Final Report

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Development of cactus (*Opuntia*) for human and animal food on semi-arid lands.

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Gonaives, Haiti

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Project Duration: August 7, 1989 through July 31, 1995.

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Executive Summary

In 1989, 37 clones of fruit, forage and vegetable cactus (Opuntia) types were established at the church related Eben-Ezer Mission near the city of Gonaives. Gonaives is the central city in Haiti's poorest northwestern region. During a final follow up visit in 1994, a dinner was prepared at the mission in which the vegetable type cactus was used in salads, cooked with meat and in a dessert. From the 37 varieties in the trial, an excellent vegetable variety (1308), an excellent forage variety (1267), an excellent fruit variety (1294), an above average fruit variety (1280) and a combination fruit, forage and vegetable variety (1271) were selected for further multiplication. Material from these selections were given to individuals working for the mission to plant and make available for further distribution.

At Texas A&M University a 4 year field trial measured a dry weight production of 17,670 kg/ha with 662 mm of rainfall. Of the 662 mm rainfall 285 mm was transpired by the plant for a transpiration water use efficiency of 162 kg water/kg dry matter. This is the highest water use efficiency ever measured under long term field conditions(including C3 and C4 plant species). This suggests cactus should be employed in development projects where water is limited.

Texas fertility trials found that fruit sugar was increased by N,P,K fertilization and that Mg was the element most highly correlated with this increase in fruit sugar.

Over 80 new Opuntia clones were collected from high elevation regions in Mexico that experience frequent freezing weather. Germplasm exchanges were conducted with Mexico, Argentina, India and Israel. Technical visits were made to Argentina, Brazil, Mexico and India. Proceedings of 5 annual cactus conventions in Texas were desktop published. An worldwide electronic email network for cactus researchers was established.

Small but long term financial support needs to be identified to help Eben-Ezer church related mission to disseminate fruit, forage and vegetable clones identified in this grant throughout northwestern Haiti.

4. Research Objectives.

(1) Due to laboratory studies suggesting that cactus had the highest water to dry matter conversion efficiency of all plants, we sought to measure this water to dry matter conversion efficiency under long term field conditions.

(2) As fruit cacti had never been grown in Texas, we sought to determine the fruit production and fruit quality of cold hardy cactus in Texas.

(3) Determine relationships between cladode nutrient concentrations and cactus fruit quality and production.

(4) Determine suitability of cactus for fruit, forage and vegetables in Haiti.

5. Methods and Results

The following publications, manuscripts and proceedings are submitted in lieu of a methods and results section.

Gregory, R.A., J.O. Kuti, and P. Felker. 1993. A comparison of *Opuntia* fruit quality and winter hardiness for use in Texas. J. Arid Environments.24: 37-46.

Felker, P. 1994. *Opuntia* forage production and utilization. *In*: Cactus pear cultivation and uses. (Inglese et al., Ed) FAO Publishers.

M.R. Karim, P. Felker and R.L. Bingham. 1996. Correlations between cactus pear (Opuntia spp) cladode nutrient concentrations and fruit yield and quality. J. Horticulture Science. In revision.

Han, H. and P. Felker. 1996. Estimation of daily soil evaporation using an artificial neural network. Soil Science Society of America Journal In press.

Han, H., and P. Felker. 1997. Field Validation of Water Use Efficiency of a CAM Plant Opuntia ellisiana in South Texas. J. Arid Environments, Submitted.

Felker, P., and J.R. Moss (Editors) (1990. 1991, 1992, 1993, 1994), Editor of First Second, Third, Fourth and Fifth, Proceedings of Texas Prickly Pear Council Convention. ca. 100 pages each.

Summary of results

A. Water use efficiency of Cacti.

The most striking, theoretical result of this work is that cactus has been found to have the highest water to dry matter conversion efficiency of any plant group. In the fourth year of this experiment, 662 mm of rainfall occurred with soil evaporation (214 mm) and runoff (143 mm) accounting for the major losses. A significant quantity of water (17 mm= 170,000 kg/ha) was stored in

the cactus that could reduce animal water needs. The cactus transpired 285 mm of water producing 17,670 kg dry matter/ha for a transpiration water use efficiency of 162 kg water/kg dry matter. This is the greatest water use efficiency of any plant species (including C3 and C4 species) that has been measured under long term field conditions. This result suggests that cactus should be employed in development projects for fruit, forage or vegetables in semi-arid regions where water is a scarce commodity.

B. Assessment of fertility requirements for cactus fruit production.

Research in both Israel and Mexico indicated that heavy cactus fruit production was strongly influenced by soil fertility. Rather than conduct empirical trials on each plot of ground to determine fertilizer amendments, we felt it was necessary to develop correlations between leaf tissue concentrations of mineral nutrients and fruit production. In this way leaf tissue samples can be taken at any site to determine if the plant has below normal, adequate or surplus concentrations of nutrients. In developing leaf tissue tests for Opuntia, it is important to know if the leaf tissue test is valid for only one species or cultivar, or if it has general applicability to the 4 or 5 major fruit bearing species, each of which contains dozens of cultivars.

U.S. AID supported graduate student Mohammad Karim examined the

relationship between fruit production and cladode nutrient concentrations in a field trial with N,P,K and micronutrient additions. Fruit production and cladode nutrient concentrations were measured. Highly significant differences in fruit sugar concentration occurred with the fertilizer treatment containing 100 kg/ha of N, P, and K yielding the highest fruit sugar content.

Correlation analyses between the 10 nutrients examined and fruit sugar content found that the cladode Mg concentration was significantly correlated with fruit sugar content. A quadratic equation was identified that correlated fruit sugar with Mg concentrations. Given the importance of Mg in regulating the first enzyme in photosynthetic sugar production, this finding does not seem unusual. This study also found significant relationships between fruit yield and cladode N, K and Na. Figures were reported illustrating the relationship between fruit yield and these tissue nutrient levels.

C. A comparison of Opuntia fruit quality and winter hardiness for use in Texas.

This publication compared the fruit quality, fruit production and winter hardiness for over 20 Opuntia clones over a 3 year period. Except for the germplasm backups maintained in the greenhouse, all of the fruit cultivars froze to the ground in the Christmas 1989 freeze thus necessitating additional collections from zones that

experience freezing weather.

D. Opuntia forage production and utilization. In: Cactus pear cultivation and uses.

This publication for an FAO book on all aspects of cactus examined the uses of cactus for forage by sheep, goats, pigs and cattle. Basically Opuntia is only suitable for ruminants on a long term basis and must be supplemented with protein and minerals. Compositions of protein and mineral mixtures were provided with suggestions for daily cactus intakes.

E. Estimation of daily soil evaporation using an artificial neural network.

This was a methods paper that resulted from the work to estimate the water use efficiency of cacti. A major water loss in the cactus study was soil evaporation from the soil surface. This can be measured daily by inserting 5 cm diameter, 10 cm long open ended aluminum cylinders into the soil. By weighing the soil immediately and one day later, the soil evaporation can be determined. As it would be very difficult to make these measurements every day, soil evaporation is generally modeled from inputs of rainfall, humidity, wind speed and soil water content. The soil evaporation is most usually estimated from these variables with standard linear multiple regression. In this case a mathematical technique known as

an "Artificial Neural Network" was employed to estimate the soil evaporation. The average absolute percent error and the sum of squared error was 20.99% and 0.62 mm for the neural network as compared to 30.03% and 1.09 mm for the multiple linear regression technique. Thus the neural network provided substantially lower errors of prediction than the more standard approach.

F. Texas Prickly Pear Council Proceedings.

For five years annual cactus conventions with speakers ranging from cattlemen, chefs, food brokers, nopalito (vegetable producers), fruit producers and agronomists were held in Texas. Each year proceedings of about 100 pages in length were compiled and printed in desktop publishing form. These publications have served as useful background information for scientists and lay people wishing more integrated information on cactus.

6. Impact, Relevance, and Technology Transfer.

While the primary technology transfer portion of this grant was officially aimed at a relationship with Haiti, significant cactus technology transfer was achieved in Argentina, Brazil, India and Israel. Additionally by serving as the Technical Coordinator of the FAO Cactus Network, Felker impacted the 21 other countries in the FAO network. Details of the technology transfer to other countries follow.

Collaborative *Prosopis* and *Opuntia* activities in Haiti.

Due to the pressing need for economic development in Haiti, and the lack of professional research personnel, the primary focus of this collaboration has been economic development. In 1989, 37 clones of fruit, forage, and vegetable types of cactus were established near the city of Gonaives in Haiti's semi-arid region. In May 1994, Peter Felker went to Haiti to determine the status of the cactus project for the final report and to assist with the dissemination of genetic materials of erect, thornless fast-growing *Prosopis* clones.

On arrival at the Eben-Ezer Mission in Gonaives, Felker was delighted to find an entire meal prepared in various ways with the cactus being used in salads, cooked with meat and included in a dessert. The people at Gonaives were quite excited about continued development of cactus as a vegetable crop for the dry northwest. The completely spineless varieties in the trial makes food preparation much easier than when spiny varieties are used.

From the 37 varieties in the trial, an excellent vegetable variety (1308), an excellent forage variety (1267), an excellent fruit variety (1294), an above average fruit variety (1280) and a combination fruit, forage and vegetable variety (1271) was selected for further multiplication. Material from these selections were given to individuals working for the mission to plant under the

understanding that the Eben-Ezer Mission would buy back individual "leaves" for planting stock at $0.15 each. The vegetable variety 1308 will produce 50 "leaves" from one leaf in a single planting season. Thus considerable planting stock should be available at the end of the first growing season.

As Eben-Ezers funds for planting stock are limited, it would be most beneficial if AID or CARE could help with the financing, production and distribution of these plants in the northwest. This relationship with CARE deserves particular attention since Eben-Ezer Mission already has a good relationship with CARE's food distribution program for the northwest.

Despite the embargo and the high cost of transportation, in 1994 Joshua Jean and Peter Felker made the 200 mile round trip to the Prosopis progeny trial to obtain budwood of erect, thornless and fast-growing Prosopis. A demonstration on how to graft superior genetic materials onto existing Prosopis around their homes was given to about 20 residents. Everyone present was provided budwood, and grafting tape to topwork their own trees. We have since learned that many of these grafts have taken. The grafted trees will be erect and should produce pods that are considerably sweeter than the native Haitian Prosopis. This accomplishes 2 goals. First it brings improved genetic materials to northwestern Haiti and perhaps more importantly, it brings the notion that the well-adapted trees in Haiti like Prosopis are subject to management

and they should be paid more attention by development people and local people alike.

Technical cooperation with Argentina.

In 1994 we conducted an *Opuntia* germplasm exchange of 30 clones with Ing. Judith Ochoa de Cornelli at the University of Santiago del Estero in Argentina. Argentina recently obtained a large amount of planting stock from a limited number of fruit producing clones from Italy. These clones were a gift from the government of Italy to the President of Argentina who has planted them on his ranch. Due to the limited number of clones in the Italian exchange, they were interested in expanding the genetic diversity of the Argentina material. The living collection of *Opuntias* at Kingsville is evidently the largest collection of economically useful *Opuntias* in the world and thus is in considerable demand. Due to the exciting results of the TAMUK research on nutrient effects on *Opuntia* fruit production and quality, we have been requested to provide assistance in designing a fertility study for *Opuntia* fruit production in Argentina.

Technical cooperation with Brazil on Prosopis and Opuntia.

While the usual thoughts of Brazil are of the tropical rain forests, the 3 states of Pernambuco, Ceara, and Paraiba in northeastern Brazil all have extensive semi-arid zones in which

both cactus and mesquite have been used to a great extent. While there has been some research on feeding cactus to cattle, there has been virtually no research on mesquite for the arid zones. Thus the objective was to use new genetic strains and management practices for both mesquite and cactus in Brazil's semi-arid zones. There was a severe drought in 1993 and 1994 that has exacerbated this situation and lead to enquiries for more sustainable solutions.

Personnel from TAMUK have been visiting Brazil and working with their agriculture researchers since 1984. The most recent trip was funded by the Department of Agriculture of the State of Pernambuco and the Livestock Producers of Pernambuco, with the assistance of the U.S Consul. As a result of this constituency, the trip was much more development oriented.

Peter Felker gave a presentation that focused on developing all commercial aspects of Prosopis and Opuntia. He especially focused on concentrating on the highest value products from these plants and marketing approaches to stimulate commercialization. The superb furniture qualities of Prosopis wood and techniques to efficiently and economically process small logs for lumber were highlighted. Also discussed was the opportunity to market flour from Prosopis pods in specialty human food applications and the need to involve chefs at major restaurants in both Prosopis and Opuntia food products. An annual fair to highlight all the commercial products from Prosopis and Opuntia is being developed.

In addition he hand-carried budwood of erect, thornless, rapid growing Prosopis and demonstrated techniques for grafting the budwood onto existing trees.

Collection of cold-hardy fruit cacti in northern Mexico.

In the summer of 1989, many clones of cacti produced excellent quality fruit on the Texas A&M University-Kingsville field station thus demonstrating that excellent quality fruit production was possible in Texas. Unfortunately, the 100 year freeze of Christmas 1989, froze all the cactus in the field to the ground. Casual professional visits to Saltillo in northern Mexico observed excellent quality red, orange, yellow and green color cactus fruits at over 8,000 ft elevation. Since such great variation was observed purely by chance, it was of interest to make a more intensive collection of cold hardy cactus that would concentrate on the high elevation sites in northern Mexico.

With funding from the International Arid Lands Consortium, Dr. Avinoam Nerd of the Ben Gurion University of the Negev in Israel, and Peter Felker made a trip in northern Mexico to collect cold-hardy, fruit producing Opuntia strains. In October 1993 a collection trip was made that covered nearly 2,000 miles and obtained 52 new clones that were immediately planted at TAMUK. Of especial interest were fruit clones obtained 2 hr drive west and south of El Paso at Casas Grandes at 5,000 ft elevation. Since this

was the same elevation as El Paso and since El Paso is much colder than south Texas, we believe these clones should have increased cold hardiness. At this location we obtained cactus with red, orange, yellow and purple fruit colors. All clones were shared between researchers from Mexico, Israel and the United States.

Food and Agricultural Organization (FAO) cactus pear network.

In August 1993, FAO sponsored an international meeting in Guadalajara, Mexico to bring researchers together who were working on cactus. The purpose was to fund an international cactus pear network. Representatives from Italy, Israel, S. Africa, Bolivia, Peru, Argentina, Brazil, Chile, Mexico and the United States were present. A list of priority issues for research and development for the network was developed. A major need is for funding to bring the participants together on a regular basis. A positive output of the network is an FAO sponsored book on applied uses of cactus written by specialists in many fields. The book should be available late in 1996.

The FAO Cactus Pear Network met again in December 1994 in Palermo Italy to outline further collaborative projects. Following that meeting Felker developed a Cactus email network that currently has over 100 subscribers from Asia, Africa, Europe, North America and South America. This email network has been very useful in exchanging information about seed germination, graduate

assistantships, germplasm and itineraries for national and international meetings.

In September 1995 cactus professionals held a joint meeting at the San Antonio Botanical Garden and the Sheraton Fiesta to establish a Professional Association for Cactus Development. This organization plans to be a professional society to parallel the official work of the FAO Cactus network. In November 1995, a Cactus meeting was held in Guadalajara, Mexico that included the major cactus researchers in Mexico as well as a few speakers from other countries. Felker was fortunate enough to have given the opening presentation at this meeting.

Cactus collaborative efforts in India.

In 1991, FAO visiting fellow Dr. Gurbachan Singh spent 4 months at Texas A&M University-Kingsville, primarily for Prosopis work. However, Dr. Singh attended a cactus meeting with us in Mexico and on his return he took fruit, forage and vegetable varieties to India. These varieties have done very well indeed(See attached article on Wastelands). The Director General of the Indian Council of Agricultural Research has requested that these varieties be distributed to the arid areas of India. A cactus collection of 30 clones supplied to Dr. N. Nimbkar, when we hoped India was going to be a collaborator in this grant, has been distributed to the Dryland Horticultural Institute in India.

7. Project Activities/Outputs

Theses

Huien Han 1993. Water use efficiency of *Opuntia ellisiana* under field conditions in south Texas. Masters Thesis(Plant and Soil Science). Texas A&M University-Kingsville, 129 pp.

Huien Han 1995. Implementation of a neural network of radial basis function to estimate daily soil evaporation. Masters degree (Computer Science). Texas A&M University-Kingsville, 44 pp.

Mohammad Rezaul Karim. 1994. Correlations between Cactus Pear(Opuntia spp) cladode nutrient concentrations and fruit yield and quality. Masters Thesis. Texas A&M University-Kingsville, 93 pp.

Publications

Gregory, R.A., J.O. Kuti, and P. Felker. 1993. A comparison of *Opuntia* fruit quality and winter hardiness for use in Texas. J. Arid Environments.24: 37-46.

Felker, P. 1994. *Opuntia* forage production and utilization. *In*: Cactus pear cultivation and uses. (Inglese et al., Ed) FAO Publishers.

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yield and quality. J. Horticulture Science. In revision.

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Germplasm developed/released

Spineless, glochidless, low-mucilage, high year around nopalito producing variety "Texas A&M 1308" that is now being grown commercially in Texas.

Following 5 Opuntia clones selected for dissemination in Haiti; an excellent vegetable variety (1308), an excellent forage variety (1267), an excellent fruit variety (1294), an above average fruit variety (1280) and a combination fruit, forage and vegetable variety (1271).

80 new Opuntia clones collected in northern Mexico and planted on Texas A&M University field station.

Germplasm exchanges of 30 Opuntia clones made with India, Argentina and Israel.

Meetings organized

Five annual Texas Prickly Pear Council Conventions.

Meetings attended

Mexican Horticultural Congress, Saltillo Mexico -August 1991.

Mexican Fifth Annual Cactus Pear Convention-November 1995.

FAO Cactus Net meetings; Guadalajara, Mexico August 1993; Palermo, Sicily December 1994.

International New Crops Symposium, Indiana October 1995.

Email networks established

In January 1995 a listserv for both cactus (Cactus-L@taiu.edu) and for Prosopis (Prosopis@taiu.edu) were established.

8. Project Productivity

It would have been desirable to have worked more closely with our Haitian collaborators in germplasm evaluation, selection and dissemination. Due to difficulty in maintaining telephone and FAX contact and the coup and resulting embargo, we feel fortunate to have accomplished what was done.

9. Future work

At Texas A&M University-Kingsville, we will continue to measure fruit production and yield of the recently collected "cold hardy" fruit clones. On an international level we will continue to work with the FAO Cactus Net to facilitate Opuntia scientific exchanges for economic development purposes.

There is great opportunity to diffuse the selections of fruit, forage and vegetable clones throughout Haiti's poverty stricken, semi-arid northwestern region. Now that the democratically elected government is back in power, we hope there will be opportunities for continued development in this region. We will stay in contact with our Haitian collaborators to provide all the assistance we can by long distance.

With the great interest in vegetable uses of cactus by the people of semi-arid Haiti, there is a great opportunity for AID to be of assistance by providing funds to further disseminate the genetic materials throughout northern Haiti. It is recommended that the CARE food relief efforts be expanded to include distribution of vegetable cactus planting stock and training by locals on the growth and food preparation of cactus for vegetables.

10 Literature Cited.

Appropriate citations to the *Opuntia* literature are contained in the attached manuscripts and publications.

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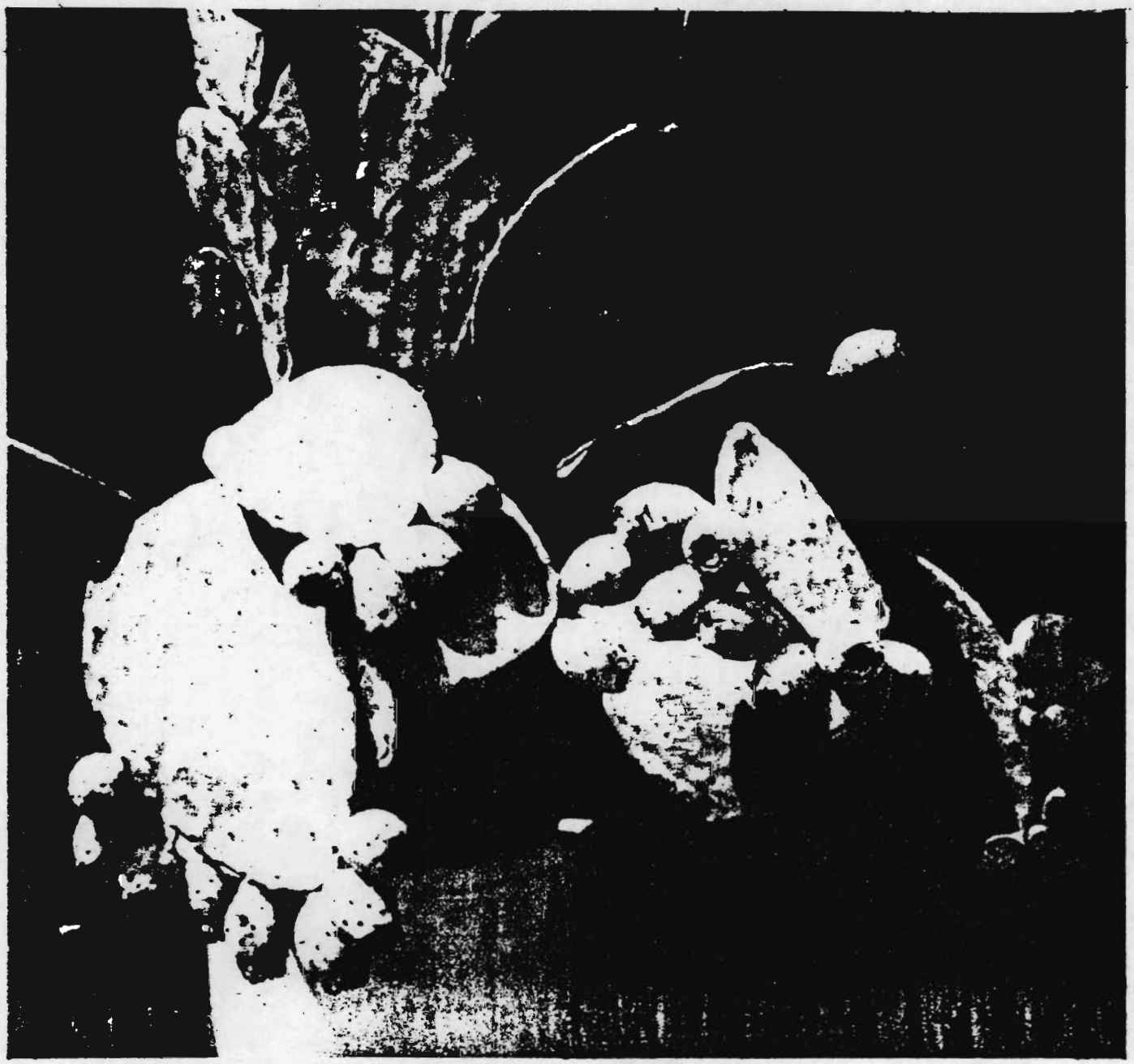

Edible and aesthetic fruits—from a cactus (see page 58)

SPWD SOCIETY FOR PROMOTION OF WASTELANDS DEVELOPMENT

Edible Cactus—A New Hope for Wastelands Development

by Gurbachan Singh* and Peter Felker**

Cactus *(Opuntia ficus-indica)* commonly known as Prickly Pears belongs to family Cactaceae. The Cactaceae contain about 130 genera and nearly 1500 species, which were originally native to the new world. Cacti have a special carbon dioxide fixation pathway, known as Crassulacean Acid Metabolism (CAM), and can have a four to five-fold greater efficiency in converting water to dry matter than even C-4 plants. Being so water-use efficient, they are highly useful in arid and semi-arid environments. In addition, certain genera, such as *Opuntia* and *Nopalea* have economically useful plant parts. The fruits of domesticated *Opuntia* cultivars, known as prickly pears in south western United States or *tunas* in Latin America, can be very sweet and are highly regarded. They have been sold as a desert fruit in the markets of USA, Chile, Mexico, Brazil, North Africa, Spain, Italy and Greece. The tender young pads of *Opuntia* and *Nopalea* species, known as *nopalitos*, are extensively used as a fresh green vegetable in Mexico and Texas.

Many species of cactus are found growing as wild plants in arid and semi-arid regions of India. Generally, these species are used as live fences to protect agricultural fields from human and animal encroachments. With few exceptions, there has, so far, been no attempt to cultivate the plant as a horticultural crop in India. In countries such as Mexico, USA, Spain, Italy and northern Africa, where the crop is commonly known, it already forms an important part of the people's dietary requirement. In addition to the excellent quality and flavour of the fresh fruit, the young leaves serve both as a vegetable and salad dish and the immature fruit is used to make mock gherkins.

Germ Plasm Introduction

Keeping in view the potential of cactus for fruit, vegetable and forage production with minimum input and water use in arid and semi-arid regions, promising edible clones of cactus were introduced in 1991 from Dr. Peter Felker's collections in the Centre for Semi-arid Forest Resources, Texas A and M University Kingsville Campus, Texas (USA). Clones introduced are :

Clone No.	Use
1270	High protein forage and fairly sweet pale-green fruits
1271	Fast-growing and fairly sweet fruits
1280	Thornless with pretty good yellow fruits
1287	Thorny, but best fruit variety
1308	Very fast-growing vegetable variety

Multiplication and Evaluation

These clones were planted in November 1991 in ceramic pots of 20 kg capacity each using good soil blended with farm-yard manure at the rate of one kg per pot for germ plasm multiplication and field evaluation trials. The vegetable clone 1308 took nearly 57 days for sprouting while the fruit clone 1287 sprouted last taking about 85 days. The data on number of cladodes formed per plant 180 days after planting is given in Table1.

Table:1 Days taken for growth initiation and number of cladodes formed by different cactus clones

Clone	Days for sprouting	Cladodes per plant
1308 (V)	57	6
1270 (F.F)	68	4
1271 (F)	91	3
1280 (F)	98	2
1287 (F)	100	1

Sodicity Tolerance

Cactus performance was evaluated in different pH soil (pH_2 8.1, 8.4, 8.7, 9.4 and 10.0) in pots. Growth initiation was affected markedly by the pH levels of the medium. At pH 8.1, the growth started after 54 days of planting, whereas at pH 10.0 the sprouting took about 90 days. The number of cladodes formed per plant were significantly less above pH 8.7. The plant formed cladodes even at pH 10.0,

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identifying it as a very useful plant which can even grow under high pH levels. This study showed that owing to its low water requirement and moderate tolerance for salt stress it can be grown as a companion crop with low water demanding and highly salt tolerant trees of the genus *Prosopis* to augment fuelwood, forage, fruit and vegetable needs of inhabitants in arid environments.

In February 1993, these clones were planted in the field for large scale germplasm multiplication. All clones have been raised successfully without any supplement irrigation even under the field conditions.

Flowering and Fruiting

In April 1995 (nearly 3 and half years after planting) flower initiation took place in all the clones (which later-on developed into fruits. The fruits started ripening by the first fortnight of June and all fruits were harvested by July 20, 1995. Maximum fruiting took place in clone 1270 and minimum in clone 1287. The fruits were oval shaped, pale-green in colour and weight of each fruit ranged from 50 to 100 grams. Each cladode of clone 1270 bore 8 to 15 fruits (nearly 1 kg fruit per pad. Total fruit yield from 20 plants of clone 1270 planted in the pots was nearly 40 kg. This could be much higher when planted under field conditions. The potted plants were given no other inputs except nutrient solution of 2 per cent urea, 0.5 per cent super phosphate and 0.2 per cent zinc sulphate annually.

Dr. R.S. Paroda, Director-General, ICAR, and Secretary DARE, Government of India visited these experiments in March 1995 and appreciated the research efforts. He desired that the material be distributed to research centres located in Rajasthan, Gujarat and Haryana. Accordingly, all the five clones have been supplied for planting to CAZRI, Jodhpur and our regional research station, Anand, Gujarat. The material is also being sent to the Directorate of Arid lands and fruits, Bikaner.

Production Potential

Fruiting starts 3 years after planting, full production reaches in the 12th year and continues for at least 20 years thereafter. Normally fruits appear on 1 to 2 years old cladodes. Unlike other crops, fruit is fully formed when flowers first appear; after pollination and fertilization all that happens is that the seed cavity is filled with seed and the edible portion. A well established crop (planting geometry 4m x 2m) can yield fruits to the tune of 10 to 40 t/ha per year. With proper irrigation and fertilization even 2 crops/year can be taken, one between March and July and the other between October and December. In

Chile people have found that tuna production with less infrastructural costs is as profitable as tree fruits or grapes on their marginal lands.

