Forum

Opuntia Forage Production Systems: Status and Prospects for Rangeland Application

J. C. Guevara,[1] P. Suassuna,[2] and P. Felker[3]

Authors are [1]Research Scientist, Argentinean Institute for Arid Land Research (IADIZA–CONICET) and Adjunct Professor, Department of Economics, Legal and Social Sciences, Agronomy Faculty, National University of Cuyo, Mendoza, PO Box 507, 5500, Mendoza, Argentina; [2]Agricultural Engineer and Semiarid Tropical Consultant, Paulo Suassuna Consultoria Ltda., PO Box 166, Recife, PE, Brazil; and [3]Research Scientist, D'Arrigo Bros, PO Box 850, Salinas, CA 93902, USA.

Abstract

This paper reports recent findings in *Opuntia* genetics, nutrient fertilization, and cultivation with promise to overcome limitations for *Opuntia*-based forage production systems. The essentially spineless, fast-growing *Opuntia ficus-indica* (L.) Mill. has been planted on millions of hectares for forage in tropical areas of Brazil and North Africa. The spiny, cold-hardy *Opuntia* species have been used for forage in Mexico and the southwestern United States, after the cladodes have been chopped or singed to remove the spines. Due to the recent increases in fuel prices, burning of the spines is more costly. Where only spiny varieties exist, some range animals forage on them without manipulation. As a result, spines frequently penetrate and form lesions on mouth and esophageal tissues, leading to serious health issues. Slow growth and low protein (ca. 5%) of the native *Opuntia* spiny species on nonfertilized rangeland is an impediment to greater use of *Opuntia* for forage. The only spineless species adaptable to US Department of Agriculture cold hardiness zones < 8 (i.e., *Opuntia ellisiana* Griffiths) is relatively slow growing. Full sibling crosses indicate spine heritability is probably single-gene controlled. Interspecific hybrids between the frost-sensitive, fast-growing, and spineless *O. ficus-indica* with cold-hardy, spiny, slower-growing *O. lindheimerii* Engelm. have produced spineless progeny, with greater cold hardiness than *O. ficus-indica*, and greater productivity than cold-hardy, spineless *O. ellisiana*. Nitrogen limitations on water-use efficiency of *Opuntia* have been overcome for the 120 million ha of semiarid northeastern Brazil with added nitrogen and phosphorus fertilization. With control of competing vegetation and fertilization, this system has 40 t dry matter $\cdot ha^{-1}$ of 9.2% crude protein forage with 600 mm rainfall in 16 mo. *Opuntia ficus-indica* plantations were profitable even though a duplication of fertilizer current prices was considered.

Resumen

Este trabajo reporta los hallazgos recientes en genética, fertilización, y cultivo de *Opuntia* que aseguran superar las limitaciones para los sistemas de producción de forraje que se basan en esta especie. La especie de crecimiento rápido *O. ficus-indica* (L.) Mill. que es una especie sin espinas que se ha plantado en millones de hectáreas para forraje en áreas tropicales de Brasil y norte de África. Las especies de *Opuntia* con espinas, más tolerantes al frío, se han utilizado para forraje en México y el sudoeste de Estados Unidos, después que se han picado o levemente quemado las plantas para remover las espinas. Debido al alza reciente de los precios del combustible, la quema de las espinas ha pasado a ser mucho más costosa. Donde sólo existen variedades espinosas, algunos animales las ingieren sin ningún manejo. Como resultado de ello, las espinas penetran y forman lesiones en la boca y en los tejidos del esófago, que conducen a serios problemas de salud. El crecimiento lento y el contenido bajo en proteína (alrededor del 5%) de las especies espinosas de *Opuntia* nativas en pastizales nativos no fertilizados es un obstáculo para un uso mayor de *Opuntia* para forraje. La única especie sin espinas adaptable a las zonas de tolerancia al frío del Departamento de Agricultura de los Estados Unidos de Norteamérica < 8 (*O. ellisiana* Griffiths) es de crecimiento relativamente lento. Cruzas totales entre hermanos indican que la heredabilidad de las espinas está probablemente controlada por un gen simple. Híbridos interespecíficos entre *O. ficus-indica*, de crecimiento rápido, sensible al frío y sin espinas con *O. lindheimerii* Engelm., resistente al frío, con espinas y de crecimiento más lento, han identificado progenie sin espinas, con mayor resistencia al frío que *O. ficus-indica* y mayor productividad que *O. ellisiana*, especie sin espinas y tolerante al frío. Se han superado las limitaciones de N sobre la eficiencia del uso del agua por parte de *Opuntia* para las 120 millones de hectáreas de la zona semiárida del noreste de Brasil mediante la fertilización con nitrógeno y fósforo. Este sistema ha producido 40 toneladas de materia seca por hectárea con 9,2% de proteína bruta con 600 mm de lluvia anual mediante el control de la vegetación competitiva y la fertilización después de 16 meses. Las plantaciones de *O. ficus-indica* resultaron rentables aún si se considera una duplicación del precio actual de los fertilizantes.

Key Words: cold hardiness, cultural practices, economic feasibility, fertilization, progeny

INTRODUCTION

As forage for range livestock, Opuntias have both advantages and disadvantages. Spines and smaller glochids of the areoles are a distinctive feature of nearly all cacti that cause mechanical injury to the skin, face, and digestive tract, and are a strong

Research was funded in part by the National University of Cuyo, Program P-05.

Correspondence: J. C. Guevara, IADIZA, PO Box 507, 5500, Mendoza, Argentina. Email: jguevara@mendoza-conicet.gov.ar

Manuscript received 7 November 2008; manuscript accepted 14 June 2009.

deterrent to most herbivores. Feeding these species requires mechanical or flame treatments prior to feeding. Occasionally, sheep, goats, and cattle eat spiny cactus that have not had the spines removed, resulting in infected lesions in their digestive tract and poor health or death of these livestock (Migaki et al. 1969; Merrill et al. 1980).

