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Cacti (*Opuntia* sps.) as forage in Argentina dry lands

Cactus (*Opuntia* sps.) como forraje en las tierras secas de Argentina

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Abstract

Studies on cactus carried out mainly in Mendoza plain, Argentina, and in other country areas were reported. Variations in nutrient contents with three cladode age classes were examined for seven *Opuntia* forage clones. For all age classes combined, clones showed high organic matter: 84.4%, *in vitro* organic matter digestibility: 78.9% and low crude protein (CP) content: 4.0%. High doses of fertilizer almost doubled the mean CP content of the cladodes from *O. ficus-indica* (L.) Mill. x *O. lindheimerii* Engelm. cross when it was compared with the treatment in which no fertilizer was added (7.8 and 4.3%, respectively). The response to fertilization at the highest application rate was near 4-fold increase over the biomass of the zero fertilization treatment, 3.2 to 12.7 kg DM plant^{-1}.

Of this cross, clone 42 produced a dry matter (DM) biomass of 40 t DM ha^{-1} in 4 years with a total of 625 mm rainfall which is the greatest DM production recorded to date for such a low rainfall. *O. spinulifera* Salm-Dyck f. *nacuniana* Le Houér. appears to be the most promising species for forage production in areas with extremely cold winters. Clones 46, 80, 83, 89 and 94 had zero frost damage. Economic analysis of *Opuntia* plantations and the use of cactus for replacing corn in small ruminant diet were included. The cost-benefit relationship of using pre-emergent herbicides on biomass production and fertilizer application on biomass production and protein levels were analyzed. The cactus/corn cost relationship indicated the possibility of replacing corn by cactus in small ruminant diet.

Keywords

Opuntia sps. • forage productivity • nutrient content • cold hardiness • economic feasibility • dry lands • Argentina

Resumen

Se informan las conclusiones de los estudios realizados principalmente en la llanura de Mendoza, Argentina, y en otras áreas del país. Las variaciones en los contenidos de nutrientes en tres clases de edad de cladodios se examinaron para siete clones forrajeros de *Opuntia.* Para todas las clases de edad combinadas, los clones mostraron altos valores de materia orgánica: 84,4% y digestibilidad *in vitro* de materia seca: 78,9% y bajo contenido de proteína bruta (PB): 4,0%. Altas dosis de fertilizante casi duplicaron el contenido medio de PB de los cladodios del cruzamiento entre *O. ficus-indica* (L.) Mill. y *O. lindheimerii* Engelm, cuando el mismo fue comparado con el tratamiento en que no se agregaron fertilizantes (7,8 y 4,3%, respectivamente), mientras que la biomasa se incrementó en aproximadamente 4 veces respecto del control no fertilizado (3,2 a 12,7 kg MS planta^{-1}).

El clon 42 de este cruzamiento produjo una biomasa de 40 t de MS ha^{-1} en 4 años con un total de 625 mm de precipitación, la cual es la producción de MS más alta registrada hasta el presente para tal baja lluvia. *O. spinulifera* Salm-Dyck f. *nacuniana* Le Houér. Parece ser la especie más promisoria para la producción de forraje en áreas con inviernos extremadamente fríos. Los clones 46, 80, 83, 89 y 94 no tuvieron daño por heladas. Se incluyeron los análisis económicos de las plantaciones de *Opuntia* y el uso de cactus para reemplazar al maíz en la dieta de pequeños rumiantes. Se analizó la relación costo-beneficio del uso de herbicidas pre-emergentes sobre la producción de biomasa y de la aplicación de fertilizantes sobre la producción de biomasa y niveles de proteínas. La relación de costos cactus/maíz indicó la posibilidad de reemplazar al maíz por cactus en la dieta de pequeños rumiantes.

Palabras clave
Opuntia sps. • productividad de forraje • contenido de nutrientes • resistencia al frío • factibilidad económica • tierras secas • Argentina

Introduction

Some 2.6 million hectares are cultivating in the world, where the greatest use of cactus for forage or fodder occurs in Tunisia: 600,000 ha, Algeria: 150,000 ha, Mexico: 230,000 ha (39), South Africa: 525,000 ha and Ethiopia: 355,000 ha (46), Brazil: > 600,000 ha (50) and Southern Morocco regions: 90,000 ha (1). For Argentina there is information on area cultivated with *Opuntia* only for fruit production: 2,000 ha in 2003 (44). The major limitation to cultivation of cactus in some areas of Argentina is cold winter temperatures. Similar situations occur in northern Mexico (6), the Mediterranean Basin (32), the arid highland steppes of western Asia (33) and the south-western United States (45).

Under different climatic conditions, the thermal limit for frost sensitive species such as *Opuntia ficus-indica* (L.) Mill. is indicated by a mean daily minimum temperature of the coldest month (*m*) of 1.5 to 2.0°C (31). Cactus and other drought-tolerant and water-efficient fodder shrubs can survive under rainfall as low as 50 mm in a particular year, but with neither growth nor production. Mean annual rainfall of 100-150 mm corresponds to the minimum required to successfully establish rainfed plantations (30), provided soils are sandy and deep (32).

Plantations of drought-tolerant and water-efficient fodder shrubs, especially *Opuntia* species, have been established as buffer feed reserves as a strategy to mitigate the effects of drought in animal production systems of various arid and semiarid areas of the world (29). Cacti have greater water-use efficiency due to the Crassulacean Acid Metabolism (CAM) photosynthetic pathway (28, 41, 42) and this makes them especially suited for forage production in arid lands.

Opuntia species have the ability to withstand prolonged drought, high temperatures, as well as wind and water erosion.

This review reports the findings of the studies on cactus carried out mainly in the north central Mendoza plain of mid-western Argentina (33°29'26" S, 67°58'27" W, 520 m asl) and in other areas of the country. Economic analysis of both *Opuntia* plantations and the use of cactus for replacing conventional forages in small ruminant diets are also included.

