Thresholds of Leaf Nitrogen for Optimum Fruit Production and Quality in Grapefruit

Z. L. He,* D. V. Calvert, A. K. Alva, D. J. Banks, and Y. C. Li

ABSTRACT

Fertilization is critical for sustainable production of citrus on sandy soils. However, information on nutritional diagnosis standards for grapefruit (*Citrus* × *paradisi* Macfad.) is lacking and this information is needed for implementation of best management practices (BMPs). A field experiment was conducted from 1997 to 2000 on a Riviera fine sand (loamy, siliceous, hyperthermic, Arenic Glossaqualf) with 30-yr-old+ white Marsh grapefruit trees on sour orange (*Citrus aurantium* L.) rootstock to evaluate irrigation and fertilization effects on fruit yield and quality and to validate leaf nutrient concentration standards for guiding fertilization of grapefruit. Fertilizers were applied as water soluble granular (WSG, 3 applications yr^{-1}), by fertigation (FRT, 15 applications yr^{-1}), or as controlled-release fertilizers (CRF, 1 application yr^{-1}) and at five rates (0, 56, 112, 168, or 224 kg N ha^{-1} yr^{-1}) with an N:P:K blend (1.0:0.17:1.02). Fruit yield and quality were not affected by irrigation treatments or fertilizer sources. There was a significantly positive correlation between leaf N concentrations and N rates (r = 0.98). Fruit yield was linearly related to N rates or leaf N concentrations. At 90% of maximum yield, leaf N concentrations (dry weight basis) were 22 to 23 g kg^{-1}. Fruit quality parameters such as soluble solid concentration (SSC), juice, and total soluble solids (TSS) were positively correlated with leaf N concentrations, whereas fruit titratable acidity (TA) was negatively related to leaf N concentrations or N rates. The effect of N rate on TA outweighed that on SSC and consequently, the SSC/TA ratio decreased with increasing N rates or leaf N concentration. Fruit size was quadratically related to N rate or leaf N concentration. Overall, fruit sizes and SSC/TA ratios were acceptable for fresh marketing or processing at leaf N concentrations of 22 to 23 g kg^{-1}. Therefore, this leaf N concentration of 22 to 23 g kg^{-1} can be considered the optimal concentration guideline for fertilization of grapefruit provided that other nutrients are sufficient.**

NITROGEN FERTILIZATION plays an important role in the fruit yield and quality of citrus, especially when grown on sandy soils that contain small amounts of available N (Calvert, 1969, 1970; Smith et al., 1969; Futch and Alva, 1994). Leaf analysis is the most important tool for evaluating nutrient status of citrus trees and for guiding fertilization of citrus. Leaf samples are often collected in July through September from nonfruiting branches of 4- to 6-mo-old spring flush (Tucker et al., 1995). The critical leaf concentration standards for N, P, K, and some other nutrients are well established for orange trees (Embleton et al., 1975; Koo et al., 1984; Tucker et al., 1995), but this information is lacking for grapefruit trees. Current fertilization practices for grapefruit are mainly based on a few studies conducted more than 30 yr ago (Reitz and Hunziker, 1961; Sites et al., 1961; Smith, 1966; Smith et al., 1969). The recommended N rates from the studies above range from 100 to 260 kg ha^{-1} yr^{-1}, depending on potential fruit production target at the standard of 7.06 kg per Mg fruit (or 0.3 lb N per box fruit) (Koo et al., 1984). Timing of N application was reported to have minimal effects on fruit production (Smith et al., 1969).

Most of the studies cited above were conducted in groves of low planting densities (130–160 trees ha^{-1}) with maximum yield around 46 Mg ha^{-1} (or 500 boxes per acre). Leaf N concentration was not suggested as a guide for N fertilization of grapefruit during 1960's to 1980's. Futch and Alva (1994) conducted a 3-yr field experiment using 30-yr old Marsh grapefruit trees on sour orange rootstock at 177 trees ha^{-1} density. Three N rates (168, 224, and 275 kg ha^{-1} yr^{-1}) were used, with two thirds of the N applied in suspension using a strip sprayer and the other third as dry blend broadcast. This study demonstrated that by using suspension materials, the N rate could be reduced from 275 kg ha^{-1} yr^{-1} to 168 kg ha^{-1} yr^{-1} without any adverse effects on fruit yield and/or quality. The concentration of N in mature spring flush foliage during the 3-yr period was 22 to 24 g kg^{-1}. However, no critical leaf N concentration was suggested in this study because of limited data (only three high N rates), although 168 kg ha^{-1} yr^{-1} became the highest recommended N rate for mature grapefruit trees (Futch and Alva, 1994).

