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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, Texas field trial examined correlations between cactus pear fruit characteristics, with and without 100 kg ha^{-1} each of N, P, K, and cladode concentration of N, P, K, Ca, Mg, Na, Fe, Zn, Mn and Cu. Seven Mexican fruit clones of cactus pears were used. While 100 kg ha^{-1} N, P, K did not significantly influence fruit yield, it significantly increased the fruit sugar (soluble solid) content. Different results emerged depending on whether the correlations were based on the mean of many cladodes per plant or at the individual cladode level. At the whole plant level, cladode tissue N and K concentrations were positively correlated with fruit yield and Na concentration was negatively correlated with fruit yield. Mg concentration was correlated positively with fruit sugar content. The optimum Mg content was estimated to be 2.2%. Correlations also were assessed for 5 accessions between fruit number per cladode and the nutrient content of the cladode. Cladode K concentration was negatively correlated with the number of fruit on the same cladode for 2 of the 5 accessions. For only two of the five accessions, fruit number per cladode was correlated with cladode P concentration. The relationships between fruit production or quality versus cladode concentrations were very different for these clones. It may be necessary to develop individual fruit quality or production relationships for individual cultivars.

Key words: Cactus pear, fruit quality, cladode nutrient content.

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 Crassulacean Acid Metabolism (CAM) plant (Kluge and Ting, 1978) cactus has high drought resisting ability and high water-use efficiency. Due to high water conservation ability and drought tolerance, prickly pear has been used widely 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 used widely as a green vegetable in Mexico and Southern Texas (Russell and Felker, 1987). Significant work on cactus fruit-quality was done as early as 1906 (Griffiths and Hare, 1907). The average

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fruit fresh weight is 111 g, 78% of which is edible. The sugar content of cactus pears is approximately 14%, primarily glucose and fructose in 60/40 ratio (Sawaya *et al.*, 1983). Although most cactus pears are consumed fresh, they have also been processed into various syrups, and candy products (Saenz, 1996).

There has been significant work examining the influence of soil fertility and fertilization on fruit and biomass production of cactus pear (Nobel *et al.*, 1987; Gathaara *et al.*, 1989; Nerd *et al.*, 1989; Nerd *et al.*, 1993, Monjauze and LeHouerou, 1965; Gonzalez, 1989; SAG, 1976). However, as correlations between cladode nutrient concentrations and fruit quality and yield did not exist, we examined fruit-cladode correlations in several Opuntia fruit clones to provide rapid field assessment of nutrient limitations on cactus pear production.

Materials and Methods

The experiment was conducted in a previously described (Gregory *et al.*, 1993) two-year-old (third growing season) *Opuntia* plantation in Kingsville, Texas, using the 7 accessions in Table 1. Two soil series, Hidalgo and Palobia, occurred in these plots (USDA, 1975). Hidalgo is most extensively distributed. This series is taxonomically identified as a member of fine loamy mixed hyperthermic family of Typic Calcistolis (USDA, 1978). These soils lack a fluctuating ground water table in their deep layers. They are well-drained, have slow run off, and are moderately permeable. They have high inherent fertility and high production potentials. Mean values for five soil samples were organic matter 0.5%, pH 6.5 and nitrate N 3 mg kg^{-1}.

In 1993, the number of fruits 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 per cent 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.

Table 1. Origin and species of the Opuntia accessions used in fertility assessment

Accession	Species	Spines	Fruit colour	Origin (UAAAN#)
1277	*Opuntia ficus - indica*	-	Yellow	Mexico
1287	*Opuntia hyptiacantha*	+	Yellow	Mexico
1281	*Opuntia streptacantha*	-	Yellow	Mexico
1294	*Opuntia ficus - indica*	-	Orange	Mexico
1380	*Opuntia megacantha*	-	Yellow	Mexcio (AN-V1)
1376	*Opuntia ficus - indica*	+	White	Mexico (AN-V1)
1392	*Opuntia ficus - indica*	-	Red	Mexico

+ = with spines, - = without spines. The UAAAN is the code for *Universidad Agraria Autonio Narro* (Saltillo, Mexico) selections.

