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Forage Potential of *Opuntia* Clones Maintained by the USDA, National Plant Germplasm System (NPGS) Collection

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ABSTRACT

Short term gas exchange measurements and long term field trials have confirmed the several fold greater water to dry matter conversion efficiency of cactus than C3 and C4 plants. The protein and dry matter digestibility of *Opuntia* typically are in the 60 to 70% range and are on par with other high quality forages. While the protein content is low (ca. 6%), as is usually observed in unfertilized rangeland, fertilization can increase the protein to 10 to 15%. The high mineral content (4.2% Ca and 2.3% K) would appear to be beneficial to lactating animals. The high water content, maintained in drought periods, is useful in meeting animal water requirements. In both Mexico and the USA spiny varieties have been utilized by burning off spines in the field with propane torches, or by use of stationary forage choppers at the dairy/feedlot. Spineless varieties require intensive fencing for protection against wildlife and uncontrolled livestock. Spineless varieties generally have less tolerance to freezing weather than spiny varieties. It has been estimated that about 400 000 ha of spineless varieties have been planted in Brazil, from 700 000 to 1 000 000 ha in northern Africa and that cactus was an important forage component on 3 million ha of grazing lands in northern Mexico. The majority of the spiny and spineless types used worldwide for forage are preserved in the USDA NPGS germplasm collection. This paper reviews the environmental adaptability and most important nutritional characteristics of major forage clones. Spineless clones are described that are adaptable to USDA cold hardiness zones 7, 8, and 9.

The several fold greater conversion of water to dry matter in crassulacean acid metabolism (CAM) plants than either C4 or C3 plants (Han and Felker, 1997; Nobel, 1991, 1994) offers exceptional possibilities for large quantities of biomass in water-limited areas that are useful for livestock feed. However, it is to be cautioned that the flat stemmed opuntias, such as those described in this paper, are not true desert xerophytes and will not survive conditions found in areas like Bikaner, India with a monthly mean daily maximum temperature of 42.9°C and 240 mm annual rainfall, without supplemental irrigation (O.P. Pareek, personal communication, 1997). *Opuntia* has low height growth compared to grasses, e.g., *O. ellisiana* only grows about 40 cm in height pear year and *O. ficus indica* only about 100 cm in height per year. However, due to annual extension of as many as 100 cladodes of average 1.5 kg fresh weight (ca 150 g dry weight) over the surface of a several year old plant, the productivity can be high. For example, when *O. ellisiana* achieved a leaf area index of 2, it had a dry matter productivity of 17 Mg ha^{-1} yr^{-1} with only 662 mm rainfall (Han and Felker, 1997). However at 4 yr with 38 dry ton per ha, the height of this stand was only about 1m. With a typical composition of 90% water (fresh weight basis), 6% protein (dry weight basis), 4% calcium (dry weight basis), 75% in vitro dry matter digestibility, and 72% digestible protein, cactus offers a highly digestible source of energy, a rich source of calcium for lactating animals, and high water content to offset the animal drinking requirements during drought periods (Felker, 1995). Because of the low protein content it is necessary to supplement animal rations based on unfertilized cactus with protein, mineral, and vitamin supplements, such as soybean or cotton seed meal (Felker, 1995).

HISTORY AND CURRENT USE

In spite of the large quantities of cactus used for forage in Texas, northern Mexico, and other arid regions of the world, publications related to cactus forage use have generally occurred primarily in regional extension publications, often in Spanish, and thus outside the normal scientific literature base. Fortunately, a recent compendium of cactus uses as forage has been compiled by the Food and Agricultural Organization (Mondragon-Jacobo and Perez-Gonzalez, 2001). In the United States, due to the need to protect spineless types from intensive wildlife herbivory, and the lack of freezing tolerance of most spineless types, all of the cactus used commercially for livestock food is of the wild spiny type. These spiny species are *O. engelmannii var. lindheimeri* in Texas (Felker, 1995) and to a lesser extent *O. polyacantha* in Colorado (Shoop et al., 1977). USDA publications as early as 1905 (Griffiths, 1905, and 1906) recounted the use of cactus to feed oxen that were used to transport cotton from the Confederate states through Texas to Mexico during the Civil War to avoid the Union blockade. Even in drought years of the 1990s in Texas and Mexico, a common occurrence was burning spines off the cactus pads to provide livestock feed. Approximately one liter of propane is needed to burn enough cactus for the ration of one adult cow per day and some ranchers have purchased as much as 50 000 L of propane/yr (W.A. Maltsberger, personal communication, 1998).