Promising vegetable clones such as clone 1308 can yield biomass production of 80 to 90 t/ha/year. In countries like South Africa, South America and the USA, harvested material is sold as vegetable in the markets. Material not sold in the vegetable market is being used as cattle fodder. It has been reported that it imparts a better flavour and quality to the milk and also enhances the colour of the butter. Dairy products coming from cattle fed with cactus pads get a premium price in the market.

Prickly pears can be a good alternative forage crop on land that is presently deemed marginal for other crops. The spines can be burnt before feeding the cattle. In Mexico and south-west Texas, propane torches known as pear burners have been used to burn off cactus spines. Though cactus leaves are low in proteins, it can serve as a very good source of roughage, especially in areas which are rainfed and prone to severe drought. In countries like north-

eastern Brazil, cactus is grown as a fodder crop on its sizeable area.

Nutritional Value

Nutritional value of cactus is considered to be comparable with various other popular fruits. Table 2 indicates the nutritional composition of edible portion of the prickly pear as estimated by Sawaya, et. al 1983, and USDA Agricultural Products Quality Analysis Laboratory Weslaco, Texas. The fruit is rich in sugars, vitamins, minerals and amino acids. Some scientists are also of the opinion that it may reduce sugar and cholestrol levels in the human blood.

Table 2. Nutritional Value of Opuntia Fruits

Parameter	As% of fresh fruit mass
Water content	85.6
TSS	12--15
pH	5.8
Sucrose	0.2
Glucose	7.0
Fructose	4.8
Crude protein	0.21
Crude fat	0.12
Crude fibre	0.02
Ash	0.44
Acid	0.02
Pactin	0.19
Vitamin C	22.00 mg/100 gm
B-Carotene	traces
Calorific value	47.30 K cal/100 gm
Calcium	27.60 mg/100 gm
Mg	27.20 mg/100 gm
Sodium	0.80 mg/100 gm
Potassium	161.00 mg/100 gm
Phosphorous	15.40 mg/100 gm
Iron	1.50 mg/100 gm

In addition to fruit, vegetable and forage source, prickly pear has a number of other uses. It is considered a delicacy by people in many European countries; thus it has a great export potential. Countries such as Mexico, Italy, South Africa and Greece are exporters of prickly pears. Other alternative uses of prickly pears include, preparation of mock gherkins, vegetable and salad dishes, jams and syrups, soap from its leaves, alcoholic drinks, fruit juices, seeds for medicinal purposes, honey and cheese production etc.

Cultural Practices

Since prickly pears are basically drought-resistant, they are particularly suited to those areas where rainfall is scarce and irrigation water limited. Areas of high rainfall (>800 mm) are not suitable for its cultivation as the crop becomes more liable to pests and diseases. The optimum condition for its growth are available in summer rainfall regions having average rainfall between 300 to 600 mm. Hot sunny days and cool dry winter where temperatures do not fall below -5°C are most suitable for cactus production. A large part of India is therefore most suitable for its cultivation.

Prickly pears thrive best on sandy and sandy loam soils. However, it does well even on heavy soils with adequate drainage. Gravelly or stony lands especially at the foot hill slopes are also suitable. Further, it thrives well on slightly alkaline soils rich in calcium and potassium. Any type of soil which is not suitable for other crops can be planted to cactus provided that is not subject to prolonged waterlogging.

Planting Material

Prickly pears are both self-and-cross pollinated. They can be raised both from seed and vegetative parts. However, the most common method of propagating prickly pears is by leaves that are at least one year old. The best way of planting is the upright method. In this case, leaves are planted upright in the soil with the cut end in the ground keeping one third of leaf below ground and two-thirds above. Before planting leaves should be allowed to wilt for 4 to 6 weeks in semi-shade. Further, leaves should be dipped in some fungicide solution before planting to check root rot caused by soil-borne pathogens. Immediately after planting, apply 8 to 10 litres of water to each plant; no subsequent irrigation until growth starts. It is better to plant prickly pears on ridges than on a flat surface. As most of the feeding roots of prickly pear are very superficial, it is important that the upper 30cm of soil is in good physical condition to promote maximum root development. It can be achieved by adding of some porous material (river sand) and cattle manure in the planting pit.

Though prickly pear can be planted anytime of the year the best time is September-October and February-March. Spacing depends upon the type of cultivar and the purpose for which the crop is being raised. In general, prickly pear gives best production when planted in a 4m x 3m planting geometry.

Since the plant is highly resistant to drought, a rainfall of between 300 to 600 mm spread uniformly throughout the summer season takes care of its total water requirement. If the rainfall is scanty and not evenly distributed 2 to 3 irrigations especially during fruit formation stage enhances production and checks the problem of fruit cracking. Since its root system is very shallow, very light irrigation should be applied.

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Pruning

Pruning is an important practice for the species. It is generally done for giving proper shape to the plant, reducing competition for light, improving yields, fruit quality, fruit size and rejuvenation. The best time for pruning is when the crop has been reaped and the plant is no longer growing actively. The low hanging leaves should be removed first. The damaged leaves should also be removed. Never prune cactus, during active growth stage as it may severely reduce production.

Upto 30 fruits may be borne on a single prickly pear leaf. If all fruits are allowed to stay for ripening, fruit size and quality are adversely affected. To maintain optimum fruit number (10 to 15) per leaf it is advisable to practice pruning. The best time for thinning may be between fruit bud formation and flower initiation. The fruits should be thinned in such a way that the remaining fruits are evenly spaced around the leaf.

Fruit Picking & Handling

Prickly pear fruit being very delicate requires utmost care during picking and handling. Since the fruits have small thorns called glochids, a person should wear gloves at the time of picking. After picking, the thorns must be removed by rubbing the fruit on grassy surface or washing the fruit with a sack or rotating brushes. The dethorned fruits can be packed in specially designed trays. We used egg trays for storing the fruit.

Conclusion

When multipurpose use of cactus are taken into consideration it is strongly concluded that this crop may prove a boon for the rehabilitation of degraded sites including waste lands. The low cost of its establishing and producing the crop as well as its tolerance to drought conditions and salt stresses make it eminently suited to become a viable industry in the future in India. The areas where this crop can bring revolution are : Thar desert in Rajasthan, Rann of Kutch in Gujarat, South Western parts of Haryana and similar other rainfed areas prone to severe drought problems.

Cactus has immense potential for arid and semi-arid India. It would be most helpful if we could make a research and development plan involving people having similar interests to import and exchange *Opuntia* germ plasm. To start with, a centre for germ plasm collection and maintenance should be identified. Possibilities must be explored for international collaboration involving people from those countries where the crop is commercially cultivated and has already become a part of their dietary requirements. There is also a need for coordinated effort within the country to promote cactus and its linking with the already existing international networking on cactus.

Role of NGOs in the Promotion of Biogas

by C. Hari Narayana Rao*

NGOs with their grassroots orientation and integrated approach to rural development play a crucial role in the promotion of non-conventional energy resources like biogas,wind energy, solar energy etc., which have an important bearing on rural sanitation and environment. These natural resources are not only renewable but also cost-effective. They check indiscriminate deforestation and help restore ecological balance. The non-conventional energy sources reduce the workload of rural women, particularly the girl child, and also curb the health hazards of people.

The Non-conventional Energy Development Corporation of Andhra Pradesh Limited (NEDCAP) was set up in 1986 in order to explore and promote the use of alternative energy sources in collaboration with NGOs, wherever possible. The NGOs which are engaged in the integrated watershed programme with the dual objectives of achieving eco-regeneration and upliftment of marginalised sections can be involved in the promotion of non-conventional energy resources as well. The present study aims at assessing the role of the Rural Development Trust, an NGO active in the Anantapur District of Andhra Pradesh, in promoting biogas programme in liaison with NEDCAP. It attempts to: (i) examine the physical and functional status of biogas units promoted by Rural Development

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★ ★ SOUTHWEST EDITION WEDNESDAY, FEBRUARY 7, 1996 BEAUMONT, TEXAS

Do You Hate to Eat Wet, Slimy Leaves? Relief May Be Here

* * *

Boosters Say the '1308' Cactus Is Dry and Even Crunchy; But Will It Mushroom?

By FRANK BASS
Staff Reporter of THE WALL STREET JOURNAL

KINGSVILLE—In the annals of gastronomic history, the slime content of food hasn't normally been a selling point.

But, here in South Texas, some farmers plan to change all that. With a cactus.

Not just *any* cactus, though. The Great Green Hope is the Texas A&M 1308 Nopalito, a special variety that the farmers believe may be just the ticket to get people all over the state eating cactus. "I'd like to see it mushroom," says farmer Ernest Bippert Jr. "That's my dream, anyway."

Cactus leaves—nopalitos—have been a staple of Latin and Mediterranean diets for more than five centuries. (Huevos con nopalitos is a common breakfast dish, for instance.) They're especially prized during Lent, when much of the heavily Catholic Latin population in South Texas gives up meat and relies upon nopalitos for their high protein content. Every day during the season, an average of 40,000 pounds of nopalitos cross the border into Texas.

And, of late, the leaves—flat, green, and generally the size of an index card—have been gaining acceptance in Anglo cuisine as well, showing up in salads, main courses and even desserts.

The leaves would be even *more* popular, Mr. Bippert and his associates say, minus the ooze. Enter the 1308.

Thorny Issues

Although there are packaged nopalitos on the market, many are sold raw, like any other vegetable. And, as such, the farmers insist, the cactus leaves are difficult to prepare: Aficionados must don gloves and use razor blades to scrape away the prickly thorns. And, when that's done, what's left is mucilage—a slimy, viscous substance something akin to stewed okra. Less than appealing, the farmers say.

The 1308 solves a lot of those problems. It's spineless, contains almost no slime—in fact, it's crunchy—and the farmers claim it has a much longer shelf life than the average nopalito. Eaten raw, it tastes a little like a sweet bell pepper. And, unlike stan-

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Group of Farmers Say They've Found A Better Cactus

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dard nopalitos, the 1308 can be pickled. (It tastes like, well, a pickle.)

In their second year of production, the farmers are hoping to get their product on the shelves during Lent. They currently have seven acres set aside for growing the 1308, and this spring they plan to double their acreage.

But they concede that their nopalitos are as alien to most people as kiwi and asparagus once were. "It's an educational process," particularly for the Anglo community, says Robert Wagner, Mr. Bippert's nephew and partner.

Stalking the Perfect Cactus

The 1308 is so named because it was the 1,308th plant specimen collected by researchers at Texas A&M University's Center for Semi-Arid Forest Resources in Kingsville. Peter Felker, a plant physiologist, gathered samples of the cactus in 1984 on an expedition to Central Mexico.

When cactus leaves started to take off in Texas around 1987, Mr. Felker saw an opportunity to gain some insight into his area of study: using cactuses as food in arid regions. If there were ever a cactus that would be widely accepted, he figured, it was the 1308. And if he could convince a Texas farmer to raise and market his nopalito, he could find out once and for all if a broad spectrum of people would accept cactuses as food.

HAI KNAFO

Low-slime '1308' cactus leaves

It wasn't until 1994 that he met growers who were "serious" about the project: Messrs. Bippert and Wagner. The two men, who operate Kingsville-based Wagonwheel Farms Inc., a 2,500-acre operation specializing in cotton, grain and sorghum were swayed by what Mr. Felker calls his "overzealous salesmanship."

One of the key arguments: The 1308 is easy to grow. On a four-acre plot, Mr. Bippert used about 400 pounds of standard fertilizer to get the four-inch cactuses started. That's about as much as he uses for his other crops. But, after that, the cactuses need much less attention: Without irrigation—and with just a minimum of watering—he estimates the cactuses will yield 15,000 pounds per acre, harvested twice a year. The potential yield of this year's crop? Try 210,000 pounds of nopalitos.

There are, of course, some risks. The lack of spines makes the plants easy pickings for roaming javelinas and deer. And, unlike other varieties of cactus, the 1308 doesn't stop growing to protect itself when a cold front hits, so it's vulnerable to sudden temperature dips.

Unjust Deserts?

And marketing has also been thorny. Last year's effort to sell the vegetable, Mr. Felker concedes, could have been handled better. The entrepreneurs first erred by selling their nopalitos only in 20-pound bags. The bulk strategy was fine for connoisseurs, such as restaurants, but hardly appealed to the larger market that Mr. Felker and the farmers hoped to capture.

There also wasn't any packaging to speak of—just a nondescript box. Again, hardly conducive to high sales volume.

"It was my fault," Mr. Felker concedes. "They just didn't move. We were outsold 200-to-1 by the sliced-and-diced stuff. Ours were just wilting on the shelf." (Mr. Felker advises the farmers, but isn't a business partner.)

So, this year, Messrs. Bippert, Wagner and Felker are prepared. Armed with a total of $100,000 in grants from the U.S. Department of Agriculture, Texas Legislature and the Kingsville-based Caesar Kleberg Wildlife Research Institute, they're redesigning their packaging. This year's crop will be available in one-pound bags—with bright yellow and green stickers—that feature stir-fry and fajita recipes.

And the team is working on brand extensions. Mr. Bippert's sister developed a pickled nopalito in kosher dill and bread-and-butter flavors that are currently being sold in airport gift shops. The farmers view the pickled nopalitos as an easy sell for such specialty markets: They're reasonably cheap (between $8 and $14 for a one-quart jar), and don't involve the emotional commitment of cooking.

Rick Martin, a former Navy pilot who markets exotic meats from Kingsville, is helping the team get their wares into stores. He says that until consumers get better acquainted with the 1308, selling the nopalito will require a lot of legwork. "It's a sample-intensive operation," he says.

But over the long haul, says Mr. Felker, there's reason to be optimistic. "We have a real opportunity," he says. "You don't have to be a rocket scientist to know that this is the nopalito you want to use."

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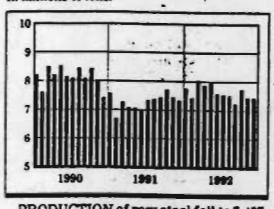
Steel Production

In millions of tons.



PRODUCTION of raw steel fell to 7,437,829 tons in December from 7,449,192 tons in November, the American Iron and Steel Institute reports.

Thorny Question: Will the Prickly Pear Be Kiwi of the '90s?

* * *

The Cactus and Its Fruit Have Many Possible Uses as Food But Some Nasty Drawbacks

By ROBERT JOHNSON
Staff Reporter of THE WALL STREET JOURNAL

KINGSVILLE, Texas – At first glance, the prickly pear cactus seems to be the forbidden fruit. Eat of it at your own risk.

For starters, it grows about as far from paradise as possible: in parched, rocky terrain that is home to the javelina – a kind of wild boar uniquely capable of chomping though the prickly pear's vicious spines. For human beings, making the cactus user-friendly often takes a flamethrower, to burn off the spikes. But the cactus paddles make for good eating, as does the fruit, which resembles a hand grenade and contains big seeds that look like lead shot.

"This is the next kiwi fruit if we can improve its image," says Karen Caplan, a produce distributor in Los Angeles. Thus, she says, "We don't call it 'prickly' anymore, just cactus pear."

Still Obscure

But the prickly pear cactus is still rather obscure. You certainly won't find cactus pear recipes in the Better Homes and Gardens cookbook. The farmers who call themselves the Texas Prickly Pear Council have had to put out their own pamphlet with instructions for preparing cactus jelly and prickly pear punch.

But the prickly's pear's popularity is growing. Imports from Mexico and South America of the list-size, five-ounce fruit – whose taste has been compared to honeydew melon – rose 51% from 1987 to 1989, to 2.7 million pounds. U.S. farmers are planting hundreds of acres from California to Texas. Although that hardly makes it a staple, the fruit of the prickly pear cactus does fetch prices comparable to kiwi

Prickly Pear Cactus

fruit – about $2 a pound – in those few supermarkets that stock it.

Produce buyers for stores say they could probably sell more of it if it didn't come in so many confusing shades of red, pink, yellow and green – defying shoppers to tell whether it is ripe. Says Dianna Howard, who makes and sells prickly pear jelly: "There's a tendency for people to buy prickly pear because it sounds like fun and then let it rot because they can't figure out what to do with it."

The fruit can be eaten sliced and unadorned, or in a range of processed prickly pear products that even includes a margarita cocktail mix.

But the prickly part is the problem. The inch-long spines that they blast off at harvest time readily draw blood, but a second, nearly invisible set of stickers called glochids lurk to stab those who would go too near the prickly pear in the produce department. Glochids are sharp at both ends. Dr. Peter Felker, a plant physiologist at Texas A&I University here who has studied the prickly pear cactus under a $100,000 federal grant, recommends re-

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Thorny Question: Will the Prickly Pear Be Kiwi of the '90s?

Continued From First Page

moving them from your skin with tweezers. Use your teeth and they are likely to stick in your tongue, and that really smarts, he says.

Dr. Felker, a slender, 45-year-old former U.S. Army agricultural adviser to Vietnamese rice farmers in the Mekong Delta, says he goes through a pair of gloves a week tending the 70 varieties of prickly pear he has growing on four acres at Texas A&I. "Gloves of thick cotton, leather and asbestos – these spines punch through anything," he says.

But Dr. Felker is a fan, who sees considerable potential in the nettlesome desert plants. "They will grow anywhere. They could be providing food for the hungry in arid regions such as Somalia," he says.

The prickly pear cactus, with its split personality, sprouts both an edible fruit – from the flower – and a nutritious vegetable in its paddle-like leaves. The fruit is packed with vitamin C and calcium and the cactus paddle, with a taste not unlike bell pepper but with a slightly slimy mouthfeel, is great in salads.

An About-Face

But the cactus – fruit and vegetable – is dismissed as a mere novelty by the Department of Agriculture. Indeed, until just a few years ago, the prickly pear cactus was considered such a nuisance in the U.S. that most domestic cactus research was aimed at finding better ways to eradicate it.

Says Robert Mick, a Texas farmer who recently planted 15 acres of prickly pear next to his 2,000 acres of sorghum and cotton: "My grandfather worked to clear this land of cactus 80 years ago. And I would have thought you were crazy to suggest planting it until I realized that people today are willing to pay good money for it. Times change."

Mary Mahaffey, who distributes produce to fancy restaurants in Austin, says she can't get enough prickly pear. "It's a comer with the high-end chefs," she says. But Ms. Mahaffey says grocery-store shoppers are still put off by the prickly pear. "This is a strange-looking thing to eat – bumpy outside even with the spines off and then those seeds. Please."

But cactus pears are worth the effort, says Dianna Howard, who packed and sold 4,000 jars of pear jelly last year for customers as far away as Japan, doubling her sales from 1991. At $7.00 for a 10-ounce jar, the product is something of a luxury item.

With a Name Like Smuckers

The price could come down if sales increased, but is prickly pear jelly good enough for the J.M. Smucker Co. market? Rumors abound among cactus suppliers that the jelly and jam giant based in Orrville, Ohio, has been scouting around for supplies before it introduces prickly pear preserves. A Smuckers spokesman denies the company is cooking up any cactus concoctions, but adds, "I wouldn't tell you if we were."

In any event, Texans aren't waiting for big business to take the plunge into the cactus patch. Laurie Harrel, who owns a drugstore in Kingsville, is peddling "Truly Texas" brand cactus salsa. "You can taste a sample," she says, plopping some on a cracker with cream cheese, "but I'm sold out and there are a dozen people on my waiting list."

To wash such treats down, you might try a prickly pear margarita. The increasingly popular recipe for the drink calls for marinating the fruit in two or three ounces of tequila for three days. "You need that long to turn the golden-colored liquor just the right shade of deep red and to let the flavor develop," says Monica Marvin, manager of Zuni's, a restaurant on the Riverwalk in San Antonio. She says Zuni's is selling more than 1,000 of the cactus drinks a week, at $8 each.

All of which seems like quite a stretch for a plant Christopher Columbus discovered in 1492 and tried to pass off in Spain as evidence that he had found India. He called prickly pears Indian figs, and they're still called that in Italy.

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Opuntia forage production and utilization

Peter Felker

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A Review for an FAO Textbook.

Introduction

There are a number of excellent regional reviews covering the uses of cactus for forage in North Africa (Monjauze and LeHouerou, 1965), South Africa (DeKock, 1980; Wessels, 1988), Mexico (Flores-Valdez and Aguirre-Rivera 1979, Fuentes-Rodriguez, 1991, Borrego-Escalente and Burgos-Vazquez, 1986), Brazil (Domingues, 1963), and the United States (Russell and Felker, 1988; Hanselka and Paschal, 1989; Felker, 1990, 1991, 1992). Much of this stemmed from Griffith's (1905, 1906, 1908, 1915) classic work at the turn of the century in Texas.

Rather than review the historical accounts of uses throughout the world, an attempt will be made to synthesize the experiences of the various time periods and regions into common recommendations for use and management. Research recommendations will also be made to significantly improve the utilization of cactus for livestock feed.

<u>Opuntia</u> is particularly attractive as a feed because of its high efficiency in converting water to dry matter and thus digestible energy- see Nobel this volume. Cactus is not just useful because it can withstand drought, but because its conversion efficiency is greater than C3 grasses and C4 broadleaves.

Opuntia has been successfully fed to dairy and beef cattle, oxen, sheep and hogs if extreme care is taken to remove all the spines but not horses (Griffiths, 1905). Due to the extreme predation of spineless Opuntia by rabbits it would appear possible to use spineless Opuntia in the diets of rabbits and possibly other small rodents. In India, parrots cause serious damage to spineless Opuntias by eating away the margins of the cladodes (Felker, unpub obs.).

Despite the overall favorable use of cacti for stock, there have been some problems. While cactus is highly valued for livestock in southern Texas, in northwest Texas where the rainfall is lower and the cactus are smaller there have been problems. In northwestern Texas, sheep and goats begin eating the fruits and then cladodes of the cactus without the spines being burned off. As a result spines and glochids become lodged in their gastrointestinal tracts and bacterial infections of these lesions may follow (Merrill, et al., 1980; Migaki et al., 1969).

In contrast there are about 300,000 ha of spineless cacti being grown in the semi-arid region of northeastern Brazil for livestock feed (Domingues, 1963). In the spring of 1993, Felker observed that due to the drought the maize crop did not emerge from the soil. In contrast about every 10 km there was a 2- 10 ha plantation of spineless cacti that was alive and growing.

In Brazil plantations of spineless cacti in Brazil are protected by only a standard 1.2 m tall wire or wooden fence. In contrast in Texas and northern Mexico spineless plantations must be extremely well protected (2.4 m tall netwire fence with 5 cm mesh at the bottom) against herbivory from rabbits, rats, and wildlife especially deer and peccaries. In other countries goats, sheep, cattle and camels could be expected to be a major problem. Possibly by use of portable electric fences, it would be possible to allow stock to graze one row of a spineless cactus plantation at a time.

In contrast to the need to protect the spineless plantations, the spiny types do not require fencing. However they must have their spines singed off with a flame thrower (pear burner in Texas) before being fed to cattle or sheep. Thus the flame thrower is the management tool that allows the rancher to decide when and how much of this resource to use at a given time.

Wild spiny cactus are below the U.S. National Research Council cattle requirements for protein but in excess for Ca. Cactus are high in percentage of Total Digestible Nutrients (about 60-70 %) and water. The water requirements of cattle and sheep are greatly decreased when prickly pear constitutes a major part of the diet.

Due to the low percentage of crude protein and certain mineral nutrients it has been necessary to supplement with protein and trace elements. Generally about 1 kg of 40 % protein cottonseed cake, 0.4 kg of a balanced mineral salt mixture and 45 kg of cactus leaves will provide a ration on which cattle can grow, reproduce and lactate. Dried forages have also been added to this diet to reduce the moisture content of the fecal matter.

Historical Uses of Cactus for forage

"Nopal or common prickly pear which grows so abundantly on our western prairies is becoming valuable as food for stock... poor sheep will fatten on it in 12 days and they eat it with relish... He cuts the pear, burns the thorns off over a brush fire and chops it in pieces .. and feeds it to his sheep in long narrow troughs. Two or three pounds a day is sufficient for sheep. Two wagonloads of nopal will feed 2,000 sheep.. Two men can feed several thousand head. Corpus Christi [Texas] Caller Times, March 22, 1883. (cited in Lehman, V. 1969).

The literature on the uses of cactus by livestock is most colorful. During the U.S. Civil War, freighters loaded with cotton were pulled by oxen to the only safe port of export at the southern tip of Texas (Brownsville). The route passed through extensive stands of spiny Opuntia. The teamsters

scorched the cactus by burning with brush, and chopped or slashed it with an ax, spade or machete to feed to their oxen (Griffiths, 1905). Due to the high water content of the cactus, the oxen only had to drink water only once a week in the winter and 2 to 3 times a week in the summer.

In early part of century pressurized, backpack, white gasoline pear burners were used in Texas to singe the spines from prickly pear so that cattle would eat it (Pluenneke, 1990). Kerosene became available in the 1930's and replaced "white gasoline". In the 1950's butane gas became available in South Texas. The liquid propane gas was then placed in pickup trucks, and rigs with multiple hoses (Pluenneke, 1990).

Spineless cactus were introduced into South Africa for livestock feed following Burbanks work in California (DeKock, 1980). South Africans distinguish between the green leaf varieties i.e. Opuntia ficus-indica and the blue leafed O. robusta varieties. There are 3 recognized cultivars of the blue leafed (O. robusta) variety Robusta, Monterrey and Chico. Robusta and Monterrey produce the highest yields while Chico is more cold resistant[However all 3 varieties froze to ground level in Texas during a -12 freeze of Christmas 1989].

Productivity of cactus for forage

There has been a great deal of data published in the literature on the productivity of cactus for forage, some with very high yields. However much of this data was not obtained in replicated field trials with adequate control over the influences of border effects. Accordingly, great caution should be used in relying on these results for economic development projects. While there is little that can be done for trials that have already been completed, future trials should employ the following guidelines (1) each plot should be replicated minimum of 3 (and preferably 4) times, (2) the data used to extrapolate per hectare yields should be from the interior of the plot surrounded by a minimum of 2 border or guard rows around each side of the sample plot, (3) the methods to determine the dry weight should be reported. Due to the difficulty in drying Opuntia it is important to know the drying time, the drying temperature and whether the samples were weighed until a constant weight was obtained. If only the fresh weight was reported, a dry weight percentage ranging from 6-17% could be used to obtain the dry weight.

The very high Opuntia forage productivity rates i.e. > 80 metric/tons/ha-year obtained in small (<100 m^2) hand weeded, fertilized research plots are probably seldom obtained in practice. Probably the greatest single factor affecting productivity of Opuntia in forage plantations is the presence of competing vegetation i.e. weeds. Felker and Russell

(1988), have measured a 300 % increase in the productivity of Opuntia lindheimerii when cultivation plus herbicides were used for weed control. In a 1993 Brazilian field trip during a severe drought, newly planted spineless cacti and those with little vegetation between the rows had turgid new growth. In contrast those with much herbaceous and woody vegetation between the rows had little new growth and the existing cladodes were flaccid.

In Texas research plots a 1.5-2.0 % solution of glyphosate (Roundup) was used to kill existing weeds and the preemergence herbicide tebuthiuron was used (@ 2-4 kg/ha) to prevent new weeds from emerging. Tebuthiuron will control weeds for several years at this rate. Tebuthiuron is very toxic to trees i.e. Acacia, Prosopis and Quercus and cannot be used where it is desirable to grow both trees and cacti.

In developing countries where use of herbicides is not possible, cactus could be grown on spacings wide enough to permit animal drawn cultivation or intercropping. Griffiths (1908) describes animal drawn cultivation and notes uncultivated fields were withered during a severe drought, while cultivated plots had no visual signs of water stress. Apparently intercrops uses considerably less water than weeds due to the fact that intercrops normally are only grown for 90- 120 days and the fact that intercrops usually only use substantial amounts of water during the last third of their

cycle when the leaf area index is high. Obviously if spiny Opuntias are grown for forage, it is possible to let cattle eliminate the competing herbaceous vegetation.

Having pointed out the practical difficulties in capturing the full productivity possible with cacti, it is useful to review the maximum production rates for forage Opuntias that have been obtained in research settings. Barrientos (1965) developed a special forage clone designated COPENA F-1 whose productivity was examined at various spacings near Mexico City. When a spacing of 1 m x 0.25 m was used with 100 tons of cow manure, 200 kg N/ha and 2 harvests/year a fresh weight of 400 tons/year was obtained. The dry weight would probably be about 40 metric tons/ha-yr. Unfortunately the full experimental details of this trial are not available. Another study from Mexico (Blanco, 1957) recommended harvesting not more than 40 % of the plant for each harvest and allowing 2 years between harvests. Blanco (1957) stated that the yield ranged from 100 to 200 tons fresh weight/yr (about 10-20 tons dry weight).