In the continental United States, another negative attribute of *Opuntia* is that native spiny Opuntias are slow growing whereas the spineless, fast-growing species such as O. *ficus-indica* (L.) Mill. are not cold-hardy and are poorly adapted to most US rangelands. The low protein concentration of unfertilized cactus (5–6% crude protein [CP]; Everitt and González 1981; Meyer and Brown 1985) is another limitation when feeding grazing animals.

On the positive side, these cacti have greater water-use efficiency due to the crassulacean acid metabolism (CAM) photosynthetic pathway that is several times more efficient in converting water and CO_2 to dry matter plants than either C_4 or C_3 plants (Nobel 1991, 1994; Han and Felker 1997). Cacti can produce more dry matter per milimeter of rainfall than any other type of plant. When high population densities are planted, *O. ficus-indica* is very productive. Simulations (García de Cortázar and Nobel 1990) under natural conditions led to a maximum predicted productivity of about 20 t dry matter $\cdot$ $ha^{-1} \cdot yr^{-1}$ worldwide. Measurements with no water limitations gave 40 t dry matter $\cdot$ $ha^{-1} \cdot yr^{-1}$ in Chile (García de Cortázar and Nobel 1991). A very high density planting (24 plants $\cdot$ m^{-2}) with unlimited water and ample nutrients led to 50 t $\cdot$ $ha^{-1} \cdot yr^{-1}$ in Chile (García de Cortázar and Nobel 1992) and *O. ficus-indica* fertilized and watered daily had a productivity of 47 t $\cdot$ $ha^{-1} \cdot yr^{-1}$ in Mexico (Nobel et al. 1992). With high nitrogen (N) and phosphorus (P) applications in Texas to *O. lindheimerii* Engelm., González (1989) obtained 62 t dry matter $\cdot$ $ha^{-1} \cdot yr^{-1}$.

Worldwide, the greatest use of cactus for forage occurs in Mexico, South Africa, Tunisia, and Brazil (Mondragón-Jacobo and Pérez-González 2001; Felker et al. 2006). Flores and Aranda (1997) reported that 18 *Opuntia* species were used as forage on more than 3 million ha of rangeland in northern Mexico with 150 000 ha of cactus being planted by ranchers and small producers using government support. López et al. (1996) reported that 25 species and 12 varieties of *Opuntia* are being used for forage in the Mexican state of Coahuila. Flores and Aranda (1997) reported that more than 650 000 cattle died during the 1993 to 1996 drought in northern Mexico yet ranchers with nopales (*Opuntia*) appeared to have fewer livestock losses than ranchers without nopales. Furthermore, reproduction rates and production levels were greater for animals supplemented with nopales.

In Brazil (Domingues 1963; Cordeiro Dos Santos and Gonzaga de Albuquerque 2001) and Tunisia (Monjauze and Le Houérou 1965; Nefzaoui and Ben Salem 2001), there are plantations with several hundred thousand hectares of spineless *Opuntia* that are used for livestock feed. Extensive spiny *Opuntia* stands in Tigray, Ethiopia, also have been used for livestock food after the spines have been chopped (Brutsch 1997). In South Africa considerable scientific study has been devoted to utilization of cactus for forage (De Kock 2001). All of the cacti used commercially for livestock in the United States is of the wild spiny type, i.e., *O. lindheimerii* in Texas (Felker 1995) and to a lesser extent *O. polyacantha* Haw. in Colorado (Shoop et al. 1977).

CAM species show an average increase in biomass productivity of 35% in response to a doubled atmospheric CO_2 concentration (Drennan and Nobel 2000), predicted to occur before the end of the twenty-first century (Nobel 1996). With increasing temperature and drought duration, the percentage enhancement of daily net CO_2 uptake caused by elevated CO_2 concentration increases. Thus net CO_2 uptake, productivity, and the potential area for cultivation of CAM species will be enhanced by the increasing atmospheric CO_2 concentration and the increasing temperatures associated with global climate change (Drennan and Nobel 2000). Similarly, Nobel (1996) indicated a further expanding of CAM plants in the regions where they profitably can be cultivated.

Nutrient content of *Opuntia* spp. depends on the genetic characteristics of the species or clones, the cladode's age, the cladode sampling location, the cladode harvesting season, and the growing conditions, such as soil fertility and climate (Monjauze and Le Houérou 1965; Boza et al. 1995; Nefzaoui and Ben Salem 2001; Gugliuzza et al. 2002; Guevara et al. 2006). *Opuntia ficus-indica* was high in calcium (Ca), normal in magnesium (Mg), and low in sodium (Na), potassium (K), and P contents in relation to ruminant requirements from a diet, and similar to common temperate or tropical grasses and legumes (Tegegne 2001). Iron and aluminium are found in traces (López-García et al. 2001). In *Opuntia* spp., Ca is the main mineral constituent of the plants. It is found in a free form or as calcium oxalate. This salt can reach from 8% to 50% of dry matter (DM) and to 85% in the ashes of old plants (Tovar-Puente et al. 2007). Cactus cladodes have high oxalate content; total oxalate is about 13% of the DM, of which 40% is in a soluble form. These oxalates are probably bound to Ca, making this mineral less available to animals. Cactus feed, i.e., cladodes aged 1–3 yr is rich in provitamin A and vitamin C (Le Houérou 1996). Vitamin A is likely the vitamin of most practical importance in cattle feed. Vitamin A does not occur as such in plant material; however, its precursors, carotenes or carotenoids, are present in plants in various forms (National Research Council [NRC] 2000). The content of carotenoids is 29 μg 100 $\cdot$ g^{-1} and the content of ascorbic acid is 13 mg 100 $\cdot$ g^{-1} (Felker 2001). The nutrient content of seven *Opuntia* forage clones and three age classes (about 1 yr, 2 yr, and 3 yr old) was determined in the Mendoza plain, Argentina (Guevara et al. 2004). The nutrient content for all clones and age classes pooled was the following (% DM): organic matter (OM), 81.6% to 86.8%; in vitro organic matter digestibility, 69.5% to 82.1%; CP, 3.2% to 5.0%; neutral detergent fiber, 22.7% to 27.1%; acid detergent fiber, 12.0% to 16.0%; DM, 7.3% to 11.5%. A significant ($P < 0.05$) or nearly significant ($P = 0.08$) linear negative relationship between each nutritional parameter and age classes was found for all clones, except for OM that showed a significant linear relationship with only two clones.