Correlations were examined between fruit yield and fruit sugar concentration for whole plants and individual cladodes. In the case of whole plant correlations, more than 20 plants of accessions 1277, 1287, 1281, 1380, 1376, and 1392 from Table 1 were used. To four plants in each accession, N, P, K (100 kg ha^{-1} each) were applied around the base in mid-October of 1992 and 1993. Four control plants received no fertilizer application. The fertilized and non-fertilized plants were located in 2 blocks on a 1-m in-row spacing and a 4-m between-row spacing.

Very different results emerged, depending on whether the correlations were obtained from the mean of many cladodes per plant (whole-plant level) or from the data of individual cladodes (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. In the analyses of relationships (parameteric and non-parametric) between individual cladodes and fruit yield or sugar concentration, 38 cladodes from 5 accessions were used.

In the experiment to examine the relationship between cladode nutrient concentrations versus fruits per cladode, accession 1294 was added to this experiment and accessions 1281 and 1392 were deleted due to a more favorable range in fruits per cladode.

In the case of K, if 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 per cladode (up to 17) 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 the cladode level.

For the whole plant correlations, five core samples were taken from each plant for chemical analyses in July 1993. Samples were collected from the terminal, upright cladodes in the center and pooled per plant to assess whole-plant effects. Fruit yield measurements were taken both in 1993 and 1994, but no chemical analysis were performed in 1994.

A 0.75-m-long, sharpened, stainless steel pipe (to avoid contamination from Fe and Zn) of 3.2-cm inner diameter was used for sample collection (Huffman and Jacoby, 1985). The coring device was dipped in 70% ethanol 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.

Tissue nitrogen was determined colorimetrically following micro-Kjeldahl digestion (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, (Cline *et al*., 1986) 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 that the nutrient concentrations were within the referenced standard error. Tissue concentrations of all nutrients are reported on dry matter basis.

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 precipitation was recorded; Jan. 14 mm, Feb. 43 mm, Mar. 61 mm, Apr. 87 mm, May 188, 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 Mg ha^{-1} of manure was applied to the field in the winter of 1991/1992. Weeds were controlled using a 2% (v/v) glyphosate (Roundup) solution.

Results and Discussion

In the analysis of variance for fruit yield, there were no significant (P>0.05) fertilizer or accession effects in 1993 or 1994. However, there was a significant (p = 0.03) interaction between accessions and fertilizer treatments in 1993.

Correlations at the whole plant level

Correlations were examined between fruit yield in 1993 and 1994 and tissue concentrations of N, P, K, Mg, Ca, Na, Cu, Zn, Fe or Mn. Only non-parametric rank correlations (Spearman) were significant for 1993 fruit yield and 1993 cladode

