Short-Term and Long-Term Research Needs for *Opuntia ficus-indica* (L.) Mill. Utilization in Arid Areas♦

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ABSTRACT

The decade of the 1990s has seen a great expansion in national and international cooperative research and development on cactus, including plant physiology and orchard management, new *Opuntia* hybrids, descriptor list for *Opuntia*s, intensive breeding and selection work on columnar and vine fruit cacti, new commercially available processed products of cactus pears and various major international symposia to integrate researchers and professionals of different fields worldwide. While a mixture of basic and applied research is still required in critical areas, the scientific database is now sufficiently mature to guide international development efforts. Based on our experiences, this paper suggests priorities for basic and applied research of scientists from different fields.

Keywords: cactus pear, genetic resources, fruit, forage, medicinal uses

INTRODUCTION

According to Sene (1996), "drylands occupy about 3400 million hectares of emerging lands, which harbor over 500 million people who are among the poorest communities and 800 million people exposed to a number of survival problems including food insecurity, inadequate access to drinking water and sanitation facilities, inadequate energy supply and heat from fuelwood, etc." As opposed to the number of scientists and financial resources available for research on traditional dry-land crops, i.e., sorghum, millet, cotton, etc., the resources devoted to cacti research and development is infinitesimally small. Therefore, it is important to identify the most critical areas for future research and development and to concentrate on these problems. There have been many interesting physiological and technical problems that have arisen from field observations. Resolution of these problems would be both interesting from a scientific standpoint and also could lead to management options or assist in development of new varieties that may have considerable economic impact. Thus, the focus of this paper is to highlight some of these new observations and the identification of the short- and long-term research, marketing, policy, and legal issues which require resolution in order to fully exploit the drought resistance, high water-to-dry matter conversion efficiency and genetic diversity of *Opuntias*.

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VARIETAL DIFFERENCES AND WATER STRESS

Recently, it has been observed that large-fruited yellow varieties, such as TAMUK accessions 1277 and 1390 (with elliptic cladode shape) (Chessa and Nieddu, 1997), have high fruit-abscission rates under drought, while the fruits of pinkish clones, such 1392, 1379, and 1389 (with ovate cladode shapes), do not abscise in droughts (Cowan and Felker, 1997). Casual observations suggest that the varieties with high fruit-abscission rates have a greater leaf area than the varieties that do not abscise, suggesting that latter varieties might transpire less total water, leading to less water stress. It is unknown whether cultivars for commercial fruit or forage production differ in terms of water requirement to give sustainable yields. Indeed, commercial production of cactus pears implies irrigation if no rainfall occurs during the fruit development period or when the annual rainfall is <300 mm. The reduction of fruit size in rain-fed orchards occurs far before any visible symptom of water stress appears, and fruit thinning does not result in any significant increment of fruit size unless irrigation is applied (La Mantia *et al.*, 1998). A comparison of the same 12 *Opuntia* clones in Argentina and Texas with the same latitude but with much greater rainfall during the last two months of fruit maturation in Argentina (Felker *et al.*, 2002), found that the Brix was virtually the same in both environments but that the fruit sizes were much larger in the environment with greater moisture availability during fruit maturation.

These results suggest that it may be necessary to develop different fruit varieties for irrigation vs. dry land, together with effective methods to measure plant water requirements also in terms of timing and to maximize fruit growth.

VARIETAL DIFFERENCES IN DRY MATTER PARTITIONING, PRODUCTIVITY, AND FRUIT QUALITY

There are just a few observations on dry matter partitioning for mature, fruiting plants of cactus pear. Inglese *et al.* (1999) indicates values of relative annual dry matter allocated to fruit (harvest index) that are quite similar to those of many perennial fruit trees, but there is no information related to cultivar and training systems. Cortazar and Nobel (1992) showed a marked increase of vegetative vs. reproductive growth as a result of high-density planting systems; Inglese *et al.* (1994) and Luo and Nobel (1994) investigated the source-to-sink relationship on mature fruiting plants, indicating a massive carbon flow of assimilates among cladodes of different ages and the competition of fruit vs. cladode growth, with their relative strength changing along with the developmental stages of the seasonal growth of fruit and cladodes (Inglese *et al.*, 1999). However, the more than 10-fold range in fruit production of similarly sized *O. ficus-indica* clones under the same environments (Parish and Felker, 1997) suggests major genetic differences in dry-matter partitioning also occur. Investigation on planting and training systems that maximize fruit yield and quality are completely lacking and do represent one of the most outstanding challenges for future research, together with the reduction of field variability in yield and fruit quality. Indeed, fruit that do not attain the prime quality in terms of size have 50% to 70% less market value than the top quality ones and their relative occurrence changes greatly (often more than 50%) according to horticultural systems and management. Understanding the sources of this variability would greatly enhance orchard profitability, without necessarily increasing yields.

It also would be useful to know if the differences in fruit production (cladode fertility) could be attributed to differences in net photosynthetic rates, or dry-matter partitioning. Similarly, it would be interesting to know if the differences in fruit sugar concentration could be attributed to differences in the photosynthetic rates of the cladodes, or translocation of sugars from the cladodes to the fruits. It would be important to study the translocation of sucrose from cladodes to fruits in cladodes with high or low fruit loads. Great differences in fruit quality, i.e., sugar content, taste, and shape, have been encountered for the leading Italian cultivar “Gialla” grown in northwestern Argentina (Catamarca), as related to the standard expression of the genotype in its homeland of Sicily. Under the prevailing conditions of Catamarca, “Gialla” seems to loose flavor and taste, while the local cultivar, “Santiagueño sin espinas,” gives lower yield with fruits having a higher sugar content than “Gialla”. This behavior is likely to be related to the high temperature prevailing during the fruit development period in the Catamarca region, which could affect the accumulation of sugar during the ripening period (Inglese, pers. obsv.). Inglese *et al.* (1995) found that different cladode loads do not necessarily imply differences in fruit sugar content, even if fruit size and ripening size are deeply affected by cladode load. Eventually, understanding the genotype × environment interaction in term of fruit quality (size, flavor, taste, ripening time) could allow a better definition of the most suitable conditions for the full expression of the fruit quality.