Appropriated places for planting cactus in Argentina

About two thirds of continental Argentina is associated with arid and semi-arid rangeland ecosystems (13). The bioclimatic classification of those regions (19) allowed determining 13 sites of the country, located in nine Provinces in which it is possible to cultivate *O. ficus-indica*.

At Mendoza study site, daily mean annual minimum and maximum temperatures range respectively from -3.8 to 15.6°C and 14.2 to 33.0°C. Mean annual rainfall is 293.1 mm (SD=112.8) with nearly 80% occurring during the growing season: October-March (records of IADIZA, not published). Those climate conditions are similar in the severity of winters and rainfall to other world sites (12).

Salinity is a concern in Argentina, which ranks third after Russia and Australia in land area affected by this condition (48). The soils in the arid and semiarid regions of Argentina, approximately 210 million hectares, are generally characterized by the presence of salts in the profile, because rains are insufficient for their leaching (R. Casas, pers. comm.). *Opuntia* sps. are not very tolerant to the presence of dissolved salts in their root zone. Sodium is not readily transferred from the roots to the shoot or from basal cladodes to new daughter cladodes (5). As is the case for nearly all plant parts, the Na content of the cladodes of *O. ficus-indica* does not meet the nutritional needs of cattle for this element (43).

Salt tolerance of two *Opuntia* forage species, *Opuntia spinulifera* Salm-Dyck f. *nacuniana* Le Houér. and *Opuntia robusta* Wendl. were evaluated when they were irrigated with saline water with high content of sodium chloride (7). From this assay, both *Opuntia* species may be considered as mid tolerant of salt stress. *O. spinulifera* may be considered less tolerant to soil salinity than *O. robusta.*

Nutrient content, productivity and cold hardiness of *Opuntia* clones and *Opuntia ellisiana* Griffiths

Nutrient content of *Opunti*a sps. depends on the genetic characteristics of the species or clones, cladode age, cladode sampling location, pad harvest season and growing conditions, such as soil fertility and climate (27, 38). *Opuntia* is not a balanced feed. It is fairly rich in energy, minerals, beta carotene and water, but poor in fiber and nitrogen (30). Variations in organic matter (OM), *in vitro* organic matter digestibility (IVOMD), crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and dry matter (DM) with cladode age were examined for seven *Opuntia* forage clones (22). These clones were chosen to represent diverse origins and growth forms.

Nutritional parameters were measured for three age classes. For all age classes combined (22), clones showed high OM (81.6 to 86.8%) and IVOMD (69.5 to 82%) and low CP content (3.2 to 5.0%). Clones had NDF from 22.7 to 27.1%, and ADF from 12.0 to 16.0%; DM ranged from 7.3 to 11.5%. Mean values for all clones were DM 9.1, OM 84.4, IVOMD 78.9, CP 4.0, ADF 14.7 and NDF 23.8%, with a significant ($p<0.05$) or close to be significant ($p=0.08$) linear relationship between each nutritional parameter and age classes was found for all clones, except for OM that showed a significant ($p<0.05$) linear relationship only for two clones.

According to quality standards for legume, grass, and legume-grass mixed hays (49), the conditions of a quality Prime forage are CP >19%, ADF <31%, NDF <40% and digestibility dry matter (DDM) 65%. According to this, all the *Opuntia* forage studied have high DDM, appropriate ADF and NDF contents, but a low content of CP.

Nutrient content for 1 to 2 year-old cladodes from 21 *Opuntia* sps. accessions was determined in Santiago del Estero Province, Argentina (2). This study included seven accessions of *O. ficus-indica*. Means and standard error were: CP = 3.66 ± 0.14; NDF = 40.19 ± 0.97; ADF = 16.31 ± 0.83 and IVDMD = 90.24 ± 0.81 %. Our determinations, in Mendoza plain, for the three accessions of *O. ficus indica* (mean of 1 and 2 year-old cladodes) were higher for CP (4.85 ± 0.32) and lower for NDF (24.47 ± 0.70) and ADF (14.45 ± 0.48) than those reported for Santiago del Estero.

One-year-old cladodes of *O. ellisiana* exhibited CP, OM, ash and IVDMD of 5.8, 82.7, 17.3 and 78.3 %, respectively (21).

Regarding the sampling procedure for determining cladode nitrogen content, it was determined which part of the non-fruiting cladodes of *O. ficus-indica* would represent the average nitrogen content of the entire cladode in order to take minimally destructive samples. It was found that 40 sampling locations that are grouped in a rectangular fashion in the central-basal area of the cladodes faithfully represent the average N-concentration of the entire cladode (mean ± 95%, confidence interval = 8.12 ± 0.60 mg g^{-1} DM).

However this study did not determine the optimum number of cladodes and cores to sample from this middle section for determining differences among genotypes or treatments (23).

Biomass was based on a total above-ground harvest of typical plants of each *Opuntia* clones. The 3-year biomass production, kg DM plant $^{-1}$, of *O. spinulifera* (1.98) and *O. ficus-indica* 'San Juan' accession (2.05) established in a dune was higher ($p<0.05$) than that of *O. paraguayensis* [(1)] (0.76) and *O. robusta* (0.98). 'San Rafael' (1.84) and 'Cuenca' (1.68) accessions yielded higher biomass ($p<0.05$) than *O. paraguayensis*. 'San Juan', 'San Rafael', 'Cuenca' and *O. spinulifera* do not differ statistically between them.

At 3 x 1 m spacing, annual biomass production (kg DM ha^{-1} $year^{-1}$) in unweed plots would be 2,200 for *O. spinulifera*; 2,060 as the mean for the three *O. ficus-indica* accessions; 1,090 for *O. robusta*, and 840 for *O. paraguayensis*, under a mean annual rainfall of 294 mm (18). This translates into rain-use efficiency (RUE) of 7.5, 7.0, 3.7, and 2.9 kg DM ha^{-1} $year^{-1}$ mm^{-1}, respectively.

The RUE from *O. ficus-indica* accessions was twice as high as rangelands (15). Since unweeded cactus plots were shown to have 300% less biomass production than weeded plots (11), probably the greatest single factor affecting productivity of *Opuntia* sps. in forage plantations is the presence of competing vegetation (9).