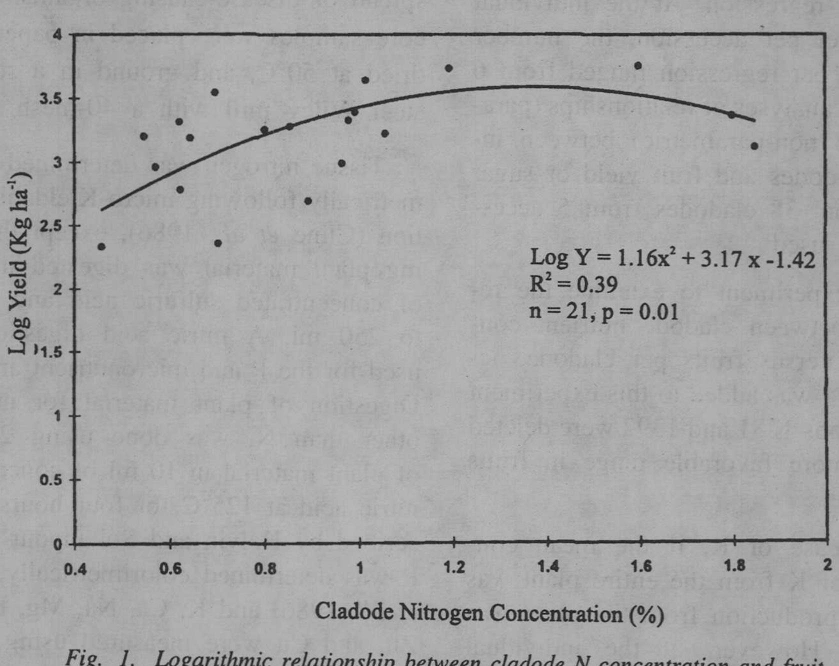

Fig. 1. Logarithmic relationship between cladode N concentration and fruit yield of Opuntia accessions 1281, 1380, and 1392 at the whole plant level.

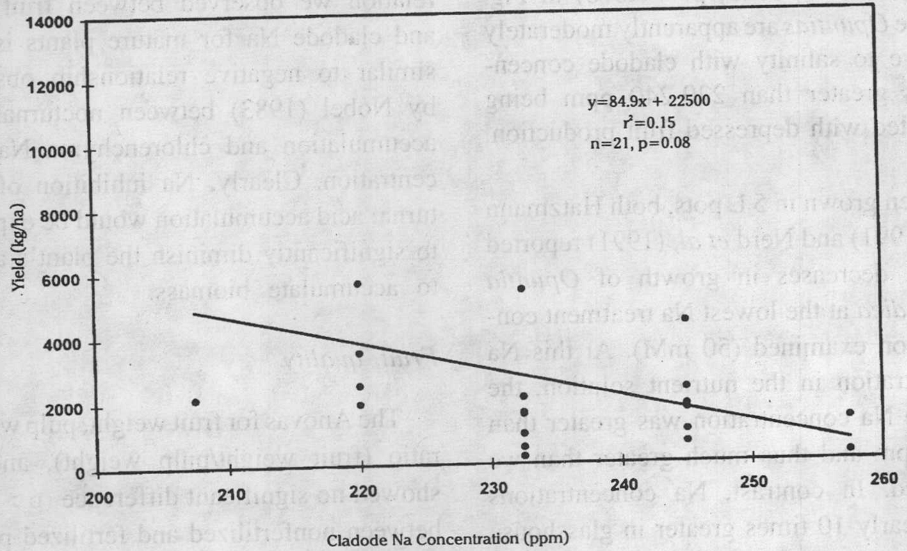

Fig. 2. Linear relationship between cladode K concentration and fruit yield of Opuntia accessions 1277, 1281, 1287, 1376 and 1392 at the whole plant levels.

N (r = 0.452, p = 0.034) and 1993 cladode N (r = 0.433, p = 0.044). The rank correlation between 1993 fruit yield and 1993 cladode K was almost significant (r = 0.376, p = 0.084) while the rank correlation between 1994 fruit yield and 1993 cladode K (r = 0.432, p = 0.044) was significant. P concentration and yield were not correlated using either rank or Pearson correlations.

Due to the importance of N for fruit production ascribed by other workers (Nerd *et al.*, 1993), and the presence of a significant rank correlation between cladode N and yield, regression analysis was used to model $\log_{10}$ yield as a function of cladode N% using the data for 1993. The estimated relationship (Fig. 1), $\log_{10}$ yield (kg ha^{-1}) = $1.4211 + 3.1684$ N% - $1.1586N^2$%, was significant (p = 0.0117) where both the linear and quadratic coefficients were significant (P <0.03). The detransformed root mean-square error was 2609 and a detransformed maximum yield of 3865 kg ha^{-1} occurred at N% of 1.37.

The estimated linear relationship (Fig. 2), yield (1994 kg ha^{-1}) = -22,237 + 3,425 K, was significant ($R^2 = 0.3287$, p = 0.0103). The fact that no downward trend in yield was observed for increasing K, suggests that K levels were not sufficiently high to obtain maximum yields.