EXTREME HEAT/DROUGHT STRESS LIMITS TO DRY-LAND *Opuntia* PRODUCTION

An intriguing question in the utilization of *O. ficus-indica* is: What are the most extreme heat/drought conditions in which it can produce fruit, forage, or vegetables without irrigation? In the area of greatest biodiversity in the central plateau of Mexico (elevation 1800 m to 2200 m) the rainfalls are less than 500 mm, the mean annual temperatures range from 16°C to 18°C and the long-term daily maximum temperatures for the hottest month do not exceed 35°C (Pimienta, 1990). While *O. ficus-indica* currently occurs in extensive areas in northern Africa (Monjauze and Le Houerou, 1965) and the Republic of South Africa (Wessels, 1988) it is conspicuously absent in regions that have conditions of less than 350-mm rainfall and daily summer maximum temperatures greater than 42°C, such as the Sahelian African cities of Niamey and Khartoum, the California Mojave Desert, or the Rajasthan Desert of India (Felker, unpub. obs.). Indeed, a collection of 60 *Opuntia* clones had to be irrigated to have any significant growth when grown at the Dryland Horticulture Research Center in Bikaner, India, where the rainfall is less than 350 mm/year and where temperatures exceed 40°C for extended periods each year (O.P. Pareek, 1999 pers. comm.). Also, episodic periods of several days with temperatures in the 40°C to 44°C range in Santiago del Estero, Argentina, produce bleaching of chlorophyll on the sides of some cladodes of some clones that are directly perpendicular to the northwest cardinal direction. In contrast, the side of the cladode exposed to the southeast direction experiences no chlorophyll bleaching.

One exception to the presence of *Opuntia ficus-indica* where temperatures are greater than 40°C and the mean annual precipitation is less than 350 mm are in Adigrat, Ethiopia, (Brutsch, 1997) or perhaps in northeastern Brazil where it is used for livestock feed.

Given the extreme poverty of African Sahelian countries, such as the Horn of Africa and extreme drought conditions of these countries, it would seem urgent to test a broad-based collection of *Opuntia* forage, fruit, and vegetable clones in representative areas. Care should be taken to avoid clones that could become weedy and to select clones that have demonstrated superior tolerance to drought stress.

PHOTOPERIOD AND CHILLING REQUIREMENTS FOR FRUIT PRODUCTION

Although definitive data does not exist on these problems, whenever cactus scientists gather for international symposia, the following issues inevitably arise: Does chilling have a role to play in fruit production and is photoperiod important for fruit production?

These issues have had only limited discussion in the international literature, probably because definitive experiments to resolve these problems have not been conducted and/or reported.

The yellow Italian fruit “Gialla” variety has been widely introduced into Argentina where it matures in about 120 days (C. Soulier, 1999 pers. comm.), while the same variety in Sicily matures in about 70 days to 90 days, depending on bloom time (Inglese, 1999).

The area in Sicily where the "Gialla" grows is about lat. 38° N, while the area in Santiago del Estero, Argentina, where the variety grows is at lat. 27° S. On the summer solstice of 21 June and 21 December, respectively, the growing regions in Argentina and Sicily have 14.8 hours and 15.9 hours of daylight, respectively. Thus, it is possible that the 1.1 hours per day of additional photosynthetically active radiation in Sicily contributes to the shorter maturation period in that country. However, another possible explanation comes from the work of Inglese *et al.* (1999) who related the duration of the fruit development period to the amount of thermal time accumulated from fruit set to harvest.

Fruit coming from the spring flush and ripening in summer (70 days) and those coming from the second flush, which results from the spring-flush removal (scozzolatura), that ripen in fall (90 days) had a different length of the fruit development period, when measured in terms of days, whilst no differences appear when the same period was expressed as thermal time, that is, the amount of Growing Degree Hours (GDH from Anderson *et al.*, 1986) accumulated from fruit set to harvest. Thus, the analysis of thermal time requirement for fruit growth of available cultivars may allow a better estimation of their environmental requirements and could be useful to predict plant behavior (fruit-ripening time) in a new environment. Eventually, high temperature shortened the third stage of fruit growth, when most of the flesh growth occurs, resulting in smaller fruits, with lower firmness and sugar content than autumn fruits (Inglese *et al.*, 1999).