Flores and Aranda (1997) reported that 18 *Opuntia* species in Mexico were used as forage on the more than 3 million ha of rangeland in northern Mexico, and that 150 000 ha of cactus were planted by ranchers and small producers with government support. Lopez et al. (1996) reported the use of 25 species and 12 varieties of *Opuntia* for forage in the state of Coahuila. Flores and Aranda

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Abbreviations: CAM, crassulacean acid metabolism.

(1997) reported that due to the extended drought from 1993 to 1996, more than 650 000 cattle died. However, ranchers with cactus did not suffer as great a loss as those whose cactus ran out. Furthermore, reproduction rates and production levels were greater for animals that received cactus supplements.

In Brazil (Domingues, 1963, Dos Santos and de Albuquerque, 2001) more than 400 000 ha of cactus are used for forage, and in northern Africa (Tunisa, Algeria, and Morocco) (Monjauze and LeHouerou, 1965, Nefzaoui and Salem, 2001) from 700 000 to 1 million ha have been estimated to be used for livestock feed. Extensive spiny *Opuntia* stands in Tigray, Ethiopia have also been used for livestock food after the spines have been removed (Brutsch, 1997).

Major *Opuntia* germplasm introductions have been made to the Central Institute for Arid Horticulture, Bikaner, India (Singh and Singh, 2003) and to the Central Soil Salinity Research Institute in Karnal, India (Singh, 2003). They are being evaluated there for forage, fruit and vegetable uses in India's extensive arid lands.

In 2002, the USDA established an *Opuntia* germplasm collection with 203 accessions of 17 species at the National Arid Land Plant Genetic Resource Unit (NALPGRU) in Parlier, California. It included accessions collected and evaluated over an 18 yr period by the senior author as well as many other accessions. This collection included spineless accessions used as forage in South Africa and Brazil, spiny varieties used by Texas ranchers and spineless accessions that have greater freeze hardiness than *Opuntia ficus-indica* varieties. This paper reviews data on environmental adaptability and nutritional characteristics of *Opuntia* major forage clones. We have focused on accessions that have been reported as being important for forage internationally, or for which our 18 yr of evaluations suggest important forage characteristics. Some management techniques to fully utilize their forage potential are also described.

Characteristics of Major Forage Types

Data for the major forage types (Table 1) are confounded with years, investigators, and sites and thus are not directly comparable. However, it is possible to arrive at some general conclusions. The USDA germplasm contains the most important forage types in the USA and internationally. These include 5 wild *Opuntia engelmannii var. lindheimeri* selections (Texas A&M University Kingsville (TAMUK) #1503–1507) made by Texas rancher W.A. Maltsberger that vary considerably in spininess, 3 major forage types grown on several hundred thousand hectares of forage plantations in Brazil known as 'Palma doce'/'P. miuda' (*O. cochinilifera*; TAMUK #1269), 'Palma redonda' (*O. ficus-indica*; TAMUK#1270) and 'Palma gigante' (*O. ficus-indica*; TAMUK # 1271), and 3 *O. robusta* selections (O. *robusta* var. *chico*; TAMUK #1240; O. *robusta* var. *Monterrey,* TAMUK #1241; and *O. robusta* var. *robusta*, TAMUK #1242) made by Burbank (De Kock, 1980) and used for forage in South Africa. The *robusta* types are preferred for forage as they are more resistant to the major insect pest cochineal (*Dactylopius coccus*) than

Table 1. Passport data and plant characteristics of most important *Opuntia* forage clones in the USDA, NPGS germplasm collection.