Concurrently, has been shown that eliminating competition with native range species for water and nutrients increases production and RUE by a factor of 2-3 (30). Consequently, it can assume that if the plots in this experiment had been weeded, the yields would have been at least twice as high, *i.e.* 4,120 kg for *O. ficus-indica* accessions, equivalent to a RUE of 14.0. These yield and RUE values are close to those obtainable in arid regions under

1 At present *O. elata* Salm-Dyck.

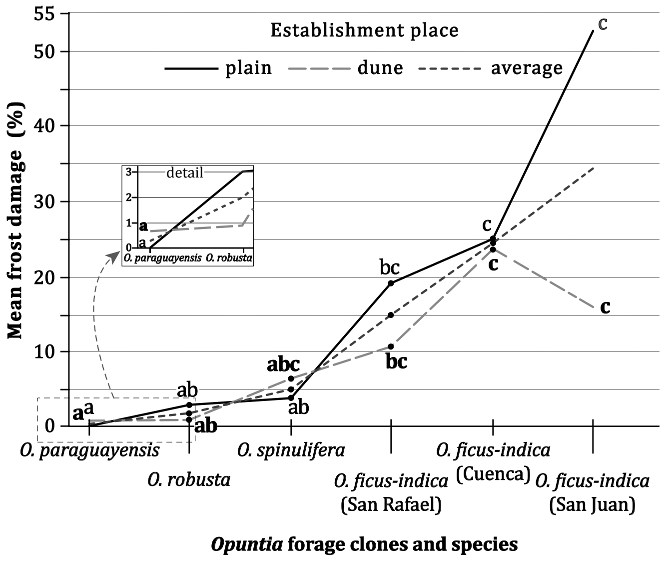
mean annual rainfalls of 200 to 400 mm, *i. e.* 3 to 9 t DM ha^{-1} year^{-1} and 15 to 22.5 kg DM ha^{-1} year^{-1} mm^{-1}, respectively (32).

In the case of using a pre-emergent herbicide (cost of herbicide + application = U$S 66.15 ha^{-1}), would have achieved an increase of biomass in the three accessions of *O. ficus-indica* of 2,060 kg DM ha^{-1}, at a price of U$S 140.08. The benefit-cost relationship would be 2.1 (140.08/66.15). This implies that it is appropriate to apply herbicides to duplicate the cactus biomass.

Mean biomass of *O. ellisiana* from plants obtained by micropropagation reached only 170 kg DM ha^{-1} after the 2-year growth period (21). This low production could be explained mainly by the small size of the plant material used for establishing the plantation and the low stem-area index (0.03).

Cold hardiness is a difficult issue to quantify since species survival depends on acclimatization prior to freezes and various combinations of the duration and absolute minimum temperature of the freeze (52) that is required to reach the core critical temperature for tissue mortality (40).

Monitoring of the artificially established plantations of *Opuntia* forage clones in the Mendoza plains showed that the major limitation to its cultivation is cold winter temperatures. Frost resistance of these clones was assessed for different plant ages after freezes of -16°C and -17°C. Frost damage was visually estimated, integrating the individual cladode damage over the entire plant (figure 1). Young cladodes from 9-month-old plants had damage higher than 85%.



Different letters indicate significant differences (Tukey's HSD test, p< 0.05).
Diferentes letras indican diferencias significativas (Tukey's HSD test, p<0,05).

Figure 1. Mean frost damage for *Opuntia* forage clones in the Mendoza plain and dune.

Figura 1. Daño medio por heladas para clones forrajeros de *Opuntia* en la llanura y en la duna de Mendoza.

The 3-year-old plants exhibited mean frost damage that ranged from 0.3% in *O. paraguayensis* to 34.4% in 'San Juan' accession of *O. ficus-indica*, with mean values of 17.4 and 9.7% for plain and dune, respectively (18).

Opuntia ellisiana is the only spineless *Opuntia* fodder species that is completely cold hardy in Texas (28) and was completely tolerant to 20 hours below -7°C, with a minimum of -16°C (9).

Cold damage of *O. ellisiana* plants obtained by micropropagation was estimated visually after 1- and 2-year growth periods in field conditions. One-year-growth plants suffered no frost damage when temperatures dropped to -15°C on two occasions in the winter of year 2000. Frost damage reached only 0.9% in 2-year-growth plants after freezes of -14.5°C and -13.7°C in the winter of year 2001. Plants of *O. ellisiana* obtained by micropropagation appear to be tolerant to freezing temperatures occurred in areas with extremely cold winters (21).

With only 3 years growth, conclusions on the most promising *Opuntia* forage clones for the plain of Mendoza must be considered with caution. However, some trends emerged from this study (18) in which *O. ficus-indica* appears to be less tolerant to frost than others *Opuntia* species (figure 1, page 268).

Assessment of progenies of *Opuntia* sps.

Based on productivity and disease resistance, it was selected ten thornless progenies *O. ficus-indica* x *O. lindheimerii* to compare their biomass, CP content and cold hardiness. The evaluation site was selected in the Mendoza plains where *O. ficus-indica* cannot survive due to frost damage (25).

Progenies of the interspecific cross between two wild, spiny Texas native *O. lindheimerii* Texas A&M University Kingsville (TAMUK) accession 1250 male parents (cold hardy, red fruits, bluish pads) and a spineless commercial *O. ficus-indica* fruit type TAMUK accession 1281 (low cold hardy, spineless, fast growing, red fruits, greenish pads) were transferred from Texas A&M to the University of Santiago del Estero, Argentina and then to the research site in Mendoza (25).