Below we discuss some factors limiting the use of *Opuntia* for forage and provide methods to overcome these limitations.

Fertilization to Increase Crude Protein Contents

With N fertilization, typically low protein concentrations of *Opuntia* can be increased to attain 10% CP (N $\times$ 6.25), a level meeting the needs of a lactating cow (González 1989). Nobel (1983) measured N concentrations of *O. ficus-indica* cladodes in a California plantation near Los Angeles. In his study, cladodes averaged 15.3% CP. Nitrogen fertilization in O. *ficus-indica* fruit plantations near Salinas, California has resulted in cladode protein concentrations of 15% in 1-yr-old cladodes (P. Felker, unpublished observations, August 2008).

The protein concentration in *Opuntia* is quite sensitive to soil nutrient status. González (1989) conducted a fertilizer trial using N and P fertilizer on yield and tissue concentration of the Texas spiny wild O. *lindheimerii* and found that the CP increased from 4.5% for the control (no N and P additions) to 10.5% protein for additions of 224 kg $N \cdot ha^{-1}$ and 112 kg $P \cdot ha^{-1}$. There are reports of N-fixing symbiotic relationships of *Opuntia* with *Azospirillum* (Rao and Venkateswarlu 1982; Mascarúa-Esparza et al. 1988; Caballero-Mellado 1990) that need to be tested in the field for enhanced productivity and protein content.

Fertilization and Cultural Practices to Increase Productivity to $\geq$ 300 $t \cdot ha^{-1} \cdot yr^{-1}$ Fresh Weight

Three studies in Texas looked at methods to increase productivity of the native O. *lindheimerii*. Hanselka and Falconer (1994) noted that after root plowing, prickly pear populations exploded and dominated the community with approximately 16.8 $t \cdot ha^{-1}$ wet weight. In a trial adding N and P amendments in a factorial design, González (1989) measured a mean annual dry matter biomass productivity of a wild O. *lindheimerii* variety in a 430-mm annual precipitation zone. In this study he measured total biomass of 52 $t \cdot ha^{-1}$ after 4 yr with the highest N and P application rates. In a water-balance study that estimated surface, runoff, soil evaporation (microlysimeters), and drainage (neutron probes), Han and Felker (1997) reported that the 17.7 $t \cdot ha^{-1}$ dry matter productivity of O. *ellisiana* Griffiths was measured during the fourth year's growth after photosynthetic area (analogous to Leaf Area Index) reached 2.02. This level of productivity was achieved with 662 mm rainfall and 285 mm water being transpired, for a transpiration water-use efficiency of 162 kg $water \cdot kg^{-1}$ DM.

Despite the fact that O. *ellisiana* grows slower than most commercially raised Opuntias this is among the highest transpiration water-use efficiencies measured in replicated studies (Han and Felker 1997). This is an important attribute when considering most climate change scenarios for most arid and semiarid environments.

Snyman (2005) found that 95% of O. *ficus-indica* roots were in the upper 15 cm of soil. Thus, when fertilization is applied to Opuntias, it is important to apply frequent, low application rates to avoid leaching the nutrients below the root zone. Possibly due to this very shallow root system, Felker and Russell (1988) measured a 300% increase in *Opuntia* biomass when herbicides were used to control vegetation competing with *Opuntia*.

Unfortunately the advantage of potentially large water-use efficiency of CAM metabolism in Opuntias cannot be realized with very low annual N inputs (ca. 1–2 kg $N \cdot ha^{-1} \cdot yr^{-1}$) typical of semiarid lands (Geesing et al. 2000). As a result, the productivity of Opuntias on nonfertilized rangelands can be very low and the CP concentration of the edible portion of 1- and 2-yr-old cladodes is often as low as 4–5% and thus well below the minimal requirements for a beef cow (6–13% $CP \cdot DM^{-1}$; NRC 2000). When the N inputs/effluxes from a rangeland ecosystem are in a hypothetical steady state equilibrium, there is no net change in soil and vegetation pool sizes in N. In this case no more N can be taken from the system than enters the system. If only 2 kg $N \cdot ha^{-1} \cdot yr^{-1}$ enter the system, no more than that can be taken off in a sustainable manner. Assuming a low cladodal concentration of 0.8 kg $N \cdot 100$ kg DM^{-1} (5% CP), then only 250 kg $DM \cdot ha^{-1} \cdot yr^{-1}$ can be sustainably harvested without external N inputs.

Nobel (1983) has demonstrated that increased chlorenchyma N increased nocturnal acid accumulation. This increased nocturnal acid concentrations, increasing the total amount of phosphoenol pyruvate carboxylase (PEP) enzyme that is the first step in CAM metabolism. If the total PEP activity increased, this would create a greater flux of CO_2 into the cladodes. Because water-use efficiency is the ratio of water transpired per carbon gain, increased N could increase the water-use efficiency of cacti. Felker and Bunch (2009) have assumed constant water-use efficiency for CAM, C_4, and C_3 plants in a graphic representation of productivity vs. annual rainfall containing fixed ceilings on productivity that were placed according to annual N inputs. This clearly demonstrated that high water-use efficiencies of cacti cannot be utilized unless considerable N inputs are applied.