With regard to the issue of chilling requirement for fruit production, Nerd and Mizrahi (1995) examined the induction of floral and vegetative buds in detached cladodes that experienced different temperatures in the winter. These authors found that detached cladodes that experienced the lowest winter temperatures produced the most fruit buds the following spring. Similar results were reported by Gutterman (1995) who examined 18 light/temperature combinations of detached cladodes and found that detached cladodes produced significantly more fruit with 8 hours of light grown outside in cool temperatures than with 8 hours of light in a heated greenhouse. Nobel (1996) also examined organ development in detached *Opuntia ficus-indica* (1279) cladodes but did not find a clear-cut stimulus to floral bud initiation. However, in a more recent experiment, Nobel and Castaneda (1988) indicate an increase in fruit production on detached cladodes held at 15°C/5°C against cladodes left at 25°C/15°C day/night temperatures. Parish and Felker (1997) reported that one third of a Texas field trial of more than 60 accessions failed to produce fruit in a greenhouse, while many of the accessions produced abundant fruit in adjacent blocks outside the greenhouse. However, cactus pear do produce fruits in the Valley of Catamarca, northwestern Argentina, and in the Canary Islands, where no more than 150 C.U. accumulate in winter, and it is even able to reflower several times in the same season as it naturally occurs in Chile or California or as it is artificially induced in Italy and Israel (Inglese *et al.*, 1995). Apparently, these out-of-season blooms occur with no relation to any previous chilling period. Moreover, in Ayacucho (Peru), *O. ficus-indica* blooms several times in the year with no apparent relation to chilling.

The reflowering that is promoted by extensive fertigation in Israel (Nerd and Mizrahi (1995), occurs on current season's cladodes in late summer, i.e., before they could experience any winter chilling. A clear improvement of our knowledge would result from specific investigation that should quantify the variability of chilling requirements among cultivars and define the critical temperature that satisfies the chilling requirement of the species.

Differences in chilling and heat requirement could also explain the variability of date of flowering and fruit ripening. A Texas trial with nearly 100 clones found fruit maturation in the same field varied over a 2-month period, depending on the clone (Cowan and Felker, 1999). In general, the coldest hardy species were the last to flower and set fruit. For example, of all the clones in the Texas trial, *O. ellisiana*, which is by far the most cold hardy of all these species, shows a delayed bloom. This behavior is typical of cultivars with a high chilling requirement and it is often related to cold hardiness in many fruit species. Similarly, Pimienta (1990) has noted a nearly 8-month variation in date of fruit maturation in the Mexican central plateau.

Potgieter (2000) in South Africa, examined eight varieties representing the basic morphological types (long-leafed candelabra and bush types) at low, medium, and high elevation sites in a randomized complete-block trial. At each site there was a complete weather station to record daily minimum and maximum temperatures, chilling units, and precipitation. Significant changes in ranking of the clones among the three sites indicate a clear-cut cultivar × environment interaction.

CLADODE NUTRIENT CONCENTRATIONS AND YIELD/FRUIT QUALITY

Quantitative relationships between soil nutrients, foliar (cladode) nutrients, and fruit quality/production have not yet been developed for *Opuntia*s. As in many other crops with high productivity, N has been shown to be important in fruit yields and also in stimulating off-season fruit production (Nerd *et al.*, 1991; Nerd *et al.*, 1993). Vazquez (1999) has recently produced a comprehensive review on the role of total N, ammonia, and nitrate on *Opuntia* growth and yields. Nobel *et al.* (1987) have reported correlations between yield and N, P, and boron concentrations from field work in Mexico. Gathaara *et al.* (1988) have reported an interaction of N and P in fruit yields of the noncommercial *Opuntia lindheimerii*, and Karim *et al.* (1997) have reported correlations between fruit yields and N, P, K, and Na.

Unfortunately, these workers observed that various clones had different correlations between yield and cladode nutrient concentrations, suggesting that it may be necessary to develop correlations specific for each variety. N values found in cladodes of the same age ranged greatly in experiments carried out in the field or under artificial laboratory conditions (Inglese *et al.*, 2000; Potgieter *et al.*, 2000).

Moreover, to date, correlations do not exist from replicated field trials between soil-test values, cladode nutrient concentrations, and yield/quality. Given, then, the fact that K is the nutrient with the highest concentration in cactus pears (Karim *et al.*, 1997) and the previously demonstrated interaction between N and P, it may not be possible to optimize fruit yield/quality for N, P, and K in experiments that examine only one of these nutrients.

BREEDING AND GENETIC ISSUES

Fundamental to the full utilization of the *Opuntia* gene pool, is a quantitative analysis of the sterility barriers between various sections, species, commercial cultivars, and clones. A high priority should be assigned to develop a working knowledge of these barriers.

Many reviews have highlighted the great genetic diversity within the 150 to 300 species within the subgenus *PlatyOpuntia*, (Monjauze and LeHouerou, 1965), the dozens of commercial fruit types (Barbera *et al.*, 1995), and the natural occurrence of interspecific *Opuntia* hybrids (Benson, 1982). These genetic materials and breeding systems have suggested that combinations of useful economic traits, such as fruit characters, could be combined with resistance to environmental and edaphic factors, such as cold tolerance or salinity, to produce more versatile economically useful clones. In considering the potential application of this gene pool to a breeding program, it is important to know where the sterility barriers to hybridization occur within the subgenus and/or the currently commercial species, such as *O. ficus-indica, O. robusta, O. hyptiacantha, O. megacantha*, etc. In one of the first studies with deliberately created hybrids, Wang *et al*. (1996) found that *O. lindheimerii* could hybridize with *O. ficus-indica*, but that *O. ellisiana* could not hybridize with either *O. lindheimerii* or *O. ficus-indica*. Other research needs for genetic improvement include the determination of the percentage of selfing and/or apomixis in a range of clones, and techniques to store pollen. Mondragon (2001) has recently made a major contribution to this with the finding that apomixis frequently occurred in 17 Mexican cultivars. Pollen storage would be useful in international breeding programs and when lack of coincidence in flowering in breeding programs requires pollen to be stored for the next year.