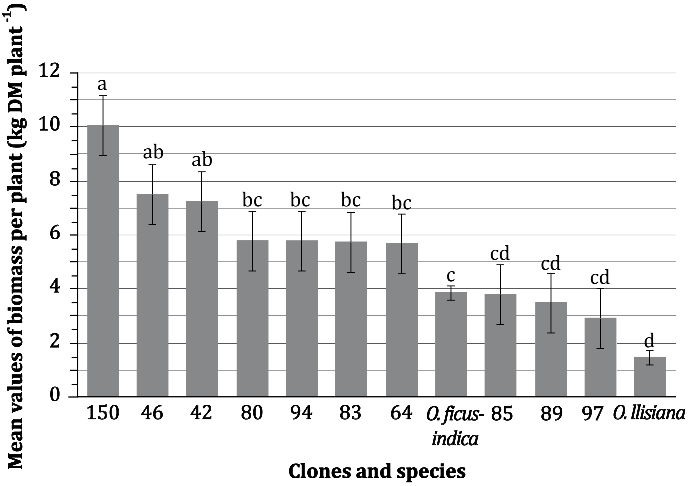
Ten of the segregants that had characteristics of the cold hardy, spiny male parent (small fruits and bluish cladodes) but without spines (24) were examined for forage production and freeze hardiness in trials described in (25). Three trials were established with different objectives.

Trial 1 ranked 10 clones (clon 42, 46, 64, 80, 83, 85, 89, 94, 97 and 150), *O. ficus-indica* and *O. ellisiana* for determining biomass productivity, CP content and frost hardiness. An initial fertilization of 100 g of 15N−15P−15K per plant to reduce possible differences in soil fertility was applied at the beginning of the rainy season.

There were significant differences among clones for biomass production. Results showed that there was a group of clones (clon 85, 89, and 97) that was no significantly different from *O. ellisiana* (figure 2, page 270).

A second group (clones 64, 83, 94, and 80) did not differ from *O. ficus-indica*.

The third group contained 3 clones (42, 46, and 150) that were different from both *O. ficus-indica* and *O. ellisiana* (p=0.041). At a 5 x 3 m spacing (667 plants ha^{-1}), clone 150 produced about 6.7 t DM ha^{-1} at the end of the four year of growth. In this trial, the production ratio of *O. ellisiana* to *O. ficus-indica* was about 0.38, similar to the findings of other authors (3, 28) who reported a production ratio from 0.30 to 0.35.



Different letters indicate significant differences (LSD Fisher test, $p < 0.05$).
Diferentes letras indican diferencias significativas (LSD Fisher test, p< 0,05).

Figure 2. Mean values and standard errors of dry matter (kg DM plant^{-1}) for clones and species after four growing seasons in the Mendoza plain.

Figura 2. Valores medios y errores estándar de materia seca (kg MS planta^{-1}) para clones y especies después de cuatro estaciones de crecimiento en la llanura de Mendoza.

The range of the CP content of clones and species considered was 4.95 and 7.92% for clones 42 and 97, respectively. Two clones (97 and 89) had the same CP content than *O. ficus-indica* (figure 3, page 271).

The mean CP concentration of clones 97, 89 and *O. ficus-indica* could satisfy (37) the CP requirements of a cow of 400-kg live weight during the last third of the pregnancy but not for a lactating cow of the same live weight (8.0 and 10% CP, respectively). There is evidence that the protein content of cactus can be increase to meet the minimum requirement of a lactating cow with N fertilization (P. Felker, pers. comm.). Indeed (14), cited by Felker (2001) found that CP content in *O. lindheimerii* increase from 4.5% from the zero fertility treatment to 10.5% for the treatment containing 224 kg N and 112 kg P ha^{-1}. This author examined eight fertilization treatments on the native *O. lindheimerii* over a four-year periods in a zone with 430 mm yr^{-1} rainfall.

The dry biomass productivity in this trial increased from 7 to 62 t DM ha^{-1}year^{-1} for these doses of fertilizers and recommended fertilizing cactus with 224 kg N ha^{-1} every two years to maintain CP levels at about 10%, with productivity in the 50 t DM ha^{-1}year^{-1} range. If in that experience (14) we consider an investment of U$$ 297.05 (1.33 U$S kg N^{-1}) per hectare for applying 224 kg N every two years, would be obtained 5000 kg CP ha^{-1} at a cost of 0.06 U$S CP kg^{-1}. In this way would not be advisable to replace the protein from the cactus for a protein substitute as expeller soybean costing 0.73 U$S CP kg^{-1}.