There is replicated productivity data for a trial in which Gonzalez (1989) examined 8 fertilization treatments ranging from 0,0,0 kg/ha to 224 kg N & 112 Kg P/ha on the spiny Texas native O. lindheimerii. They planted cuttings with 2-3 cladodes at a spacing of 102 cm by 46 cm. The plots were 12 m by 12 m and were replicated 4 times. Mean annual rainfall was

430 mm. The growth was slow the first 2 years but at the end of the 4th year, the dry biomass from the high N&P plots were 208 metric ton/ha and 248 metric ton/ha or an annual rate of 52 metric ton/ha or 62 metric ton/ha. Clearly these growth rates are comparable to any other forage species at this level of rainfall. Even these productivities seem unusually high and it is possible that at the end of 4 years, the cacti were large enough to create a substantial border effect. When a 3.3 m long "typical" portion of a 5 year old unfertilized 50 ha O. lindheimerii plantation was harvested, it was found to contain 96,000 kg/ha fresh weight (Kay and Kay, 1990). Although this is a much lower productivity, it was estimated to be worth $434 in feeding value (Kay and Kay, 1990).

In South Africa, DeKock (1980) found that spineless cactus responded exceptionally well to a single irrigations during summer months. They obtained 10,500 kg of dry matter with a 305 mm irrigation plus 178 mm rainfall for a total water input of 483 mm.

Environmental constraints to cactus forage production

It is important to recognize that the central plateau of Mexico, which is probably the origin for the fast-growing spiny and spineless cactus, does not experience extremes of high or low temperature. Temperatures seldom reach 40 C or

-12 C in these regions. Certainly adaptation of the spineless O. ficus-indica and O. robusta varieties to Texas and other continental climates is not possible due to lack of tolerance to sustained time periods (10-20 hr) below temperatures of -7 C. The spineless O. ellisiana described by Griffith (1915) is completely tolerant to 20 hr below -7 C with a minimum of -16 C. Unfortunately this spineless species is much slower growing than O. ficus-indica or O. robusta. In 1993, the first 2 years of a 4 year biomass productivity/water use efficiency field trial of O. ellisiana was completed. The first years dry biomass was only 1,600 kg/ha but the dry biomass at the end of the second year was 6500 kg/ha. Since the leaf area index at the end of the second year was only 0.39, a high biomass productivity was not expected (Huien, 1993).

Surprisingly cold-hardy, albeit very small Opuntia polyacantha has provided significant source of forage to pronghorn antelope in Alberta, Canada after lightning created grass fires that burned the spines off the cacti(Stelfox and Friend, 1977). This indicates the potential for forage production from cacti for much of the worlds semi-arid regions with breeding and management.

It is not known how well the fast-growing spineless Opuntia's will tolerate continued high temperatures and low humidity levels of Sahelian conditions such as in Niamey, Niger or

Khartoum, Sudan where mean daily maximum temperatures for the month of April are 42 C and 40.5 C respectively. Field trials with diverse genetic collections are the only way to answer these questions. Should it be possible to produce forage cactus in Sahelian Africa, the benefits for this extremely destitute and frequently drought stricken region would be immense.

Cactus as a source of energy, water, protein, minerals and vitamins

A number of workers have examined the nutritional quality of *Opuntia* for use in animal diets (Griffiths and Hare, 1906; Shoop et al., 1977, DeKock, 1980; Meyer and Brown, 1985; and Retamal et al., 1987). In general *Opuntia* has been felt to be high in moisture content (about 85%), high in *in vitro* digestibility (about 75 %) but low in protein.

While there is substantial data on the protein and mineral contents of *Opuntia* being used to produce fruit, there is surprisingly little digestibility or metabolizable energy data to assist in formulating animal rations. The protein and mineral data from fruit plantations exhibits marked variation according to the age of the plant (Gregory and Felker, 1992; the fertility of the soil (Gonzalez, 1989; Gathaara et al., 1989) and the season of the year (Retamal et al., 1987).

From an animal nutritionist point of view, other frequently overlooked advantages of Opuntia are the relatively high "vitamin A" content and the high water content[There is little data on the carotenoid precursor concentration in the animal literature but Rodriguez-Felix and Cantwell, 1988 reported 29 ug of carotenoids and 13 mg of ascorbic acid per 100 g of immature cladodes used for human consumption]. For example in South Africa, sheep did not have to drink water due to the high water content of the Opuntia. Where water is scarce in drought prone semi-arid regions, the water in the cactus could be most beneficial. While Opuntia is not particularly high in Vitamin A precursors compared to alfalfa, fertilized bermuda grass, etc. it is often the only source of green dry matter in drought periods. Thus plants that normally would be green during the rainy season are brown and desiccated in the dry season. It is at this time, that Opuntia with a normal content of vitamin A precursor and high water content is a welcome addition to the diet of domestic stock.

The amino acid profile of the Opuntia stems are not particularly important if they are to be fed to ruminants, since the ruminant microorganisms can synthesize the required amino acids. If however the Opuntia stems were to be fed to non-ruminants or humans, the amino acid composition of the protein would be of interest. Teles et al., (1984) found that the free plus hydrolyzable amino acid composition of immature

Opuntia stems had a biological value of 72 compared to egg as 100.

Unfortunately there is very little quantitative data on the metabolizable energy, in vitro or in vivo digestibility of Opuntia for use use in animal studies. The metabolizable energy and digestibility data that exists is primarily for wild Opuntia in Texas and Colorado and not for O. ficus-indica that is so widely used in the semi-arid tropics. Although Everitt and Gonzalez, (1981) found that O. lindheimerii in Texas had one of the lowest protein contents (6%) of numerous range species, it had the highest dry matter digestibility (76%) of all the species examined. The high digestibility was confirmed by Meyer and Brown (1985) who found that O. lindheimerii had higher digestibility (75%) throughout the year than the other 9 plants in their study.

Shoop et al., (1977) conducted a comprehensive forage analysis of the small Opuntia polyacantha that occurs on the ranges of Colorado. While the Opuntia was lower in crude protein (5.3%) than grassland hay (5.7%) or alfalfa hay (16.8%), it had equivalent digestible energy (2.61 Mcal/kg) to grassland hay (2.08 Mcal/kg) and alfalfa hay (2.64 Mcal/kg). As compared to alfalfa hay, O. polyacantha had 85 % as much neutral detergent fiber, 70 % as much acid detergent fiber and 15 % as much cellulose, but it contained 55 % more hemicellulose and 40 % more soluble carbohydrates than

alfalfa. It should be pointed out that O. polyacantha is a completely unselected species and it would be extremely useful to obtain similar data the much faster growing and more widely used Opuntia ficus indica and related species.

Woodward et al., (1915) conducted a comprehensive two year study on the value of spiny Texas native cactus as a feed for dairy cattle. Due to the early period of this work the energy (therms) and protein (albuminoid) measurements are different than in use today. In this case the spines were burnt with a gasoline torch and the cactus chopped by hand. Jersey milk cows were fed from 45 kg to 68 kg/day with 1 kg of cottonseed meal. The prickly pear caused an increase in the quantity of milk produced and a decrease in the percentage and total amount of fat. Analyses of the fecal matter indicated the digestibility of the prickly pear was 62 % for dry matter, 38 % for ash, 72 % for crude protein, 43 % for crude fiber, 72 % for nitrogen free extract, 66 % for ether extract and 67 % for organic matter. Prickly pear produced a highly colored butter but no effect on the flavor or keeping quality. Prickly pear had a laxative effect on the cattle, especially at the higher feeding rates (i.e. 68 kg/day). Addition of common salt (NaCl) did not reduce the laxative effects. They recommended feeding moderate quantities (27 kg to 34 kg/day) since large quantities (54 to 68 kg/day) caused excessive scouring and unsanitary conditions in the milking parlor.

One of the few studies that provides energy values for spineless Opuntia ficus-indica is that of Retamal et al., (1987). These authors examined the content of O. ficus-indica proteins, minerals, ether extract, crude fiber and energy as a function of developmental stages at various times throughout the year. The energy values changed little throughout the year with values ranging from 14,000 to 14,900 kJ/kg dry weight.

Supplements for use with cactus to balance minerals and protein and reduce scours.

Since the primary attribute of cactus is its high digestible energy value and its high water content, it is necessary to balance the ration for protein and minerals.

Fuentes-Rodriguez (1991) surveyed 7 dairies in northern Mexico with a total of 447 cattle. The average amount of prickly pear consumed per day was 25.7 kg and the average milk production was 15.4 kg/day. For all the dairies the prickly pear was burned and chopped and supplemented with corn stover. Three of the dairies supplemented with milo and 3 supplemented with range and/or alfalfa. Prickly pear was commonly fed in the winter from January to May. While these production figures are quite low, they were obtained on communal production units (ejidos) with very limited resources.

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To reduce the high water content of the fecal matter, commonly known as scours, Griffiths (1906) recommended supplementing prickly pear with sorghum hay.

In a South African study (DeKock, 1980) spineless O. robusta varieties were being fed to sheep. Unfortunately they were so low in crude protein (4 %) that the sheep would have had to eat 5 to 6 kg of cactus/day. Since they could only ingest 4 kg of cactus/day, due to volume considerations, it was necessary to provide supplements. Thus DeKock (1980) supplemented the sheep diets with equal portions of bonemeal, NaCl, and biuret. However they found the best supplement for sheep to be 100 g of lucerne hay per day with spineless cactus fed ad libitum.

Griffiths (1905) reported that over a one and a half year period, 230 hogs were given a daily ration of 1363 kg of prickly pear and 2.5 barrels (ca 200 liters) of meat and bread scraps. In addition for the entire 1.5 year period they were fed 400 bushels (ca 10,000 kg) of corn. However, it was necessary to take extreme care to remove all of the spines since about 1/2 % of the hogs were killed by the spines.

With over several hundred ha of native spiny cactus been planted and utilized for emergency drought feed, Maltsberger, (1991) has had some of the most extensive experience in feeding cactus to cattle. Although Maltsberger routinely

supplemented cactus with cottonseed meal and allowed the cattle free range, there was subtle evidence of other problems. After considerable testing of blood and tissues of cattle for micronutrients, Maltsberger (1991) found that his cattle were low in copper, molybdenum and zinc. Based on these analyses, Maltsberger began using a mineral supplement of the following composition; Steamed bonemeal 454 kg, meat and bonemeal 150 kg, NaCl 280 kg, $ZnSO_4$ 12 kg, $CuSO_4$ 5.4 kg, Ethylenediamine dihydriodide 0.09 kg, and $CoSO_4$ 0.045 kg for a total of 901 kg. This supplementation seemed to reduce considerable abnormalities in new-born calves. Maltsberger(1993 pers. comm.) feels that the mineral deficiencies in the animals are not caused directly by the cactus, but are a result of the cattle going for many months without any other herbaceous or woody forage. Regular vitamin E injections have also been helpful after many months on this cactus diet.

Techniques to increase the protein content of cactus forage

There are 3 ways in which the protein content of the cactus can be increased, thus reducing the need for protein supplementation. The first method is use of N & P fertilizers. Gonzalez (1989) found that the crude protein went from 4.5 % for the zero fertility treatment to 10.5 % for the 224 kg N/ha and 112 kg P/ha treatment. Since the protein requirements for a dry cow and lactating cow are 6 %

and 9.25 % respectively, the fertilizer treatment raised the protein level above the requirements for a lactating cow. Unfortunately the % P only increased from 0.08 % to 0.18 % which is barely adequate for a dry cow. In contrast the requirement for a lactating cow was 0.39 %. The Ca, K, and Mg concentrations of 4.2 %, 2.3 % and 1.4 % exceeded beef cattle requirements of 0.44 %, 0.8 % and 0.18 % respectively. In addition high levels of N&P fertilizer increased yields from about 7 metric ton dry matter/ha-yr to about 60 Mg metric ton dry matter/ha-yr. Foliar urea applications have also been shown to increase the N content of Opuntia cladodes (Belasco et al., 1958).

The second technique to increase the phosphorus and protein content of the cattle forage is through clones that have greater nutrient contents. Gregory and Felker (1992) examined 8 forage clones and found that forage clones from Brazil had over 11 % protein over all 4 age classes, while the Texas native Opuntia forage had only 7.1 % protein averaged over all age classes. It was also significant that the Brazilian high protein clone also had a P content of 0.41 % which was over 4 times greater than the P content of the Texas native species. Even when the native Opuntia was fertilized with 224 kg of N/ha and 112 kg of P/ha, the native Opuntia only had a P content of 0.20 %.

The third possibility for increasing the protein content of Opuntia for forage is through inoculation with free-living nitrogen fixing bacteria associated with cactus roots belonging to Azospirillum (Rao and Venkateswarlu, 1982). Cabellero-Mellado (1990) and Mascarua-Esparza et al., (1988) has shown that inoculation with this bacteria caused a 34 percent increase in the cactus root dry weight, and a 63 percent increase in the nitrogen content of the roots. While they did not measure the total N of the Opuntia with and without Azospirillum, they demonstrated an 86 % increase in total N/plant over maize plants without Azospirillum inoculation. Not only was the Azospirillum useful in increasing root volume and root N but also in preventing disease. In laboratory culture media, Azospirillum inhibited growth of pathenogenic bacteria such as Xanthomonas, Erwinia and Agrobacterium tumefaciens.

Processing of cacti-pear burning, chopping, chaffing and silage

The enormous water content of Opuntia (about 85 %) makes it prohibitively expensive to transport it for long distances. Thus cactus is usually used in place by burning off the spines and allowing the livestock to come to the cactus rather than vice versa. "Pear burning" has played such an important role in Texas in relieving drought that the U.S.

federal government has added propane to be considered for payment in lieu of relief emergency government feed.

Maltsberger (1989) has found that one gallon of propane will feed from 3 to 5 cows depending on weather and the size of the calves. In warm dry weather a good man could burn enough for 200 cow units in a day but a cold, wet day would require more time and propane. Before freezing weather Maltsberger (1989) recommended supplementing with greater quantities of energy feeds. Maltsberger recommended to always burn more than the cattle would eat till the next feeding. He recommended not over-utilizing the resource by leaving at least one joint above the stump coming out of the ground. Prime prickly pear was judged to be 5 -8 year old cactus from plantings or 4 -7 year regrowth from stumps.

Howell (1989) stressed the need to not overcook the pear, but also the importance of removing the spines on both sides of the pad. Due to the danger of utilizing propane under pressure and long hoses in the proximity of hungry cattle and thorn scrub, Howell (1989) stated the importance of using good hoses, regulators and not overfilling the propane tanks.

Kay and Kay, (1990) determined the economics of burning pear in a 5 year old cactus plantation with 96,000 kg/ha of fresh weight. These authors determined that 15.1 liters of propane @ $ 0.18/liter were required for 14 cows/day and that 8

man-hour @ $3.65/hr were required to prepare feed for 200 cattle/day. The cactus ration contained 50 kg of cactus, 1.36 kg cottonseed meal and 0.091 kg of salt/meat/bone meal. Using a commercial least cost ration analysis they computed the value of the prickly pear to be $0.010/kg which at 96,000 kg/ha would be equal to $960/ha for 5 years of growth. Paschal (1989) reported that a Texas Agricultural Extension Service survey found that 20 % of ranchers burned pear and that the average cost of the feed was $0.22 per head/day.

The labor and fuel costs to burn spiny cactus is greatly reduced by planting the cactus in rows as described by Plunneke (1990). In this way one does not have to walk through the brush, from cactus bush to cactus bush, turning on and off the burner.

Even when the cactus is burned in rows, there is considerable waste as the cattle knock over and step on burned portions of cactus. For this reason as well as the need to take forage to penned groups of mother cows and young calves in beef operations (Maltsberger, 1989, 1991) and dairies (Fuentes-Rodgiguez, 1991), cactus has been harvested and taken to the animals. In Texas the spiny plants were severed in the field with a hand tool, loaded onto a truck by hand, and brought back to a central location where the cactus was windrowed into 2 m tall piles and then the spines burned off. The cactus was then hand fed to a tractor powered ensilage

chopper. The chopped cactus was then placed in troughs and fresh cotton seed meal placed on it.

In northern Mexico (Fuentes-Rodriquez, 1991) motorized choppers were used at all 7 dairies surveyed in order to process the cactus before being fed to milk cows. In South Africa (DeKock, 1980) the cactus was mechanically chopped into 20 by 30 mm strips and fed to sheep in troughs, thus reducing the waste of allowing the sheep to come into the plantation. These strips were also allowed to dry and ground in a hammermill through a 6 mm sieve. This facilitated storage during droughts.

To facilitate storage, spineless cactus has been converted into silage by chaffing the pads of spineless O. robusta with oat straw, low grade lucerne hay on the basis of 84 parts spineless cactus to 16 parts roughage and 2 parts molasses (DeKock, 1980). In Mexico, grain sorghum and a urea-molasses mix were found to be the best additives for prickly pear silage production (Castra et al., 1977).

It would be useful if a self-propelled or tractor pulled ensilage harvester could be adapted to harvest, chop and blow the spiny cactus into a wagon pulled behind. There has been some feeling that after cactus has been processed through an ensilage harvester the spines are sufficiently modified as to not be a problem for cattle. However as noted above,

Maltsberger burns the spines from the cactus before chopping it. Clearly it would be beneficial if cactus could be severed and chopped in the field and brought back to a central location where it could be more efficiently mixed with protein and mineral supplements.

While cactus has been successfully chopped by hand feeding to ensilage choppers, the cactus is probably too thick and tough for conventional forage harvesters too sever the main stem. It is also necessary to greatly reduce the pressure on the feed rollers of ensilage harvesters to avoid totally squashing the cactus before it makes contact with the chopping blades(Felker, unpub. obs). Perhaps rotary disk mower conditioners, which can cut more difficult material, could be used to sever and windrow cactus in the field. After 4-6 weeks when the cactus was partially dry, it would be useful if a modified forage harvester could move down the rows, pick up the dried cactus, chop it and blow it into a wagon. This would be a very useful development project for a national research team.

Economic implications of using cactus for livestock feed.

Long droughts of uncertain duration are a certainty in semi-arid regions. As the drought proceeds, forage from grass and forbs becomes less and less available. At the same time prices of hay and feed grains increase, while the prices of

cattle drop. Ranchers try to hold on for one more day, week or month hoping for rain before the necessity to sell off the cattle at prices below cost. After a prolonged drought the cattle population is low as many ranchers have sold cattle at a loss. When the rains finally come and grass production is abundant, the rancher's desire to buy cattle to restock the ranges drives the price of cattle up. Thus the rancher has to "sell low and buy high".

We have seen that with management 100,000 kg of fresh cactus/ha can be obtained after 4-6 years. With a daily consumption of 50 kg/day, one ha with 100,000 kg would provide a reserve of 2,000 animal days of feed (5.5 animals/year). Thus reserves of cactus could avoid the economic losses associated with selling cattle during a drought. There would also be the opportunity to plant cactus without having cattle, purchase cattle in the middle a drought at low prices and then sell the cattle at the end of the drought at higher prices.

Need for testing Opuntias in Sahelian Africa and the Indian subcontinent.

While there are major reviews on the use of *Opuntia* for animal feed in north Africa (Monjauze and LeHouerou, 1965) and South Africa (DeKock, 1980), there is a disturbing and conspicuously absence of information about the use of *Opuntia*

in the Sahelian Zone of Africa. Perhaps Opuntia cultivation has been attempted and failed. Perhaps the long dry seasons and low humidity levels make CAM metabolism non-functional in Sahelian Africa. Perhaps the similar appearance of spineless Opuntias to Euphorbia tirucalli whose milky latex may cause blindness if inadvertently gotten in the eyes makes people unwilling to try forage cactus species.

Felker has seen Opuntia in dry regions of Kenya but it is forbidden to import cactus to Kenya. Without a lack of proper supervision, this is probably an excellent rule. However, due to the extreme palatability of spineless cactus to livestock it is highly unlikely that it could spread rapidly in semi-arid Africa. Certainly the spiny ones should only be examined under careful supervision for at least 10 years.

Summary: Cacti have been an extremely useful livestock forage in times of drought, primarily by providing digestible energy, water and vitamin A. It is necessary to supplement cactus with both protein and minerals to balance the diet for cattle. The vast majority of the livestock uses of cactus have been for cattle, but it has also been used for pigs. Spineless cactus have been used for forage but they must be protected extremely well against herbivory from domestic stock and wildlife. Spiny types are more cold-hardy, slower growing, do not have to be protected against herbivory but it

is necessary to burn the spines before being used for livestock food.

While cacti have been critically important in maintaining livestock populations during drought, the use and management of cacti for forage has not received serious attention from any research center in the world. Five to ten years of serious R&D in a well-focused program could dramatically improve the well being of livestock producers in both the developed world (USA, Mexico, Brazil) as well as the extremely destitute semi-arid regions of the Sahel, southern Africa and the Indian subcontinent. The following priority research areas are critically needed;

Research needs:

(1) Evaluate a broadbased genetic collection of useful forage cacti, under strict quarantine conditions, in representative semi-arid regions of Sahelian Africa and the Indian subcontinent.

(2) Examine genetic potential for high protein concentration in cactus.

(3) Develop better planting, weeding, herbicide, fertilization packages for use with improved Opuntia forage

clones for scenarios with and without herbicides and tractor drawn cultivation.

(4) Measure the influence of Azospirillum on the growth rates and crude protein contents of several Opuntia forage clones in the field.

(5) Develop a machine capable of severing, chopping and blowing chopped cactus into a trailer.

(6) Reexamine the influence of trace mineral and various kinds of protein supplements on livestock weight gain in different sociological and ecological conditions.

(7) Develop rations for feeding cactus to non-ruminants such as pigs and rabbits.

(8) Legitimize the study of the applied uses of cacti in undergraduate and graduate curricula of major universities.

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Correlations between cactus pear (Opuntia spp.) cladode nutrient concentrations and fruit yield and quality.

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Abstract

A non-irrigated field trial in Texas examined the influence of N, P, K and micronutrient fertilization on the fruit yield and quality of six Mexican fruit clones i.e. *Opuntia ficus-indica* (accessions 1277, 1376 and 1392), *Opuntia hyptiacantha* (accession 1287), *Opuntia streptacantha* (accession 1281) and *Opuntia megacantha* (accession 1380). A 100 kg ha^{-1} application of N, P, K did not significantly ($p>.05$) influence fruit yield, but it significantly ($p=.024$) increased the fruit sugar (soluble solid) content. Correlation analyses were done between cladode concentrations of N, P, K, Ca, Mg, Na, Fe, Zn, Mn and Cu at the 'whole plant level'. The means of five cladodes per plant versus total fruit yield per plant were used to compute 'whole plant level' and 'individual cladode level' correlations. The Spearman correlation for cladode tissue N concentration and fruit yield was positive ($r=.452$, $p=.034$). Correlation between cladode K concentration and fruit yield was positive ($r=.432$, $p=.044$). Correlation between cladode Na and fruit yield was negative ($r=.443$, $p=.044$). Cladode Mg concentration was correlated with fruit sugar content ($r=0.477$, $p=.024$) at the whole plant level. The optimum Mg content appeared to be 0.22 %. 'Cladode level' correlations were obtained for 5 accessions between paired values of fruit number per cladode and nutrient content per cladode. For K, the 'cladode level' correlation was negative ($p=<.05$) for 2 of the 5 accessions, while the 'whole plant level' correlation was

positive (r=.432, p=.044). The negative 'cladode level' correlation has been attributed to export of large quantities of K from cladodes to fruits. For only two of the five accessions (accession 1294 and 1376), fruit number per cladode was correlated with cladode P concentrations (p=<.05) at 'cladode level'. The relationship between fruit production or quality versus cladode nutrient concentrations were very different for these clones. Apparently it will be necessary to develop individual fruit quality or production relationships for individual cultivars.

Key Words: arid lands, fertility, prickly pear, CAM

Introduction

Cactus pears (Family Cactaceae, genus Opuntia) grow in the semi-arid regions of the world and hold considerable potential for providing fruit, vegetables and fodder (Russell and Felker, 1987). As a CAM plant (Kluge and Ting, 1978) prickly pear has high drought resisting ability and high water use efficiency. Due to high water conservation ability and drought tolerance, prickly pear has been widely used as an emergency livestock feed during extreme drought periods (Hanmante, 1920, Russell and Felker, 1987). The young tender pads of Opuntia and Nopalea, known as nopalitos, have been widely used as a green vegetable in Mexico and Southern Texas (Russell and Felker, 1987). Significant work on cactus fruit quality has been done as early as 1906 (Griffiths and Hare, 1907). The average fruit weight is 111 g, of which 78% is edible. The sugar content of cactus pears is generally about 14 % with no sucrose and the reducing sugars glucose and fructose being present in a 60/40 ratio (Sawaya, et al., 1983). While most cactus pears are consumned fresh, they have also been used in preparation of juice (Griffiths and Hare, 1907), jam (Sawaya et al., 1983) and candy (Nobel, 1988).

Numerous investigations have been conducted on the physiology (Chow et al.,1966; Szarek and Ting, 1973) utilization (Griffiths and Hare, 1907; Hoffman, 1980), economy of production (Griffiths, 1915), animal feeding trials (Griffiths, 1920), effect of herbicides (Felker and Russell, 1988), effects of thinning on fruit production (Barbera et al., 1991) and

fertilizer influences on fruit and biomass production of cactus pear (Nobel et al.,1987; Gathaara et al., 1989; Nerd et al., 1989; Nerd et al., 1993).

Manure application improved Opuntia biomass productivity in Chile (SAG, 1976) and Tunisia (Monjauze and Le Houerou, 1965). Similarly fertilization with N increased biomass production (Nobel et al., 1987) and P application significantly increased fruit production in Texas (Gathaara et al., 1989). Besides N, boron was found significantly correlated with productivity in Mexico (Nobel et al., 1987). Late-summer application of N fertilizer increased floral bud production in Israel (Nerd et al., 1993). Monjauze and Le Houerou (1965) recommended application of 20 to 30 t ha^{-1} of manure, 20 kg ha^{-1} N, and 100 kg ha^{-1} P before planting. In a fertilizer trial in Texas, it was found that total biomass productivity for three years' growth of Opuntia engelmannii Salm-Dick was not correlated with N and P soil applications (Gathaara et al., 1989). In contrast, Gonzalez (1989) reported that N and P application increased total biomass productivity of Opuntia lindheimeri Engelm. approximately five-fold 7 years following planting. This author also reported that N and P fertilization increased the nutritive value of prickly pear.

Correlations between cladode nutrient concentration and fruit yield and quality would be helpful in establishing optimum nutrient levels of prickly pear. Unfortunately little is known about the relationships between cladode elemental nutrient

concentrations and yield of prickly pear. Fruit production was found significantly related to cladode N and P concentration in a native, non-commercial fruit variety (Gathaara et al., 1989). The number of floral buds was highly correlated with soluble reduced-N concentration of cladode in autumn (Nerd et al., 1993).

As fruit productivity from the Opuntia ficus-indica Linnaeus Miller. in our collection was lower than expected, and as the research in Israel (Nerd et al., 1993) indicated a strong influence of N on fruit productivity, we assessed the influence of N, P, K and micronutrients on productivity and fruit quality. Additionally, we sought to develop more definitive relationships between cladode nutrient concentrations and fruit yield/quality.

Materials and methods

The experiment was conducted in a two year old (third growing season) Opuntia plantation of seventy accessions in Kingsville, Texas. Most of the accessions were collected from Mexico but other accessions were obtained from Algeria, Chile, Brazil, New Mexico and Arizona (Gregory et al. (1993).

The predominant soils of the study area were Hidalgo and Palobia series (USDA, 1975). The soil was fine loamy, in the hyperthermic family of Typic calciustolls (USDA, 1978). A total nitrogen content of 540 mg kg^{-1}, sodium bicarbonate extractable phosphorus concentration of 1.3 mg kg^{-1} and a pH of 6.7 was found on immediately adjacent plots (Wightman and Felker, 1990). Mean daily maximum temperatures exceed 30 C from April through October. Mean daily maximum temperatures are 35 C for June and 36

C for July and August (U.S. Dept of Commerce, 1965). In 1993 the following on site precipation was recorded; Jan 14 mm, Feb 43 mm, Mar 61 mm, Apr 87 mm, May 188 mm, Jun 201 mm, Jul 6 mm, Aug 20 mm and Sep 28 mm. The flowering and fruiting period was from late April till late August. This amount of rainfall was above the long term average of 660 mm for the entire year. Approximately 15 t ha^{-1} of manure was applied to the field in the winter of 1991/1992.