An emerging issue for which little quantitative data exists is: What is the level of variability within commercial cultivars? Much of the planting stock of commercial varieties in Italy, Mexico, Chile, and Argentina, i.e., *Blanca*, *Roja pelon*, *Fafayuco*, *Santigueno*, *Morado*, etc. are purchased from nearby farmers without any assurance of yield, fruit quality, disease resistance, or genetic uniformity. Certainly, in most countries there is no repository for standard tuna cultivars.

It seems important to evaluate the variability that exists in current plantations that cannot be traced back to individual plant repositories. Clonal selection could identify outstanding single plants possessing a balance of yield, quality, and disease resistance, that will be eventually examined in replicated trials. Recent work in Argentina, in a randomized complete block design, found a three-fold difference in the productivity of eight Argentina "Santiagueño type" clones that could not be distinguished morphologically (Felker *et al*. unpubl. obs.).

TAXONOMY AND GENETIC AFFINITIES IN *Opuntia*

Recent DNA molecular-marker data has raised significant doubts on the validity of the traditional taxonomic approaches to the classification of the commercial *Opuntia ficus-indica* fruit types. Wang *et al.* (1999) examined RAPD patterns in what were presumed to be eight very contrasting *Opuntia* clones. These clones included the TAMUK clones; 1308 *O. cochinillifera* nopalito clone, *Opuntia ellisiana* clone 1464, spiny *O. hyptiacantha* clone 1287, and various spineless *Opuntia ficus-indica* types. The DNA data clearly showed that the 1308 and *O. ellisiana* clone were very different from the other fruit types. However, the two most similar clones were the spiny *O. hyptiacantha* 1287 and the spineless *O. ficus-indica* clone 1281. Moreover, *O. ficus-indica* clone 1281 had a greater genetic affinity to *O. hyptiacantha* clone 1287 than the other *O. ficus-indica* clones 1279, 1321, and 1294. The major distinguishing feature between *O. ficus-indica* clone 1281 and *O. hyptiacantha* clone 1287 is the presence of spines. In other plants (*Prosopis alba* and *Gleditsia triacanthos*), the presence or absence of spines often occurs in the same species and it would not seem unreasonable to believe that spininess could be controlled by a single gene.

If one looks at the taxonomic key of Scheinvar (1995), one will find that if the plants do not have spines they are *O. ficus-indica* but if they do have spines they are either *O. hyptiacantha, O. streptacantha*, or *O. megacantha*. Thus, spine characters are used to distinguish taxa above the level of species. If, indeed, spines are single-gene controlled in *Opuntia*, as they are in other species, it would seem inappropriate to use spines as a taxonomic character for distinguishing species. A recent traditional taxonomic work based on segregation of morphological characters within *Opuntia* progeny (among other characters) Kiesling (1999) has also come to the conclusion that spine characters should not be used to differentiate species among the commercial *Opuntia* fruit types. It seems more worthwhile at this time to focus on genetic issues such as where in the genus are the genes that control (a) seed size and quantity; (b) cold hardiness; (c) total soluble solids content; (d) fruit firmness; (e) yield of fruits; (f) color of fruits; (g) resistance to cochineal, bacterial soft rots, and black rots; and (h) spine characters. Full sibling crosses will be needed to determine the dominance, heritability, and linkage of these characters. For example, will these characters segregate independently or will there be problems with negative correlations between important characters, such as yield and fruit sugar content?

It will be of interest to know if all the genomes of the polyploid hybrids in the commercial fruit varieties contribute equally to the phenotypic characteristics.

Fortunately, more than 300 progeny from 20 full sib hybrid crosses made by Wang *et al.* (1998) are being grown under drip irrigation in Argentina to examine segregation between parents with and without spines and with various fruit colors, yields, and sugar contents. A population of 128 progeny from the wide cross between a *O. lindheimerii* (1250) × *O. ficus-indica* (1281) is also being grown in Argentina to be used to compare DNA analyses to morphological and fruit characters to begin development of a gene map.

The descriptor list developed by Chessa and Nieddu (1997) is very helpful in identifying the many forms, varieties and cultivars within the commercial fruit types on the basis of external morphological characters, such as overall plant architecture, pad morphology, spine characters, and fruit characters. Lastly, the isozyme work of Chessa *et al.* (1996) and the RAPD data of Wang *et al.* (1999) have begun to identify unique proteins and DNA fragments to clones that are nearly identical morphologically.

BREEDING OBJECTIVES: DEVELOPMENT OF LOW-SEEDY VARIETIES

One of the leading U.S. importers of cactus pears (Caplan, 1990), as well as marketing surveys realized in Italy (Battaglia, 1996), have suggested that one of the most important breeding objectives should be the development of low-seedy varieties. Pimienta and Engelman (1985) have stated that true seedless varieties are not possible because the pulp of the fruit develops from the funiculus of the seeds. Despite this, Israeli workers (Weiss *et al.*, 1993) reported a parthenocarpic clone (BS1) that produced 100% aborted seeds without growth hormones. Unfortunately, this variety was not commercially acceptable because of low fruit size because the fruits consisted almost entirely of peel tissue. A spiny selection of *O. amyclaea* (var. *leucosarca*) does grow in Italy, and produces almost seedless fruit (5-10 seeds) with stenospermic “empty” seeds, reasonable fruit size (100 g to 120 g) and good percent flesh (50% to 55%). Parish and Felker (1997) reported a range of 2.19 g to 6.37 g seeds/fruit for *Opuntias* grown under the same environment in Texas.