						Cladode character			Fruit character			Spines	
TAMUK No.	NPGS ID No.	Species	Local name	Origin and country of use	USDA cold hardiness zone	Protein (%)	IVDMD (%)	Size Length × width (cm)	Fruit weight (g)	Brix (%)	Fruit pulp color	% of areoles with spines	Spine length (cm)
1233	PARL 300	*O.* sp.		USA	[3] 8			[7] 34 × 26	[7] 26	[7] 6	[7] red	[7] 0	[7] 0
1240	PARL 238	*O. robusta*	[1] Var. chico	South Africa	[3] 9				[7] 180		[7] purple	[7] 0	[7] 0
1241	PARL 301	*O. robusta*	[1] Var. Monterrey	South Africa	[3] 9	8.4			[7] 180	[9] 10.0	[7] purple	[7] 0	[7] 0
1242	PARL 302	*O. robusta*	[1] Var. *robusta*	South Africa	[3] 9				[7] 180		[7] purple	[7] 0	[7] 0
1269	PARL 242	*O. cochinillifera*	[2] Palma doce, P. miuda	Brazil	[3] 10	[2] 2.55, [4] 10.1					[7] red	[7] 0	[7] 0
1270	PARL 311	*O. ficus-indica*	[2] P. redonda	Brazil	[3] 9	[2] 4.21, [4] 11.4		[7] 30 × 25	[8] 121	[8] 11.8	[8] orange yellow	[7] 0	[7] 0
1271	PARL 243	*O. ficus-indica*	[2] P. giganta	Brazil	[3] 9	[2] 4.83			[9] 121	[9] 12	[8] orange yellow	[7] 0	[7] 0
1364	PARL 324	*O. ellisiana*		USA	[3] 7	[5] 5.8	[6] 78.0	[7] 17 × 13	[7] 14	[7] 8	[7] red	[7] 0	[7] 0
1503	PARL 400	*O. engelmannii var. lindheimeri*		USA	[3] 7	[5] 5.8	[5] 63.0		[5] 39.5	[5] 7.3	[5] red	[5] 23.2	[5] 23.0
1504	PARL 401	*O. engelmannii var. lindheimeri*		USA	[3] 7	[5] 5.2	[5] 51.8		[5] 47.7	[5] 9.4	[5] red	[5] 37.5	[5] 22.9
1505	PARL 402	*O. engelmannii var. lindheimeri*		USA	[3] 7	[5] 4.9	[5] 57.8		[5] 33.7	[5] 6.5	[5] red	[5] 42.3	[5] 28.0
1506	PARL 403	*O. engelmannii var. lindheimeri*		USA	[3] 7	[5] 4.9	[5] 60.1		[5] 53.1	[5] 8.5	[5] red	[5] 3.3	[5] 27.5
1207	PARL 404	*O. engelmannii var. lindheimeri*		USA	[3] 7	[5] 5.7	[5] 59.5		[5] 59.3	[5] 7.2	[5] red	[5] 10.8	[5] 31.0

Notes with collection: [1]DeKock, 1980; [2]Dos Santos and Albuquerque, 2001; [3]This paper; [4]Gregory and Felker, 1992; [5]Chavez-Ramirez et al., 1997; [6]Guevara et al., 2003; [7]Felker et al, unpub obs; [8]Parish and Felker, 1997; [9]Gregory et al. (1993).

ficus-indica and *cochinilifera* species (De Kock, 2001). The USDA collection in Parlier, CA also includes clones of the 33 seedlings (TAMUK# 1413–1441, PARL351–378 respectively) out of 300000 seedlings planted that survived a minus 16°C freeze in Saltillo, Mexico without damage (Martinez, 1968). However since this observation has not verified, these accessions require further testing.

There is considerable genetic variation in this collection for the presence of spines and freeze hardiness, the two major concerns in forage varieties. Generally, there is an inverse correlation between cold hardiness and spine characters, with the spiny *Opuntia polyacantha* being adapted to 56 N latitude in Alberta, Canada (Stelfox and Friend, 1977), and *O. australis* being adapted to 50 S latitude in Argentina. No spineless species exist further north than about 34 N or S latitude except than in areas where climate is moderated by large bodies of water (Pacific coast for California plantations or the Mediterranean Sea for Sardinian plantations). Griffiths (1915) and Uphof (1916) were the first to point out the limitations of cold hardy *Opuntia ficus-indica* related genetic materials in the USA. With the exception of a few low frost regions in California, the most southerly locations in Texas and sheltered areas around homes, O. *ficus-indica* is not adaptable to continental USA. There does not appear to be any physiological reason for the correlation between lack of cold hardiness and spines. Since presence/absence of spines are simply inherited, since spineless *Opuntias* are extremely palatable to wildlife and domestic stock, and since nowhere do spineless *Opuntias* exist without protection from humans, we hypothesis it is simply the lack of human intervention at the higher latitudes that is responsible for lack of spineless clones in these regions. The greater population densities and organization of indigenous peoples in central Mexico versus temperate higher latitudes is perhaps responsible for both the transition of wild diploid, Opuntias with small, low Brix fruits to octaploid large fruited, high Brix domestic varieties and the transition from spiny to spineless varieties.