Suassuna (2008) used fertilization to overcome the N and P limitations to *Opuntia* biomass productivity on a farm at 630 m elevation (lat 08°02′23.7″ S, long 37°03′23.9″ W) with about 600 mm rainfall per year in northeastern Brazil. Production practices included banded surface applications of 600 kg $urea \cdot ha^{-1}$, 1 200 kg of $phosphate \cdot ha^{-1}$, and 15 t of dry $manure \cdot ha^{-1}$ for a plant population of 60 000 $plants \cdot ha^{-1}$. Competing vegetation was overcome with use of pre-emergent (ametryne, diuron, tebuthiuron, simazine, and atrazine) and postemergent (glyphosate) herbicides. With these inputs, 40 $t \cdot ha^{-1}$ DM containing 9.2% CP was obtained in 16 mo. An example of the biomass after 16 mo in rainfed northeastern Brazil is shown in Figure 1. For 480 d (16 mo) at a daily fresh weight requirement of 40 kg for cattle, and from 3 kg to 9 kg for sheep and goats (López-García et al. 2001), 1 ha would support 25 cattle, and from 113 to 340 goats or sheep.

The productivity of 40 $t\ DM \cdot ha^{-1}$ is in agreement with that of Nobel et al. (1992), who reported an average productivity of 48 $t \cdot ha^{-1} \cdot yr^{-1}$ (564 $t \cdot ha^{-1}$ fresh weight at 8.5% DM) for O. *amyclaea* Ten. and O. *ficus-indica* that were fertilized and watered daily in Saltillo, Coahuila, Mexico and of 40 $t \cdot ha^{-1} \cdot yr^{-1}$ (470 t fresh $weight \cdot ha^{-1}$) for intensively managed O. *ficus-indica* in Chile (García de Cortázar and Nobel 1991). At 194 $t \cdot ha^{-1}$ O. *ellisiana* had less fresh weight growth during the fourth year of growth than the O. *ficus-indica* (Han and Felker 1997). However, as opposed to the continuously irrigated cacti in the Chilean and Mexican studies, for the O. *ellisiana*, 240 mm of the 662 mm annual rainfall occurred in four heavy thunderstorms that ran off or quickly percolated below the 15-cm-deep root zone.

With regard to the N fertilization sustainability, we consider that because the naturally occurring N input without legumes is only about 2 $kg \cdot ha^{-1} \cdot yr^{-1}$, then without N inputs, grazing is not sustainable if the cow consumes more than 4 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (due to the 50% loss in volatilization of N in urine and feces).

Figure 1. Harvest of 40 $t \cdot ha^{-1}$ dry weight from 16-mo-old *Opuntia ficus-indica* under intensive management in a 600-mm annual precipitation zone at 630-m elevation (lat 08°02′23.7″ S, long 37°03′23.9″ W) in northeastern Brazil.

When fed as an exclusive diet, cladodes cause diarrhea after about 6 wk for cattle, and 8 wk for sheep, limiting *Opuntia* use as a single feed to short periods (Le Houérou 1996). According to Le Houérou (1996), diarrhea easily can be prevented and/or cured by adding to the diet approximately 1% dry roughage (straw, hay, browse, grazing) on a body weight basis, in other words by offering a ration with a minimum overall DM content of 25–30%. The high amount of oxalates might explain the laxative effect of cladodes when fed to animals (Nefzaoui and Ben Salem 2001).

Genetic Improvement to Increase Cold Hardiness of Spineless Selections

Opuntia, which is insect-pollinated and has self-fertile flowers, can be diploid, triploid, tetraploid, and octaploid ($n = 11$; Weedin and Powell 1978; Powell and Weedin 2001). Wang et al. (1996) reported emasculation and bagging techniques for *Opuntia* and examined the sterility barriers between commercial *O. ficus-indica* fruit types, *O. lindheimerii*, *O. ellisiana*, and a few apparent hybrid species. *O. ficus-indica* was found to produce fertile offspring with the spiny Texas native *O. lindheimerii* but not with *O. ellisiana*, or a putative hybrid forage clone No. 1233. In Mendoza, Argentina, *O. ellisiana* suffered no frost damage when temperatures dropped to −15°C during two brief occasions (2–3 hr) in the winter of 2000 (Guevara et al. 2003a). However, as mentioned earlier, *O. ellisiana* is slow-growing. It would be desirable to have a spineless *Opuntia* with the same cold hardiness of *O. ellisiana* but with much faster growth rate.

Opuntias possess two different types of "spines" arising from the areoles that are objectionable to livestock and humans. One is the spines that can vary from about one to several centimeters in length. The other is the nearly microscopic (100 μ in diameter by about 1 500 μ long) hair-like barbed spines known as glochids. These characters appear to be under separate genetic control, because some *O. lindheimerii* have no spines on portions of their cladodes but have very abundant glochids. In contrast some *O. ficus-indica* fruit varieties with long spines have very reduced glochids. The *O. ficus-indica* variety *Opuntia ficus-indica* L. f. inermis (Web.) Le Houér. (Guevara et al. 2006) is nearly devoid of glochids and spines, whereas *O. ellisiana* (1364) has many fewer glochids than the typical "spineless" *O. ficus-indica*. Although spine length was similar for *O. lindheimerii* clones made by Texas rancher W. A. Maltsberger (Maltsberger 1996), the percentage of areoles with spines varied from 3.3% to 47.7% (Chávez-Ramírez et al. 1997).