Experimental design

The field was laid out in a randomized complete block design with three blocks. One of the three blocks was inside a non-irrigated plastic greenhouse (used for frost protection). Only the Brazilian clone (1271) produced fruit in the greenhouse leaving only two replications available for study. In each block, each accession was represented by a row of five plants with a 1 m in-row spacing and a 4 m between-row spacing. Weeds were controlled using a 2% glyphosate (Roundup) solution.

An N, P, K (100 kg ha^{-1} N, 100 kg ha^{-1} P and 100 kg ha^{-1} K) treatment was applied to over 20 accessions in mid-October of 1992 and 1993 with a band application around the base of the plants. However only 6 of the 20 accessions (Table 1) produced fruit in both blocks outside the greenhouse. Thus this study was confined to these 6 accessions (However, in the study at individual cladode level, where accessions were chosen based on the largest range of fruit per cladode, an additional accession (1294) was included). Out of the five plants in each accession,

two plants at one end of the row plot received a fertilizer treatment while the two plants on the other end were the control plants. The middle plant served as a buffer plant between the treatments.

Statistical analyses

We sought to find an explanation for the considerable variability in fruit load per cladode and per plant through correlations and regressions between cladode nutrients and fruit yield and quality. Very different results emerged depending on whether the correlations were obtained from the mean of many cladodes per plant (whole plant level) or from pairwise data of fruit number per individual cladode (cladode level). At the whole plant level the mean plant concentration of more than 20 plants was used in the regression. At the individual cladode level per accession, the number of cladodes per regression ranged from 6 to 10. Since the raw data for N, P, Ca, Mg, and Mn, were not normally distributed we used Spearman correlation analyses rather than Pearson correlation analyses.

In the case of K, when the mean concentration of K from the entire plant was high, fruit production from the plant was also high. However at the individual cladode level, very high fruit numbers/cladode were often associated with low concentrations of K. Thus we have been careful to specify whether the regressions have been obtained from the whole plant or cladode level.

Sampling technique

A 0.75 m long, sharpened stainless steel pipe (to avoid

contamination from Fe, Zn etc.) of 3.2 cm inner diameter was used for sample collection as described by Huffman and Jacoby (1985). The coring device was dipped in 70% ethyl alcohol between sampling to prevent spread of disease causing organisms. The core samples were placed in paper bags, dried at 50° C and ground in a stainless steel Wiley Mill with a 40 mesh screen.

Five samples were taken from each of the fertilized and unfertilized plants for chemical analyses in July 1993. While fruit yield measurements were taken both in 1993 and 1994, no chemical analysis were performed in 1994. Samples were collected from the terminal, upright cladodes in the center. These samples were used to study the correlation between tissue nutrient concentration and fruit yield and quality. These samples were pooled for each plant in each treatment and were used to determine "whole plant level" effects as described later.

A second experiment was conducted to examine the relationship between cladode nutrient concentrations over the widest possible range of fruits per cladode. Due to a more favorable range in fruit/cladode, accession 1294 was added to this portion of the study and accessions 1281 and 1392 were deleted. The number of fruits/cladode was then regressed against the cladode nutrient concentrations. These samples were used to determine "cladode level" fruit effects as described later.

Tissue analysis

Tissue nitrogen was determined colorimetrically following micro- Kjeldahl digestion as described by Cline et al.(1986),

except that 100 mg plant material was digested in 5 ml of concentrated sulfuric acid and diluted to 250 ml. A nitric acid digestion was used for the P and micronutrient analyses. Digestion of plant material for nutrients other than N, was done using 200 mg of plant material in 10 ml of concentrated nitric acid at 125° C for four hours as described by Halvin and Soltanpour (1980). P was determined colorimetrically and K, Ca, Na, Mg, Fe, Mn, Zn, and Cu were measured using atomic absorption spectrophotometric techniques (Halvin and Soltanpour, 1980). Using these procedures the mean elemental composition of six samples of National Bureau of Standards (Citrus leaves) were measured to ensure the nutrient concentrations were within the referenced standard error. Tissue concentrations of all nutrients are reported on a dry matter basis.

Fruit quality analysis

In 1993 the fruit number was recorded every 10 days from the beginning of floral bud initiation for yield determination. Mature fruits were harvested from the field based on their color change. The fruit size, fresh weight, pulp weight and pulp peel ratio were measured. The fruit pulp was homogenized using a kitchen blending machine and then filtered using ordinary coffee filters. The pH and percent sugar (soluble solids) content was measured on the filtrate using a pH electrode and a Bausch and Lomb Abbe Refractometer respectively. The fruits were also harvested in July 1994 for yield determination. However no fruit quality measurements were conducted in 1994.

Results

The analysis of variance for yield, summarized in Table 2, showed that there were no significant differences among treatments in 1993 or 1994 ($p>.05$). In 1993 there were significant differences among accessions for yield. However there was a significant interaction between accessions and fertilizer treatments ($p=.03$) in 1993. Fruit production in 1993 for the 6 Opuntia accessions is presented in Table 3. There was great variation among the accessions, with the non-fertilized plants often having higher production than the fertilized plants.

Correlations at whole plant level

Even though the Anova was not significant for fruit yield, Spearmen correlation coefficients (Table 4) indicated that the whole plant tissue N (%) was positively correlated with yield ($r=.452$, $p=.034$). The cladode tissue K concentration tended to be positively correlated with fruit yield in 1993 ($p=.08$) and was significantly correlated in 1994 ($r=.432$, $p=.044$). Tissue P was positively but non-significantly correlated ($p>0.20$) with fruit yield in both years.

While fruit production increased with increasing N and K tissue concentrations, depressed fruit production was associated with high concentrations of Na and Mn (p values were .044 and .049 respectively). Similarly, tissue concentrations of Cu, Mg, Zn and Ca were negatively, but non-significantly correlated to yield in 1993 or 1994.

Due to the non-normal distribution of the raw data for N, P,

K, and Na versus fruit yield, we examined ranked (Spearman) correlations between these variables. While ranked correlations for the non-normally distributed data were significant for fruit yield and N ($p=.034$), K ($p=.044$) and Na ($p=.044$), neither quadratic or linear regressions were significant. We attributed this to confounding influences of other nutrients that created "apparent outliers". Even though the parametric regressions between fruit and N, K and Na were non-significant, it is important to have some estimate of the relationship between these variables. Therefore we have presented the best quadratic expression of the N and K data and the best linear expression of the Na data in Figures 1-3. A representative model for 22 data points is provided below.

$$\text{Yield} = -6.22 + 15.38(N) - 5.71\ (N)^2$$

$$\text{Yield} = 75.33 - 18.58\ (K) + 1.22\ (K)^2$$

$$\text{Yield} = -0.08\ (Na) + 22.05$$

Where yield is in fresh weight of fruits in ton/ha, where (N)= % dry weight, (K) = % dry weight and (Na)= mg/kg of dry weight.

The estimated optimum value over the observed ranges of 22 points was 1.34% for N. The response of K tissue concentrations indicated that the plants in this study had not reached their maximum fruit production with respect to K. Opuntia fruit production apparently is moderately sensitive to salinity with cladode concentrations greater than 220-240 ppm being associated with depressed fruit production.

Fruit quality

The Anovas for fruit weight, pulp weight, ratio (fruit weight/pulp weight), and pH showed no significant difference between control and fertilized plants (p values>0.05). However there was a significant difference between the accessions in fruit weight and pulp weight respectively (p=.026 and .012).

In contrast to the lack of fertilizer influences on fruit and pulp weight and pH, the fertilized plants had a significantly (p=0.015) higher fruit sugar content (Table 5). Spearman correlation analysis indicated that the nutrient most significantly correlated with fruit sugar content (r=0.477, p=0.024) was Mg (Table 6). Linear, Langmuir and quadratic regressions were examined between cladode Mg (%) and fruit sugar content. The quadratic term was the most significant term in the models. A representative model for 22 data points was

$$\text{Fruit sugar} = 1.19 + 10.19\ (\text{Mg}) - 2.33\ (\text{Mg})^2$$

Where fruit sugar is in % of fruit fresh weight and where (Mg) is in % of dry weight.

This equation had an R^2 of 0.379 (p=0.01). Both Mg, and (Mg)2 were significant at p=0.015 and p= 0.025 respectively (Fig. 4). The optimal Mg concentration for fruit sugar appeared to be 0.22 %. Fruit sugar was positively correlated with pulp weight and pulp weight was positively correlated with fruit weight.

Correlations at individual cladode level

Fruit number varied from cladode to cladode. Some cladodes carried up to 17 fruit, while some cladode carried only a few

fruits. To better understand the nutrient requirements for fruit production at the cladode level, mineral nutrients were measured from cladodes of 5 Opuntia accessions in which the number of fruits per cladode ranged from 0 to 17. Regressions were computed between fruit number and the cladode composition of 10 nutrients. The R-square values and level of significance are presented in Table 7. Phosphorus was found to be positively correlated with fruit yield in accessions 1294 (p=.00) and 1376 (p=.04) (Fig. 5). While K was found positively correlated with fruit yield at the whole plant level, it was found negatively correlated in accessions 1277 (p=0.01), 1287 (p=0.05) and 1380 (p=0.07) with fruit number per cladode. Figure 6 for accession 1277 illustrates this effect. Clearly there are striking differences among these fruit varieties in the response to cladode nutrient content. Unfortunately it appears as if the relationships between cladode nutrients and fruit production will have to be determined for each fruit accession.

Discussion

While many of the correlations observed in this work were rather low i.e. the R^2 for the quadratic relationship between cladode Mg and fruit sugar concentration was only 0.379, the P values were high (P=.01). The low coefficient of determination (R^2) indicates that only a small percentage of the influence of fruit sugar can be explained by the cladode Mg concentration. Certainly in a field situation, edaphic factors, micro-climate factors and management factors would be expected to influence the

sugar concentrations as well as the Mg status. We believe that many of the low coefficient of determinations reported here are due to variability created by field conditions. In contrast the very high P values indicates that in spite of the variability introduced by field conditions there is a very high probability that these factors are related. Greenhouse fertility studies could provide more precise results. However, greenhouse conditions cannot duplicate influences of greater rooting depth, soil heterogeneity and weather conditions. Thus we believe more precise greenhouse results may not be readily transferrable to field conditions.

Research in Israel and Mexico indicated that high cactus fruit production required high fertility inputs (Nerd et al., 1993; Nobel et al., 1987). While in this experiment, application of N, P, K, had no effect on yield, the maximum fruiting was observed at a cladode N concentration of 1.34%. According to Nerd et al. (1989), irrigation and fertilization regimes are important for the production of cactus fruits in arid and semi-arid environment. The experimental field in this report was never irrigated but 15 ton ha^{-1} of manure was applied in 1991/1992. Because of the erratic rainfall conditions in South Texas, water availability and distribution may limit fruit production as well as fertility.

The widespread occurrence and adaptability of Opuntia on semi-arid soils that are low in N, might suggest that N was not a limiting factor for their growth and development. However since

high fruit production is not directly related to ecological adaptability, high N levels may still be required for high fruit productivity. For example, application of 120 kg ha^{-1} N in Israel increased floral flush compared to control plants (Nerd et al., 1993). In this Israeli study, use of P and K was found to be unnecessary. A plausible explanation for the high fruit production in the control plants in this trial may be due to the fact that the control plants extracted nutrients from the root zone of treated plants. This is possible since in spite of the fact that fertilizer was banded and incorporated close to the base of the treated plants, there was only a meter between the closest treated plant and the control. The interaction between the accessions and the fertilizer treatments indicates that all accessions did not respond to fertility similarly. These effects also contributed to the non-significant yield response.

The maximum yield was observed at 1.34 % cladode N concentration, which compared favorably to the concentration of 1.16 % reported by Gathaara et al. (1989). The optimum value of 1.34 % N for 6 accessions may not produce optimum fruit yield for all Opuntia accessions. For example Nobel (1983) reported a concentration of 2.45% N for Opuntia ficus-indica being grown commercially for fruit production in California.

As indicated in Table 7, regression analysis indicated that phosphorus was positively correlated to fruit yield in accessions 1294 and 1376. Even though P, and K were found to be unnecessary for fruiting in Israel by Nerd et al. (1993), a curvilinear

response between tissue P concentration and fruit yield in Opuntia engelmanni, Gathaara et al. (1989) indicated that in some species P increases fruit production.

The variability of these 5 different accessions indicates that it may be necessary to develop separate quantitative relationship between cladode elemental concentration and fruit yield for each fruit yielding clone. Gregory and Felker (1992) also observed large differences in the mean % N and % P of eight Opuntia fodder and vegetable cultivars in South Texas. These results point to the need to survey the fertility responses of a variety of genetic backgrounds before intensive fertility studies are conducted on only one accession.

At the whole plant level there was a tendency for tissue K concentration to be positively correlated to yield ($p=0.08$) in 1993. However the 1993 "whole plant" K concentration was significantly correlated with the 1994 fruit yield ($p=0.04$). It does not appear that the plants in this study had reached their maximum fruit production with respect to K. In contrast, at the cladode level, fruit number was found to be negatively correlated to tissue K for accessions 1277, 1287, and 1380 (Table 7). The apparent contradiction between the positive correlation for K and fruit yield at the whole plant level, and the negative correlation at the individual cladode level, is probably due to export of large quantities of K from the cladodes to the fruit. We attribute this later phenomenon to a source/sink relationship whereby the high K load of the fruits created a low concentration

in the cladode. This is plausible since Sawaya et al. (1983) found K to be the most abundant element in the fruit pulp and seeds (Sawaya and Khan, 1982). This result suggests that high K concentrations are associated with fruiting at an early stage, but this effect is reversed as large amounts of K are exported from cladodes to the fruits as they mature. Thus, it will be necessary to determine the mean K content of many cladodes per plant to optimize the K requirement of Opuntia for fruit yield. Alternatively, it would be useful to examine correlations between sampling dates prior to flower initiation with fruit yield. This would avoid confounding influences of cladode nutrient export to fruits on determining optimum cladode nutrient content for fruit production.

Opuntia may well an excellent model plant to study translocation of nutrients and photosynthates given the fact that high fruit numbers are attached directly to the photosynthetic surface i.e. the cladode. In contrast nutrients and photosynthates for other fruits i.e. apples, citrus, figs etc must be translocated from the leaf through a petiole to a twig and then through a stem to the fruit.

Even though the plants inside the greenhouse (block 2) were fertilized in the same manner as the other blocks, none of them produced fruit 1993. In contrast to a previous report of fruit production (Kuti, 1992) from this field only 5 months from the freeze of December 1989 which killed all cacti outside the greenhouse to the ground, we observed no fruit in this field in

1990 or 1991. In 1994 some accessions produced fruit in a portion of the greenhouse that inadvertently had the plastic cover removed in February 1994. This observation indicates that light, and perhaps decreased winter or summer temperatures were important for cactus fruit production.

This is the first report of a positive correlation between cladode Mg concentration and soluble solid concentrations in the fruits. A similar effect of Mg regulation of dry matter production in potato was reported by Cao and Tibbitts (1992). The optimum sugar content was observed at 0.22 % cladode Mg. The positive relationship between Mg and sugar content may be attributable to the fact that Mg makes up the core of the chlorophyll molecule and also activates enzymes for metabolic processes such as photosynthesis, respiration and formation of DNA and RNA (Salisbury, 1992). A key reaction of Mg is the activation of ribulose bisphosphate carboxylase which is responsible for sugar production. Thus the favorable effect of Mg on Opuntia sugar concentration may be due to effect on CO_2 assimilation and the related processes of sugar and starch production.

Conclusions

There was no significant difference in fruit yield resulting from the fertilizer applications, but there was a significant increase in the sugar content of the fruits. The whole plant nitrogen content was positively correlated with fruit yield. In contrast, whole plant level Na tissue concentrations were

negatively correlated with yield suggesting the sensitivity of fruit yield to salinity. While there was a significant positive correlation between yield and K content of the entire plant, the correlation between individual cladode K content and fruit yield were significant and negative. We attribute this phenomenon to a strong source/sink relationship with a increase in fruit numbers that extracted large quantities of K from the cladode. The tissue Mg concentration was significantly correlated with fruit sugar concentrations. The quadratic regression between cladode Mg and fruit sugar was positive with an optimal Mg concentration of approximately 0.22%. Individual clones appear to have different response to fertilizers. It appears that it will not be possible to develop a set of generic guidelines for "optimal cladode tissue concentrations" for Opuntia fruit production. Thus it will be necessary to develop cladode tissue nutrient concentration/fruit production relationships for individual Opuntia clones.

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FIGURE CAPTIONS

Fig. 1. Quadratic relationship between cladode N concentration and fruit yield of Opuntia accessions 1281, 1380 and 1392 at whole plant level.

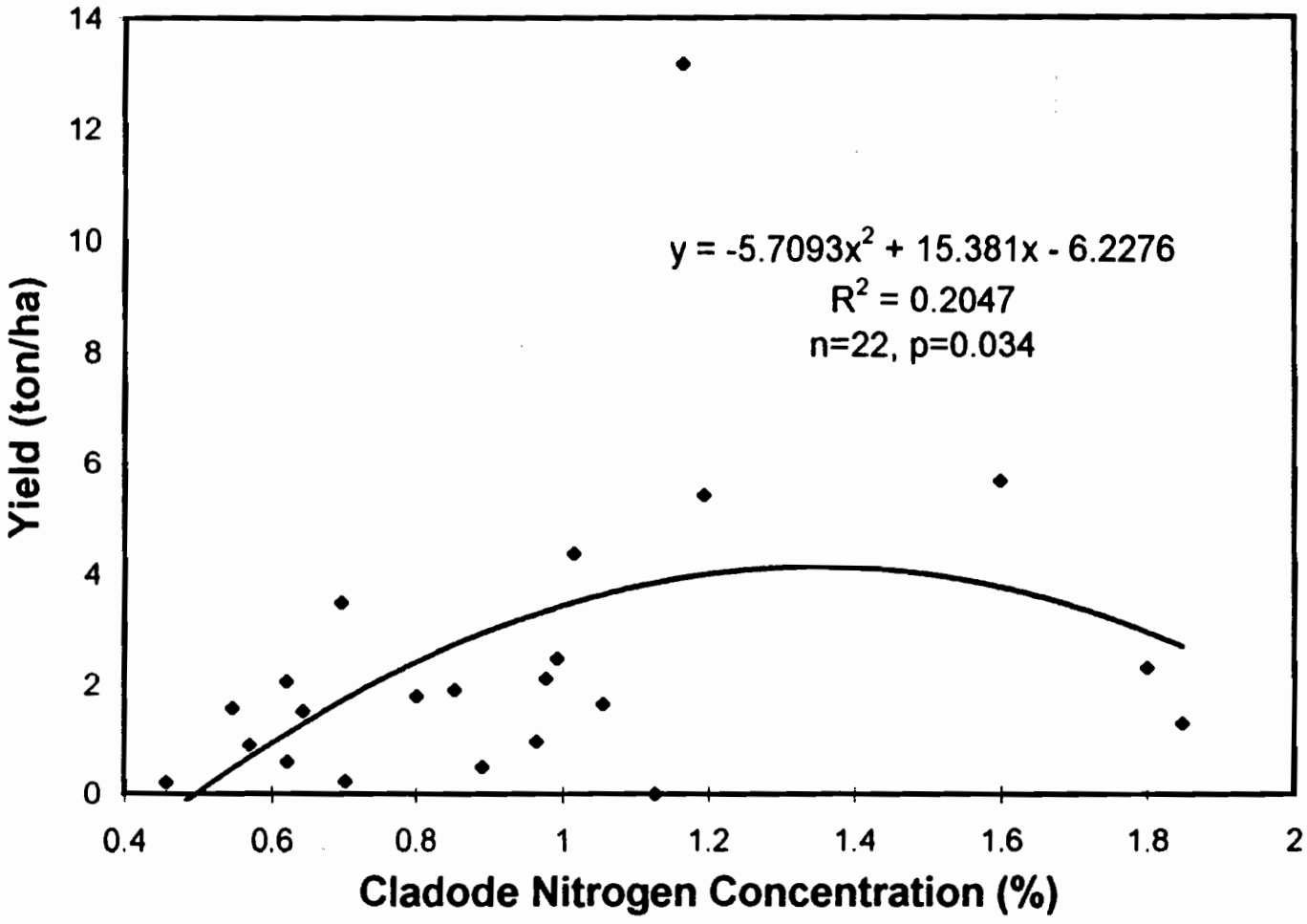
Fig. 2. Quadratic relationship between cladode K concentration and fruit yield of Opuntia accessions 1277, 1281, 1287, 1376 and 1392 at whole plant level.

Fig. 3. Linear relationship between cladode Na concentration and fruit yield of Opuntia accessions 1281, 1287, 1376 and 1392 at whole plant level.

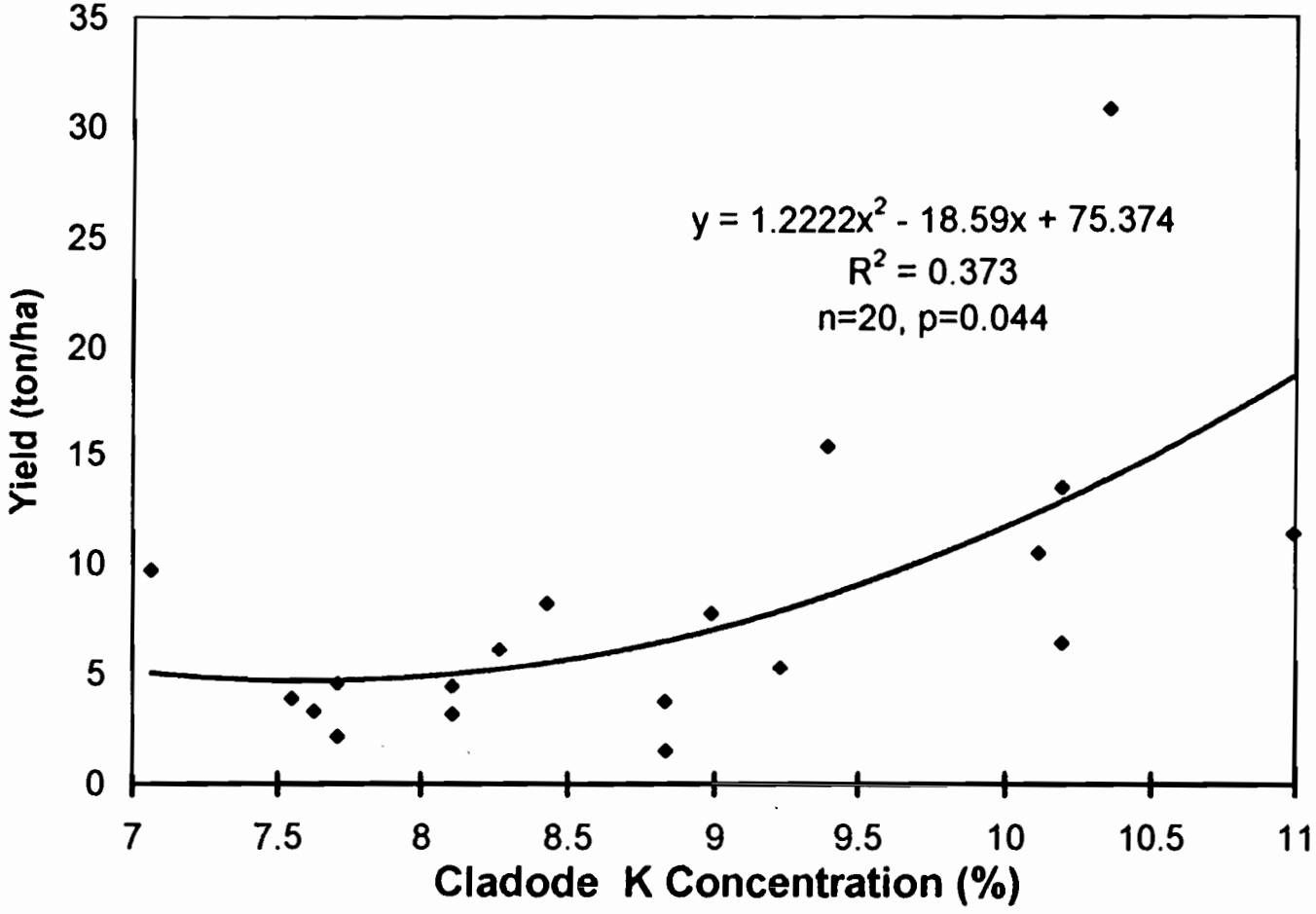
Fig. 4. Quadratic relationship between cladode Mg concentration and fruit sugar content of Opuntia accessions 1277, 1281, 1287, 1376, 1380 and 1392 .

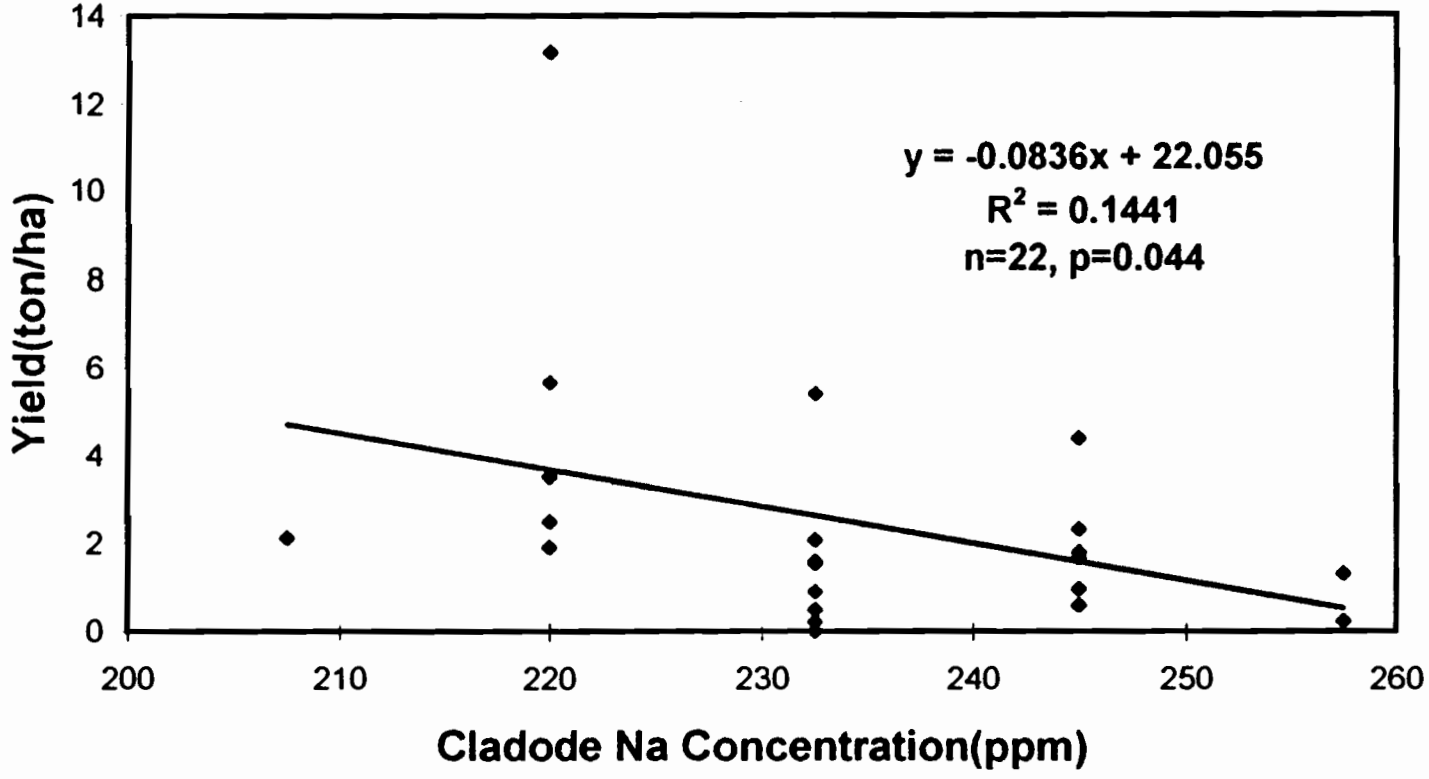
Fig. 5. Linear relationship between cladode P concentration and fruit number of Opuntia ficus-indica (1376) at cladode level.