Due to the significant negative rank correlation between 1993 yield and cladode Na levels and reports of inhibitory effects of Na on yields (Hatzmann *et al.*, 1991; Nerd *et al.*, 1991; Berry and Nobel, 1985; Nobel, 1983), we report the almost significant estimated relationship:

Yield (1993) (kg ha^{-1}) = 22,489 - 84.94 (Na %); $R^2 = 0.1543$, $p = 0.078$) in Fig. 3. These *Opuntias* are apparently moderately sensitive to salinity with cladode concentrations greater than 220-240 ppm being associated with depressed fruit production.

When grown in 5 L pots, both Hatzmann *et al.* (1991) and Nerd *et al.* (1991) reported marked decreases in growth of *Opuntia ficus-indica* at the lowest Na treatment concentration examined (50 mM). At this Na concentration in the nutrient solution, the cladode Na concentration was greater than 1000 ppm and thus much greater than we observed. In contrast, Na concentrations were nearly 10 times greater in glasshouse conditions than under field conditions (Berry and Nobel, 1985; Nobel, 1983) where Na concentrations for *Opuntia ficus-indica* rarely exceeded 60 ppm. The negative correlation we observed between fruit yield and cladode Na for mature plants is very similar to negative relationship observed by Nobel (1983) between nocturnal acid accumulation and chlorenchyma Na concentration. Clearly, Na inhibition of nocturnal acid accumulation would be expected to significantly diminish the plant's ability to accumulate biomass.

Fruit quality

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

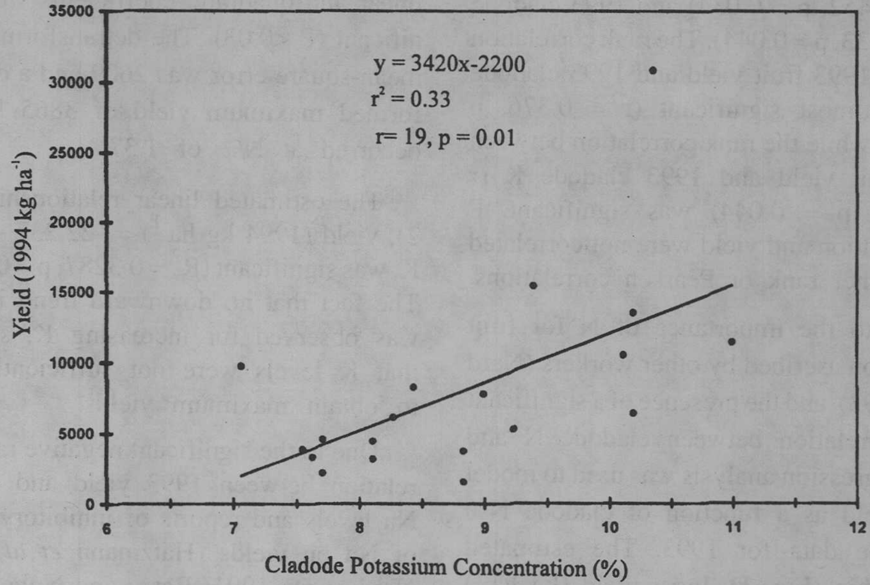

Fig. 3. Linear relationship between cladode Na concentration and fruit yield of Opuntia accessions 1281, 1287, 1376, and 1392 at whole plant level.