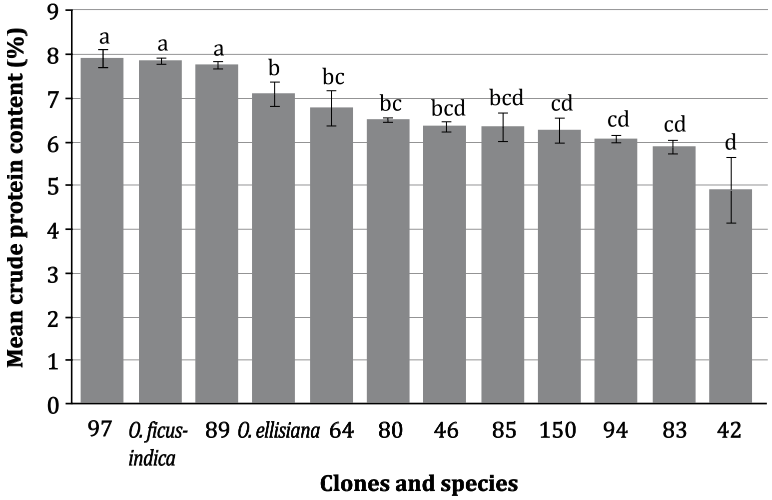


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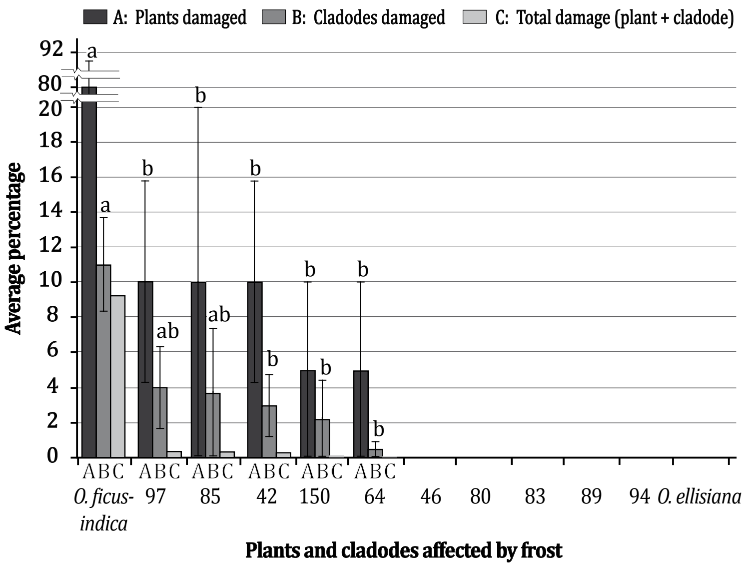
Figure 3. Mean crude protein content (%) and standard errors for clones and species after four growing seasons in the Mendoza plain.

Figura 3. Contenido medio de proteína cruda (%) y errores estándar para clones y especies después de cuatro estaciones de crecimiento en la llanura de Mendoza.

During the period May-September 2009 with 320 hours with temperatures below 0°C, there were statistical differences in the frost damage among clones and species both in the percentage of cladodes (P<0.0001) and plants (P=0.0153) that were damaged (figure 4, page 272). Frost damage in the cladodes of clones 64, 150 and 42 was significantly lower than in those of *O. ficus-indica*. Clones 46, 80, 83, 89, 94 and *O. ellisiana* had zero frost damage during the considered period. This result is in agreement with the frost damage estimates in the winter of 2007, when the minimum temperatures dropped to -9°C on two occasions (12) in which the frost damage in *O. ficus-indica* reached 15.7% and was higher than in the other clones. These results are coincident also with those found by Valdez-Cepeda, R. (2001) who reported that the most resistant varieties of *Opuntia* sps. had 0 to 10% of dead cladodes, but with lower temperatures than those in other study (25).

The plants affected by frost (figure 4, page 272) in Mendoza plain in the winter months, when plants were dormant, were significantly fewer in clones 97, 85, 42, 150, and 64 than in those of *O. ficus-indica*. The other clones suffered no frost damage (25). In contrast, others authors reported that frost damage only occurred in spring (late-seasonal frost: August to October) after a combination of frequent successive nights of freezing temperatures (between -2.06 and -9.6°C) when the plants had already started sprouting. In winter, during dormancy, no plants suffered any frost damage at freezing temperatures as low as -8°C (47).



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Diferentes letras indican diferencias significativas (LSD Fisher test, p<0,05).

Figure 4. Average percentage and standard errors of plants and cladodes affected by frost in the Mendoza plain.

Figura 4. Porcentajes medios y errores estándar de plantas y cladodios afectados por heladas en la llanura de Mendoza.

The second trial was established with clone 42 to determine the biomass production per hectare and CP content. It had 3 replications with each of them having 6 rows of 8 plants per row on 1.5 x 1.5 m spacing (4,444 plants ha^{-1}) and an annual fertilization of 100 kg N, 50 kg P, and 50 kg K ha^{-1} with the purpose to obtain maximum productivity.

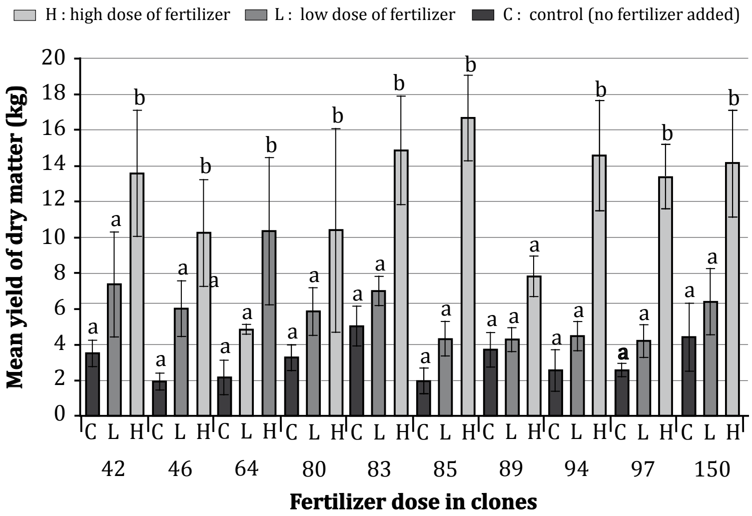
Biomass production was determined devoid of border effects. Clone 42 produced in 4 years with a total of 625 mm rainfall a mean of 9.0 kg DM $plant^{-1}$, 40 t DM ha^{-1} with CP content for 1-year-old cladodes of 4.12 %. This is the greatest DM production recorded to date for such a low rainfall (25).

The mean N content (0.66 g 100 g DM^{-1}) of clone 42 was much lower than the value of 0.97 g 100 g DM^{-1} recommended by Magallanes-Quintanar, R. (2004) for maximum production in 'nopalitos' and thus this production could be N limited.

Assay 3 was established to measure the influence of N fertilization on growth and CP content of the ten progenies mentioned in Trial 1.

The three fertilizer treatments were: a) control without fertilization; b) application a low quantity of fertilizer: 30 kg N, 30 kg P, and 30 kg K ha^{-1} every two years; and c) annual application of 100 kg N, 50 kg P and 100 kg K ha^{-1}. The spacing used was 5 x 3 m (about 667 plants ha^{-1}). Fertilizers were applied as was described for Trial 1.

In figure 5 (page 273) it is shown that there were significant differences among the means of fertilizer treatments.



H: high dose of fertilizer (annual application of 100 kg N, 50 kg P and 100 kg K ha^{-1}); L: low dose of fertilizer (application de 30 kg N, 30 kg P and 30 kg K ha^{-1} every two years); C: control (no fertilizer added).

Different letters indicate significant differences (LSD Fisher test, $p< 0.05$).