Cold Hardiness

Various publications have reported the cold tolerance of these clones after freezing weather in 1984/1985, 1989/1990, 1990/1991 and 1996/1997(Gregory et al., 1993; Nobel, 1990, Russell and Felker, 1987: Wang et al., 1997). Regarding adaptation to specific climatic zones, we believe recommendation for a specific USDA cold hardiness zone (www.usna.usda.gov/Hardzone/hzm-sm1.html; verified 11 July 2006) is more appropriate than listing the absolute minimum temperatures, since duration of below freezing temperature and prior conditioning are critical to survival and very difficult to quantify. From 1983 to 1998, more than 130 *Opuntia* clones were evaluated in Kingsville, Texas (USDA cold hardiness zone 8) for a variety of purposes, but not all were included in the same replicated trials. During this period severe freezes occurred in 1984/1985, 1989/1990, 1990/1991 and 1996/1997 in which the number of hours below freezing ranged from 40 to 129 and the absolute minimum temperatures ranged from −7°C to −12°C (Wang et al., 1997). In the first freeze, the South African O. *robusta* clones 1240, 1241, and 1242 had only 12 to 13% freeze damage, but the Brazilian forage clones Palma miuda (O. *cochinilifera* 1269) and Palma gigante (O. *ficus-indica* 1270) suffered 100% frost damage (Russell and Felker, 1987). In the 1984/1985 freeze the other O. *ficus-indica* and similar species also had 99 to 100% frost damage. In the worst freeze, December 1989 (62 consecutive hours below freezing, 16 h below −6.7°C, and an absolute minimum of −12°C), all *O. ficus-indica, O. streptacantha, O. cochinilifera,* and *O. robusta* type clones died and had no recovery from the roots. The cladodes on *Opuntia sp* clone 1233 changed from an erect to a drooping form for about 3 d but later recovered with no apparent damage. In contrast 1233 was killed by freezing weather in 1997 at the Texas A&M Research Station in San Angelo, Texas (cold hardiness zone 7) when *O. ellisiana* was not damaged (D. Ueckert, personal communication, 1998). The 1989 freeze had no apparent effect on any *O. ellisiana* cladodes (Wang et al., 1997; Parish and Felker, 1997). Later in the winter of 1989/1990 an undamaged ornamental plant of *O. ellisiana* (clone 1364) was located in San Angelo, Texas which is 450 km north of Kingsville in USDA cold hardiness zone 7. Since then we have frequently observed undamaged *O. ellisiana* clones in Austin, Alpine, and El Paso, TX. Cactus collector David Eppele in Deming, NM reports that *O. ellisiana* never freezes at that location which is in USDA cold hardiness zone 7. In Mendoza, Argentina, *O. ellisiana* was found to be the only spineless variety that withstood −16°C in December 2000. (Guevara et al., 2003). The 1989 freeze had no effect on the wild spiny *O. engelmannii var. lindheimeri* clones in Kingsville, TX.

To summarize with respect to cold hardiness, *Opuntia ficus-indica* clone 1270 is marginally acceptable in cold hardiness zone 8 in Kingsville, TX where it froze to the ground twice, between 1984 and 1998. The clone would be well adaptable to the more tropical cold hardiness zone 9, such as the Texas Rio Grande Valley where grapefruits are grown commercially. Clone 1233 "wilted" during the most extreme freezing period from 1983 to 1998 in Kingsville, TX, but it recovered without any damage. The clone is adaptable to cold hardiness zone 8. Since it froze in San Angelo in cold hardiness zone 7, it cannot be recommended for this zone. As *O. ellisiana* 1364 was not damaged by the worst freeze in San Angelo, TX over 15 yr it can be recommended for cold hardiness zone 7. The spiny O. *engelmannii var. lindheimeri* was not damaged by any of these freezes in Kingsville or San Angelo and could be recommended for either USDA zone 7 or 8.