The genetic control of spine production appears to be relatively simple. In hybridization studies among the octaploid "commercial fruit type" Opuntias, when the female parent was spineless and the male parent spiny, 57% of the progeny ($n = 84$) were spineless. When the female parent was spiny and the male parent was spineless, 63% of the progeny ($n = 84$) were spineless, and when both parents were spineless, 92% of the progeny ($n = 155$) were spineless (P. Felker, unpublished observations, July 2003). Collectively, these data suggest that spinelessness is simply inherited. The recovery of spiny genotypes from spineless parents suggests that this (albeit small) sampling of parental genotypes each contained alleles for both the spineless and the spiny condition.

One hundred and fifty seedlings from the *O. ficus-indica* × *O. lindheimerii* cross were evaluated in the field in Argentina where the majority were found to be apomicts (unfertilized seed derived from maternal tissue) and thus clonally identical to the female *O. ficus-indica* parent. However, some of the segregates had many of the characteristics of the cold-hardy, spiny male parent (small fruit and bluish cladodes) but without spines. We believe these will possess increased cold tolerance over the spineless *O. ficus-indica* and possibly the other spineless *Opuntia* types. An example of a 3-yr-old spineless progeny between *O. ficus-indica* and *O. lindheimerii* that possessed cladode shape and color of the male *O. lindheimerii* phenotype is presented in Figure 2. Ten such progeny currently are being evaluated in various cold hardiness zones of the Argentine central arid zone at lat 33°S by Juan Carlos Guevara of the Argentinean Institute for Arid Land Research (unpublished data).

Spiny and spineless seedlings emerged from the feces of wildlife that had eaten the fruit of spineless types in South Africa and later spread over vast areas. Thus sterility in forage types would be a significant advantage when introducing them to new areas. All of the bagged, nonmanipulated flowers of *Opuntia* accession No. 1233 developed into fruits, but these fruits abscised (Wang et al. 1996), indicating that this clone might be sterile.

Because *O. lindheimerii* is sufficiently cold hardy and adapted to conditions throughout most of Texas, and *O. ficus-indica* lacks cold hardiness, but is spineless and fast-growing, a combination of the two provides a genetic route to produce cold-hardy, spineless forage Opuntias for Texas. Other crosses to examine, if sexual compatibility exists, is a cross between spineless types and the spiny *O. polyacantha*, once used for forage in Colorado (Shoop et al. 1977). *Opuntia polyacantha* is adapted to lat 56°N in Alberta, Canada (Stelfox and Friend 1977) and *O. australis* F. A. C. Weber is adapted to lat 50°S in Argentina.

The new hybrids are intermediate in chromosome number between the parents (*O. linheimerii* is hexaploid, *O. ficus-indica* is octaploid, and the hybrids are heptaploid) and trials to cross these back to *O. ficus-indica* were not successful due to chromosome issues. This means that they probably will not

Figure 2. Three-year-old thornless segregant of a cross between spineless *Opuntia ficus-indica* 1281 (female parent) × *Opuntia lindheimerii* 1250 (male parent). *Opuntia lindheimerii* is a cold-hardy, native species from Texas. The progeny have many characteristics of the cold-hardy male parent. The progeny were grown in Santiago del Estero, Argentina, in a 650-mm annual precipitation zone dominated by summer rainfall. These plants were fertilized once a year with 150 g · plant^{-1} 15–15–15 fertilizer that was banded around the base of the plants, and competing plants removed with diuron and glyphosate.

cross with the wild Opuntias. Varieties without spines or glochids are extremely susceptible to herbivory from all sizes of mammals (rabbits, deer, etc.) and substantial fencing is needed to protect them.

Opuntia Pests and Diseases

Granata and Sidoni (2002) reported that the numerous pests and diseases present in *Opuntia ficus-indica* in the producer area worldwide are caused by bacteria, yeasts, fungi, phytoplasmas, and viruses, and abiotic factors such as atmospheric conditions. The diseases often result in severe damage, especially in cladodes, roots, and fruits. Because some of the diseases can jeopardize the entire cultivation, stricter control should be exercised on propagative material and on importation from other countries. Prevention often is the best way to control the diseases and keep them from spreading into areas that are not affected. The study by Granata and Sidoni (2002) reports on the major cactus diseases present in the growing areas, the characteristics of the causal agent, the symptomology, and the control measures.

The main pests that can cause economic damage to *Opuntia* in Brazil are the cochineal insect (*Diaspis* sp. and *Dactylopius opuntiae*), caterpillars, grasshoppers, and ants. The main disease that can cause economic damage to Opuntias is rotting caused by fungus. Applying insecticides (1 L · ha^{-1}) of one of the following products: Confidor, Provado, Carbaril, Endosulfan, or Carbofuran, and fungicides (1 kg · ha^{-1}) such as Metiltiofan or Cercotim, produced significant results in the control of grasshoppers, ants, and fungi (Suassuna 2008). The possibility of using biological and other alternative methods to control pest populations of *Diaspis echinocacti*, which is an important pest of *Opuntia* spp. in northeast Brazil, was studied by de Souza Born et al. (2009).

Cactoblastis cactorum is a common pest in *Opuntia ficus-indica* in the northeastern region of Argentina. To determine the efficacy of different insecticides for its control, Carbaril (CA; 0.16 L · 100 L^{-1}), Deltrametrin (DEL; 0.01 L · 100 L^{-1}), Endosulfan (END; 0.15·L 100 L^{-1}), Spinosad (SPI; 0.04 L · 100 L^{-1}), and Triflumuron (TRI; 0.03 L · 100 L^{-1}) were tested in the laboratory by Lobos et al. (2002). Mortality ranged from 20% to 100%. CA, DEL, and SPI performed well as contact insecticides and their efficacy improved when used with adjuvants.