H: alta dosis de fertilizante (aplicación anual de 100 kg N, 50 kg P and 100 kg K ha^{-1}); L: baja dosis de fertilizante (aplicación de 30 kg N, 30 kg P and 30 kg K ha^{-1} cada dos años); C: control (sin fertilizante).

Diferentes letras indican diferencias significativas (LSD Fisher test, $p<0,05$).

Figure 5. Mean yield of dry matter $plant^{-1}$ and standard errors for clones according to fertilizer doses after four growing seasons in the Mendoza plain.

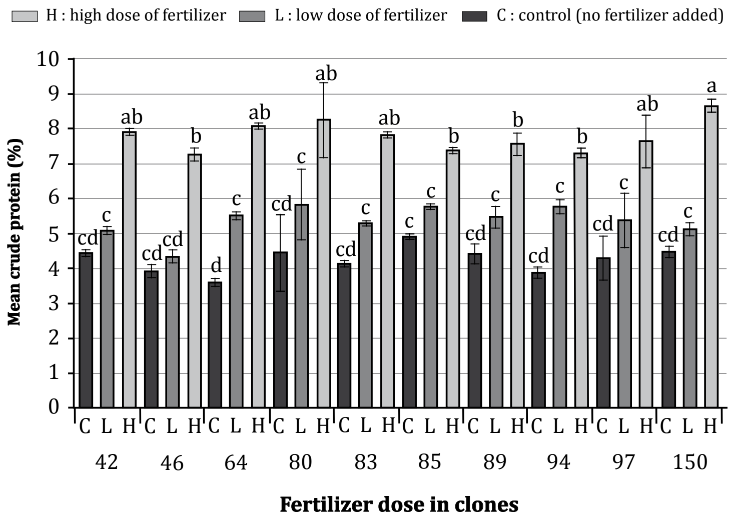
Figura 5. Rendimiento medio de materia seca $planta^{-1}$ y errores estándar de clones de acuerdo con las dosis de fertilizante después de cuatro estaciones de crecimiento en la llanura de Mendoza.

Mean yield of DM per plant was significantly higher at the highest doses of fertilizer than for low doses and control, except for clone 89 that showed no differences among the three treatments. Clone 85 was the most productive under high fertilization (11.2 t DM ha^{-1}).

Other productive clones were 83 (9.9 t DM ha^{-1}), 94 (9.8 t DM ha^{-1}) and 150 (9.5 t DM ha^{-1}). The response to fertilization at the highest application rate was a near 4-fold increase over the biomass of the zero fertilization treatment, 3.2 to 12.7 kg DM $plant^{-1}$.

The clone CP content depends on the fertilizer doses. A significant interaction between clones and fertilizer treatments was observed. With high doses of fertilizer, clone 150 had higher CP content than those of clones 89, 85, 94, and 46 (figure 6, page 274) whereas with low doses of fertilizer there was no significant differences among clones. In the treatment with no addition of fertilizer (control), the clone 85 had significant high CP content than the clone 64 (25).

The high doses of fertilizer applied almost doubled the mean CP content of the cladodes when it was compared with the treatment in which no fertilizer was added (7.8 and 4.3%, respectively).



H: high dose of fertilizer (annual application of 100 kg N, 50 kg P and 100 kg K ha^{-1}); L: low dose of fertilizer (application de 30 kg N, 30 kg P and 30 kg K ha^{-1} every two years); C: control (no fertilizer added).

Different letters indicate significant differences (LSD Fisher test, $p < 0.05$).

H: alta dosis de fertilizante (aplicación anual de 100 kg N, 50 kg P and 100 kg K ha^{-1}); L: baja dosis de fertilizante (aplicación de 30 kg N, 30 kg P and 30 kg K ha^{-1} cada dos años); C: control (sin fertilizante).

Diferentes letras indican diferencias significativas (LSD Fisher test, p<0,05).

Figure 6. Mean crude protein content (%) and standard errors for clones according to fertilizer doses after four growing seasons in the Mendoza plain.

Figura 6. Contenido medio de proteína cruda (%) y errores estándar de clones de acuerdo con las dosis de fertilizante después de cuatro estaciones de crecimiento en la llanura de Mendoza.

The use of nurse plants is an alternative to the application of fertilizers for increasing CP. In Mendoza, preliminary results (J. Grünwaldt, pers. comm.) showed an increase of 45% in CP content when the cladodes were planted under the canopy of *Prosopis* sps.

As a consequence of both, biomass and protein rise, the protein increases would be 221.8 kg CP ha^{-1}, at a cost of US$ 530.5 per fertilized with N during 4 years at a value of 2.39 US$ CP kg^{-1}. Considering that the price of soybeans is 0.73 U$S CP kg^{-1} the application of N fertilizer is not economically convenient under these conditions.

Economic view

The economic feasibility of 50-200 ha cactus plantations for drought forage and fodder production was examined by simulation models (16). Models were run with 200-400 mm annual rainfall and two management systems: cut and carry (CAC) and direct browsing (DB). Cactus production was estimated from RUE factors: 15 kg DM ha^{-1} $year^{-1}$ mm^{-1} rainfall for 200 mm of rain, 18.8 kg DM ha^{-1} $year^{-1}$ mm^{-1} rainfall for 300 mm and 22.5 kg DM ha^{-1} $year^{-1}$ mm^{-1} rainfall for 400 mm.

The value of the production was estimated using shadow prices: a) the cost of energy and protein derived from those of concentrates; and b) the price of steer meat on the hoof. Cactus production was found to be feasible in a DB system with 300 mm rainfall on a 100 ha plantation and with 400 mm rainfall on a 50 ha plantation.

With 400 mm rainfall, 100-200 ha plantations would be needed if the CAC system was adopted. The profitability calculations did not take into account the secondary benefits such as runoff and erosion control, climate buffering, increased land fertility, landscaping and amenities, stabilization of animal production or reduction of the amount of water drunk by livestock, and this resulted in a very large underestimation of the economic impact of cactus plantations. The size of cactus plantations necessary to supplement range grazing to 1,576 and 2,273 animal unit year (AUY) in a 37,500 ha cow-calf ranch were estimated to be 123 and 111 ha at 300 and 400 mm rainfall, respectively. The establishment cost of these plantations would increase the ranch investment by 7.4 to 10%, respectively.