Possible Areas of Adaptability

The adaptability of *O. ellisiana* to USDA cold hardiness zone 7 has important ramifications internationally. In North America, USDA cold hardiness zone 7 extends from the high elevation Chihuahua Desert of Mexico in the south, westward to southern Nevada and eastward through southern New Mexico, northern Texas, the states along the Gulf of Mexico and as far north as North

Carolina www.usna.usda.gov/Hardzone/hzm-sm1.html; verified 11 July 2006). This species has recently been found to be the only spineless selection capable of withstanding winter temperatures in the Mendoza plains of Argentina (Guevara et al., 2003). Tunisian researchers have obtained clones for testing in the foothills of the Atlas Mountains. Climates with USDA zone 7 are also located in the arid regions of southern Asia such as the foothills of the Himalayas in India and Pakistan.

Spine Characters

While spiny varieties are readily consumed by livestock after the spines are singed off, usually with portable burners, and while palatable spiny varieties exist, it is our experience that the majority of growers prefer spineless varieties. This is even though significant effort has to be invested in fencing to eliminate access from wildlife and domestic stock because of the high palatability of the spineless varieties. Our experience with solar powered fencing of spineless *Opuntias* in Argentina was very favorable because of the much lower cost of fencing than burning or chopping the cactus. Furthermore the solar fence greatly reduced annual maintenance labor requirements for solid brush or hybrid brush/wire fences.

All of the spineless species possess nearly microscopic (150 μm diameter) hairlike barbed spines known as glochids. *O. ellisiana* and *O. robusta* have fewer glochids than the others. Of the clones in Table 1, only the wild *Opuntia engelmannii var. lindheimeri* has spines. W.A. Maltsberger used the clones of *Opuntia engelmannii var. lindheimeri* to establish a 120 ha plantation for cattle feed. To prepare the cactus for feeding, the spines were either burnt off with a propane torch, or burnt and chopped (Model 12, John Deere, Moline, IL) with an older style forage chopper that had a lower chopping speed than current models of forage choppers. While not much difference existed for spine length among the Maltsberger clones, the percentage of areoles with spines varied greatly (from 3.3–47.7% Chavez-Ramirez et al., 1997). A cross made between a spineless female parent *O. ficus-indica* 1281 and a spiny male *O. engelmannii var. lindheimeri* 1250 resulted in a considerable number of apomicts, but also progeny with small spineless cladodes the same size as the male parent. (Felker and Paterson, unpub obs). Currently, these progeny are being evaluated in various cold hardiness zones of the Argentina central arid zone at 33° S latitude by Juan Carlos Guevara of Instituto Argentino de Investigaciones de las Zonas Áridas (IADIZA).

The genetic control of spine production appears to be relatively simple. In hybridization studies among octaploid *Opuntia* with "commercial fruit," a cross between a spineless female and a spiny male resulted in 57% of spineless progenies ($n = 84$). In a cross between a spiny female and a spineless male, 63% of the progeny ($n = 84$) were spineless, and when both parents were without spines, 92% of the progeny ($n = 155$) were spineless (Felker, unpublished data, 2003). Collectively, these data suggest that spinelessness is relatively simply inherited. The recovery of spiny genotypes from spineless parents suggests that this sampling of parental genotypes each contained alleles for both spinelessness and spininess. Thus it should be possible to obtain spineless individuals if the parents yield fertile progeny and if one of the parents were spineless.

Fruit Quality

Inglese et al. (1995) and Felker et al. (2005) have suggested that the characteristics for internationally most desired fruit quality in *Opuntia* are: fruit size > 120 g, pulp percentage > 55%, Brix > 13%, pulp firmness > 1 kg, mature yield > 20 000 kg ha^{-1}, post harvest shelf life at 2°C > 4 wk, and seediness < 3.5 g seeds per 100 g pulp. None of the clones in Table 1 meet all of these criteria. The fruit of the wild-types, clone 1233 and *O. ellisiana,* are only a fourth the minimum size for commercial varieties, and the "robusta" types have substandard Brix. While the Brazilian accessions 1270 and 1271 have fruits large enough to be used for human consumption, their Brix (12%) is generally below that found in commercially acceptable varieties. In spite of the low values of fruit quality for human use, the fruits of all these varieties are attractive to wildlife and domestic stock (Chavez-Ramirez et al., 1997).

Nutritional Value

The nutritional values for *Opuntia* cladodes arises from disparate papers on use of cactus by wildlife (Everitt and Gonzalez, 1981; Meyer and Brown, 1985), human food uses of the tender resprouts known as nopalitos (Retamal et al., 1987, Rodriguez-Felix and Cantwell, 1988), fertility studies to enhance fruit production for human food use (Karim et al., 1998, Nerd et al., 1993, Nobel, 1983), and a few papers on domestic livestock needs (Gregory and Felker, 1992, Shoop et al., 1977, Woodward et al., 1915).