In arid zones (200–300 mm mean annual precipitation) pests and diseases were not recorded (J. C. Guevara, personal observation, October 2007). The previous information implies that pests and diseases would not influence a livestock producer's decision to include *Opuntia* in their forage mix.

Economic Evaluation of *Opuntia* Forage Management Systems

The economic feasibility of 50-ha, 100-ha, and 200-ha *O. ficus-indica* plantations was evaluated for semiarid northeastern Brazil (600 mm annual precipitation) and the Argentina central arid zone (300 mm annual precipitation) under a cut-and-carry management system. Cacti plantations in Brazil included annual fertilization as was previously mentioned. Those in Argentina were not fertilized. The basic data (establishment and operating costs in January 2008 currency) were derived from our previous studies (Guevara et al. 1999; Suassuna 2008). Monetary value of cactus forage was estimated using as the shadow price the cost of energy and protein derived from those of concentrate forages (De Montgolfier-Kouèvi and Le Houérou 1980) for the period 1997–2006 (in January 2008 currency). The capital opportunity cost was assumed to be 12%. The period of analysis for computing the internal rate of return (IRR) was 20 yr. If the IRR is higher than the capital opportunity cost, cacti plantations are profitable. The results are presented in Table 1.

The IRR in Brazil was about six times the capital opportunity cost, i.e., the intensive cactus plantation has a high profitability. The threshold of 12% IRR was reached in Argentina at 15 t DM · ha^{-1} · yr^{-1} for a 100-ha plantation, with the IRR threshold being reached for all cactus production levels harvested. Most nitrogen fertilizers are derived from increasingly scarce fossil fuel. If we consider that the N fertilizer cost could duplicate the current one, the IRR for 50 ha in Brazil, for example, would drop from 73.5% to 47.2%. This implies that the probable increase in N fertilizer cost would not affect the economics of forage *Opuntia*.

MANAGEMENT IMPLICATIONS

Combining these new findings and management options creates the potential to produce 300 t · ha^{-1} yr^{-1} of fresh forage in marginal arid and semiarid environments that provide more than

Table 1. Internal rates of return of cactus plantations in Brazil and Argentina according to the planting area and the forage production (dry matter [DM]).

Zone	Plantation area (ha)	Cactus forage production (t DM · ha^{-1} · yr^{-1})	Internal rate of return (%)
Brazil	50	31.2	73.5
	100		73.9
	200		74.1
Argentina	50	5.6	3.2
		10.0	4.7
		15.0	6.2
	100	5.6	8.0
		10.0	10.6
		15.0	12.5
	200	5.6	12.1
		10.0	15.2
		15.0	17.5

9% crude protein (DM basis) and 60–70% digestible dry matter. Furthermore, it appears some planned accessions can withstand freezing temperatures to US Department of Agriculture cold hardiness zone 7.

We foresee three major types of utilization for these technologies: 1) as a year-long source of forage, 2) forage reserves during drought ("drought insurance"), and 3) to supplement seasonal forage shortages. In Argentina, need is greatest during late fall and winter when goat parturition occurs and forage reserves are scarce (Guevara et al. 2003b).

In summary, new techniques for making interspecific crosses between wild, well-adapted, spiny but slow-growing *Opuntia* species, with fast-growing spineless, domesticated species creates new opportunities for much more useful, productive, and high water-use efficiency *Opuntia* forage varieties. Combinations of these new varieties with intensive management systems, including high N inputs, show great promise for overcoming the past issues with spiny, low-productive Opuntias to dramatically improve forage production from rangeland. Cactus plantations are a profitable activity for rangelands of semiarid and arid zones.

ACKNOWLEDGMENTS

Authors thank Ed L. Fredrickson and one anonymous reviewer for providing valuable comments on a previous version of the manuscript.

LITERATURE CITED

Boza, J., J. Fonolla, and J. H. Silva. 1995. Utilización de la chumbera (*Opuntia ficus-indica*) en alimentación animal. *Avances en Alimentación y Mejora Animal* 35:3–6. (In Spanish).

Brutsch, M. O. 1997. The beles or cactus pear (*Opuntia ficus-indica*) in Tigray, Ethiopia. *Journal of the Professional Association for Cactus Development* 2:130–141.

Caballero-Mellado, J. 1990. Potential use of *Azospirillum* in association with prickly pear cactus. Proceedings of First Annual Texas Prickly Pear Council. Kingsville, TX, USA: Texas A&M University Kingsville. p. 14–21.

Chávez-Ramírez, F., X. Want, K. Jones, D. Hewett, and P. Felker. 1997. Ecological characterization of *Opuntia* clones in south Texas: implications for wildlife herbivory and frugivory. *Journal of the Professional Association for Cactus Development* 2:9–19.

Cordeiro Dos Santos, D., and S. Gonzaga de Albuquerque. 2001. Fodder use in the semi- arid northeast of Brazil. *In:* C. Mondragón-Jacobo and S. Pérez-González [eds.]. Cactus (*Opuntia* spp) as forage. Rome, Italy: Food and Agriculture Organization. p. 37–50.

De Kock, G. C. 2001. The use of *Opuntia* as a fodder source in arid areas of southern Africa. *In:* C. Mondragón-Jacobo and S. Pérez-González [eds.]. Cactus (*Opuntia* spp) as forage. Rome, Italy: Food and Agriculture Organization. p. 101–105.

De Montgolfier-Kouèvi, C., and H. N. Le Houérou. 1980. Study on the economic viability of browse plantations in Africa. *In:* H. N. Le Houérou [ed.]. Browse in Africa. The current state of knowledge. Addis Ababa, Ethiopia: International Livestock Centre for Africa. p. 449–464.

de Souza Born, F., M. J. Cerqueira de Araújo, H. Monaísy Alencar Lima, V. de Melo Rodrigues, S. M. Forti Broglio-Micheletti, R. C. Prédes Trindade, E. E. Pintos de Lemos, and D. M. Passos da Silca. 2009. Control of *Diaspis echinocacti* (Bouché, 1833) (Hemiptera: Diaspididae) in prickly-pear. *Acta Horticulturae* 811:223–226.