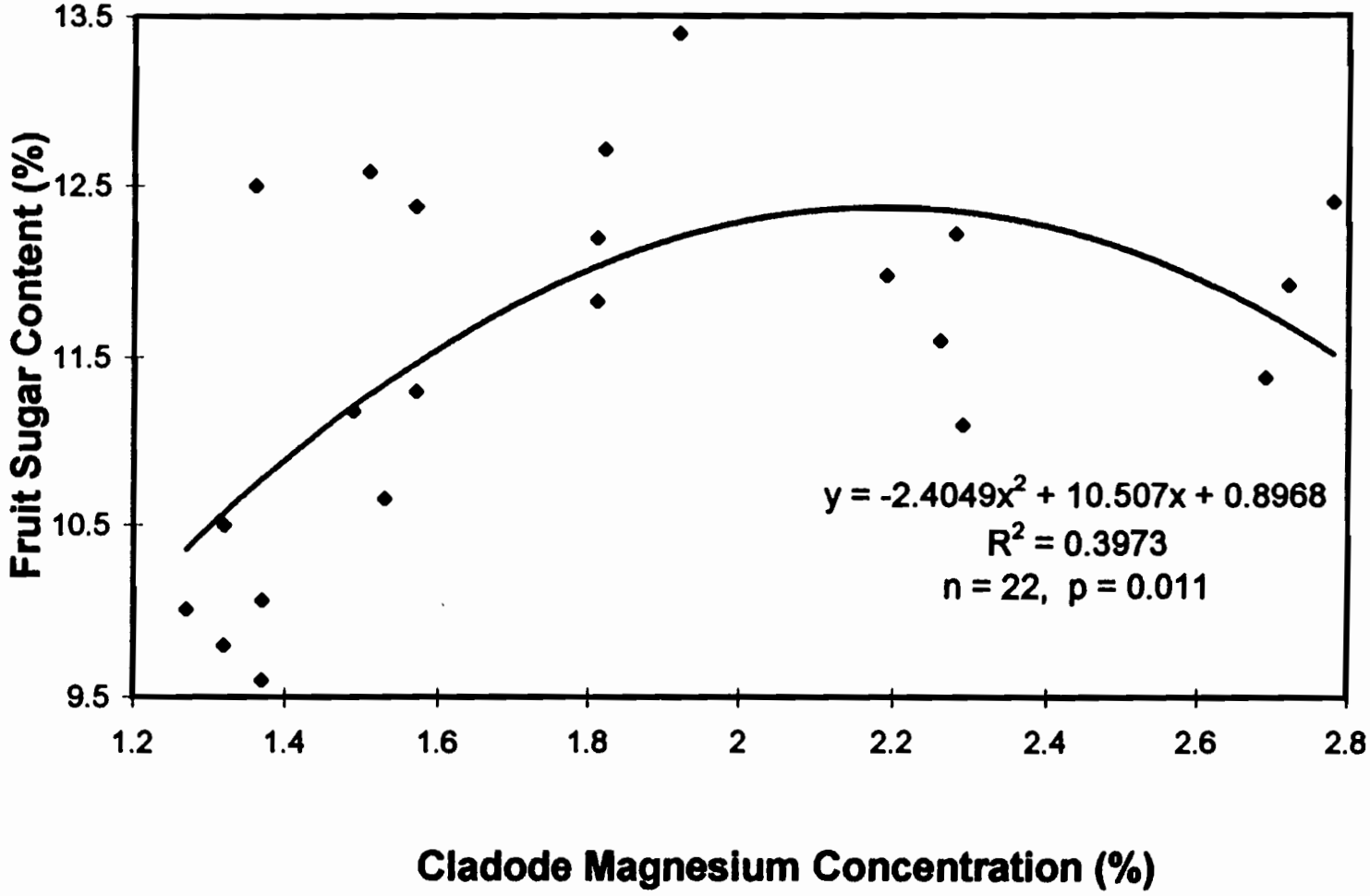
Fig. 6. Linear relationship between cladode K concentration and fruit number of Opuntia ficus-indica (1277) at cladode level.


y = -5.7093x² + 15.381x - 6.2276
R² = 0.2047
n=22, p=0.034
Yield (ton/ha)
Cladode Nitrogen Concentration (%)
0
2
4
6
8
10
12
14
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

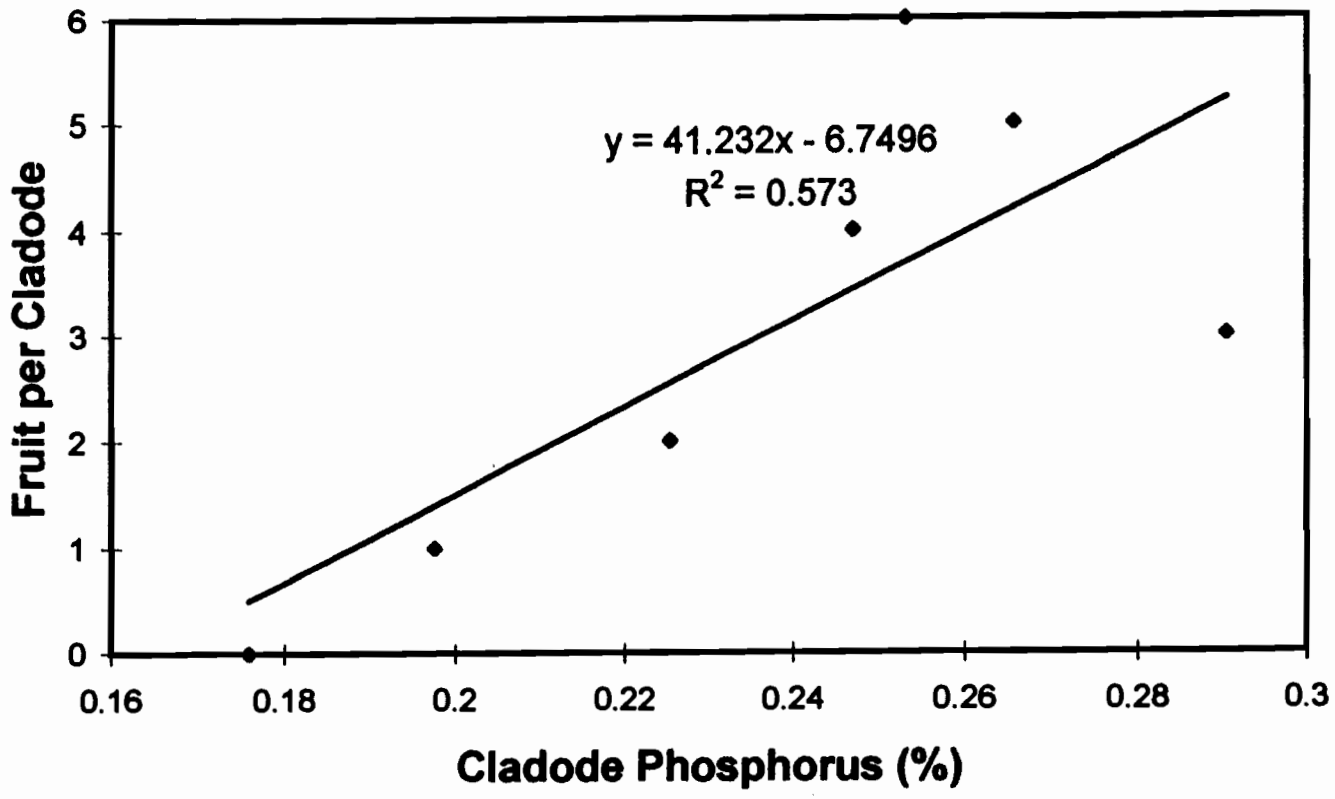
52

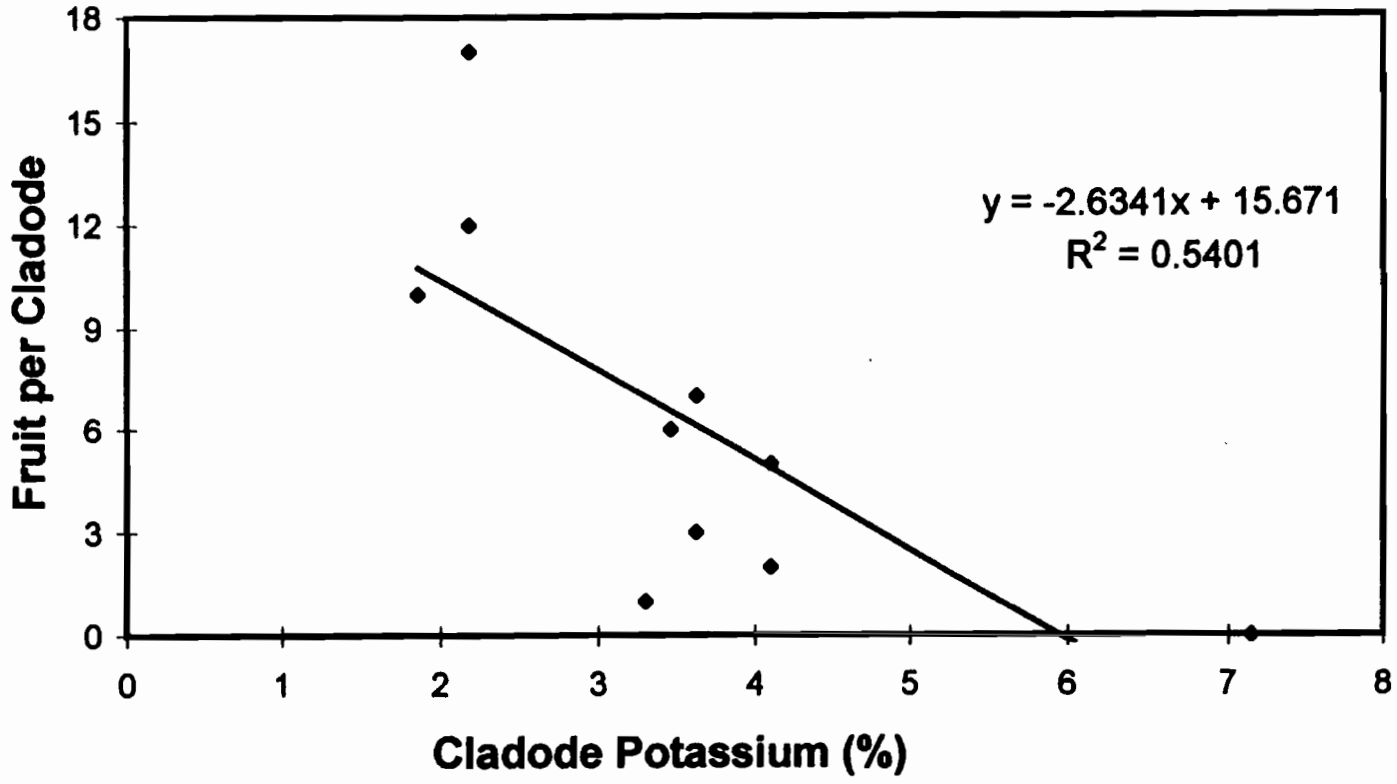

y = 1.2222x² - 18.59x + 75.374
R² = 0.373
n=20, p=0.044
Yield (ton/ha)
35
30
25
20
15
10
5
0
7
7.5
8
8.5
9
9.5
10
10.5
11
Cladode K Concentration (%)


y = -0.0836x + 22.055
R² = 0.1441
n=22, p=0.044
Yield(ton/ha)
0
2
4
6
8
10
12
14
200
210
220
230
240
250
260
Cladode Na Concentration(ppm)


13.5
12.5
11.5
10.5
9.5
Fruit Sugar Content (%)
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
Cladode Magnesium Concentration (%)
y = -2.4049x² + 10.507x + 0.8968
R² = 0.3973
n = 22, p = 0.011

55


y = 41.232x - 6.7496
R² = 0.573
Fruit per Cladode
Cladode Phosphorus (%)
0
1
2
3
4
5
6
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3


y = -2.6341x + 15.671
R² = 0.5401
Fruit per Cladode
Cladode Potassium (%)
0
3
6
9
12
15
18
0
1
2
3
4
5
6
7
8

57

Table 1. Origin and species of the 6 *Opuntia* accessions used in the N, P, K, treatment for fertility assessment.

Accession	Species	Spines	Fruit color	Origin (code)
1277	*Opuntia ficus-indica*	-	yellow	Mexico
1287	*Opuntia hyptiacantha*	+	yellow	Mexico
1281	*Opuntia streptacantha*	-	yellow	Mexico
1380	*Opuntia megacantha*	-	yellow	Mexico (AN-V5)
1376	*Opuntia ficus-indica*	+	white	Mexico(AN-V1)
1392	*Opuntia ficus-indica*	-	red	Mexico (ROJO)

Table 2. Anova for yield as influenced by N, P, K, fertilization in 1993 and 1994.

Source	df	1993 Sum of Squares	1993 F	1993 P	1994 Sum of Squares	1994 F	1994 P
Block	1	382848	2.63	0.180	5124134	0.13	0.737
Accession	5	70125276	9.63	0.023	389928480	1.97	0.265
Block* Acc.	5	23794622	3.27	0.137	285570310	1.44	0.372
Fertilizer	1	1931424	1.33	0.313	103146	0.00	0.961
Acc.* Fert	5	52633022	7.23	0.039	187817353	0.95	0.535
Error	4	5825886			158464465		

Acc. = Accession; Fert = fertilizer.

Table 3. Mean weight, pulp weight, ratio (fruit weight/pulp weight), pH, sugar content and yield of *Opuntia* accessions 1277, 1287, 1281, 1380, 1376, 1392 as effected by N,P,K fertilization.

Acc.	Fert	Frn	Fruit weight (g)	Pulp weight (g)	Ratio	pH	Sugar (Brix)	Yield 1993 (Kg ha^{-1})
1277	C	29.5	128	64.0	2.0	6.0	10.6	9425
1277	F	9.0	126	61.7	2.0	6.1	12.0	2955
1281	C	7.0	140	88.2	1.5	6.4	12.5	2450
1281	F	2.7	148	78.4	1.9	6.4	13.0	995
1287	C	0.2	84	30.1	2.8	6.1	10.5	57
1287	F	11.5	94	44.4	2.2	6.0	12.2	2705
1376	C	10.0	89	38.8	2.3	5.1	10.7	2191
1376	F	6.2	92	37.9	2.5	6.2	11.7	1447
1380	C	3.2	99	42.4	2.5	5.9	9.8	886
1380	F	5.2	97	44.4	2.2	6.1	12.2	1367
1392	C	5.5	118	60.9	2.0	6.0	12.1	1693
1392	F	2.2	131	63.9	2.0	5.4	11.2	736

Acc.= Accession; Fert=Fertilizer; C=control; F=fertilizer (N,P,K,); Frn= Mean fruit number; Ratio= Fruit weight/pulp weight; N=4.

Table 4. Correlation coefficient and p values (in parentheses) between yield and 'whole plant level' tissue concentrations for accessions 1277, 1287, 1281, 1380, 1376, 1392.

	Yield 1993	Yield 1994	N	P	K	Mg	Ca	Na	Cu	Zn	Fe	Mn
N	.452 (.034)	.195 (.383)										
P	.234 (.293)	.250 (.261)	.029 (.893)									
K	.376 (.084)	.432 (.044)	.250 (.248)	.280 (.195)								
Mg	-.063 (.777)	-.008 (.970)	-.020 (.925)	-.014 (.946)	.037 (.846)							
Ca	-.035 (.875)	-.021 (.342)	.113 (.607)	.221 (.309)	.219* (.313)	-.081 (.711)						
Na	-.433 (.044)	.045 (.840)	.026 (.904)	-.192 (.380)	-.285* (.187)	-.024 (.911)	-.118* (.589)					
Cu	-.273 (.217)	.152 (.497)	-.104 (.636)	.072 (.740)	.044 (.839)	.313 (.145)	-.289 (.181)	.048 (.827)				
Zn	-.057 (.079)	-.238 (.284)	.102 (.642)	.405 (.054)	-.102* (.640)	.213 (.327)	.006* (.977)	-.004* (.982)	.151 (.489)			
Fe	.226 (.310)	.073 (.745)	.189 (.383)	-.040 (.856)	.115 (.600)	-.275 (.203)	.136* (.533)	-.303* (.159)	-.387 (.067)	-.337 (.115)		
Mn	-.422 (.049)	-.377 (.124)	-.168 (.440	-.179 (.411)	-.146 (.503)	.498 (.015	.304 (.158)	-.138 (.527)	.132 (.545)	.231 (.288	-.199 (.360)	

* Denotes Pearson correlation coefficient used for normally distributed raw data. The remaining of the coefficients were Spearman correlation coefficient used for non-normally distributed raw data.

Table 5. Anova for sugar as influenced by N,P, K, fertilization in 1993.

Source	df	Sum of squares	F	P
Block	1	.2721	.85	.4082
Accession	5	3.6423	2.28	.2223
Block* accession	5	2.3910	1.50	.3585
Fertilization	1	5.1714	16.19	.0158
Accession* fert	5	6.3076	3.95	.1039

Table 6. Correlation coefficient and p values (in parentheses) between at 'whole plant level' fruit weight, pulp weight, ratio, pH, sugar content and nutrients for accessions 1277, 1287, 1281, 1389, 1376, 1392.

	Fruit weight	Pulp weight	Ratio	pH	Sugar
N	.040 (.859)	.142 (.529)	-.181 (.419)	-.033 (.882)	.017 (.938)
P	.180 (.422)	.182 (.416)	-.199 (.373)	-.142 (.527)	.094 (.676)
K	.168* (.453)	.282* (.203)	-.080 (.722)	.370 (.090)	.293* (.185)
Mg	.024 (.914)	.037 (.867)	-.079 (.724)	.0040 (.859)	.477 (.024)
Ca	.143* (.524)	.201* (.368)	-.383 (.077)	-.235 (.290)	-.132* (.557)
Na	-.362* (.097)	-.421* (.050)	.407 (.060)	.215 (.336)	-.182* (.416)
Cu	-.182 (.417)	-.288 (.192)	.294 (.184)	-.206 (.356)	-.288 (.192)
Zn	.138* (.538)	.059* (.793)	.028 (.900)	-.371 (.088)	-.051* (.820)
Fe	-.018* (.934)	.100* (.657)	-.077 (.732)	.201 (.369)	.002* (.990)
Mn	-.001 (.994)	-.014 (.950)	-.011 (.958)	-.373 (.086)	-.069 (.676)
Fruit weight		.956* (.001)	-.854 (.000)	.107 (.632)	.436* (.042)
Pulp weight			-.945 (.000)	.127 (.571)	.516* (.013)
Ratio				-.092 (.681)	-.508 (.015)
pH					.588 (.004)

* Denotes Pearson correlation coefficient the remaining of the coefficients are from Spearman correlation from non-normally distributed raw data.

Table 7. Regression coefficients and p values (in parentheses) of fruits per cladode (cladode level) and tissue nutrient elements of 5 Opuntia accessions.

Nutrient element	Fruit/cladode Accession				
	1277	1287	1294	1376	1380
N	-0.072	0.163	0.488	0.510	0.413
	(0.45)	(0.28)	(0.12)	(0.07)	(0.16)
P	0.024	0.053	0.873	0.574	0.157
	(0.66)	(0.55)	(0.00)	(0.04)	(0.43)
K	-0.540	-0.431	-0.148	-0.050	-0.578
	(0.01)	(0.05)	(0.45)	(0.62)	(0.07)
Ca	0.000	0.156	0.297	0.058	0.521
	(0.99)	(0.29)	(0.26)	(0.60)	(0.10)
Na	0.029	0.012	0.031	0.187	0.855
	(0.63)	(0.77)	(0.73)	(0.33)	(0.00)
Mg	-0.278	0.062	0.219	-0.210	0.456
	(0.11)	(0.51)	(0.34)	(0.30)	(0.14)
Mn	-0.162	-0.123	-0.172	-0.409	0.403
	(0.24)	(0.35)	(0.41)	(0.12)	(0.17)
Cu	-0.162	0.200	0.017	-0.476	0.114
	(0.24)	(0.22)	(0.80)	(0.08)	(0.51)
Zn	-0.397	0.276	0.053	0.007	-0.394
	(0.05)	(0.14)	(0.65)	(0.85)	(0.18)
Fe	-0.400	-0.096	-0.072	-0.012	-0.615
	(0.05)	(0.41)	(0.60)	(0.81)	(0.60)
n	10	9	6	7	6

7.187

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A comparison of *Opuntia* fruit quality and winter hardiness for use in Texas

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The fruit sugar, pH and titratable acidity of 25 *Opuntia* clones were examined in the third to fifth year of a field trial in southern Texas. Thorny and thornless types with red, purple, green, orange and yellow colored fruits were included in this evaluation. Most fruits (61%) were initiated in April and were mature in July and August. A Brazilian clone was the only one to reinitiate flowering in September. The clones which produced most fruit at 3 years of age were from Mexico and Brazil. Chilean clones produced few fruits in the Texas environment. Nine of the clones had sugar contents greater than 11%. At the end of the fifth year, all unsheltered *Opuntia* died from a −12°C freeze. The principal limitation to commercial cactus fruit plantations in Texas appears to be lack of cold hardy clones. More recent introductions from high elevation sites in Mexico may overcome this limitation.

Introduction

There has been a resurgence of interest in growing various species of *Opuntia* for fruit production in semi-arid regions in Mexico (Pimienta-Barrios, 1990; Escalante & Vazquez, 1986), Italy (Barbera *et al.*, 1991), South Africa (Wessels, 1988), Chile (SAG, 1976), Israel (Nerd *et al.*, 1989) and Texas (Felker, 1990).

Cultivation of opuntias in semi-arid regions is reasonable ecologically because *Opuntia* has a high water use efficiency attributed to CAM metabolism (Nobel, 1988), also because *Azospirillum* are associated with the roots to fix nitrogen (Mascarua-Esparaza *et al.*, 1988) and finally because the high production of fruits (8000–14,000 kg/ha), command a good market price.

While *Opuntia lindheimerii* Engelm. is well adapted and occurs widely in Texas, its fruit size is small (about 40 g) and the fruit sugar is low (< 8%). In 1984 with National Science Foundation funding, we established a germplasm collection of *Opuntia* species that were used in other parts of the world for either fruit, vegetable, or forage production.

Evidently Texas is at the northern-most limit for spineless and spiny fruit cultivars since the collection experienced major damage from freezes, e.g. −9°C in 1984/1985 (Russell & Felker, 1987), −12°C in 1989/1990 and −7°C in 1990/1991. About 3 years are required from time of planting to produce fruit, thus the interspersion of freezes has made evaluation of fruit quality difficult. Nevertheless we have been able to obtain fruit quality measurements over a 3 year period for many of these clones. It is the intent of this communication to report fruit quality data for the clones which produced fruit and to

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report companion data on date of fruit initiation, frost hardiness, and spine characters. This will permit an overall suitability index for regions that experience similar patterns of freezing weather.

Materials and methods

A description of the origins of the clones is provided in an earlier communication (Russell & Felker, 1987). Additional information is available on the forage quality of 8 of these clones (Gregory & Felker, 1992).

Field plot design. The field was laid out as a randomized complete block design with three blocks of 49 *Opuntia* accessions. In each block, each accession was represented by a row of five plants with a 1 m spacing between plants. The between row spacing was 4 m. The initial planting occurred in the summer of 1984.

Since planting, the field was disced several times a year and the herbicide tebuthiuron used at 2 kg/ha (Felker & Russell, 1988). Glyphosate was used with a shielded applicator to control johnsongrass (*Sorghum halepense*). As previously reported, freezing weather (−9°C) caused considerable mortality to many of these clones in 1984/1985. Where planting stock was available the clones were replanted. In the spring of 1989, a 17 m by 94 m unheated greenhouse was erected over all five rows of block 2. On December 25 and 26, 1989, temperatures of −12°C occurred that killed all clones described in Russell & Felker (1987) to ground level (the native *O. lindheimeri* suffered no permanent damage nor did a spineless *Opuntia* spp from New Mexico). Not even the most frost sensitive clone inside the unheated greenhouse exhibited any apparent damage.

The clones in block 1 and 3 were replanted in the spring and summer of 1990. A frost of −7°C occurred on December 1990 that caused considerable damage to the recently replanted clones outside the greenhouse. The clones were visually ranked for damage assessment. The damage assessment from the 1990 freeze is used in Table 3, which also compares agronomic and fruit characters.

Fruit initiation was recorded every seven to ten days beginning in April 1987. Field measurements were taken for length, thickness and fresh weight of fruits. Harvesting was initiated when a visible color change occurred in the skin layer indicating maturity. Some fruits were collected early due to predation by birds and insects. The fruits were placed in paper bags for one to three weeks and stored at room temperature in order to allow for full maturation. The mature fruits were then stored in a freezer until the time of lab analysis. Physical characteristics such as color, disease problems, and pulp and peel ratios were measured. The fruits were collected for analysis from July 21 through to August 8, 1987. Due to the small sample sizes of some of the clones, not all cultivars were analysed for the same measurements.

The presence of glochids were rated as (1) very few to no glochids, less than five per aerole, (2) moderate numbers of glochids and (3) many glochids, more than 20 per aerole and creating difficulties in handling the fruit.

Matured fruits were measured for chemical composition by A.O.A.C. (1970) procedures. The fruits, after being blended to form a puree and then filtered using ordinary coffee filters, were then analysed for pH, titratable acidity, and percent sugars (soluble solids). The pH of the filtrate was determined using a calibrated pH electrode. Titratable acidity was determined by pipetting 10 ml of filtrate into a beaker, diluting to 125 ml, and titrating with 0·10 N NaOH to pH 8·1. Sugars were measured by applying a filtrate smear on a Bausch & Lomb Abbe Refractometer with an automatic temperature compensator.

As the fruit in this collection were of many different colors and as we did not know the color of the mature fruit, it was difficult to estimate maturity. As the fruit matures, the cavity formed by the flower scar fills in. In some clones the fruit is mature when this cavity no longer exists, i.e. a flat circular surface occurs between the flower scar at the end of the fruit. Since *Opuntia* is reported to be non-climacteric (Laksminarayan & Estrella, 1978),

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Table 1. *Number of new cactus fruits produced monthly in 1987*

	Accession No.	Origin	Month						Total	
			April	May	June	July	August	September	Number	wt (kg)
O. ficus-indica	1118*	CH	0	1	0	0	0	0	1	—
O. robusta	1241	SA	0	1	0	0	0	0	1	—
O. hyptiacantha	1253	AG	7	0	0	0	0	0	7	0·28
O. streptacantha	1255*	AG	1	0	0	0	0	0	1	—
O. ficus-indica	1258	AG	2	0	0	0	0	0	2	0·15
O. undulata	1267	AG	23	0	0	0	0	0	23	0·58
O. inermis	1270	BZ	30	18	0	0	0	23	71	2·40
O. ficus-indica	1271	BZ	0	6	1	0	0	7	14	0·52
O. ficus-indica	1278*	MX	0	1	0	0	0	0	1	—
O. ficus-indica	1279*	MX	9	0	0	0	0	0	9	—
O. ficus-indica	1280	MX	44	6	0	0	0	3	53	2·50
O. streptacantha	1281	MX	6	1	0	0	0	1	8	0·29
O. hyptiacantha	1287	MX	4	2	0	0	0	0	6	0·24
O. megacantha	1288	MX	7	7	0	0	0	0	14	1·14
O. megacantha	1292	MX	0	13	0	0	0	0	13	0·57
O. ficus-indica	1294	MX	35	4	0	0	0	0	39	2·62
O. ficus-indica	1296*	MX	0	3	0	0	0	0	3	—
O. ficus-indica	1301	MX	24	1	3	0	0	0	28	1·40
O. ficus-indica	1319	CH	0	16	0	0	0	0	16	0·60
O. ficus-indica	1320	CH	0	3	0	0	0	0	3	0·15
Sum			192	83	4	0	0	34	313	13·44

* Weights unattainable due to bird and insect damage.
AG – Algeria, BZ – Brazil, CH – Chile, MX – Mexico, SA – South Africa.
Note: *O. inermis* is a synonym of *O. stricta*.

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our 1987 procedure of allowing fruits to ripen in paper bags probably did not result in obtaining fruits with maximal fruit sugar.

Results

The first fruit production occurred in the summer of 1987 and by 1989 (five years from planting) extensive fruit production occurred on many of the plants. The plants inside the unheated greenhouse produced an insignificant number of fruit compared to those outside the greenhouse.

Of the 313 fruits that were produced from April to September 1987, most initiation occurred in April (61·3%) with May and June accounting for 26·5% and 1·3%, respectively (Table 1). No fruits were initiated in July and August. Fruit maturation occurred in July and August. The Brazilian clones (Accession # 1270, 1271) and two Mexican clones (Accession # 1280, 1281) were the only plants to re-emerge with fruit during September. This last month accounted for 10·9% of the total production. The fruit weight is the total reproductive effort and includes non-commercial fruit and this accounts for the low mean weight of about 40 g/fruit. Clearly there appears to be a strong genetic component for early fruit production among these clones. The Brazilian clones 1270 and 1271 and the Mexican clones 1280, 1294, and 1301 appear especially promising for early fruit production. Delayed fruit production, such as occurred with clone 1270 could be an important economic factor to produce fruit in the 'off-peak' season when prices would be higher.