The economic analysis of the introduction of cactus production into goat-production systems in the northeastern plain of Mendoza were examined by a simulation model (17). The model was run with 50, 100, 150, and 200 does and annual rainfall probabilities (p) from 0.1 to 0.9. Investments and costs were derived from data recorded through establishment and monitoring of experimental cactus plantations (17). Cactus production was based on a RUE factor of 12.5 kg DM ha^{-1} $year^{-1}$ mm^{-1} and the annual rainfall probabilities in the area.

The CAC management method was considered for pen feeding during 110 days (last third of pregnancy and 60-day lactation) with 3.6 kg fresh material $goat^{-1}$ day^{-1}. A decrease in goat annual mortality from 10% to 2% and an additional annual amount of kids per goat were considered as direct benefits derived from supplementing goats with spineless cactus in the fall-winter period. As a consequence of this practice, an additional 0.2 kids appears to be obtainable in field conditions. A secondary benefit was the reduction of water consumption by goats.

The Internal Rate of Return (IRR) corresponding to 0.2 additional kids, and the annual additional amount of kids per goat necessary to reach an IRR of 12% were determined for four goat herds (50, 100, 150, and 200 does) and nine annual rainfall probabilities (p=0.1 - p=0.9).

The establishment cost of cactus plantations ranged from US$ 525 ha^{-1} (50-head goat herd; p=0.1) to US$ 242 ha^{-1} (200-head goat herd; p=0.9). Cost of fence installation was the main item of establishment cost in most the analyzed scenarios. This cost may be reduced if a fence made of spiny cactus is established. If dependable rains (p=0.8) are considered, the IRR would be lower than 12% for all goat-herd sizes, and the additional kids per goat required to reach 12% IRR would range from 0.21 to 0.29 for 200 and 50 does, respectively.

The economic feasibility of spineless cactus (*Opuntia* sps.) and saltbush (*Atriplex nummularia* Lindl.) plantations for supplementing goats in the north-eastern plain of Mendoza (mean annual rainfall = 175 mm) during the fall-winter period was examined by a simulation model (20). It was run with 50-200 goats and annual rainfall probability (p=0.1-0.9).

Cactus production was estimated from a RUE factor of 12.5 kg DM ha^{-1} $year^{-1}$ mm^{-1} and the annual rainfall probabilities in the area. Saltbush production (1.88 t DM ha^{-1} $year^{-1}$) was assumed not to be affected by annual rainfall thanks to the presence of a 5–10 m deep, moderately saline water table (3.5–5.0 dSm^{-1}). A decrease in goat mortality and an additional number of kids per goat were considered as annual benefits derived from supplementing the goat diet.

The establishment cost (US$ ha^{-1}) ranged from 812 (50 goats; p=0.1) to 317 (200 goats; p=0.9) for cactus plantations and from 691 (50 goats) to 378 (200 goats) for saltbush plantations, amounts that not all stockmen could afford. The cost of installing metal fence was the main item of establishment cost for both shrubs. Nutrient costs for shrub production were lower than those for alfalfa hay, the conventional feed used by stockmen. A decrease in doe mortality from 10% to 2% and an increase in annual kid crop ranges from 0.17 to 0.32 would economically justify shrub plantations for stockmen having more than 50 goats at annual rainfall probabilities from p=0.1 to p=0.8.

The performance and nutrient digestibility of feedlot Santa Inês sheep fed with increasing levels (0, 25, 50, 75, 100% DM basis) of *O. ficus-indica* as a replacement for corn was evaluated. It was found that the replacement of corn by cactus pear does not affect the conversion of the feed. Overall, increased levels of cactus pear in the sheep's diet favor a high digestibility of nutrients, improve the quality of forage, reduce the voluntary intake of water, and thus represent an important source of fodder and water reserves for use in semiarid regions. With an inclusion of 28% of *Opuntia* in the diet, no digestive disturbances causing reductions in DM intake or in nutrient digestibility were observed. Neither there were no liquid faeces or increased abdominal distension in the animals, probably due to that diet had 29.5 % DM^{-1} (8).

Others feeding trials reported diarrhoea when cactus fed as an exclusive diet (32), though this disorder that can prevented by adding to the diet approximately 1% dry roughage (31). High amount of oxalates (38) and moisture content (35) may also explain the laxative effect of cactus cladodes. Cactus in the diet not altered ruminal pH (4, 36).

The possible benefits of this practice (8) were analyzed using local data on production and costs of cactus and corn (26).

Establishment cost of cactus for 200 goats and the dependable rain (p=0.8) in the Experimental field of the Centro Científico Tecnológico CONICET-Mendoza (32°53' W, 68°52' S), in July 2012 currency, was calculated for three alternatives referred to two fence types -metal and electrified wire- and without fence (26).

Metal fence: U$S 855 ha^{-1} (the cost of fence installation represents 60% of the total establishment cost).

Electrified fence: U$S 547 ha^{-1} (the electrified wire cost was equivalent to 40% of that of metal wire).

Without fence: U$S 342 ha^{-1}.

Corn production cost in Mendoza under irrigation (12 t MS ha^{-1}): U$S 0.062 kg^{-1}.

Cost of purchased corn: U$S 0.175 kg^{-1}.

Productivity of *O. ficus-indica* in a 7-year-old plantation in Mendoza Province was 12,594 kg DM ha^{-1}, composed of the contribution of 3,351, 5,380, 3,863 kg DM ha^{-1}, from of 1-, 2- and 3-year-old cladodes, respectively (26). Rainfall in the three last growing periods: 2009-10, 2010-11 and 2011-12 was 57.8; 158.0 and 159.0 mm, respectively (data from the

Weather Station CCT CONICET Mendoza). The RUE for total productivity and rainfall was 33.6 kg DM ha^{-1} $year^{-1}$ mm^{-1}.