Domingues, O. 1963. Origem e introducao da palma forrageira no nordeste. Recife, Brazil: Instituto Joaquim Nabuco de Pesquisas Socias. 74 p. (In Portuguese).

Drennan, P. D., and P. S. Nobel. 2000. Responses to CAM species to increasing atmospheric CO_2 concentrations. *Plant, Cell & Environment* 23:767–781.

Everitt, J. H., and C. L. González. 1981. Seasonal nutrient content in foods of white tailed deer on the South Texas Plains. *Journal of Range Management* 34:506–510.

Felker, P. 1995. Forage and fodder production and utilization. *In:* G. Barbera, P. Inglese, and E. Pimienta-Barrios [eds.]. Agroecology, cultivation and uses of cactus pear. Rome, Italy: Food and Agriculture Organization. p. 144–154.

Felker, P. 2001. Utilization of *Opuntia* for forage in the United States of America. *In:* C. Mondragón-Jacobo and S. Pérez-González [eds.]. Cactus (*Opuntia* spp.) as forage. Rome, Italy: Food and Agriculture Organization. p. 51–56.

Felker, P., and R. A. Bunch. 2009. Mineral nutrition of cactus for forage and fruits. *Acta Horticulturae* 811:389–394.

Felker, P., A. Paterson, and M. M. Jenderek. 2006. Forage potential of *Opuntia* clones maintained by the USDA, National Plant Germplasm System (NPGS) collection. *Crop Science* 46:2161–2168.

Felker, P., and C. E. Russell. 1988. Influence of herbicides and cultivation on the growth of *Opuntia* in plantations. *Journal of Horticultural Science* 63:149–155.

Flores, C., and G. Aranda. 1997. *Opuntia* based ruminant feeding systems in Mexico. *Journal of the Professional Association for Cactus Development* 2:3–9.

García de Cortázar, V., and P. S. Nobel. 1990. Worldwide environmental productivity indices and yield predictions for a CAM plant, *Opuntia ficus-indica*, including effects of doubled CO_2 levels. *Agricultural and Forest Meteorology* 49:261–279.

García de Cortázar, V., and P. S. Nobel. 1991. Prediction and measurement of high annual productivity for *Opuntia ficus-indica*. *Agricultural and Forest Meteorology* 56:261–272.

García de Cortázar, V., and P. S. Nobel. 1992. Biomass and fruit production for the prickly pear cactus *Opuntia ficus-indica*. *Journal of the American Society for Horticultural Science* 117:558–562.

Geesing, D., P. Felker, and R. L. Bingham. 2000. Influence of mesquite (*Prosopis glandulosa*) on soil nitrogen and carbon development: implications for global C sequestration. *Journal of Arid Environments* 46:157–180.

González, C. L. 1989. Potential of fertilization to improve nutritive value of prickly pear cactus (*Opuntia lindheimerii* Engelm.). *Journal of Arid Environments* 16:87–94.

Granata, G., and A. Sidoni. 2002. Survey of diseases discovered on *Opuntia ficus-indica* in producer countries. *Acta Horticulturae* 581:231–237.

Guevara, J. C., O. R. Estevez, and C. R. Stasi. 1999. Economic feasibility of cactus plantations for forage and fodder production in the Mendoza plain (Argentina). *Journal of Arid Environments* 43:241–249.

Guevara, J. C., J. H. Silva-Colomer, and O. R. Estevez. 2004. Nutrient content of *Opuntia* forage clones in the Mendoza plain, Argentina. *Journal of the Professional Association for Cactus Development* 6:62–77.

Guevara, J. C., J. H. Silva-Colomer, O. R. Estevez, and J. A. Paez. 2003b. Simulation of the economic feasibility of fodder shrub plantations as a supplement for goat production in the north-eastern plain of Mendoza, Argentina. *Journal of Arid Environments* 53:85–98.

Guevara, J. C., J. H. Silva-Colomer, M. C. Juárez, and O. R. Estevez. 2003a. *Opuntia ellisiana*: cold hardiness, above-ground biomass production and nutritional quality in the Mendoza plain, Argentina. *Journal of the Professional Association for Cactus Development* 5:55–64.

Guevara, J. C., S. O. Trione, O. R. Estevez, and M. A. Cony. 2006. A sampling procedure to determine the nitrogen content in *Opuntia ficus-indica* cladodes. *Journal of the Professional Association for Cactus Development* 6:63–72.

Gugliuzza, G., T. La Mantia, and P. Inglese. 2002. Fruit load and cladode nutrient concentrations in cactus pear. *Acta Horticulturae* 581:221–224.

Han, H., and P. Felker. 1997. Field validation of water use efficiency of a CAM plant *Opuntia ellisiana* in south Texas. *Journal of Arid Environments* 36:133–148.

Hanselka, C. W., and L. L. Falconer. 1994. Pricklypear management in South Texas. *Rangelands* 16:102–106.

Le Houérou, H. N. 1996. The role of cacti (*Opuntia* spp.) in erosion control, land reclamation, rehabilitation and agricultural development in the Mediterranean Basin. *Journal of Arid Environments* 33:135–159.

Lobos, E., J. Ochoa, and C. Soulier. 2002. *Cactoblastis cactorum* Berg (Lepidoptera, Pyralidae) preliminary studies for chemical control. *Acta Horticulturae* 581:247–251.