In normal forage contexts, the high water content would be a serious disadvantage due to the high cost of transporting such forage. However, during droughts in arid regions, the high moisture content of cactus is a valuable asset because it greatly reduces animal drinking water requirements. Using Texas rancher W.A. Maltsberger's (1996) guidelines of 40 kg of *Opuntia* as a daily ration for an adult cow, and a 90% moisture content, cactus would contribute 36 L of water per day toward the animal's drinking requirements. As watering points in arid regions are often widely scattered, cactus helps to fulfill critical needs.

While cactus as normally consumed in unfertilized range situations is low in protein, i.e., about 5 to 6% (Everitt and Gonzalez, 1981, Meyer and Brown, 1985), with N fertilization these levels can be increased to the 10% level that is normally felt to be necessary for a lactating beef cow (Gonzalez, 1989). The highest crude protein values of 15%, reported by Nobel (1983) for fertilized fruit plantations in California, are well above the requirements for domestic livestock. The in vitro and in vivo digestibility measurements confirm the high digestibility of protein, dry matter, and organic matter and are on par with the better grass type forages (Woodward et al., 1915; Guevara et al., 2003). This high digestibility also leads to a relatively high energy content of 2.6 Mcal kg^{-1}(Shoop et al., 1977; Retamal et al., 1987). The mineral composition is very low in Na, low in P, moderate in Mg, but high in both K and Ca (Retamal et al., 1987; Karim et al., 1998; Galizzi et al., 2004). This high level of calcium presumably would be of benefit to lactating ruminants during drought periods. For example, one kg fresh weight of cactus at 90% water contains 3.1 and 1.1 times as much calcium and potassium respectively as 1 L of goat milk (www.saanendoah.com/compare.html; verified 5 July 2006). The vitamin C levels are moderate with respect to other forages (Rodriguez-Felix and Cantwell, 1988). While the carotenoid concentrations are not outstanding with respect to other forages, in drought periods when all other herbaceous forages are brown, cactus often provides the only source of vitamin A precursors (Rodriguez-Felix and Cantwell, 1988). A protein and mineral supplement has been developed by W. A. Maltsberger to correct for mineral deficiencies in the livers of cattle that have been principally fed with cactus for up to a1 yr period (Felker, 1995).

The protein concentration in Opuntia is quite sensitive to nutrient supply. Gonzalez (1989) conducted a fertilizer trial with N and P fertilizers on yield and tissue concentration of the Texas spiny wild *O. engelmannii var. lindheimeri* and found that the crude protein increased from 4.5% for the zero fertility treatment to 10.5% protein for the 224 kg N and 112 kg P per hectare treatment. Since the protein requirements for a nonlactating and lactating cow are 6 and 9.25%, respectively, the fertilizer raised the protein level above the requirements for a lactating cow. It is also possible to increase the protein content of *Opuntia* via symbiotic relationships with *Azospirillum* (Rao and Venkateswarlu, 1982). Caballero-Mellado (1990) and Mascarua-Esparza et al. (1988) have shown that *Azospirillum* resulted in a 34% increase in *Opuntia* dry weight and a 63% increase in N content of the roots. They did not measure the influence of *Azospirillum* on the N content of the cladodes.

Productivity

The voluminous works of Nobel (1991, and 1994) have shown the high productivity of *Opuntia* and have confirmed the high water use efficiency in numerous gas exchange studies. However, there were only 2 replicated trials in the USA which included border rows and direct harvest to measure productivity. One trial used the only spineless cold hardy variety *O. ellisiana* to avoid potential damage from freezing weather (Han and Felker, 1997), and one trial measured the biomass productivity of the spiny Texas native *O. engelmannii var. lindheimeri* as a function of N and P fertilizer treatments (Gonzalez, 1989). The mean dry matter biomass productivity of the wild *O. engelmannii var. lindheimeri* variety in a zone with 430 mm annual rainfall was 52 Mg/ha after 4 yr.