The pH, total acidity and sugar content of the clones over the three year period is presented in Table 2. The overall fruit pH ranged from 4·1 to 6·1, the acidity from 0·274% to 0·025%, and the sugar content from 7·50% to 13·7% (Table 2). Several clones such as 1270, 1271, 1280, 1287 and 1288 had consistently high sugar content over all three years of this study. Other clones, i.e. 1292, 1294 and 1301 failed to produce high sugar content fruit consistently in all 3 seasons, or had generally low sugar content fruits.

Generally clones with low pH values i.e. less than five also had the lowest sugar values, i.e. less than 10. Linear regression was used to determine the relationship of pH with both sugar content and acidity for twelve clones that fruited in 1987 (Fig. 1). There was a highly significant relationship between sugar content and pH ($p = 0{\cdot}002$; $r^2 = 0{\cdot}63$) and acidity ($p = 0{\cdot}0001$; $r^2 = 0{\cdot}83$).

Some of the clones with low sugar content were more suited to forage production due to the large thick pads. These forage type clones included *O. robusta* 1241, the Algerian clones 1253, 1258 and 1267. Two Brazilian clones 1270 and 1271 were intended for forage use in Brazil and are known as 'palma redonda' and 'palma giganta' respectively. Both these two clones produced large numbers of fruit with a fairly-high sugar content, in all three years. In addition they are quite high biomass producers. Clone 1270 was also found to have an exceptionally high protein content of nearly 12% (Gregory & Felker, 1992). Unfortunately as noted later, these two clones have poor resistance to freezing weather.

Most of the clones were of Mexican origin. Of the Mexican clones, 1280, 1287 and 1288 appear especially promising for consistently high fruit production and high sugar content. The Mexican clones 1287, 1288 and 1292 were also found to have the most number of glochids. The glochids on clone 1287 were the most numerous and longest. Glochids on clone 1288 were easily removed by handling during harvesting. All of the Algerian and Chilean fruit had glochids that were few in number and density. Brazilian clone 1270 not only had few glochids, but they were also very short.

The Chilean clones have produced very few fruit in Texas. However the fruits that were produced had high sugar contents. Clone 1118 and 1321 had particularly high sugar contents of 12% and 13·7% respectively.

While the analytical data indicate that clones 1270, 1271, 1280, 1287 and 1288 had similarly high sugar contents, it is Felker's opinion that clones 1287 and 1288 taste sweeter than the other clones. In addition the yellow fruited 1287 possesses a 'fruity' flavor.

Table 2. *Mean pH, percent acidity and sugars of fruit for* Opuntia *clones from 1987 through 1989*

Species	Origin	Accession No.	N	1987 pH	1987 Acidity	1987 Sugar	1988 pH	1988 Acidity	1988 Sugars*	1989 pH	1989 Acidity	1989 Sugars
O. ficus-indica	CH	1118					5·4	0·140	12·9	5·2	0·170	11·8
O. robusta	SA	1241								4·9	0·172	10·0
O. hyptiacantha	AG	1253	1	4·7	0·209	8·5				5·1	0·187	9·4
O. ficus-indica	AG	1258					5·7	0·060	8.5			
O. undulata	AG	1267	1	4·6	0·169	7·5	4·7	0·105	9·5			
O. stricta var. *stricta*	BZ	1270	2	5·7	0·083	10·8	6·0	0·080	11·7	4·7	0·198	11·1
O. ficus-indica	BZ	1271	2	5·7	0·088	10·6	5·1	0·180	13·8	5·3	0·152	12·4
O. streptacantha	MX	1273					4·1	0·302	10·6			
O. streptacantha	MX	1274					5·6	0·040	10·4			
O. ficus-indica	MX	1277								4·6	0·244	9·4
O. ficus-indica	MX	1280	2	5·6	0·085	12·1	5·3	0·140	13·4	5·4	0·143	12·7
O. streptacantha	MX	1281	1	5·2	0·123	8·5	5·5	0·010	11·5			
O. streptacantha	MX	1283					5·3	0·080	11·3			
O. hyptiacantha	MX	1287	1	5·6	0·080	10·3	5·5	0·110	12·9	5·4	0·149	13·0
O. megacantha	MX	1288	3	5·6	0·058	12·6	5·2	0·106	12·6	4·6	0·230	11·3
O. megacantha	MX	1292	1	5·6	0·074	10·0	6·0	0·044	11·7	4·3	0·274	8·4
O. ficus-indica	MX	1294	2	5·5	0·075	12·5	5·5	0·083	8·2	4·9	0·190	8·3
O. ficus-indica	MX	1296					6·1	0·025	10·1	5·3	0·167	10·2
O. megacantha	MX	1299								5·0	0·181	9·9
O. ficus-indica	MX	1300					5·7	0·045	9·4	5·0	0·183	10·3
O. ficus-indica	MX	1301	2	5·2	0·083	9·9	5·1	0·095	11·6	5·4	0·156	10·9
O. ficus-indica	CH	1319					5·7	0·090	10·1			
O. ficus-indica	CH	1320	1	5·6	0·105	11·5						
O. ficus-indica	CH	1321					5·2	0·015	13·7			

* % soluble solids.
AG – Algeria, BZ – Brazil, CH – Chile, MX – Mexico.

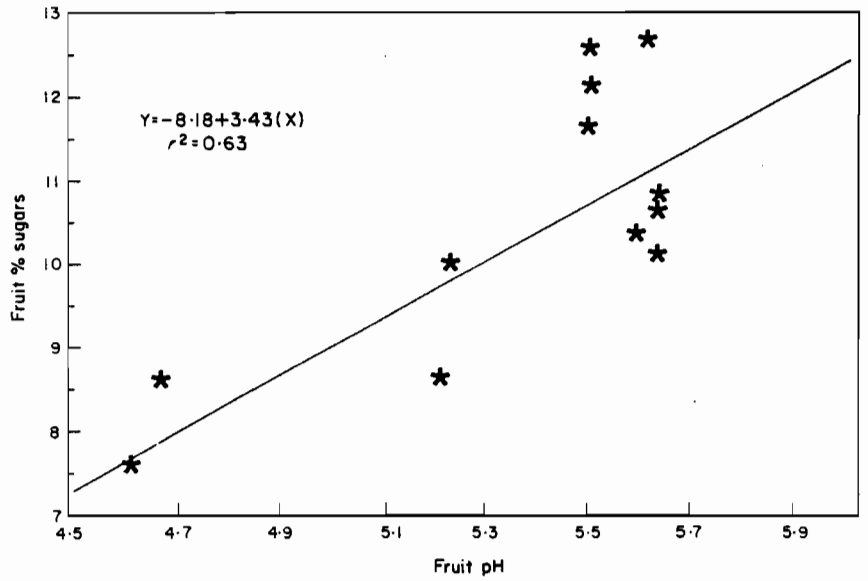

Figure 1. Sugar and pH relationship of fruit for 12 *Opuntia* spp. cultivars.

The fruit characters averaged over three years are compared to a productivity index, to presence or absence of thorns, and to their frost resistance in Table 3. Clones with low early production typically produced less than a dozen fruit in 1989, while fruits with high productivity produced hundreds of fruit that summer.

The fruit color is of importance since consumers of European descent in New York, Chicago and eastern United States have historically preferred red fruit, even if the sugar content were the same. The Chilean fruits typically are a lime-green color and the Brazilian clones had yellow to yellow/orange fruits. The Mexican varieties exhibited a great deal of variation with some being red, orange, and lime-green color. The color of the inner pulp and juice was not always identical to the outer peel. This occurred mainly in cultivars which had an orange pulp and a red to yellow peel. The fruit of the Mexican clone 1288 is a light-lime green but is listed here as white, since this is the literal translation of their most common name 'blanca' in Mexico.

Those fruits with the greatest early production included the Brazilian clones 1271 and 1270, the yellow Mexican fruit 1280, and the white Mexican fruited 1288. The especially sweet tasting orange fruited variety 1287 had moderately heavy production. Of these early producers, the Brazilian clones and the Mexican 1280 clones were thornless while the Mexican clones 1288 and 1287 were thorny.

We measured the fruit length, width and fresh weight of these clones. However as we have observed great variation in size of the fruits from the same clone, and as the number of fruits of some of these clones was limited, it would not be appropriate to report fruit sizes. The mean weight of fruits was 88·9 g, with a maximum of 145·9 g.

The pulp and seeds are the edible part of the fruit. All references to pulp include the seeds as well. The percentage of pulp vs. peel was examined for ten clones. The minimum percent pulp, of 49·4% was obtained for Algerian clone 1267. Mexican clones 1288 and 1294 ranked the highest with 72% and 67%, respectively. Brazilian cultivars 1270 and 1271 followed with each having 63% pulp. The mean pulp fresh weight was 50·3 g. The pulp weight for clone 1288 was 71·0 g.

The resistance to the freezing weather of 1990 is also presented in Table 3. The spineless *O. robusta* Wendl. clone 1241, and the spiny Algerian clone of robusta type 1253 had

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Table 3. *Fruit quality, presence of thorns and frost hardiness of* Opuntia *in Texas A&I germplasm collection*

Species	Origin	Accession No.	No. yr*	pH	Acidity	Sugar	Thorn	Fruit colour	Early† Product.	Frost‡ Resistance
O. ficus-indica	CH	1118	2	5·3	0·155	12·4	–	green	low	18 ± 25
O. robusta	SA	1241	1	4·9	0·172	10·0	–	purple	low	99 ± 1
O. hyptiacantha	AG	1253	2	4·9	0·198	9·0	+	purple	low	100 ± 0
O. ficus-indica	AG	1258	1	5·7	0·060	8·5	+	green	low	25
O. undulata	AG	1267	2	4·6	0·137	8·5	–	red	medium	0 ± 0
O. stricta var. *stricta*	BZ	1270	3	5·5	0·120	11·2	–	yellow	heavy	38 ± 18
O. ficus-indica	BZ	1271	3	5·4	0·140	12·2	–	yellow/red	heavy	44 ± 16
O. streptacantha	MX	1273	1	4·1	0·302	10·6	+		low	25
O. streptacantha	MX	1274	1	5·6	0·040	10·4	+		low	98 ± 4
O. ficus-indica	MX	1277	1	4·6	0·244	9·4	–		low	80 ± 13
O. ficus-indica	MX	1280	3	5·4	0·123	12·7	–	yellow	heavy	28 ± 32
O. streptacantha	MX	1281	2	5·4	0·067	10·0	–	red	low	47
O. streptacantha	MX	1283	1	5·3	0·080	11·3	+		low	59 ± 2
O. hyptiacantha	MX	1287	3	5·5	0·113	12·1	+	orange	medium	26 ± 6
O. megacantha	MX	1288	3	5·1	0·131	12·2	+	white	heavy	19 ± 13
O. megacantha	MX	1292	3	5·3	0·130	10·0	+	yellow	medium	25
O. ficus-indica	MX	1294	3	5·3	0·116	9·7	–	red/yellow	heavy	64 ± 16
O. ficus-indica	MX	1296	2	5·7	0·096	10·1	–		low	36 ± 40
O. streptacantha	MX	1298	0				+			92 ± 12
O. megacantha	MX	1299	1	5·0	0·181	9·9	+		low	57 ± 6
O. ficus-indica	MX	1300	2	5·4	0·114	9·9	–	purple	low	52 ± 16
O. ficus-indica	MX	1301	3	5·2	0·111	10·8	–	red	medium	56 ± 19
O. ficus-indica	CH	1319	1	5·7	0·090	10·1	–	green	medium	28 ± 14
O. ficus-indica	CH	1320	1	5·6	0·105	11·5	–	orange	low	57 ± 23
O. ficus-indica	CH	1321	1	5·2	0·015	13·7	–		low	88 ± 11

* Mean for number of years for which fruit data is based. † Fruit production based on 1987 data. ‡ Frost resistance based on survival of 4 month old single pads during a −7°C freeze of Christmas 1990.
AG – Algeria, BZ – Brazil, CH – Chile, MX – Mexico.

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essentially no damage from the freeze. Other promising cold hardy clones included the spiny Mexican clones 1274 and 1298 and the spineless Chilean clone 1321. Unfortunately neither the spiny clones 1274 or 1298 have yet set fruit, so it is not possible to ascertain the fruit potential. While the Chilean spineless clone 1321 produced only a few fruit, they had the highest sugar content (13·7%).

Some of the fruit clones with the highest sugar content had low resistance to freezing weather. For example the spiny Mexican clones, 1288 and 1287 that produced high sugar content fruits three years in a row had only 19% and 26% freeze resistance. Surprisingly while large plants (3 m tall) of 1288 did not resprout from the base after the 1989 freeze, single pads planted only four months prior to the freeze did resprout. Evidently the direction of the wind, presence of secondary infections etc have great influence on the survival of fruit cactus after a freeze.

Due to their promising fruit quality, cladodes of 1288 and 1287 were removed from the mother plant, after the first night of the disastrous Christmas 1989 freeze when temperatures reached −7°C. These cladodes were placed in a heated greenhouse to use as explants for tissue culture propagation and surprisingly the cladodes had no damage. However the next two nights temperatures reached −12°C and both mother plants froze to ground level. Due to their exceptional promise for fruit, clones 1287 and 1288 have been multiplied by slight modifications of an earlier tissue culture procedure (Escobar *et al.*, 1986). [The high protein clone 1270 has also been placed in tissue culture]. Cultures of these clones are available to other researchers.

Discussion

The total soluble solid content of the best fruit clones in this study were generally 11 to 12%. In 1988, three clones had a total soluble content of 13%. These soluble solid contents are similar to those reported in Israel [11·8 TSS in winter and 12·8 TSS in summer] (Nerd *et al.*, 1989) but they are typically lower than that reported by other workers in South Africa and Mexico. For example Wessels (1988) reported that 23 *Opuntia* clones ranged in sugar content from 11% to 14·4% with most clones having at least 13% sugar. Pimienta-Barros (1991) found that most *Opuntia* clones in central Mexico had a total soluble solids content of 12 to 14% and that some clones had as much as 17% sugar. These authors also reported that 93% of the total soluble solids content of one clone consisted of reducing sugars. However, in most clones the reducing sugars were slightly more than half of the total soluble solids. Given the varying degrees of sweetness of glucose, fructose and sucrose it will be important to determine which sugars are present in the fruits.

The low fruit production of some of the clones may be due to inadequate fertility levels. We have provided almost no fertilizer to these plants. Given the fact that the Mexican literature indicates 6000 kg/ha of cow manure to be a low dose (Pimienta-Barros, 1991), we may be able to stimulate fruit production with applications of manure.

It is clear that commercial fruit producing clones have not yet been identified for use in southern Texas. Fortunately Borrego-Escalante *et al.* (1990) at the University Autonoma Agraria Antonio Narro in Saltillo, Mexico have made considerable strides in development of cold hardy fruit varieties over the last 30 years. In March 1991, we conducted a germplasm exchange and are now examining these clones in the field.

A September 1991 collection trip to the mountains south of Saltillo at about 1700 m elevation obtained red, purple, white, yellow, pink and orange fruited clones for unidentified *Opuntia* species that withstood −12°C. We hope that a cold-hardy clone with high sugar content fruits will be identified among this material that will be useful in Texas.

Members of the Texas Prickly Pear Council discovered a thornless *Opuntia* that survived the −12°C freeze of Christmas 1989 without damage when all *O. ficus-indica* (L.) Miller, *O. robusta* types and other spineless types froze to the ground. This −12°C freeze-hardy *Opuntia* appears to be *O. ellisiana* Griffiths as described by Griffiths (1915).

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Somewhat later Benson (1982) concurred with Griffith's description of this species. This clone could be a very useful source of cold tolerant genes for hybridization with less cold hardy fruit clones.

Summary

Despite the fact that our experimental fields are nearly 10 degrees latitude further than commercial *Opuntia* fruit plantations in Sicily, freezing weather seems to be the major constraint to commercial fruit production in Texas. Even the cold hardy *Opuntia robusta* cultivars from South Africa, i.e. Chico, Monterrey and Robusta froze to the ground in December 1989. The lack of freeze hardiness is probably not due to a lack of tolerance to −12°C temperatures *per se* but lack of tolerance to these temperatures without hardening off. Texas winters may be unseasonably mild, i.e. 28°C, followed by temperatures of −12°C in less than 30 h.

Due to the low economic returns of cattle based forage systems in semi-arid regions, often $2–3/ha-y, it is necessary to seek high-value, drought-adapted crops for these regions. Development of cold-hardy *Opuntia* clones that also possess large, high-sugar content fruits and desirable agronomic characters could be a useful tool in economic development of semi-arid regions. The clones under development here will hopefully be useful in other sub-tropical semi-arid regions of the world.

In spite of their low cold tolerance, due to high sugar content, large fruit size, early and large production, the white fruited clone *O. megacantha* Salm-Dyck. 1288 and the orange fruited clone *O. hyptiacantha* A. Weber 1287 deserve pilot scale evaluation in the most southerly regions of the United States. Promising fruit clones that have produced little or no fruits in Texas but with good cold tolerance, i.e. thorny clones 1274, 1275, 1298 and thornless clone 1321 need to be monitored for fruit production and quality. Recently obtained cold hardy fruit, vegetable and forage clones from Borrego at Universidad Autonoma Agraria Antonio Narro in Saltillo and from farmers in the mountains south of Saltillo need to be examined for fruit quality.

Fortunately, spineless cold–hardy *O. ellisiana* clones exist (but with completely unacceptable fruit quality). Clones of this *O. ellisiana* species need to be hybridized with less hardy fruit clones to further increase their winter hardiness for Texas and other regions of the world.

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Estimation of Daily Soil Evaporation Using an Artificial Neural Network

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Estimation of Daily Soil Evaporation Using Artificial Neural Network

ABSTRACT

In field water-balance studies, one of the major difficulties is the separation of evapotranspiration into plant transpiration and soil evaporation. In this paper, the radial basis function (RBF) neural network was implemented using C language to estimate daily soil evaporation from average relative air humidity, air temperature, wind speed and soil water content in a cactus field study. The RBF neural network learned rapidly and converged after about 1000 training iterations. The optimum number of the hidden neurons was found to be 6. The RBF neural network achieved good agreement between predicted and measured values. The average absolute percent error and the root mean squared error was 21.0% and 0.17 mm for the RBF neural network versus 30.1% and 0.28 mm for the multiple linear regression (MLR). The RBF neural network technique appears to be an improvement over the MLR technique for estimating soil evaporation.

INTRODUCTION

In field water balance studies to determine plant water use, one of the major difficulties is the separation of evapotranspiration into plant transpiration and soil evaporation (Fisher and Turner, 1978; Boast, 1986). Evapotranspiration can be obtained by subtracting the change of water stored in the soil profile using neutron scattering method (Heitholt, 1989), surface runoff collected or measured with weirs and deep drainage, from the amount of precipitation for a given period of time (Bannister, 1986). Both plant transpiration and soil evaporation, however, are difficult to determine in the field. A review of literature by Boast (1986) and Bannister (1986) suggested that determination of soil evaporation is relatively easier and less costly than determination of plant transpiration. Therefore, soil evaporation is usually estimated to partition evapotranspiration into soil evaporation and plant transpiration. Thus, the determination of soil evaporation is one of the most important parameters that impact water balance studies.

Soil evaporation can be either directly measured or indirectly estimated. Klock, et al. (1985 and 1990), Showcraft and Gardner (1983) and Boast and Robertson (1982) used a large-scale lysimeter, minilysimeters or microlysimeters to measure daily soil evaporation. These direct measurements were accurate but costly and time-consuming.

The indirect methods developed so far employ mathematical models to predict soil evaporation based on factors relating to

soil water status, plant canopy conditions and evaporative demand. Evaporative demand is in turn related to solar radiation, air temperature, air humidity, and wind speed. Ritchie (1972) developed an empirical energy-based model in which the net radiation, air temperature and leaf area index were used to predict daily soil evaporation from a row crop field. Idso, et al. (1979) also developed an empirical energy-based model in which daily net solar radiation, daily net thermal radiation and soil albedo were used to estimate daily soil evaporation from the bare soil. Al-khafaf, et al. (1978) described two mathematical models that were used in a combined manner to estimate daily soil evaporation after rainfall or irrigation. One also might use regression techniques to establish the quantitative relationship between soil evaporation and other factors.

The artificial neural networks, derived from the structure and functioning of the human brain, have been used in a broad range of applications including pattern recognition, classification, function approximation and automatic control (Rao and Gupta, 1993; Mc Avoy, et al., 1989; Leonard, et al.,1992). In this paper, we will employ the radial basis function (RBF) neural network technique to estimate soil evaporation from a 3-year-old cactus palntation in a semi-arid region, and compare this new technique with a more conventional multiple linear regression (MLR) technique.

METHODS AND MATERIALS

The data was obtained in a 3-year-old experimental planting on a 1.0 m x 1.5 m spacing of slow-growing but cold-hardy spineless Opuntia ellisiana selection (Han, 1993). The non-irrigated field trial was located in a semi-arid, subtropical region of Texas. The leaf area index was 2.02 on April 15, 1994 when the new cladodes was coming out. By May 15, 1994 when this study began, the new cladodes were well-developed. On April 15, 1995, the leaf area index was 3.08. This study ended on February 15, 1995. The leaf area index had a small change during the course of this study. The effect of plant canopy condition on soil evaporation, therefore, was limited. The factors considered in this study include air relative humidity, air temperature, wind speed and soil water content.

Measurement of Soil Evaporation and Soil Water Content

Soil evaporation was measured using microlysimeter technique (Boast and Robertson, 1982; Shawcroft, 1983). The microlysimeters, 10 cm long and 4.9 cm in diameter, were made of 2 mm thick aluminum pipe. The portable electronic balance, used to weigh the microlysimeters, had an accuracy of 0.1 g (0.05 mm of water). The microlysimeters were weighed daily at about 0830 h CDT.

Two lysimeters were placed between the row and two lysimeters were placed under the plant canopy. These four lysimeters were replaced every day. The daily soil evaporation

rate was obtained by averaging the measured soil evaporation rate from the four lysimeters.

To account for seasonal variations in meteorological factors and soil evaporation, daily microlysimeter samplings were conducted over a 15-day period in the spring (May-June 1994), summer (July-Aug. 1994), fall (Oct.-Nov. 1994) and Winter (Jan.-Feb. 1995). The 15-day periods began after a certain amount of precipitation had occurred. No measurable rainfall occurred during the 15-day periods.

Associated with each microlysimeter measurement, gravimetric soil water content (top 10 cm) was obtained at a site adjacent to the microlysimeter location. Three gravimetric soil samples were taken with a hand probe immediately after weighing the microlysimeters. The average gravimetric soil water content over the three samples were obtained and used.

Collection of Meteorological Data

The daily average air temperature, relative humidity and wind speed were obtained from the Texas A&M University Research and Extension Center at Corpus Christi about 40 km away.

Radial Basis Function Neural Network

Artificial neural networks contain highly interconnected and interacting units (neurons) (Haykin, 1994). The artificial neural networks accept a set of inputs (an input vector) from which a corresponding set of outputs (an output vector) is produced

(Wasserman, 1993). In this paper, the radial basis function (RBF) neural network was chosen because of its rapid learning and generality (Wasserman, 1993). By generality, we mean that the network can produce the correct output vector despite insignificant deviations between the input vector and the input vectors used during the training.

A RBF neural network is a multi-layer network whose output nodes form a linear combination of the basis functions computed by the hidden layer nodes (Hush and Horne, 1993). The architecture of RBF neural network choosen in this study, depicted in Figure 1, consists of three layers: input layer, output layer and hidden layer. The input layer contains 4 neurons which receive input signals of relative air humidity (x_1), air temperature (x_2), wind speed (x_3) and gravimetric soil water content (x_4). The output layer contains one neuron which produces a corresponding output, i.e. daily soil evaporation (y), for a given input vector. The number of neurons in the hidden layer significantly affect the network performance. The optimum number of neurons in the hidden layer is determined by the inherent relationship between the input vectors and the output vectors.

All neurons are fully-connected in a feed-forward fashion. More specifically, each neuron in a given layer is connected to each neuron in the layer directly above it by an associated numerical connection weight.

The input neurons simply pass the input signal to each

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hidden neuron and perform no computation. The hidden neurons first compute the Euclidean distance between the input vector and the connection weight vector. Then, the output (activation level) of the hidden neurons is calculated by the Gaussian function (also called as basis function) of the form (Hush and Horne, 1993; Wasserman, 1993):

$$\mu_{h.j}=\exp\left[-\frac{(X-W_{h.j})^{T}(X-W_{h.j})}{2\sigma_{h.j}^{2}}\right] \qquad j=1,2,\ldots,n$$

where $\mu_{h.j}$ is the output of the jth neuron in the hidden layer ("h" indicates the hidden layer), X is the input vector, $W_{h.j}$ is the connection weight vector for the jth hidden neuron to the input neurons, i.e., the Gaussian center for neuron j; $\sigma_{h,j}$ is the normalization parameter for the jth hidden neuron; "T" indicates the transpose operation; n is the number of the hidden neurons.

The outputs of the hidden neurons are in the range from 0 to 1. The closer the input is to the Gaussian center of the hidden neurons, the larger the response of the hidden neurons. The output neuron produces the output for a given input vector by forming a weighted linear combination of the outputs from the hidden neuron. The output layer neuron equation is given by (Hush and Horne, 1993; Wasserman, 1993):

$$Y=W_{o}^{T}\mu_{h}$$

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where y is the output of the output neuron, W_o is the weight vector for this output neuron and μ_h is the vector of outputs from the hidden layer. "T" indicates the transpose operation. The overall network performs a nonlinear transformation by forming a linear combination of the nonlinear basis functions.

For a RBF neural network to map a specific input vector to target output, it must be trained based on a set of known input-output pairs. All connection weights are adjusted according to certain learning rules during training process. The inherent relationship between the input signals and the output signal(s) is stored in these connection weights.

The RBF learning process is broken into two stages: learning in the hidden layer, followed by learning in the output layer. Learning in the hidden layer is performed using K_MEANS clustering algorithm (Hush and Horne, 1993; Lee, 1991), and learning in the output layer is performed using Least Mean Square (LMS) algorithm (Hush and Horne, 1993).

During the first stage, the connection weights between the input neurons and the hidden neurons and the normalization parameters for each hidden neuron are determined. Once the clustering algorithm is complete, the normalization parameter ($\sigma_{h,j}$) is calculated as:

$$\sigma_{h.j}^2 = \frac{1}{m_{h.j}} \sum_{X \in \theta_{h.j}} (X - W_{h.j})^T (X - W_{h.j})$$

$$W_{h.j} = \frac{1}{m_{h.j}} \sum_{X \in \theta_{h.j}} X$$

where $\theta_{h.j}$ is the set of training input vectors (**X**) grouped with the Gaussian center of the jth hidden neuron ($W_{h.j}$), $m_{h.j}$ is the number of the training input vectors in $\theta_{h.j}$.

During the second stage, the connection weight between the hidden neurons and the output neuron are determined. The K_MEANS and LMS algorithms were described in detail by Hush and Horne (1993). The C programming language implementation of these algorithms can be obtained from the senior author.

Soil Evaporation Prediction by Regression Technique

Least square error fitting was conducted using SAS statistical software package to determine the multiple linear regression equation.

RESULTS and DISCUSSION

The data set consisting of 53 input-output pairs from the experiment described above was randomly split into a training set and a test set. The training set had 40 input-output pairs and the test set 13. Table 1 shows some statistics of the training set.

To improve the neural network performance, the input vector was normalized by the following procedure: each component of the input vector first decreased by the corresponding component of the mean vector (Table 1) and then this difference was divided by

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the corresponding component of the standard deviation vector (Table 1). The training data set was used to adjust the connection weight. The test data set was used to test the performance of the neural network.

Determining the Required Training Iterations and Optimum Number of the Hidden Neurons

The root mean squared error (SE) for the test data set was used to evaluate the performance of the neural network. The test data set is shown in Table 2. The SE is defined as:

$$SE = \left(\frac{\sum (Y_m - Y_p)^2}{n}\right)^{\frac{1}{2}}$$

where y_m is the measured soil evaporation, y_p is the predicted and n is the number of the input vector in the test data set (n=13).

Figure 2 gives a plot of SE vs. the number of the training iterations in the second stage when the number of the hidden neurons is 5. It can be seen that the network learns rapidly. After 1000 iterations, the network has converged.