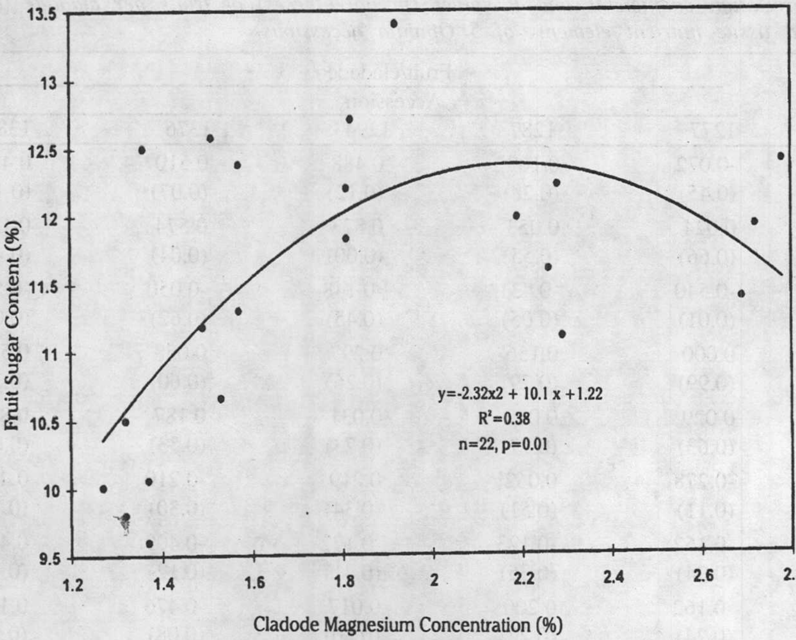

Fig. 4.. Quadratic relationship between cladode Mg concentration and fruit sugar content of Opuntia accessions 1277, 1281, 1376, 1380 and 1392.

In contrast to the lack of fertilizer influences on fruit and pulp weight and pH, the ANOVA for the effect of fertilization on sugar content found that fertilized plants had significantly higher fruit sugar content than nonfertilized plants ($p = 0.016$). Spearman correlation analysis indicated that the nutrient most significantly correlated ($r = 0.477$ $p = 0.024$) with fruit sugar content was Mg. Correlations between fruit sugar and other cladode nutrients were very low ($p = 0.938$ for N, $p = 0.676$ for P, $p = 0.185$ for K). The estimated relationship is shown in Fig. 4.

Fruit sugar (%) = 1.22 + 10.15 (Mg%) - 2.32 $(\text{Mg}\%)^2$ had an R^2 of 0.379 ($p = 0.01$) and the coefficients for both Mg and $(\text{Mg})^2$ were significant ($p = 0.02$ and $p = 0.03$, respectively). The optimal Mg concentration for fruit sugar appeared to be 2.2% for an estimated maximum sugar value of 12.34. Fruit sugar was also positively correlated with fruit weight ($r = 0.436$, $p = 0.42$), pulp weight ($r = 0.516$, $p = 0.013$) and pH ($r = 0.588$, $p = 0.004$).

Correlations at cladode level

The number of fruits varied from cladode to cladode. Some cladodes carried up to 17 fruits, whereas, some cladodes 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. Pearson cor-

Table 2. Correlation 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)	(0.085)	(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

relation coefficients were computed between fruit number and the cladode composition for 10 nutrients (Table 2). Phosphorus was positively correlated with fruit yield in accessions 1294 ($p < 0.01$) and 1376 ($p = 0.04$) (Fig. 5). Although K was found correlated positively with fruit yield at the whole-plant level, it was correlated negatively 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 cultivars 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 separately for each fruit accession.

Research in Israel and Mexico indicated that high cactus fruit production required high fertility inputs (Nerd *et al.*, 1993; Nobel *et al.*, 1987). In this experiment, application of N, P and K had no significant effect on yield, but the maximum fruiting was estimated at a cladode N concentration of 1.37%. According to Nerd *et al.* (1989), irrigation and fertilization regimes are important for the production of cactus fruits in arid and semi-arid environments. The

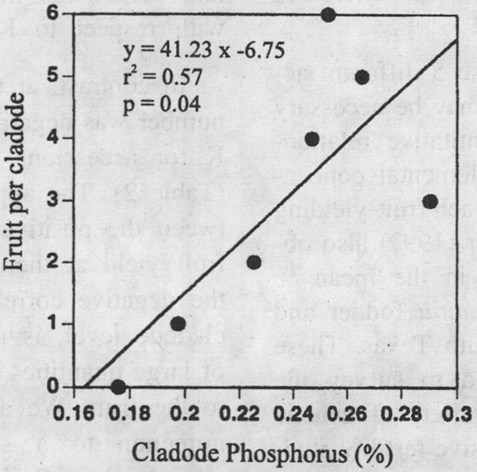

Fig. 5. Linear relationship between cladode P concentration and fruit number of Opuntia ficus-indica (1376) at cladode level.