In the trial with the slowest growing but most cold hardy of the spineless cacti, the absolute productivity the first 2 yr was low (1.8 and 4.9 Mg/ha dry matter) but after the plants reached a leaf area index of 2.0, the productivity increased to 14.2 and 17.7 Mg/ha dry matter in years 3 and 4. A water balance study that captured runoff, estimated soil evaporation with microlysimeters and measured drainage with neutron probes reported that the 17.7 Mg/ha productivity was obtained with 662 mm rainfall and 285 mm water transpired for a transpiration water use efficiency of 162 kg water/kg dry matter (Han and Felker, 1997). This is the highest water use efficiency we are aware of that is based on field dry matter accumulation. The stored water in the plants was 170 000 kg/ha which constituted a significant source of water for animals in the dry season. While *O. ellisiana* (Fig. 1) rarely produces more than 6 pads from the planted cladode in the first year, a large (50 cm long) cladode of *O. sp.* clone 1233 produced 115 cladodes the first year (Fig. 2) and we believe this species will prove to be much more productive than *O. ellisiana,* although 1233 is not adapted to USDA zone 7.

Promising *Opuntia* Forage Clones for Testing in USDA Cold Hardiness Zones 7, 8, and 9

After nearly 20 yr of research on cold hardiness selection, we feel the three most promising spineless clones warranting further testing for USDA cold hardiness zones 7, 8, and 9 are *Opuntia ficus indica* TAMUK #1270 (Fig. 3), *Opuntia* sp. TAMUK # 1233, and *O. ellisiana* TAMUK #1364. We obtained # 1270 from Dr. Severino Gonzaga Albuquerque in CPATSA Petrolina, Brazil in 1983 where it is known as Palma redonda and used as a forage variety; # 1233 was collected by H.N. LeHouerou from a yard planting in Hargill, TX in 1984 as it was not damaged from the severe 1983 freeze; and # 1364 was collected near the U.S. Fish and Wildlife Building in San Angelo, TX in January 1990 as it was not damaged by the freeze of −20°C in December 1989. Clone 1270 and 1364 fall within the taxonomic description of *O. ficus-indica* and *O. ellisiana* (Griffiths, 1915), respec-

Fig. 1. Approximate four year-old *O. ellisiana* grown in Crystal City, Texas.

Fig. 2. One year-old *O.* spp. clone 1233 that produced 115 cladodes from one cladode in Santiago del Estero, Argentina without irrigation.

tively. However spineless clone 1233 with undulating leaf margins does not fit any standard key for *Opuntia*. We believe it to be a mutant or hybrid with the Texas native *O. engelmannii var. lindheimeri* as one parent. This is borne out by the RAPD data of Wang et al. (1998). All of these clones had a bushy compact form as opposed to other more erect open types as can be seen in Figures 1–3.

GENETICS OF FORAGE VARIETIES

Wild *Opuntia* can be diploid, triploid, tetraploid and octaploid ($n = 11$) (Weedin and Powell, 1978; Powell and Weedin, 2001). Evidently due to insect pollination of *Opuntia*'s perfect, self-fertile flowers, today's commercial *O. ficus-indica* land races for fruit use are octaploid (Pimienta, 1990). While Weedin and Powell (1978) reported a diploid spineless *O. ficus-indica* in Alpine, Texas, the species designation for this accession was later determined to be *O. ellisiana* (M. Powell, personal communication, 2004). Wang et al. (1996) reported emasculation and bagging techniques for *Opuntia* and examined the sterility barriers between the commercial *O. ficus- indica* fruit types and *Opuntia* from similar ecological zones. They found that *O. ficus- indica* produced fertile offspring with the spiny Texas native *O. engelmannii var. lindheimeri* but not with *O. ellisiana* or the forage clone 1233. Thus neither *O. ellisiana* nor clone 1233 will serve as a source of genes for cold hardiness to create spineless individuals.

Fig. 3. Four year-old *O. ficus indica* clone 1270 grown on Texas A&M University-Kingsville field station without irrigation.

Some of the segregants in the *O. ficus-indica* × *O. engelmanniii var. lindheimeri* cross appear to have many of the characteristics of the cold hardy spiny parent (small fruit and bluish cladodes) but without spines. We are hopeful that these progeny will possess increased cold tolerance over the spineless *O. ficus-indica* and possibly the other spineless *Opuntia* types. Even if these segregants do not have greater frost hardiness than the currently available spineless *O.* sp. 1233 and O. *ellisiana*, at least a genetic route is now available to produce cold hardy spineless types. Possibly additional backcrossing to the cold hardy *O. engelmannii var. lindheimeri* parent may lead to both increased biomass production and increased cold hardiness of spineless individuals.