In theory, the RBF neural network is capable of forming an arbitrarily close approximation to any continuos nonlinear mapping (Park, 1991). For a given input-output space, the number of hidden layers and the number of neurons in the hidden layer significantly affect the performance of the neural network (Li, et al., 1993). Figure 3 gives a plot of SE vs. the number of hidden neurons for a converged network (with 1200 training

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iterations). As computation time increases dramatically with the number of hidden neurons, it was determined that six hidden neurons were optimum.

The Performance of RBF Neural Network and Multiple Linear Regression

The predicted soil evaporation shown in Table 2 was obtained from the converged RBF neural network with six hidden neurons. As can be seen good agreement is achieved. The average, maximum and minimum absolute percent error compared to the measured value are 21.0%, 49.6% and 1.9%. The root mean squared error was 0.17 mm.

To compare the RBF neural network with MLR, the same 40 input-output pairs in the normalized training data set were used to obtain the following regression equation:

$$Y_p = 0.726 - 0.054x_1 + 0.181x_2 + 0.057x_3 + 0.549x_4 \quad (R^2 = 0.76)$$

Where Y_p is the predicted daily soil evapotranspiration (mm), x_1 is average relative air humidity (%) , x_2 is average air temperature (°C) , x_3 is average wind speed (km hr^{-1}) and x_4 is gravimetric soil water content (g g^{-1}).

The same 13 input-output pairs were used to test the performance of the MLR. From Table 2, the average, maximum and minimum absolute percent error were found to be 30.1%, 95.1% and 2.0%, respectively. The root mean squared error was 0.28 mm.

It can be seen that the RBF neural network in this study had a lower absolute percent error and root mean squared error in predicting soil evaporation than did multiple linear regression

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technique. What is more important, the RBF neural network (the artificial neural network technique in general) offers significant advantages over the MLR and other conventional methods in predicting soil evaporation because it is not necessary to specify the form of the mathematical model before fitting the data. Any processes in a agronomic system have many factors involved and change with time. It is often difficult to find an appropriate mathematical model to describe these processes. We strongly feel that the neural network is a promising technique in understanding the processes in the complicated and dynamic agronomic system.

The RBF neural network described here was used to estimate yearly soil evaporation and thus separate plant transpiration from evapotranspiration in a 4-year field study to measure water use efficiency of Opuntia ellisiana. We obtained annual soil evaporation estimates of 249 mm in 1993 and 244 mm in 1994. While the RBF neural network appears promising in estimating soil evaporation, it will be necessary to test it using data sets from different geographical regions and compare it with a currently accepted model. In the future the RBF neural network could be further generalized with incorporation of factors such as leaf area index.

Table 1. Simple statistics of the data set used to train the RBF neural network to predict daily soil evaporation (n=40).

Factors	Mean	SD	Minimum	Maximum
Relative Humidity (%)	76.91	10.01	56.49	96.27
Air Temp. (°C)	22.30	6.63	9.17	30.00
Wind Speed (km/h)	11.28	4.23	4.93	21.46
Top 10 cm Soil Water Content (g/g)	0.084	0.026	0.040	0.172
Dail Soil Evap. (mm)	0.73	0.57	0.19	2.44

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Table 2. Test data set, measured soil evaporation and predicted soil evaporation using both RBF neural network and multiple linear regression.

No.	Relative Humidity (%)	Air Temp. (°C)	Wind Speed (km/hr)	Soil Water Content (g/g)	Y_m† (mm)	Y_p‡ (mm) RBF	Y_p‡ (mm) MLR	APE§ (%) RBF	APE§ (%) MLR
1	88.80	23.86	11.80	0.148	1.58	1.75	2.05	11.09	29.66
2	74.26	22.41	4.12	0.116	1.04	1.27	1.31	22.49	26.79
3	78.92	24.17	8.13	0.084	0.58	0.29	0.73	49.56	25.46
4	86.20	28.47	8.81	0.097	0.96	1.04	1.09	8.72	12.97
5	82.73	27.56	5.96	0.083	0.74	0.58	0.75	20.98	1.97
6	79.89	27.86	11.22	0.051	0.37	0.25	0.18	31.89	52.09
7	80.93	28.61	13.73	0.051	0.32	0.43	0.23	34.98	28.87
8	87.12	19.59	18.74	0.090	0.42	0.55	0.83	29.36	95.09
9	86.56	28.83	6.81	0.108	1.51	1.57	1.30	3.68	14.23
10	85.62	24.88	4.93	0.122	2.13	2.00	1.46	6.51	31.63
11	80.47	28.33	14.39	0.051	0.41	0.44	0.23	7.04	43.45
12	67.17	13.07	14.20	0.098	0.77	1.12	0.86	44.71	11.44
13	83.46	25.17	5.22	0.128	1.93	1.97	1.61	1.94	16.77

†the measured soil evaporation.
‡the predicted soil evaporation.
§the absolute percent error.

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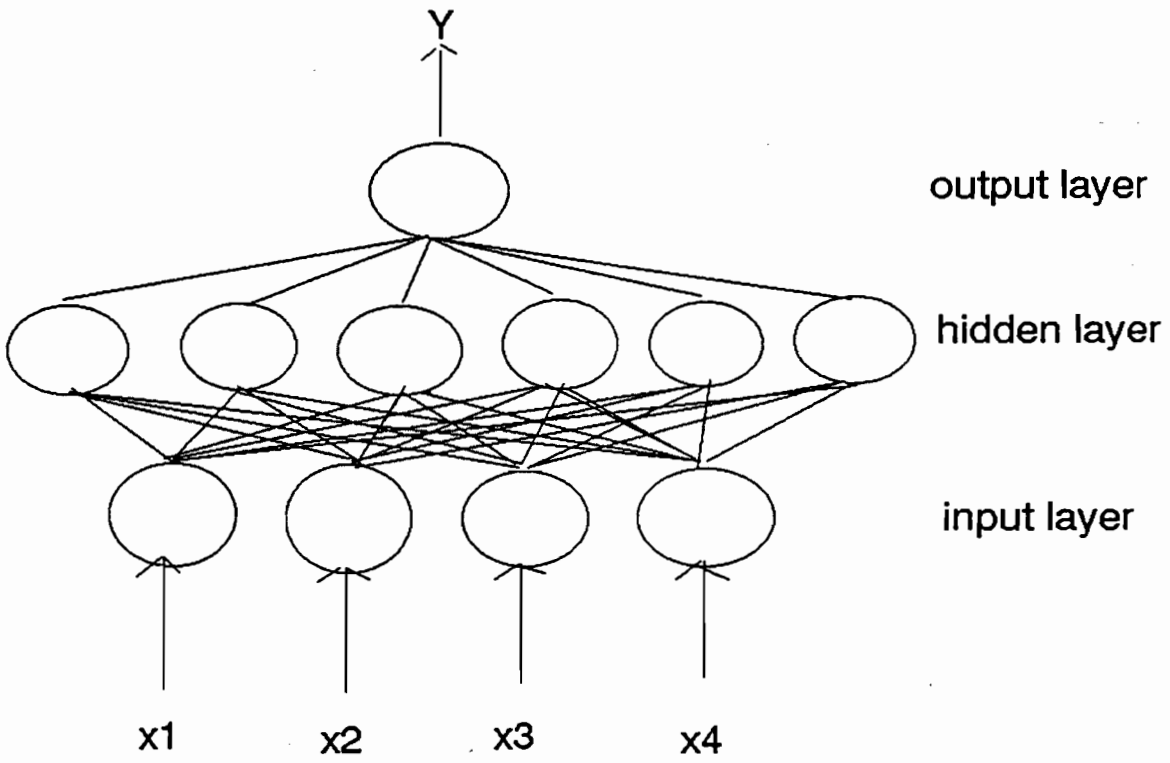

Fig.1. Architecture of the RBF neural network.

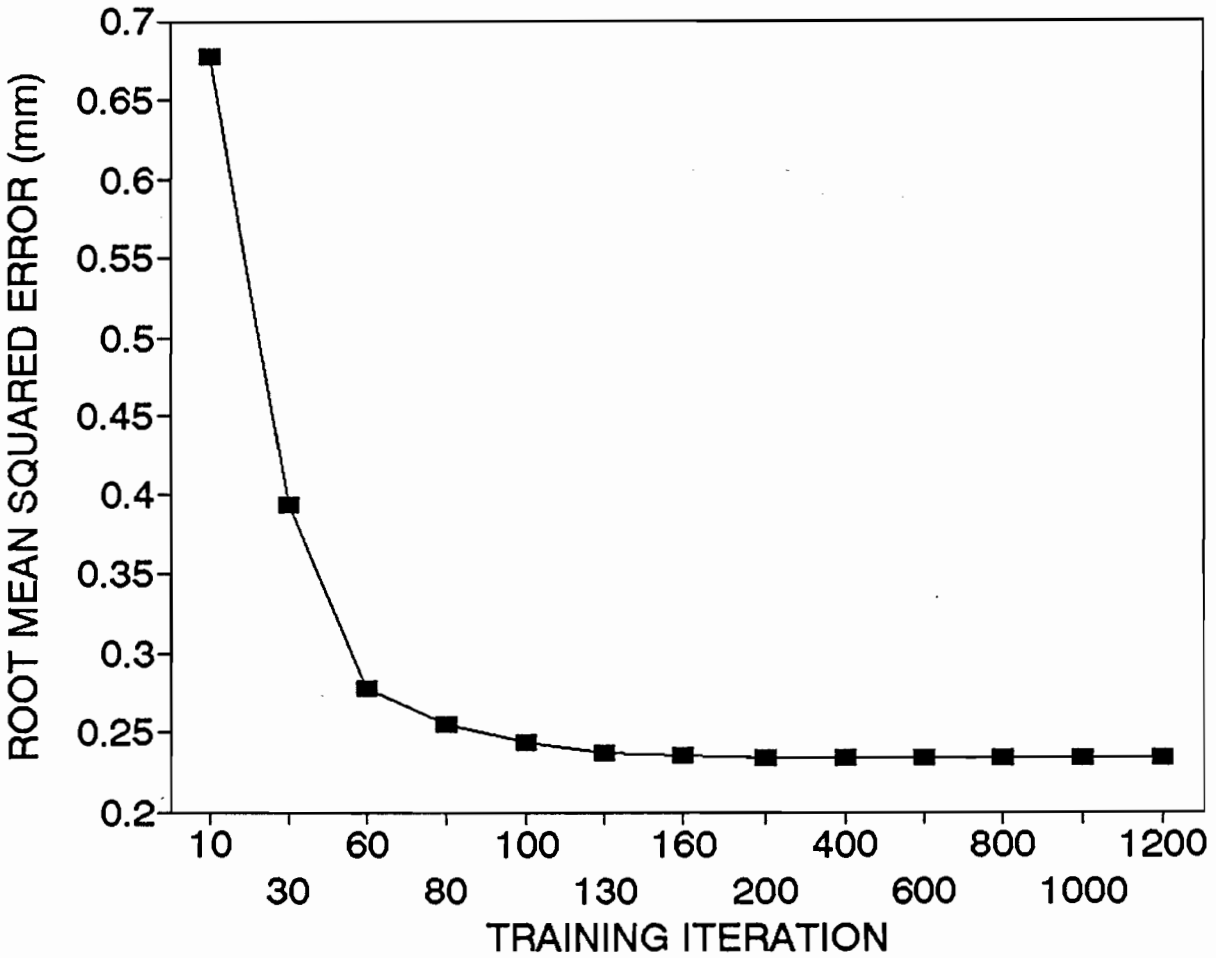

Fig. 2. Predicted root mean squared error vs. training iterations.

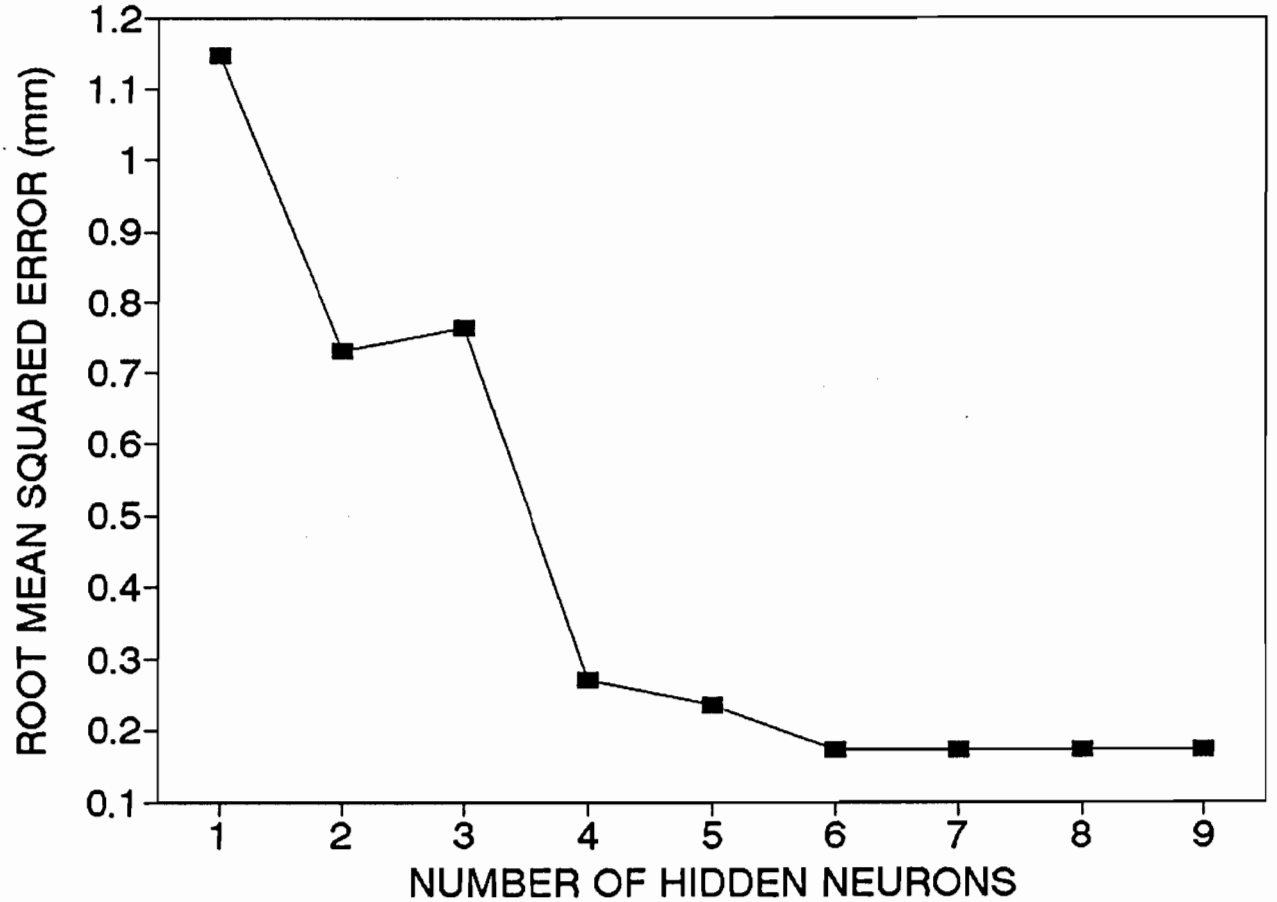

Fig.3. Predicted root mean squared error vs. number of hidden neurons.

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Field Validation of Water Use Efficiency of a CAM Plant *Opuntia ellisiana* in South Texas

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Field Validation of Water Use Efficiency of a CAM Plant *Opuntia ellisiana* in South Texas

ABSTRACT

In single plant studies, at time scales less than a growing season, the conversion efficiency of water to dry matter, has been shown to be several times greater for CAM plants than either C3 or C4 plants. The objective of this work was to determine if this high conversion efficiency would occur at the field level over an entire growing season.

Thus *Opuntia ellisiana* water use efficiency values were obtained under field conditions in the third and fourth years growth of a plantation. Although *O.ellisiana* is the slowest growing of all the spineless *Opuntias*, it was used because it is the only spineless *Opuntia* that is completely cold hardy in Texas. Aboveground dry matter production was obtained by complete harvest and by estimating aboveground biomass with regression techniques. Evapotranspiration was estimated as the precipitation minus runoff, deep drainage, change in soil water content and water stored in the plant. In the fourth year, surface runoff was captured and measured in below ground tanks. Based on the measurements, surface runoff in the third year was estimated using the regression technique. Soil evaporation was directly measured over a 2 week period, at 4 times year^{-1} using microlysimeters. Using these direct soil evaporation measurements and companion meterological data, yearly transpiration was computed using a Radial Basis Function (RBF) neural network. This yearly soil evaporation estimate allowed the

separation of transpiration from evapotranspiration.

At the beginning of the fourth years growth Opuntia ellisiana achieved a LAI of 2.02. In the fourth year, 662 mm rainfall occurred. Soil evaporation (214 mm) and runoff (143 mm) were the major losses. A significant quantity of water (17 mm = 170,000 kg ha^{-1}) was stored in the cactus that could be of use for animal drinking water. The cactus transpired 285 mm of water producing 17,670 kg dry matter ha^{-1} for a transpiration water use efficiency of 162 Kg H_2O Kg^{-1} dry matter. This is the greatest water use efficiency of any plant species(including C3 and C4) that has been measured under long term field conditions. While this particular species is not particularly useful, other less cold hardy Opuntias are widely used for fruit, vegetable and forage. Given water shortages on arid lands, much more development attention needs to be given to useful Opuntia species.

INTRODUCTION

Water use efficiency (WUE) has been defined as the amount of water used per unit of plant material produced (Kramer, 1987). This definition may be too broad in that it embraces water use efficiencies obtained in diverse time and process scales. The plant material can be expressed as carbon dioxide assimilation, total biomass, or yield; the water use can be expressed as transpiration, evapotranspiration or total water input to the ecosystem; and the time-scale can be instantaneous, daily or seasonal (Sinclair, 1984). Sinclair (1984) stressed that water use efficiency obtained at different time and process scales should not be interchangeably used.

Frank (1987) compared WUE of field grown cultivars of crested wheatgrass [Agropyron desertorum (Fish. ex Link) Shult.], intermediate wheatgrass [Thinopyrum intermedium (Host) Back Worth and Dewey], and western wheatgrass [Pascopyrum smithii Rybd (Love)] to identical plants grown in a controlled environment. The results showed that the ratio, A/E, of the net CO_2 assimilation (A) to transpiration rate (E) were consistently larger than WUE calculated from dry matter accumulation and total evapotranspiration for field grown plants for the three cultivars. Moreover, the rankings for these grass species between A/E values determined in the controlled environment and WUE values determined in the field were different with crested wheatgrass having the smallest A/E but the highest WUE. Fisher and Turner (1978) also suggested that plant characters such as

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leaf morphology, stomatal apertures and plant ontogeny in addition to the environment can significantly affect WUE estimated from gas exchange ratios.

It has been widely accepted that plants possessing Crassulacean Acid Metabolism (CAM) have higher water use efficiency than C_3 and C_4 plants. Black summarized (1973) that the transpiration ratio for CAM plants ranged from 50 to 125 kg H_2O kg^{-1} CO_2, which is much higher than from 450 to 950 kg H_2O kg^{-1} CO_2 for C_3 plants and from 250 to 350 kg H_2O kg^{-1} CO_2 for C4 plants. The transpiration ratio of 50 kg H_2O kg^{-1} dry matter for pineapple was reported by Joshi (1965). Neales (1968) estimated transpiration ratios of 154 kgH_2O $kg^{-1}CO_2$ for Aeonium hawarthii, 47 kgH_2O $kg^{-1}CO_2$ for Agave americana and 116 kgH_2O $kg^{-1}CO_2$ for pineapple. Meinzer (1973) obtained a transpiration ratio of 135 kgH_2O kg^{-1} dry matter for Echeveria pumila (a CAM plant) in greenhouse experiments. These studies were conducted at leaf or single plant level in a controlled environment over a short period of time. Studies on water use efficiency of CAM plants at plant community level under field conditions over a whole growing season has not been reported in the literature. From an agronomical point of view, however, this kind of study is of great significance, both in theory and in practice.

The main objective of this study was to determine whether the high water use efficiency of CAM plants reported in greenhouse studies and short term, single "leaf" field studies could be obtained in the field. To accomplish this, the cold

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hardy, spineless Opuntia ellisiana was grown in the field where the precipitation, runoff, soil evaporation and moisture changes in the soil profile were measured to determine plant transpiration. Three plots were harvested at 1,2,3 and 4 years of age to determine dry matter productivity. From the annual dry matter productivity and plant transpiration, the water use efficiency was determined.

METHODS AND MATERIALS

Site Description

The study site was located on the northwestern part of the Texas A&M University - Kingsville campus, in Kingsville, Texas. The Hidalgo fine loam soil was well-drained and lacked a fluctuating ground water table in its deep layer.
Mean daily maximum temperatures exceeded 30°C from April through October. Mean daily maximum temperatures were 35°C for June and 36 °C for July and August. The mean annual precipitation was 700 mm with 22.8% occurring during May and June and 29.8% during August and September. September was the month with the greatest amount of precipitation (NOAA,1991).

Experimental Design

The experiment used a randomized complete block design with 3 blocks and 4 treatments (harvest dates) per block (total of 12 plots). Dry matter production was determined by harvesting 3 plots of cactus every year for 4 years on April 15 of 1992, 1993,

1994 and 1995. The crop water use was obtained from a water budget involving measurements of soil water evaporation, soil water extraction in the profile, estimates of surface runoff and precipitation.

Opuntia ellisiana Griffiths. was planted using single cladodes on a 1.5 m between-row spacing and a 1 m in-row spacing on April 1,1991. Although this species is slower growing than other spineless species such as Opuntia ficus-indica, it is the only spineless Opuntia species that survived the freeze in 1989 (-12°C) without any damage. Due to the necessity for working closely among the plants it was desirable to use a spineless species.

Plots were separated from field and each other by dikes (Fig. 1). Each 12 m long and 9 m wide plot had 6 rows of 12 plants per row. In each plot, 5 access tubes were placed between the two rows in the middle of the plots and 3 tubes were placed in the rows (Fig.1). This was done to assess differences in moisture use within and between rows. The access tube was 130 cm above the ground and below the ground.

To avoid fertility limitations on WUE, 91 kg ha^{-1} of N, P_2O_5 and K and 2.4 kg ha^{-1} S, 0.81 kg ha^{-1} B, 1.92 kg ha^{-1} Cu, 4.5 kg ha^{-1} Fe, 4.8 kg ha^{-1} Mn, 0.024 kg ha^{-1} Mo and 2.7 kg ha^{-1} Zn were applied each spring.

Since unweeded cactus plots were shown to have 300% less biomass production in the first year of growth than weeded plots (Russell and Felker, 1987), herbicides were used for weed

control. To control the troublesome perennial grasses, Johnson grass (Sorghum halepense) and Bermudagrass (Cynodon dactylon), the herbicide glyphosate (Roundup) (N-(phosphonomethyl) glycine) was used at a concentration of 1.5%. For long term pre-emergence weed control, the herbicide tebuthiuron (Spike) (N-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-N,N'-dimethylurea) was used at a rate of 2.5 kg/ha. The plots were virtually free of grasses and broadleaf weeds during entire experimental period.

The fungicide BANROT (5-ethoxy-3-trichloromethyl-1,2,4-thiadiazole and dimethyl 4,4'-O-phenylenebis), the bacteriacide agri-strep (streptomycin sulfate) and insecticide ORTHENE (acephate (O,S-dimethyl acetylphosphoramidothioate)) were also applied to prevent or control diseases and insects.

Determination of Evapotranspiration and Plant Transpiration

The soil water balance equation desribed by Fisher and Turner (1978) was used in determining evapotranspiration and plant transpiration. Due to the fact that cactus can store a large amount of water in its aboveground part, in this study, an additional component called plant water content change (ΔP_w) was included in the soil water balance equation.

$$P=ET+Rs+Rd+\Delta S+\Delta P_w=E+T+Rs+Rd+\Delta S+\Delta P_w \qquad (1)$$

Where P is precipitation, ET is evapotranspiration, E is soil evaporation, T is transpiration, Δs is soil water content change, Rs is surface runoff and Rd is deep drainage. When precipitation, surface runoff, soil water content change, plant

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water change and deep drainage are known, ET can be calculated as:

$$ET=P-Rs-Rd-\Delta S-\Delta P_w \qquad (2)$$

When soil evaporation is known, T can be calculated as:

$$T=ET-E=P-Rs-Rd-\Delta S-\Delta P_w-E \qquad (3)$$

Precipitation

Each rainfall event was measured with three Tenite rain gauges that had an accuracy of 0.21 mm.

Soil water content change

A Troxler 4300 neutron probe was used to measure volumetric soil water contents. The neutron probe was calibrated both in the laboratory and in the field. We chose our field calibration curve over the laboratory calibration curve because it had a lower estimate error of regression. The field calibration curve was:

$$SWC=-0.0435+0.6793xCR \quad (R^2 = 0.83)$$

where SWC is volumetric soil water content (g cm^{-3}) and CR is the neutron probe count ratio. During the field calibration process, the soil bulk density was found to be 1.93 g cm^{-3}, 1.75 g cm^{-3}, 1.76 g cm^{-3}, 1.80 g cm^{-3} and 1.85 g cm^{-3} for the 25 cm, 50 cm, 75 cm, 100 cm and 125 depth respectively.

Neutron probe readings were taken at 25 cm depth increments from 25 cm to 125 cm once a month. The measurements began on April 15, 1991 and ended on April 15, 1995. Because the top 15 cm soil water content could not be accurately measured by the

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neutron probe, the moisture content of this zone was measured by the oven-drying method (at 105°C). When the neutron probe readings were taken, three soil samples of the top 15 cm were taken from 2 widely separated plots, and converted into volumetric soil water content using the soil bulk density. The average volumetric soil water content for these 2 plots was used for all 12 plots.

The volumetric soil water content data obtained by the neutron probe from 12.5 to 137.5 cm and the oven-drying method of top 15 cm were combined to calculate the change of water stored in the entire soil profile from 0 to 137.5 cm. As there was very little change in neutron probe readings at the 137 cm depth throughout the year, we assumed the deep drainage to be negligible (Rd=0).

Soil evaporation

To obtain yearly estimates of soil evaporation we directly measured daily soil evaporation over a 15-day period in the spring (May-June 1994), summer (July-Aug. 1994), fall (Oct.-Nov. 1994) and Winter (Jan.-Feb. 1995) with microlysimeter measurements. Then a radial basis function (RBF) artificial neural network was developed to estimate daily soil evaporation throughout the year from air temperature, relative air humidity, wind speed and soil water content (Han and Felker, 1995). The RBF neural network was implemented using C programming language and trained based on 40 measured input-output pairs. The RBF neural network had a substantially lower standard error for

prediction of soil evaporation than did a multiple linear regression with the same 4 input variables.

The 10 cm long and 4.9 cm diameter microlysimeters were made from 3 mm thick aluminum pipe. A portable electronic balance used to weigh the microlysimeter had an accuracy of 0.1 g (0.02 mm of water). The microlysimeters were weighed daily at about 0830 h CDT. Two lysimeters were placed between the row and two lysimeters were placed under the plant canopy. Soil cores in the four lysimeters were replaced every day.

For each microlysimeter measurement, a paired gravimetric soil water content (top 10 cm) was obtained at a site adjacent to the microlysimeter location. Three gravimetric soil samples were taken with a hand probe immediately after weighing the microlysimeters.

The daily average air temperature, relative humidity and wind speed were obtained from the Texas A&M University Research and Extension Center at Corpus Christi about 40 km away.

Surface runoff

Surface runoff was measured in 2 plots the fourth year by collecting the runoff in cylindrical tanks 2.18 m in diameter and 1.82 m tall that were placed in below-grade pits (Fig.1).

Based on the surface runoff measurement in the fourth year, a multiple linear regression technique was employed to establish a quantitative relationship between surface runoff, rainfall amount and top 10 cm soil water content prior to the rainfall. This regression was also used to estimate the surface runoff in

the third year.

Plant Water Content Change

Plant water content change is defined as the change of water stored in the aboveground plant materials over a given period of time. It can be measured by determining the aboveground fresh weight and plant water content at the beginning and the end of the period.

Dry matter production

The aboveground biomass production was measured by a complete aboveground harvest. While all 6 rows in the plots were harvested, to avoid a border row influence on the biomass estimation, the biomass estimates excluded the plants in the outer 2 rows and the 2 plants on the end of each row. Thus, the entire weight of the 16 individual plants in the interior 2 rows were measured. To determine the moisture content, sample plants were placed in a drying room at 70°C until no further change in the weight was observed.

One estimate of yearly dry matter production was obtained by subtracting the dry matter production (average over three plots) from one harvest date from that (average over three plots) in the subsequent harvest date. However, some error was incurred due to the nonuniformity of soils and different microclimates between plots.