The clones with the lowest seed contents were also associated with a much thicker peel than low seedy varieties, and the clones with the lowest seed content were comparable to the "parthenocarpic" BS1 variety from Israel. In the Texas trials, clones 1319 and 1321 from Chile were especially promising as they had both low seed content and high sugar content. Additionally, two Mexican clones with highly desirable dark purple fruits also had low seed contents of (2.2 g fruit^{-1} for 1282 and 2.3 g fruit^{-1} for 1279). Unfortunately, the yields of the Chilean clones 1319 and 1321 were much lower than other varieties with more seeds. However, more recent work in Argentina found that when the varieties were compared on the basis of seeds per gram of edible pulp, and not the entire fruit, much of these differences disappeared (Felker et al., 2002).

It is tempting to speculate that a hybrid with virtually all abortive seed could be developed, yet still have enough physiological stimulus from the abortive seeds to produce a commercially acceptable sized pulp. The advantage of the abortive seeds is that they are small enough to be consumed with little difficulty even by first-time consumers. Fortunately, a rapid test for the percentage of aborted vs. normal seeds has been developed. Cowan and Felker (1999) reported that all normal *Opuntia* seeds were retained on a 1.7-mm screen, while the abortive seeds passed this screen size but were, in turn, retained on a 1.0-mm screen.

VARIETIES AND/OR POSTHARVEST TECHNOLOGIES TO EXTEND AVAILABILITY OF CACTUS PEARS

The period from first to last harvest of cactus pears for the same variety in the same location is typically about 30 to 50 days and "the standard cactus pear" has a storage life of less than 6 weeks. The high production of cactus pear plantations often causes depressed prices in the short period due to overproduction, while unfortunately providing very few cactus pears outside of a total harvest plus storage window of approximately three months. While *scozzolatura* (removal of first flush) techniques have been used in Italy to extend the harvest period (Inglese *et al.*, 1995) and N fertilization techniques have been used in Israel to extend the cactus harvest periods (Nerd *et al.*, 1991, 1993), most locations lack marketable cactus pears for 6 months to 9 months of the year. In order to even out the price fluctuations due to variations in supply and to facilitate the availability of fresh fruit to both the retail consumer and the restaurant industry, it is important to develop cultivars and/or storage conditions to provide more year-round availability. Schirra *et al.* (1999) indicate 6 weeks as the longest postharvest storage period for “Gialla” fruit, with different sensitivity to decay and freezing injury related to ripening. Corrales *et al.* (1997) examined six different cultivars in long-term controlled storage (9°C and 95% relative humidity) and found the varieties Cristalina and Burrona had acceptable firmness (0.8 kg) after 3 months in storage, while the varieties Copena torreoja and Copena T5 had essentially zero firmness after the second month.

Since Corrales *et al.* (1997) found such high variation among only six clones, it seems reasonable to believe that even greater phenotypic variation for postharvest shelf life could be found with a search of additional clones.

Our recent work in Argentina has lead to some new insights on fruit quality measurements (Felker *et al.*, 2002). For example, while the peel firmness of the Italian variety “Gialla” was acceptable in being greater than 1 kg, the pulp firmness of the same variety at maturity was often less than 0.3 kg and, thus, unacceptable. It seems that pulp firmness measurements greater than 2 kg, 1.5 kg, 1.0 kg, and less than 1.0 kg should be rated excellent, good, fair, and unacceptable, respectively. Before fruits get to the point that they are unacceptably overmature for fresh consumption, it is our opinion that they are often overmature for processing into juices or ice cream due to the incipient formation of sectors of aerobic fermentation that serves to inoculate larger batches of processed juice. In one case, 300 liters of a 1000-liter batch of frozen juice had to be discarded due to an aerobic fermentation that lead to bursting of plastic buckets due to gas formation caused by both inadequately rapid freezing and the presence of incipient fermentation sectors in the fruits. In some varieties these sectors can be visually identified after slicing the pulp in half vertically and looking for a change from an opaque to a translucent/watery type appearance. This transition first appears near the fruit apex, proceeds down the center axis, and then spreads to the entire fruit. This transition from good quality to overmaturity is also associated with a rapid loss in pulp firmness that presumably is related to changes in the cell walls. Obviously, detailed bacteriological and anatomical analyses of these changes would be of great interest.

INCREASING COLD HARDINESS IN FRUIT AND FORAGE CLONES

When one moves either north or south outside the true tropics, *Opuntia ficus-indica* types begin to experience significant limitations due to lack of tolerance to freezing weather. Examples of regions where *O. ficus-indica* fruit production is questionable due to frequent severe freezing weather are the northern Chihuahuan desert, i.e., Juarez in Mexico (lat. 32° N), southern Texas, i.e., Kingsville (lat. 27° N) and Mendoza, Argentina, (lat. 33° S). However, where warm bodies of water, or mountains, restrict movement of severe winter storms, commercial cactus fruit production occurs at much greater latitudes such as the Gilroy, California, D'Arrigo Bros. plantation at lat. 37° N or Sassari, Sardinia at lat. 41° N.

As a general rule, if below-freezing temperatures occur only for a few hours with minimums of -7°C, only minimal damage to the current-years terminal growth occurs. However, sustained below-freezing temperatures for several days with minimums of -12°C have been demonstrated to kill all *O. ficus-indica* and *O. robusta* types to ground level (Wang *et al.*, 1998). These latter conditions caused no permanent damage to the Texas native, *O. lindheimerii*, to a putative *O. lindheimerii* by *O ficus-indica* hybrid clone 1233 or to *O. ellisiana* clones 1360 and 1364.

