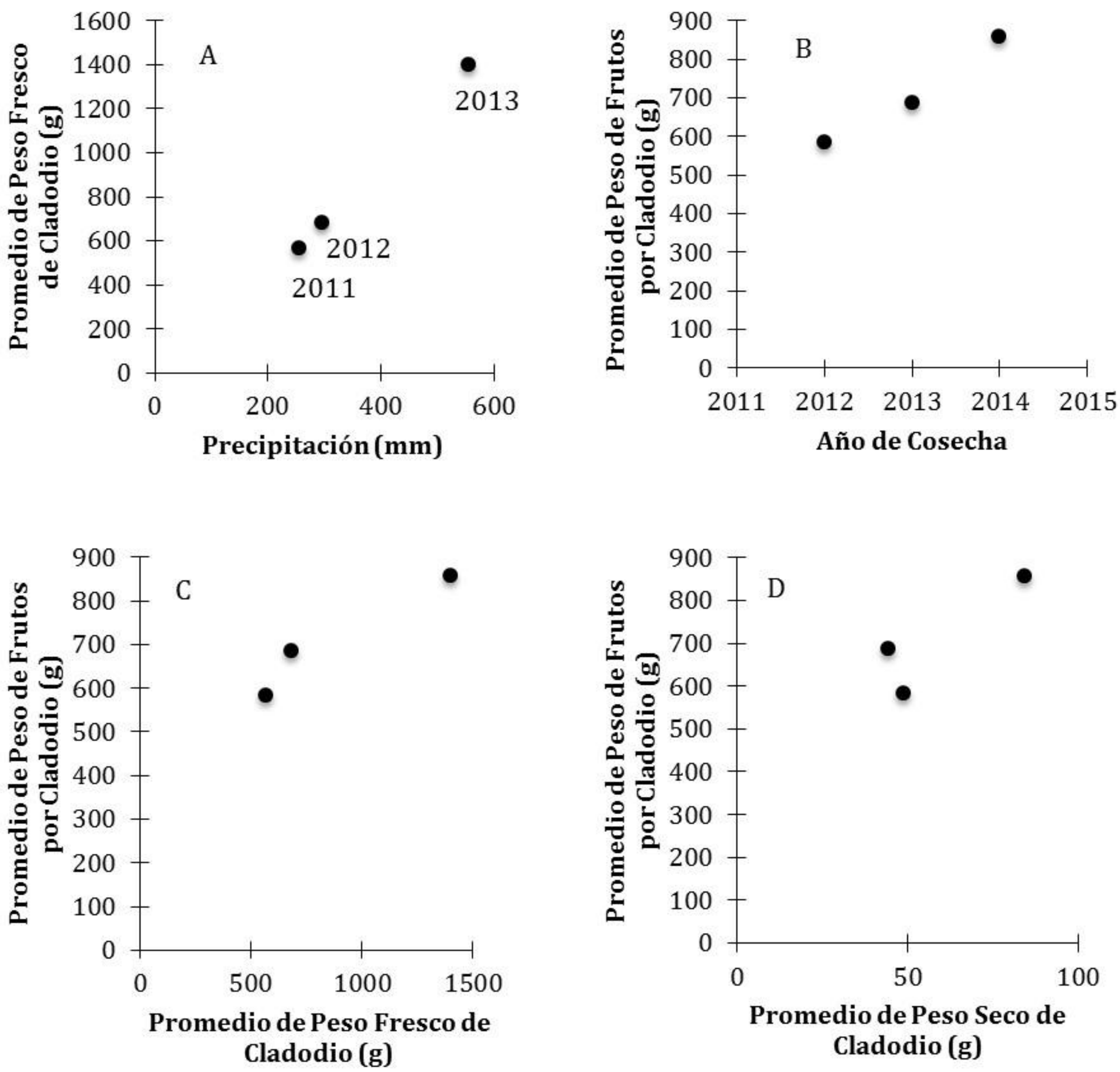

Figura 1. Precipitación anual durante el año de su crecimiento (A), peso de frutos por cladodio (carga) (g) y año de cosecha (B), peso de frutos por cladodio (carga) y peso fresco de cladodio (C) y Peso de frutos por cladodio (carga) y peso seco de cladodios (D) en *Opuntia ficus–indica* (L.) Miller variedad 'Rojo Pelón'.

Agradecimientos

Los autores agradecen el financiamiento parcial del proyecto de investigación al 'Instituto de Investigación en Horticultura, Universidad Autónoma Chapingo'.

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