To avoid this problem, the dry matter production in non-harvested plots was nondestructively estimated by regression techniques. Two types of regression were evaluated for use in

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non-destructive predictions of the standing biomass (Table 1). The first technique applied a regression equation between cladode width and cladode fresh weight to all the cladode widths on the chosen plant. The second technique involved harvest of about 50 plants to determine the relationship between total plant fresh weight and total plant cladode number.

For small plants in the first year, the cladode width approach gave the lowest standard error. However as the plants became larger, the total cladode weight per plant derived from cladode widths, consistently underestimated the plant weight. Perhaps this was attributable to heavier cladodes in the lower portions of the plant that had the same cladode width as lighter, less mature cladodes.

Leaf (cladode) area index (LAI)

The leaf area index was determined by applying the regression equation: $A=-110.69+23.54(MW)$ where A is leaf (cladode) area (cm^2) and where MW is maximum cladode width (cm), to the maximum width of all cladodes on 2 of the 16 sample plants. This equation was based on paper tracings of 53 randomly selected cladodes. The cladode area of the remaining 14 plants per replicate was obtained based on the ratios of their cladode number to the cladode number of the 2 sample plants.

Calculation of Evapotranspiration Water Use Efficiency (WUEet) and Transpiration Water Use Efficiency (WUEt)

Evapotranspiration and transpiration water use efficiency

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were calculated as:

$$\text{WUEet (Evapotranspiration Efficiency)} = \frac{\text{Evapotranspiration}}{\text{Dry Matter Production}}$$

$$\text{WUEt (Transpiration Efficiency)} = \frac{\text{Transpiration}}{\text{Dry Matter Production}}$$

RESULTS

Dry Matter Production and Leaf Area Index

The standing dry biomass, annual growth, leaf area index and rainfall for 4 the year period are presented in Table 2 and Table 3. The annual growth increased by about 250% from the first to second year and from the second to third year but only a 30 % increase in the fourth growing season. There is no apparent trend between the rainfall of 1016, 675, 833 and 622 mm in the first to four years growth and the annual rainfall. In contrast, these growth rates parallel the leaf area indices of 0.06 ± 0.01, 0.39 ± 0.08, 2.02 ± 0.49 and 3.88 ± 0.50 at the end of the first to fourth years growth respectively.

Evapotranspiration and Plant Transpiration

Due to the low leaf area index and high soil evaporation during the first 2 years, we only present evapotranspiration and plant transpiration for the last two years.

The rainfall that occurred during the last two years growth is presented in Fig 2. The total rainfall was 833 mm for the third year and 662 mm for the fourth year. We considered a

rainfall event whose amount was equal to or greater than 40 mm as a heavy rain storm and rainfall event whose amount was less than or equal to 5 mm as a light rain. In the third year, there were 44 rainfall events. Of these 7 were heavy rain storms with a total rainfall of 452 mm, which accounted for 54 % of the 833 mm annual rainfall. In the fourth year, there were 51 rainfall events. Of these 4 were heavy rain storms with a total rainfall of 240 mm, which accounted for 36 % of the annual rainfall of 662 mm.

The number of the light rainfall events in the third year was 15, which accounted for 34% of the total of 44 rainfall events of 44 for a total rainfall of 38 mm. The number of light rainfall events in the fourth year was 23, which accounted for 45% of the total rainfall events for a total rainfall of 61 mm.

The predicted total surface runoff in the third year was 252 mm, which was 30% of the annual rainfall. The measured total surface runoff in the fourth year was 143 mm, which was 22% of the annual rainfall.

The yearly change in soil water content, grouped according to year of harvest is presented in Table 4. In the fourth growing season, the change in soil water content for the profile was nearly the same whether the plots had never been harvested (standing dry biomass ranging from 36,454 to 41,926 kg/ha) or whether the plots were nearly bare with a harvest only 1 year earlier. The 4-year results (data are not included in this paper) showed that water stored in the soil profile increased not

more than 15 mm even in the rainy season and decreased not more than 10 mm even in the dry season. We believe the small changes in soil moisture in the 15 to 135 cm depth are the result of the occurrence of the significant amount of surface runoff and soil evaporation, and Opuntia ellisiania's shallow root system. This confirms early finding of Nobel (1988) that the cactus root system is very shallow in being confined to the top 15 cm (where unfortunately is not possible to use neutron probes).

Based on the precipitation characteristics in this study area as discussed earlier and the surface runoff measurements for each rainfall event in 1994 (Table 5), it is quite safe to assume that rainfall event less than 15 mm does not result in surface runoff irrespective of the soil water content prior to the rainfall. If it does, the amount of the surface runoff is negligible. Correlation coefficients between surface runoff and rainfall amount and between surface runoff and antecedent soil water content were 0.85 ($p=0.001$ and $n=11$) and 0.52 ($p=0.106$ and $n=11$). Stepwise regression found that the partial regression coefficient for the rainfall amount was 0.73 ($p=0.0008$) and for the antecedent soil water content 0.18 ($p=0.0035$). This indicated that both rainfall amount and antecedent soil water content had an significant effect on surface runoff. The estimation equation was:

$$S_R = -23.9129 + 0.6438(P) + 143.0971(ASWC)$$

where S_R is surface runoff (mm) , P is rainfall amount (mm) and ASWC is antecedent soil water content ($g\ g^{-1}$). The R^2 value

for this model was 0.91 and the root MSE of this model was 5.69 mm. This equation was used to estimate the surface runoff generated by the rainfall events in the third year (Table 6).

Examples of the daily soil evapotranspiration obtained in the third year and fourth year with the trained RBF neural network(Han and Felker, 1995) are presented in (Table 7). It was assumed that the daily soil evaporation was negligible when the daily rainfall was greater than 5 mm. The estimated daily soil evaporation ranged from 0.20 mm d^{-1} to 2.5 mm d^{-1}. The potential soil evaporation in this area ranges from 3 to 5 mm depending on the evaporative demand. The total soil evaporation (E), the sum of the daily soil evaporation, was 249 mm for 339 days (average daily soil evaporation was 0.73 mm) in the third year and 214 mm for 337 days (average daily soil evaporation was 0.64) in the fourth year.

The average evapotranspiration (ET) over plots 3,4 and 11 was 559 mm in the third year and 499 mm in the fourth year. The computed average transpiration was 310 mm in the third year and 285 mm in the fourth year.

The water balance for the third and fourth year of this trial (Table 8) shows that less than half of the precipitation was transpired. In the third year which had higher rainfall, the runoff and soil evaporation were nearly identical, while in the fourth year with lower rainfall, the soil evaporation was considerably greater than the runoff. In both years the soil water content change was relatively insignificant.

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While the water content of the plant is normally not reported in water balance studies, in the case of cacti with very high moisture content, the amount of water contained in the annual growth was greater than the soil water content change. The water content for the 4-year-old Opuntia ellisiana was 90.9%. It is obvious that the water contained in the 4th years growth (176,516 Kg H_2O ha^{-1}) could greatly reduce water requirements for livestock in water short arid lands.

To facilitate comparison of our data with other reports where soil evaporation was not measured, we have included the water use efficiency based on both the transpiration and evapotranspiration in Table 8.

The mean transpiration water use efficiency of 162 kg H_2O kg^{-1} dry matter for the fourth year obtained in Table 8 is greater than that obtained for any plant in any other replicated field trial where the influences of border effects were taken into account.

DISCUSSIONS AND CONCLUSIONS

While the biomass productivity of this cold hardy cactus was very low in the first 2 years, after the cacti reached a Leaf Area Index of 2.02, a dry biomass productivity of 17,670 kg ha^{-1} $year^{-1}$ was achieved that is comparable to many C_3 and C_4 plants. The low productivity in the early years of the planting seems due to low LAI and not rainfall since the rainfall was highest in the first year and since Garcia and Nobel (1986) found that Opuntia

ficus-indica required a leaf area index of about 4 for high productivity.

Other studies with cacti have reported productivities even greater than the 17,670 kg dry matter ha^{-1} $year^{-1}$ that we measured. In a replicated, non-irrigated fertility trial, Gonzalez (1989) obtained a dry matter productivity of 62,000 kg dry matter ha^{-1} $year^{-1}$ha over the last 4 years of his experiment where the annual rainfall was 430 mm/year. When irrigated and fertilized, Opuntia ficus-indica and Opuntia amyclea had productivities of 47,000 and 45,000 Kg ha^{-1} yr^{-1} in Santiago, Chile and Saltillo, Mexico (Nobel, 1992).

However, caution must be excercised with these high productivities since the full disclosure of experimental details regarding control of border influences on productivity of small plots was not provided in these reports. To illustrate the problems of influence of border on productivity, Zavitkovsky (1981) found that for closely planted trees, (0.3 m x 0.3 m) the outer row had 800 % greater biomass than the plot interior and that the border influence extended 5 rows into the plot.

Opuntia ellisiana is a slower growing species compared to other Opuntia species such as Opuntia ficus-indica. For example, while these O. ellisiana were less than 1.5 m tall at the end of 4 years, other less cold-tolerant Opuntia ficus indica planted at the same time in adjacent plots for fruit production were over 4 m tall in same time period. Thus it would be very interesting to repeat this experiment in a frost-free region where the WUE of

faster growing cacti could be measured. Dry-matter-based WUEt of these species can be expected to be higher than Opuntia ellisiana. In contrast to these managed Opuntia plantations, the productivity of non-managed arid zones is typically much less i.e. on the order of 1000 kg aboveground dry matter ha^{-1} yr^{-1} (Leith and Whittaker, 1975).

More significantly than the high production of biomass, the cacti achieved this productivity while only transpiring 285 mm water for a water use efficiency of 162 kg H_2O kg^{-1} dry matter. Neither the comprehensive review of Fisher and Turner (1978) or the classic work of Briggs and Shantz (1914) report dry matter based water use efficiencies as high as those reported here.

The transpiration ratio (equivalent to transpiration water use efficiency) has been reported to range from 50 to 125 Kg H_2O kg^{-1} dry matter for CAM plants, from 250 to 350 Kg H_2O kg^{-1} dry matter for C_4 plants and from 450 to 950 for C_3 plants Kg H_2O kg^{-1} dry matter (Black, 1973). Joshi et al (1965) reported that for an 80-day period, pineapple growing in a green house in North Carolina during the winter had a transpiration ratio of 50 Kg H_2O kg^{-1} dry matter. The pineapple is the fastest growing species among CAM plants (Kluge and Ting, 1978). Neales et al (1968) reported transpiration ratios of 154 mg H_2O mg^{-1} CO_2 for Aeonium hawarthii, 47 mg H_2O mg^{-1} CO_2 Agave americana and 116 mg H_2O mg^{-1} CO_2 for pineapple. Nobel (1977) found that the barrel cactus, Ferocactus acanthodes, growing in natural stands, had transpiration ratios of 105 mg H_2O mg^{-1} CO_2 during the hot months

and 18 to 24 mg H_2O mg^{-1} CO_2 during the cooler season.

Because of the difficulty of partitioning evapotranspiration into soil evaporation and plant transpiration, evapotranspiration water use efficiency were most often obtained in the field studies. Sryman (1989) reported the WUEet for grass species Cymbopogen plurinodis and Panicum stapfianum during the 1986-1987 season was 1277 kg H_2O/kg dry matter and 2119 kg H_2O/kg dry matter. When given a high rate of N fertilizer (168kg/ha), a mixed prairie plant community whose major species were western wheatgrass (Agropyron smithii) and needleandthread (Stipa comata) in Montana had a dry matter production of 2389 kg/ha and WUEet of 1160 kg H_2O/kg dry matter when it reached maturity (Wight and Black, 1978). Wight and Black (1979) also reported that the annual precipitation use efficiency for a fertilized mixed prairie plant community in eastern Montana ranged from 987 kg H_2O/kg dry matter to 3184 kg H_2O/kg dry matter over a 10-year period. Under favorable water and nutrient conditions, a plant community comprising of blue grama (Bouteloua gracilis) and western wheatgrass in Mandan,North Dakota had a WUEet of 2236 kg H_2O/kg dry matter (Smika,1965). WUEet of corn with a population density of 74,000 plants/ha from planting to harvest (about 6 months) was about 385 kg H_2O/kg dry matter (Alessi and Power, 1976).

The relationship between WUE obtained at different process and time scales are complicated. For a given plant species, the WUEt based on the dry matter production will necessarily be lower

than the WUEt at gas exchange level (Fisher and Turner, 1978). For example, some of CO_2 fixed during the day will be respired during the night and in nonphotosynthetic tissue. The photosynthetic activity ceases at night while the transpiration is still active. Dry matter might be lost due to water stress, diseases and insects. Root dry matter is usually not included as is the case in this study. Also the WUE for the same crop (such as summer and winter wheat) will be lower in the summer than in the winter due to the greater vapor pressure deficit in the summer (Fisher and Turner, 1978).

In the field water balance studies, one of the major difficulties is the separation of evapotranspiration into plant transpiration and soil evaporation (Boast, 1986; Fisher and Turner, 1978). Fortunately the ratio of E to ET decreases as the crop matures and the LAI increases (Jagtap and Jones, 1989; Richie, 1972; Sinclair, 1989) making it easier to accurately estimate transpiration. Ritchie (1972) reported that when the soil water supply to plant roots was not limited, the plant transpiration was negligible when the LAI was less than 0.1; transpiration accounted for 25% of total water loss when the LAI was 0.5; the plant transpiration accounted for nearly 100% of the total water loss when the LAI reached 3. Sinclair (1989) reviewed that for a fully developed leaf canopy, E/ET is generally in the range of 0.15 to 0.25. In our study, LAI was 0.39 at the beginning of the third year, 2.02 at the end of the third year and 3.88 at the end of the fourth year. Due to the greater

precision in estimating E and thus T at a greater LAI, we have greater confidence in our 4th years measurements than the third years measurements.

The average transpiration water use efficiency (WUEt) and evapotranspiration water use efficiency (WUEet) of Opuntia ellisiana over plots 3,4 and 11 were 218 Kg Kg^{-1} and 393 Kg Kg^{-1} in the third year and 162 Kg Kg^{-1} and 283 Kg Kg^{-1} in the fourth year. As discussed above, surface runoff and soil evaporation might be underestimated in the third year. As a result, values of WUEt and WUEet in the third year should be smaller than what reported here.

The neutron probe measurements to estimate the change in stored soil moisture from 15 to 125 cm depth found no differences among non-harvested or harvested cactus plots. Thus it appears as if all the water uptake by cactus is in the top 15 cm. This confirms the work of Nobel (1988) who reported a shallow root system for cacti.

Precipitation is the only water input into this plant-soil system. The availability of rain water to plants depends on the characteristics of rainfall event such as intensity, duration and amount (Fisher and Turner, 1978). In this study area, precipitation had the following two prominent properties which greatly limited the availability of rain water to plants. First, a large proportion of the rainfall occurred in heavy storms which caused significant surface runoff. Second, the number of the light rainfall events accounted for a large percentage of the

total rainfall events. When the vegetation cover was incomplete most of the water from these light rainfall events was evaporated from soil surface. When the vegetation had a high LAI, the light rains were intercepted by the plant canopy and evaporated from the plant surfaces. In both cases the light rains were not effectively used by the plant.

Whether cropping systems in arid regions are rainfed or irrigated, pressure on the water resource base mandates that water be used with the greatest efficiency possible. The Opuntia ellisiana cactus in this study is not economically promising as it does not produce edible fruit and produces insufficient immature growth on a year round basis to be a vegetable (nopalito) variety. However Opuntia ellisiana could be a useful forage variety in locations that were too cold for O. robusta or O. ficus-indica. Indeed, the yearly fresh weight of 194,187 kg ha^{-1} in the fourth year would be sufficient for 4315 cows/day at 45 kg/day (Felker, 1995). This variety was chosen because it was spineless and sufficiently cold hardy to live through the required 4 year growth period. Nevertheless there are many other much faster growing cacti (FAO in press) that produce excellent quality fruit and vegetables. As nearly all of the 130 accessions in our germplasm collection have greater height growth than Opuntia ellisiana under the same rainfall conditions, it would appear that they might have even greater water use efficiencies.

Now that a long term field study, with adequate control over border influences has clearly demonstrated that cacti have

greater conversion efficiency of water to dry matter than any of widely used C4 and C3 species, we suggest that serious development efforts be made to develop cactus based fruit, vegetable and forage based systems for arid lands.

Fig. 1. Illustration of the experimental plot, plant conditions and the neutron probe access tubes.

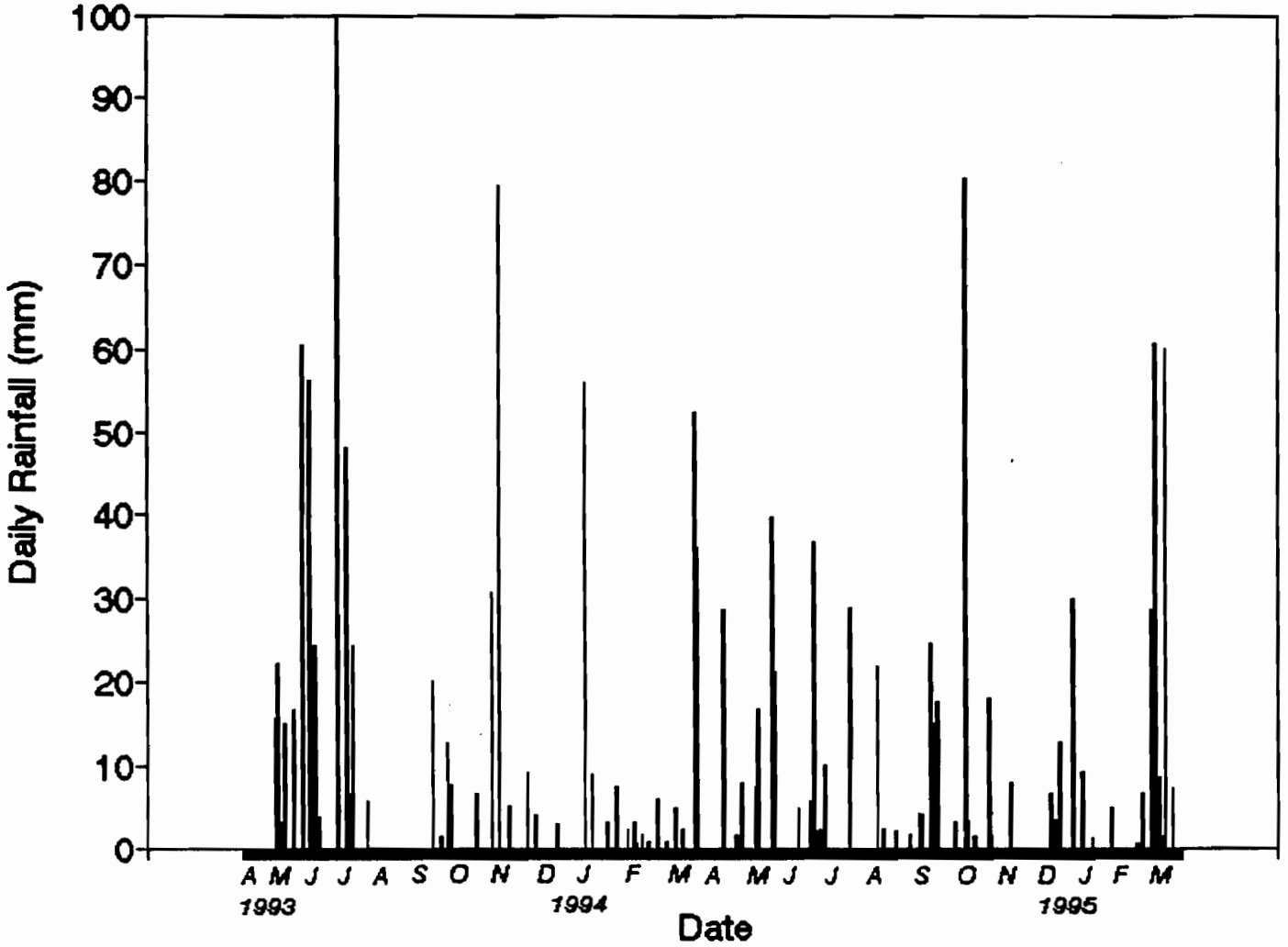

Fig 2. Distribution of daily rainfall from April, 1993 to April ,1995.

Table 1. Comparison of regression equations to predict biomass†.

Year	Cladode width equations	R^2	SE	Cladode number equations	R^2	SE
1	$FW=0.58(MW)^{2.40}$	0.93	54.0	PFW=-0.349+0.394(PCN)	0.83	79.2
2	$FW=0.88(MW)^{2.27}$	0.90	62.0	PFW=-1.466+0.407(PCN)	0.90	49.9
3	$FW=0.97(MW)^{2.58}$	0.81	71.3	PFW=-7.795+0.497(PCN)	0.88	56.6

† FW is fresh weight of cladode (g), MW is maximum width of cladode (cm), PFW is plant fresh weight (kg), PCN is plant cladode number, and SE is the standard error of regression (g per cladode).

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Table 2. Standing dry biomass for *Opuntia ellisiana* for the one-year, two-year, three-year and four-year growth periods.

Plot	Dry Matter Production ($Kg\ ha^{-1}$) one-year	two-year	three-year	four-year
1	1622†	/	/	/
2	1805‡	6486†	/	/
3	1902‡	6419§	20658‡‡	37794†
4	1901‡	7768§	23036‡‡	41926†
5	1880‡	6573†	/	/
6	1581‡	5909§	18821†	/
7	1942†	/	/	/
8	1210‡	4337§	17184†	/
9	1307‡	4272§	16695†	/
10	848†	/	/	/
11	1751‡	6170§	19465‡‡	36454†
12	1643‡	6515†	/	/

† Total dry matter harvested.

‡ estimated using Equation: $FW=0.58(MW)^{2.40}$. FW: cladode fresh weight, MW: cladode maximum width. Total dry weight= R_1*total fresh weight. R_1=0.071: ratio of dry weight to fresh weight for the first harvest. R_1 was determined by the harvest method.

§ estimated using Equation: PFW=-1.466+0.407(PCN), PFW: plant fresh weight, PCN: plant cladode number. Total dry weight =R_2*total fresh weight. R_2=0.074: ratio of dry weight to fresh weight for the second harvest. R_2 was determined by the harvest method.

‡‡ estimated using Equation: PFW=-7.795+0.497(PCN), PFW: plant fresh weight, PCN: plant cladode number. Total dry weight =R_3*total fresh weight. R_3=0.089: ratio of dry weight to fresh weight for the third harvest. R_4 was determined by the harvest method.

Table 3. The annual growth of *Opuntia ellisiana* for plots 3,4 and 11, annual rainfall and leaf area index for the four consecutive years.

Year	Dry Matter Production ($Kg\ ha^{-1}\ yr^{-1}$) plot 3	Plot 4	Plot 11	Rainfall (mm)	LAI†
1	1902	1901	1751	1016	0.06
2	4517	5867	4419	675	0.39
3	14239	15268	13295	833	2.02
4	17136	18890	16989	622	3.88

† LAI is measured at the end of the year.

Table 4. Average soil water content change over three plots which harvested in the same year for four one-year periods.

Plots by Year of Harvest	Change in soil water content (mm)			
	Year 1	Year 2	Year 3	Year 4
First year (1,7,10)	21	-26†	4	2
Second year (2,5,12)	1	-29	2	3
Third year (8,9,6)	30	-34	7	1
Fourth year (3,4,11)	14	-35	8	3

† the negative value indicates plot lost water during that period.

Table 5. The measured surface runoff for the rainfall events occurred from April 15, 1994 to April 15, 1995.

Date	Rain	ASWC	Runoff
	mm	$g\ g^{-1}$	mm
1994			
2 May	16.7	0.125	4.4
13 May	39.1	0.063	5.8
14 May	21.2	0.152	5.8
14 May	36.4	0.074	1.7
1 Aug	21.8	0.023	0.3
10 Sep	24.5	0.027	0.2
15 Sep	16.2	0.113	1.1
7 Oct	80.4	0.054	33.6
1995			
24 Feb	28.6	0.087	5.9
27 Feb	60.5	0.144	36.5
6 Mar	58.9	0.178	47.3

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Table 6. The predicted surface runoff for the rainfall events occurred from April 15, 1994 to April 15, 1995.

Date	Rain	ASWC	Runoff
	mm	$g\ g^{-1}$	mm
1993			
28 Apr	22.2	0.141	10.6
17 May	60.3	0.099	29.1
22 May	56.1	0.115	28.6
12 Jun	42.2	0.065	12.6
13 Jun	48.8	0.165	31.1
14 Jun	23.1	0.177	16.3
21 Jun	47.7	0.101	21.3
25 Jun	24.3	0.125	9.6
8 Oct	55.9	0.045	18.5
19 Dec	65.3	0.187	44.8
1994			
14 Mar	52.3	0.028	13.7
16 Mar	36.0	0.112	15.3

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Table 7. Estimated daily soil evaporation data obtained from average air relative humidity, air temperature, wind speed and soil water content using RBF neural network.

Date	Relative Humidity	Air Temperature	Wind Speed	Soil Water Content	Soil Evaporation
	%	C	km h^{-1}	g g^{-1}	mm
1993					
29 Apr	82.8	20.9	5.7	0.141	1.57
2 May	95.9	22.2	3.5	0.115	1.99
3 May	92.4	22.7	2.7	0.095	1.72
11 May	88.4	21.3	3.7	0.123	2.02
16 May	88.8	23.9	4.6	0.069	0.80
16 Jun	89.6	26.5	2.5	0.130	2.05
20 Jun	88.0	26.6	6.4	0.055	0.47
4 Jul	82.5	28.4	6.1	0.045	0.31
9 Aug	80.2	29.2	2.7	0.024	0.31
13 Aug	78.3	29.3	3.6	0.024	0.25
6 Sep	79.2	27.5	1.8	0.125	1.69
8 Sep	76.9	28.8	2.7	0.075	0.58
9 Oct	70.6	27.1	3.9	0.091	0.69
11 Oct	63.2	26.1	4.6	0.068	0.46
6 Nov	69.2	10.8	7.6	0.084	0.67
9 Nov	85.5	16.9	5.3	0.057	0.59
1 Dec	70.6	21.1	5.9	0.038	0.36
1994					
7 Jan	67.9	11.2	7.8	0.070	0.65
13 Jan	84.2	14.2	4.6	0.114	1.49
14 Feb	62.4	10.9	4.1	0.038	0.58
24 Feb	57.2	9.8	3.4	0.053	0.61
7 Mar	90.4	21.3	7.1	0.050	0.53
17 Mar	91.3	16.8	3.1	0.148	1.81
1 Apr	71.5	17.1	4.5	0.037	0.29
8 Apr	80.4	19.3	6.5	0.108	1.14
5 May	87.9	23.1	4.3	0.110	1.31
6 May	92.6	24.0	4.4	0.101	1.01
7 Jun	83.3	28.2	3.9	0.053	0.37
16 Jun	89.6	27.8	5.7	0.130	1.77
10 Jul	83.4	28.0	3.6	0.141	1.19
19 Jul	76.6	28.1	5.3	0.062	0.46
5 Aug	89.9	26.6	2.1	0.081	0.59
15 Aug	78.6	27.9	2.4	0.061	0.21
6 Sep	79.2	28.0	2.6	0.045	0.20
13 Sep	91.8	25.8	1.9	0.135	1.91
13 Oct	75.7	18.6	2.1	0.101	0.81
14 Nov	76.7	24.1	4.0	0.103	1.00
18 Dec	84.1	13.4	3.6	0.107	1.43

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Table 8. Summary of soil water balance and water use efficiency of *Opuntia ellisiana* for plots 3,4 and 11 during the third year, fourth year and the two-year period.

Parameter	Year 3		Year 4		Year 3+Year 4	
	Mean	STD†	Mean	STD	Mean	STD
Rainfall (mm)	833	/‡	662	/	1495	/
Soil Water Content Change (mm)	10	2	3	2	13	4
Plant Water Content Change (mm)	12	3	17	4	29	6
Surface Runoff (mm)	252	/	143	/	395	/
Soil Evapo-ratipon (mm)	249	/	214	/	463	/
Evapotrans-piration (mm)	559	5	499	6	1058	10
Transpiration (mm)	310	4	285	6	595	10
Dry matter Production (Kg ha^{-1})	14267	987	17671	1057	31939	1998
WUEet§ (Kg Kg^{-1})	393	30	283	19	332	23
WUEt (Kg Kg^{-1})	218	18	162	12	187	14

† STD stands for standard deviation.
‡ STD do not apply
§ WUE stand for water use efficiency.

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