A common horticultural practice in the management of freeze damage is to wait until bud break occurs in the spring to determine the position of frost damage and then prune off the dead portions. When this procedure was followed after the most severe Texas freeze of 1989, many green portions of the stem 50-cm to 100-cm high were apparent 4 to 6 weeks later. Thus, 3-m to 4-m tall *Opuntia*s were pruned to the location where significant green tissue occurred. None of these cacti resprouted from the base. In contrast, some homeowners immediately cut the cactus at ground level and their cactus resprouted from the base. Apparently, secondary infections in the high-moisture-content damaged parts became established and later killed the remaining live portions of these plants.

If sustained below-freezing temperatures for several days occur, it would be most useful to immediately examine pruning to ground level and 25%, 50%, and 100% of plant height (no pruning in the latter case) to determine interactions between freezing damage and secondary plant infections.

Work to develop more cold-hardy fruit types has pursued additional collections in regions where severe freezing weather is common (Borrego-Escalente *et al.*, 1990), in selecting seedlings after severe freezes (Martinez, 1968), and in hybridizing commercial fruit types with more cold-hardy nonfruit types (Wang *et al.*, 1996). As many *platyOpuntias* resist severe freezing weather, such as *O. polyacantha* in Colorado and in Alberta, Canada (Nobel, 1988), it is tempting to speculate that these *Opuntia*s could be hybridized with the commercial fruit types to increase their cold hardiness. However, as Wang *et al.* (1996) have shown, the *O. ficus-indica* types do not make fertile hybrids with either the cold hardy *O. ellisiana* types or with the spineless cold-hardy type *Opuntia*. spp 1233. Fortunately, hybrids with the cold-hardy Texas native *O. lindheimerii* 1250 and various *O. ficus-indica* types have been made. Thus, it appears as if the genetic route to improved cold hardiness in *O. ficus-indica* will be to pursue hybrids and back crosses to the Texas native *O. lindheimerii*. While a spineless cold hardy parent is not available to use in these crosses, a great percentage of progeny of the spineless *O. ficus-indica* 1281 by *O. lindheimerii* 1250 cross are spineless. If spine characters and cold hardiness are not genetically linked, it may be possible to arrive at a cold-hardy spineless fruit type.

In contrast to the difficulties in producing acceptable cold-hardy fruit varieties, excellent progress has been made in selecting spineless *Opuntia*s with increased cold hardiness for forage applications. The spineless clones *O.* spp 1233 and *O. ellisiana* 1360 and 1364 withstood the 1989 Texas winter with nearly three consecutive days below freezing with very minor frost damage when all *O. ficus-indica* and putatively cold-hardy *O. robusta* types from South Africa were killed. As discussed later in the forage section, clone 1233 is highly productive. In contrast, this clone was killed in an early 1997 winter snowstorm in San Angelo, Texas, that did not damage *O. ellisiana* (D. Ueckert, pers. comm.).

Clones of *O. ellisiana* produce few cladodes per year, only obtain a maximum height of about 1.2 m and "appear" to have very low productivity. However, Han and Felker (1997) have shown that once *O. ellisiana* reaches a leaf area index of 2, indicated by Nobel (1988) to be optimum for productivity, this species produced 194,000 kg fresh weight containing 17,670 kg/ha dry weight with 662 mm rainfall. As this clone is perfectly well adapted without damage to Deming, New Mexico (D. Eppele, pers. comm.), with absolute minimum temperatures or -22°C, this clone probably could be grown at all elevations in Mexico, in all of Texas, and in many semiarid high-elevation regions of the tropics (ca 3000 m to 4000 m) where forage from grasses is scarce.

FORAGE ISSUES

Cactus has had, and can have in the future, a great impact for small farmers in semiarid regions. It is important to consider the regional impacts that are possible with large-scale implementation of an *Opuntia*-based forage-production system. For example, while the semiarid provinces of northwestern Argentina have extensive beef and goat production systems, collectively these provinces have a $205 million deficit in meat (Rearte, 1996). This is attributable to the fact that after excellent forage productivity due to summer rains, forage availability becomes scarce or economically nonexistent in the winter and hot dry spring with the result that livestock producers are forced to sell undernourished livestock to nearby provinces with high rainfall at unfavorably low prices.

Opuntia clones can be selected that are especially adapted for livestock use. Such characteristics include a more prostrate shrubby habit (as opposed to erect, fruit types with “open” canopies), to permit direct browse and high productivity from rapid leaf-area-index development. Fruit production would be of secondary importance and spinelessness would be an advantage if predation from wild herbivores were not of concern. Such characteristics have been used to identify three forage clones, depending on the degree of cold tolerance desired. Forage clone

TAMUK accession 1270 has been shown to have higher than normal protein contents of 11% (Gregory and Felker, 1992) and has a habit with cladodes close to the ground. This clone is only cold tolerant to -9°C for short periods. TAMUK clone 1233 is spineless, with undulating cladodes and is highly productive. Clone 1233 is much more tolerant of freezing weather than 1270, as described earlier. Last, where extreme cold temperatures of -15°C to 20°C are routinely reached, the cold-hardy *O. ellisiana* accessions 1360 and 1364 are the only spineless clones adaptable for forage production.

Eventually, planting and management systems to grow *Opuntia*s for forage or fodder should be better defined to establish their crop potential, with the final goal to enhance production.