López, J. J., A. Rodríguez-G, L. Perez-R, and J. M. Fuentes-R. 1996. A survey of forage uses of cactus in northern Mexico. *Journal of the Professional Association for Cactus Development* 1:10–19.

López-García, J. J., J. M. Fuentes-Rodríguez, and R. A. Rodríguez. 2001. Production and use of *Opuntia* as forage in northern Mexico. *In:* C. Mondragón-Jacobo and S. Pérez-González [eds.]. Cactus (*Opuntia* spp) as forage. Rome, Italy: Food and Agriculture Organization. p. 29–36.

Maltsberger, B. 1996. Cactus as a resource for cattle and wildlife. *Journal of the Professional Association for Cactus Development* 1:3–10.

Mascarúa-Esparza, M. A., R. Villa-González, and J. Caballero-Mellado. 1988. Acetylene reduction and indoleacetic acid production by *Azospirillum* isolates from Cactaceous plants. *Plant and Soil* 106:91–95.

Merrill, L. B., C. A. Taylor, R. Dusek, and C. W. Livingston. 1980. Sheep losses from range with heavy prickly pear infestation. *In:* D. N. Ueckert and J. E. Huston [eds.]. Rangeland resources research. San Angelo, TX, USA: Texas Agricultural Experiment Station Consolidated Progress Report 3665. 91 p.

Meyer, M. M., and R. D. Brown. 1985. Seasonal trends in the chemical composition of ten range plants in south Texas. *Journal of Range Management* 38:154–157.

Migaki, G., L. E. Hinson, G. D. Imes, and F. M. Garner. 1969. Cactus spines in the tongues of slaughtered cattle. *Journal of the American Veterinary Medical Association* 155:1489–1492.

Mondragón-Jacobo, C., and S. Pérez-González. 2001. Germplasm resources and breeding *Opuntia* for fodder production. *In:* C. Mondragón-Jacobo and S. Pérez-González [eds.]. Cactus (*Opuntia* spp) as forage. Rome, Italy: Food and Agriculture Organization. p. 21–28.

Monjauze, A., and H. N. Le Houérou. 1965. Le role des *Opuntia* dans l'economie agricole Nord Africaine. *Bulletin de l'Ecole Nationale Superiéure d'Agriculture de Tunis* 8–9:85–164.

Nefzaoui, A., and H. Ben Salem. 2001. *Opuntia* spp. A strategic fodder and efficient tool to combat desertification in the WANA region. *In:* C. Mondragón-Jacobo and S. Pérez-González [eds.]. Cactus (*Opuntia* spp) as forage. Rome, Italy: Food and Agriculture Organization. p. 73–89.

Nobel, P. S. 1983. Nutrient levels in cacti-relation to nocturnal acid accumulation and growth. *American Journal of Botany* 70:1244–1253.

Nobel, P. S. 1991. Tansley Review no. 32. Achievable productivities of CAM plants: basis for high values compared with C_3 and C_4 plants. *New Phytologist* 119:183–205.

Nobel, P. S. 1994. Remarkable agaves and cacti. New York, NY, USA: Oxford University Press. 180 p.

Nobel, P. S. 1996. Responses to some North American CAM plants to freezing temperatures and doubled CO_2 concentrations: implications of global climate change for extending cultivation. *Journal of Arid Environments* 34:187–196.

Nobel, P. S., E. Garcia-Moya, and E. Quero. 1992. High annual productivity of certain agaves and cacti under cultivation. *Plant, Cell and Environment* 15:329–335.

NRC [National Research Council]. 2000. Nutrient requirements of beef cattle, 7th revised ed. Washington, DC, USA: National Research Council. 248 p.

Powell, A. M., and J. F. Weedin. 2001. Chromosome numbers in Chihuahuan Desert Cactaceae. III. Trans Pecos Texas. *American Journal of Botany* 88:481–485.

Rao, A. V., and B. Venkateswarlu. 1982. Associative symbiosis of *Azospirillum lipoferum* with dicotyledonous succulent plants of the Indian desert. *Canadian Journal of Microbiology* 28:778–782.

Shoop, M. C., E. J. Alford, and H. F. Mayland. 1977. Plains prickly pear is a good forage for cattle. *Journal of Range Management* 30:12–17.

Snyman, H. A. 2005. A case study on in situ rooting profiles and water-use efficiency of cactus pears, *Opuntia ficus-indica* and *O. robusta*. *Journal of the Professional Association for Cactus Development* 7:1–21.

Stelfox, J. G., and H. G. Friend. 1977. Prairie fires and pronghorn use of cactus. *The Canadian Field Naturalist* 91:282–285.

Suassuna, P. 2008. A review of applied *Opuntia* forage production technologies and costs for north eastern Brazil. *Journal of the Professional Association for Cactus Development* 10:171–197.

Tegegne, F. 2001. Nutritional value of *Opuntia ficus-indica* as a ruminant feed in Ethiopia. *In:* C. Mondragón-Jacobo and S. Pérez-González [eds.]. Cactus (*Opuntia* spp.) as forage. Rome, Italy: Food and Agriculture Organization. p. 91–99.

Tovar-Puente, A., M. Pando-Moreno, H. González-Rodríguez, L. Scott-Morales, and S. de J. Méndez Gallegos. 2007. Densidad de cristales de oxalato de calcio en quince cultivares de nopal. *Journal of the Professional Association for Cactus Development* 9:91–98.

Wang, X., P. Felker, A. Paterson, Y. Mizrahi, A. Nerd, and C. Mondragón-Jacobo. 1996. Cross-hybridization and seed germination in *Opuntia* species. *Journal of the Professional Association for Cactus Development* 1:49–60.

Weedin, J. F., and A. M. Powell. 1978. Chromosome numbers in Chihuahuan desert Cactaceae. Trans-Pecos Texas. *American Journal of Botany* 65:531–537.