experimental field in this report was never irrigated but 15 t manure ha^{-1} were applied in the winter of 1991/1992. Because of the erratic rainfall conditions in south Texas, water availability and distribution may limit fruit production as well as soil 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 its 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 N ha^{-1} in Israel increased floral flush compared to control plants and the use of P and K was found to be unnecessary (Nerd *et al.*, 1993). The interactions between the accessions and the fertilizer treatments indicates that all accessions did not respond to fertility similarly. These effects also contributed to the significant fertilizer by accession interaction that lead to non-significant response of fruit numbers to fertilizer application.

The maximum yield was estimated to be 1.37% cladode N concentration, which is similar to the value of 1.16% reported by Gathaara *et al.* (1989). The optimum value of 1.37% 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 2, correlation analysis indicated that phosphorus was positively correlated to fruit yield in accessions 1294 and 1376. Even though P and K fertilization 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 fertilization increases fruit production.

The variability of these 5 different accessions indicates that it may be necessary to develop separate quantitative relationships 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 in 1993. Furthermore, the 1993 ''whole plant'' K concentration was significantly correlated with the 1994 fruit yield. From Fig. 2 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 negatively correlated to tissue K for accessions 1277, 1287, and 1380 (Table 2). 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 latter 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

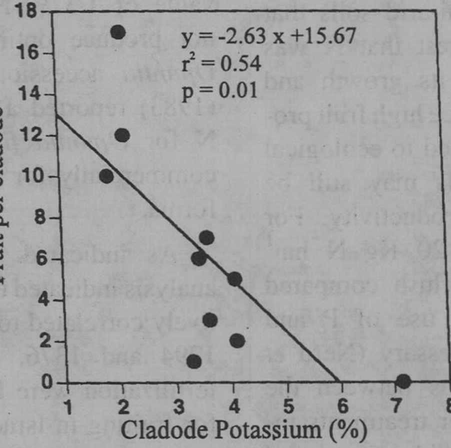

Fig. 6. Linear relationship between cladode K concentration and fruit number of Opuntia ficus-indica (1277) at cladode level.

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 be 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 fruits such as apples, citrus and figs must be translocated from the leaf through a petiole to a twig and then through a stem to the fruit.

In addition to the plants described in this communication, another replicate was located in a 17 m by 90 m unheated plastic greenhouse, physically located between the other 2 replicates. The plants in this greenhouse were watered from rainfall captured from the roof made available to the plants by a series of gutters. Even though the plants inside the greenhouse were fertilized in the same manner as the other blocks, none of them produced fruit in 1993. 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. In contrast to a previous report of fruit production (Kuti, 1992) from this field, only 5 months after 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.

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 mater production in potato was reported by Cao and Tibbitts (1992). The optimum sugar content was estimated at 2.2% cladode Mg. The positive relationship between Mg and sugar content may be attributable to the fact that Mg occupies a central role in the chlorophyll molecule and also activates enzymes for metabolic processes such as photosynthesis, respiration and formation of DNA and RNA (Salisbury and Ross, 1992). A key reaction of Mg is the activation of ribulose bisphosphate carboxylase which initiates sugar production. Thus, the favourable 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 application, but there was a significant increase in the sugar content of the fruits with fertilizer application. 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 Na^+. 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 an increase in fruit numbers that extracted large quantities of K from the cladode. The tissue Mg concentrations were significantly correlated with fruit sugar concentrations. The quadratic regression between cladode Mg and fruit sugar was positive with an optimal Mg concentration of approximately 2.2%. Individual clones appear to have different response to fertilizers; therefore, it may not be possible to develop a set of generic guidelines for ''optimal cladode tissue concentrations'' for *Opuntia* fruit production. Until such time, as indicated otherwise, it would appear that cladode tissue nutrient concentration/fruit production relationships need to be developed for individual *Opuntia* clones.

Acknowledgements

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