NEW USES

As more research is conducted with cactus it is possible to begin to tie together some widely known anecdotal uses of cactus and to suggest additional uses. For example, there is much anecdotal information suggesting that "muddy water" in Argentina, Chile, and Mexico, and mine tailings in Arizona, has had the suspension rapidly precipitated (flocculated) with addition of chopped *Opuntia* cladodes. Due to the rheological and high-molecular-weight properties of the pectin-like polysaccharide of the *Opuntia* mucilage described by Cardenas *et al.* (1997), Gardiner *et al.* (1999) compared the use of cactus mucilage to polyacrylamides for use in increasing soil water infiltration on soils with low hydraulic conductivity. These authors found the hydraulic conductivity to be 28 mm/min for the control, 71 mm/min for a 10% dilution of the cladode extract, 128 mm/min for the undiluted cactus extract and 107 mm/min for the standard polyacrylamide treatment. Thus, the cactus cladode polysaccharide was equivalent to the standard treatment. This is the first report of any benefit to the cactus polysaccharide. It would be of considerable interest to follow up this result with additional research on flocculation of "muddy water" with various purified fractions of the cactus polysaccharide.

Furthermore, the observation of Cardenas *et al.* (1997) that the rheological properties of cactus mucilage were more similar to high-value okra (*Hibiscus esculentus*) gum than the more common and inexpensive guar gum, could lead to interesting commercial applications. Given the yield of about 0.7 g of gum/kg of cladodes (Cardenas *et al.*, 1997) and annual yields of 100,000 kg of cladodes, about 70 kg of gum might be possible. If the gums could be extracted and sold for the $3 to $4/kg typical of other high quality gums, with the cladode byproducts being used for cattle feed, significant returns for arid lands could result.

As the soluble carbohydrates in cladodes have been examined for the blood glucose and insulin-lowering properties in Type II diabetic patients (see the section below on medical uses), it would be of interest to know if the same polymers might be responsible for increasing water infiltration in problematic soils.

Various authors have reported that the fatty-acid composition of *Opuntia ficus-indica* seeds has excellent food properties (Saenz, 1996; Pimienta, 1990). Furthermore, McCarthy (1996) has suggested that the ground *Opuntia* seeds are an excellent condiment with a chocolate/cumin taste useful in various culinary applications. As large quantities of seeds become available as byproducts from *Opuntia* fruit-juice processes, it will be interesting to explore the potential applications of the ground seeds.

While prevention of soil erosion on steep slopes is generally thought of as a developing-country issue, special cactus cultivars could be very conveniently used to stabilize steep slopes in arid regions of developed countries. Given the difficulty in establishing grass species with erratic rainfall, erratic on steep slopes where it is not feasible to cover grass seeds with soil, and where access to steep slopes is limited, cladodes could be chopped into pieces and blown onto steep slopes on highway embankment projects or dropped from helicopters. An additional advantage of *Opuntia* cover on steep slopes is that during severe droughts, the moisture content of *Opuntia* would be much higher than shrubs or grasses, thus reducing the fuel load and the potential fire hazard. Given the extreme damage that has been caused to residential areas by fire, as occurred recently in California, firebreaks and steep-slope revegetation with *Opuntia* should be given very serious consideration.

LEGAL ISSUES

In addition to the biological and cost problems with shipment of high-water-content cladodes across international boundaries, there are significant legal problems. Some agricultural customs agents are not aware that cladodes of *Opuntia* subgenus are specifically exempt from the Convention on International Trade in Endangered Species (CITES), unlike most of the endangered Cactaceae. Due to the infrequent shipment of cladodes for propagation, agricultural officers do not have ready lists of prohibited pathogens or insects common to *Opuntia* which might spread to other crops in the country of importation.

In contrast to legal problems with importation of cladodes for propagation, there are legal issues with importation of cactus pears to Europe with respect to pesticide residues. In Europe, cactus pears are placed in the same category as stone fruits in which the flesh is eaten, in contrast to fruits such as citrus in which the peel is not consumed. Thus, the permitted residue levels on the peel of cactus pears are much lower than for citrus (F. Viljoen, President South African Assn. Prickly Pear Growers, 1997 pers. comm.). As pesticides are used to control cochineal and cactoblastis in South Africa, this regulation needs to be changed to put cactus pears in the same classification as citrus.

Further compounding this issue is the lack of pesticides registered for use on *Opuntia*. In 1997, the only pesticide registered in the United States for *Opuntia* was carbaryl (Sevin™) for use in controlling cochineal on fruits. It would be extremely useful to have Roundup™ and diuron registered for weed control, additional insecticides for control of cochineal and cactoblastis, and fungicides and/or antibiotics for controlling bacterial and fungal pathogens.

Cactus fruits are not permitted to be imported to the United States from Argentina due to the presence of the Mediterranean fruit fly (*Ceratitis capitata*) in Argentina. This is despite the fact that a methyl bromide treatment (T101-d-3) is approved for control of the Mediterranean fruit fly on *Opuntia* species and pitahaya from other countries. Extended storage at 2^{o}C, as might occur during refrigerated ocean freight, is also approved for control of the Mediterranean fruit fly, but it is not known which of any of the cactus pear varieties can resist these low temperatures without sustaining chilling injury.