The cactus/corn cost relationship was determined on the basis of the use of fence or lack of it at the site of cactus implantation, the contribution of biomass according to the age of the cladodes harvested, and the different price of corn depending on whether it was produced or purchased in the market (table 1).

A cactus/corn cost relationship less than 1 indicates the possibility of replacing the corn by cactus in diet, because of the lower relative price of the latter. So in this situation, replacement of corn by cactus would be appropriate in 11 out of the 18 alternatives.

Figure 7 (page 278) shows the economic feasibility of replacing corn by cactus in different percentages, taking into account the price of purchased corn and the cost of cactus for the situations previously described. In all the alternatives, except for metal fence and 1 year-old cladodes, replacement of corn by cactus implies a decrease in the diet cost when the replacement level of cactus increased.

The situation without fence and using 1+2+3-year old cladodes to replace the 25, 50, 75 and 100% of corn in the diet, would result in savings of U$S 1.04, 2.07, 3.11 and 4.14, respectively, for every 100 kg of ration (26).

Table 1. Relationship cactus/corn costs according to fence type, corn prices and cladodes ages.

Tabla 1. Relación de costos cactus/maíz de acuerdo con el tipo de alambrado, precios del maíz y edades de los cladodios.

Fence	Cactus cost		Corn cost (U$S kg DM^{-1})		Cactus/corn cost	
	(U$S ha^{-1})	(U$S kg DM^{-1})	Produced	Purchased	Produced	Purchased
			0.062	0.175		
Metal	855					
1-year		0.255			4.11	1.46
1+2-year		0.098			1.58	0.56
1+2+3-year		0.068			1.10	0.39
Electrified	547					
1-year		0.163			2.63	0.93
1+2-year		0.063			1.02	0.36
1+2+3-year		0.043			0.69	0.25
Without fence	342					
1-year		0.102			1.65	0.58
1+2-year		0.039			0.63	0.22
1+2+3-year		0.027			0.44	0.15

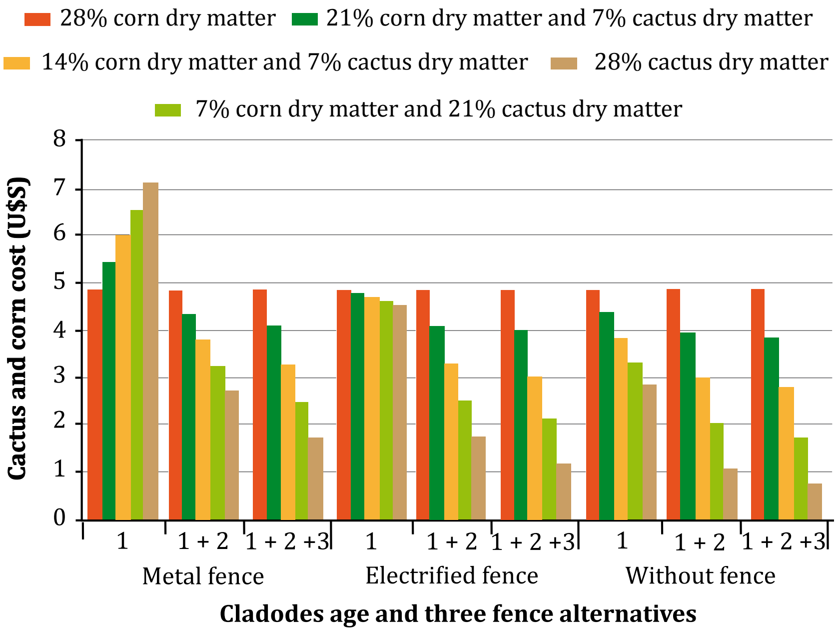


Figure 7. Cost of cactus plus corn (U$S) for the purchased corn price, cactus cost of 1-year, 1+2 year and 1+2+3-year-old cladodes and the three fence alternatives.

Figura 7. Costo de cactus más maíz (U$S) para el precio de maíz comprado. Costo del cactus de 1-año, 1+2 años y 1+2+3 años de edad de los cladodios y las tres alternativas de alambrado.

Conclusions

The future of arid and semiarid regions depends on the development of sustainable agronomic systems and the implementation of suitable crops. Cactus can meet these requirements and act as strategic food reserves to mitigate the effects of drought on livestock production systems of the above regions. Cactus plantations could be successfully developed in most of the arid and semi-arid regions of Argentina, provided frost-tolerant species or clones were used.

O. spinulifera emerges as one promising species for forage production in Mendoza plain, not only by its frost hardiness in areas with extremely cold winters: $-5<(m)<3$°C, but also high biomass production and CP content (2.0 kg plant^{-1} and 6.5%, respectively). However, due to the high frequency of absolute minimum temperatures in the study site, it appears to be necessary to protect the plants in winter for 1 or 2 years after planting.

The studies done so far, such as, identification of *Opuntia* clones and progenies of high productivity and cold hardiness, and also economic feasibility of cactus plantations, are a starting point for further researches. These should address animal performance in both rangeland and feedlot in response to supplementation of their diet with cactus, including it in different forms such as fresh, dehydrated, silage, multi-nutrient blocks. Other efforts could be directed to provide a propitious abiotic environment for a cactus to achieve higher biomass productivity and improved protein levels by interacting with nurse plants, such as *Prosopis* sps. Another interesting alternative to try for reducing the use of N-fertilizer could be testing whether endophytic nitrogen-fixing bacteria such as *Gluconacetobacter diazotrophicus* fix N in *Opuntia*.

The relationship cactus/corn cost indicates the possibility of replacing the corn by cactus in diet, by the lower relative price of the latter.

The establishment cost of cactus plantations appears to be high and out of reach for most ranchers and graziers. Intensive research and extension efforts are needed to make cactus plantations more attractive to them in terms of feed value, to highlight their role as "drought insurance" and economic benefits, and in particular to reduce their cost of establishment. At the same time, government should consider appropriate incentives for establishing fodder cactus plantations and legal tools favoring security of land tenure in some areas.

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