While all of the bagged, non-manipulated (selfed) flowers of the 1233 clone developed into fruits, these fruits abscised, indicating that this clone may be sterile (Wang et al., 1996). As 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 as a weed, sterility in forage types would be a significant advantage in introduction to new areas.

RAPD data comparing several *O. ficus-indica* types, an *O. hyptiacantha* fruit type (1287), *O. ellisiana*, *O.* sp. 1233, and the vegetable (nopalito) producing clone *O. cochinilifera* 1308 indicated that one *O. ficus-indica* clone 1281 was more closely related to the *O. hyptiacantha* clone than the other *O. ficus indica* clones (Wang et al., 1998). As the only major morphological difference between the *O. ficus-indica* clone and the *O. hyptiacantha* clone was the presence of spines on *O. hyptiacantha*, doubt was raised on the utility of spine characters in the assignment of species designation.

Sources of the Genetic Materials Outside North America

In addition to the USDA NPGS germplasm base, some of these promising clones (1270, 1233, and 1364) are available (as unrooted cladodes weighing about 1 kg each) from Dr. Ali Nefzaoui at the Institut National de la Recherché Agronomique de Tunisie, rue Hedi Karray, Ariana 2049, Tunisia, from Dr. Gurbachan Singh, Head, Central Soil Salinity Research Institute, Karnal, India, Dr. R.S. Singh, Central Institute for Arid Horticulture, Bikaner 334006, India, and from Juan Carlos Guevara, Instituto Argentino de Investigaciones de las Zonas Áridas (IADIZA), CC 507 (5500), Mendoza, Argentina.

Propagation and Planting Methods

Opuntia species are clonally propagated by placing an unrooted cladode (technically, a stem segment) in the soil which then roots and establishes a new plant. The major problem in establishing new plantations is loss of plants to rot. Thus treatment of the planting stock is the opposite of what is recommended for seedlings and shrubs. Typically 1 yr old cladodes are harvested, the cut ends dipped in a lime/copper fungicide mixture and placed vertically with the cut ends up for several weeks. This allows the cut ends to "heal over" preventing infection. The cladodes are planted in dry soil and not watered until resprouts appear or for several weeks. The growth of young cladodes is susceptible to competition from grasses and forbs. With the exception of picloram, Opuntias are resistant to virtually all herbicides including hexazinone, bromacil, diuron, etc. (Felker and Russell, 1987). One year old cladodes with a thick cuticle are also not damaged by glyphosate sprays. In Argentina for 5 yr we have used a combination of diuron at 4 kg a.i. per hectare per year, and glyphosate without cultivation. Snyman (2005) has found that the roots of 1 yr old cladodes extend horizontally to 1.5 m the first year, with 50% of them being in the top 5 cm, and thus no-till cultivation with herbicides is an interesting option. For maximum production for "cut and carry" systems, close spacing of about 1.2 × 1.2 m is useful, but where direct grazing is desirable, in-row spacing ranging from 1.0 to 1.5 m, and between row spacing of 3 to 5 m is desirable. For *O. ellisiana* with slow height growth, grazing could not begin before about the third year, while for the faster growing clones 1233 and 1270, under favorable conditions, grazing might begin about 2 yr after establishment. Grazing needs to be controlled so that only one and 2 yr old cladodes are consumed with the "woody" base not being damaged. Subsequent grazing is possible at 1 to 2 yr intervals depending on the rainfall and weed control.

CONCLUSIONS

Extensive use has been made of the high water to dry matter conversion efficiency of CAM metabolism in spiny and spineless *Opuntia*s for forage in arid regions of United States, Mexico, Brazil, South Africa, and North Africa. This extensive utilization has occurred despite the lack of any standardized varieties and with very little management input from the scientific community. Extension programs to apply what is known about weed control, fertilization to improve yield and nutrient quality, and ration formulation would have immediate benefits to extensive arid regions of the world. We believe the spineless clones 1233 and 1364 for USDA cold hardiness zones of 7 and 8, in addition to excellent forage clones previously described for USDA zones 9 and 10 (1269, 1270, 1271, 1240, 1241, 1242), and new hybrid combinations between the wild *O. engelmannii var. lindheimeri* and *O. ficus-indica,* have the potential to greatly benefit livestock production in arid regions.

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