MEDICAL ISSUES

Although quantitative data on the consumption of immature cladodes of *Opuntia ficus-indica, O. streptacantha*, etc. to control Type II non-insulin-dependent diabetes in Mexico is not available, as evidenced by the number of publications, this practice is widespread. Indeed a U.S. Patent (Gruwell and Preene, 1937) was awarded in 1937 for use of a boiled extract of *O. phaecantha* to control diabetes. Most papers have been published in Mexican journals that are difficult to retrieve. Among one of the most notable is the paper of Frati-Munari *et al.* (1983) in which the serum lipids, beta cholesterol, and blood-glucose levels were examined in 8 healthy, 14 obese, and 7 diabetic patients over a 10-day period. The intake of *Opuntia* before meals significantly decreased blood-glucose levels. Other more recent and accessible papers have confirmed these effects (Frati *et al.*, 1990a; Frati *et al.*, 1990b). In model systems with guinea pigs, Fernandez *et al.* (1990) found that cactus pear soluble fiber significantly lowered plasma cholesterol levels. A private laboratory in Israel (Assutech, Rehovot, Israel) has reported that extracts of flowers from *O. ficus-indica* reduced benign prostatic hypertrophy. However, the correct doses, possible contraindications with other foods or drugs, or methods of preparation that affect this property are not known. Obviously, if cladodes have significant medical benefits, this could be a major economic stimulus to development of this crop. It would be helpful to confirm these results to identify the mechanism of action of the glucose and insulin-lowering properties when nopalitos are consumed.

MARKETING

In considering marketing approaches, it is essential to follow two parallel routes to market development; one for the small subsistence farmer who sells fresh fruit and some artisanally processed products locally and one for the large farmer who has the resources to transport cactus products to distant locations in the same country or internationally.

The rationale for government programs to assist the subsistence farmer is obvious. In contrast, government programs may fail to see the need to assist medium- and large-size farmers. If care is taken to ensure that products from the small-scale farmers can be purchased from the larger farmer/processor to flow into a market with greater volume and price stability, competition from the subsistence and medium-scale farmer need not arise.

Therefore, marketing programs are necessary to meet both the needs of the small subsistence farmer to assist with the provision of his/her daily basic necessities and to assist with national/international market development to attract significant new capital into arid regions.

As discussed earlier, excessive production of cactus pears during peak harvest results in prices of \$0.70/kg to \$0.90/kg to growers in Italy (Basile and Foti, 1997) and Mexico (Moreno and Flores, 1996). While some Argentine growers receive \$2/kg for despined cactus pears wrapped in tissue and delivered 1000 km from the point of harvest to Buenos Aires, most small growers sell fruit for local consumption for prices of only \$0.30/kg (Felker pers. obs.). As the farmers fields are usually distant from main marketing centers and as the continuous chain of refrigeration that is required for attractive, high-quality fruit is not always available to farmers, much fruit is simply left to waste in the fields. For this reason it is important to convert part of cactus pear production into products that can be sold all year long.

In the past, the juice of the cactus pears (after straining out the seeds) has been heated for extended periods of time over open fires to reduce the water content to develop products with long shelf life. Depending on the level of water removed, these products have consistencies of jams (*arrope de tuna* in Argentina) or soft cheese (*queso de tuna* in Mexico) (Griffiths and Hare, 1907), with little resemblance of the initial fresh fruit taste in these processed products.

Over the last several decades there has been an increasing trend in the United States and Europe to minimally processed foods that have higher vitamin contents, greater nutritional quality, and flavors more resembling the fresh product. Thus, it is important to also develop products from cactus pears that have a long shelf life, good flavor, and nutritional quality. The private firm D'Arrigo Bros. have been the world leaders in developing both pasteurized frozen purees and room-temperature-stable mixes of cactus pear and pineapple juice (to lower the pH and prevent bacterial growth) (Bunch, 1996, 1997; Thomas, 1998). These types of products have great potential to absorb excess fresh fruit during peak production. With the availability of cactus pear products in commercial quantities, it will also produce a wide variety of new products, such as candies, ice creams, juices, etc. that will expand consumer awareness, which is of critical importance when the fresh fruit crop is available in the market.

Unfortunately, at present the technology for the pasteurized and frozen products only exists in the private sector and is not available in the public domain. Saenz (1996) has stated that due to the neutral pH of the juice, growth of Lactobacillus is a problem that mandates the use of 121°C sterilization (rather than 98°C pasteurization), which causes loss of flavor and color. However, a commercial fruit-processing firm in Argentina has developed stable cactus juice products by both pasteurization and ultra-high-temperature sterilization (Felker, unpub. obs.). Additionally, chefs in the food industry have suggested (Yankov Miodrag, 1999, pers. comm.) that frozen pulp, with the addition of 10% sucrose, can be stored for long periods without deterioration (Given 16% glucose in juice and additional 10% sucrose, the total osmotic potential would be 2.0 + 0.6 = 2.6 MPa at 0°C). Saenz (1996) has stated that quick-frozen cactus pulp (at –40°C) has very good color and taste, but looses texture upon thawing. Obviously this latter problem would not be a problem with use in ice creams and sorbets. It is possible that combinations of preservatives, such as ascorbic acid, potassium sorbate and sucrose, and pasteurization, may permit the long-term storage of frozen cactus pulp and consequent utilization in the food industry. However, with the ever-increasing public scrutiny in Europe and the United States, care will have to be taken in formulation of products with chemical additives.

Despite technical difficulties in formulating cactus-pear products with long shelf life and flavor resembling the initial fresh fruit, it is imperative to pursue R&D in this area. These products are critically important to relieve the depressed fresh-fruit price due to overproduction, to utilize excellent quality small and/or blemished fruits and to increase year-long availability of cactus pear products to stimulate the food industry.

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