The USA ranks number one in grapefruit production in the world with more than 90% of the crop produced in Florida (FASS, 2000). The Indian River area in Florida is known across the world for its production of high quality grapefruit. Many changes have occurred to citrus groves in the last 30 yr in the Indian River area, including an increase in tree density from 120 to 150 trees ha^{-1} to 250 to 300 trees ha^{-1} (Davies, 1997), adoption of irrigation systems (Alva and Paramasivam, 1998), and use of fertigation or controlled release fertilizers (Boman, 1993, 1996). As a result, yields of grapefruit have increased from 25 to 40 Mg ha^{-1} to 50 to 80 Mg ha^{-1} (He et al., 2000). In light of these changes, the previously established N fertilization recommendations need to be reevaluated for applicability to the modern commercial groves, and some useful diagnostic standards regarding N nutrition of grapefruit trees, such as leaf N concentration standards, must be developed.

Fruit quality affects economic return, especially for the fresh market, and is an important component of citrus production. Half of the grapefruit produced in Florida goes to the fresh market, with increased value of pro-

Z.L. He, D.V. Calvert, and D.J. Banks, University of Florida, IFAS, Indian River Research and Education Center, Fort Pierce, FL34945; A.K. Alva USDA-ARS-PWA Irrigated Agriculture Research and Extension Center, 24106 N. Bunn Road, Prosser, WA 99350; Y.C. Li, University of Florida, IFAS, Tropical Research and Education Center, Homestead, FL 33031. Received 24 Aug. 2001. *Corresponding author (zhe@mail.ifas.ufl.edu).

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Abbreviations: BMPs, best management practices; CRF, controlled release fertilizer; DW, dry weight; FRT, fertigation; SSC, soluble solid concentration; TA, titratable acidity; TSS, total soluble solids; WSG, water soluble granular.

duction (FASS, 2000). Thus, fruit quality needs to be carefully considered in the evaluation of plant nutrition status and fertilization practices.

The objectives of this study were to examine the effects of irrigation, N fertilizer type, and N rate on yield and quality of grapefruit; to evaluate the relationship between leaf N concentrations and fruit yield or fruit quality, and to determine optimal leaf N concentrations and N rates for grapefruit production in the Indian River area.

MATERIALS AND METHODS

A field experiment was conducted from 1997 to 2000 on a Riviera fine sand (loamy, siliceous, hyperthermic, Arenic Glossaqualf) with 30-yr-old+ white Marsh grapefruit trees on sour orange rootstock (269 trees ha^{-1}). The soil, typical of the types used for grapefruit production in the Indian River area, was very sandy, especially at the 0- to 60-cm depth, had a pH about 7.5, and contained 11.1 to 17.3 g kg^{-1} organic matter in the 0- to 60-cm soil depth (Table 1). The natural fertility of the soil is relatively low and fertilization and irrigation played a critical role in the sustainable production of grapefruit on this soil.

The experiment was arranged in a factorial split-split-plot design with two irrigation treatments as main plots, three different fertilizer sources as sub-plots, and five N rates as sub-sub-plots with four replications. Each plot consisted of five uniform trees planted at 6- by 6-m spacing (269 trees ha^{-1}). The two irrigation treatments were (i) irrigation at low soil moisture tension, i.e., irrigation was scheduled when the 15-cm depth tensiometers reading attained 15 kPa, (equivalent to 25% depletion of available soil moisture content) and (ii) irrigation at high soil moisture tension, i.e., irrigation was scheduled when the 15-cm depth tensiometer readings attained 30 kPa (equivalent to 40% depletion of available soil moisture content). Percent depletion of available soil moisture was calculated from previously determined soil moisture characteristic curves developed on undisturbed soil core samples, taken from eight locations within the experimental area. We chose 25 and 40% available soil moisture depletion (ASMD) for irrigation in following standard procedures of best management practices identified in Florida (Boman et al., 1999). Twenty-five percent ASMD represents the lower limit of optimal soil moisture (Boman et al., 1999). Tensiometers were read with a portable Tensimeter (Soil Measurement Systems, Tucson, AZ). The irrigation was applied using under-tree microirrigation with one emitter per tree with a delivery rate of 40 L h^{-1}.

Subplot treatments consisted of three fertilizer sources: dry water-soluble granular (WSG, 3 applications yr^{-1}), fertigation (FRT, 15 applications yr^{-1}), or controlled-release fertilizers (CRF, 1 application yr^{-1}). The sub-sub-plot treatments were five rates of N (0, 56, 112, 168, and 224 kg N ha^{-1} yr^{-1}) with an N:P:K blend (1.0:0.17:1.02). For the WSG fertilizer, N was derived from NH_4NO_3, P from triple superphosphate, and K from KCl. For the FRT fertilizer, N and K were derived from KNO_3, $Mg(NO_3)_2$, and $(NH_4)_2SO_4$, and P from H_3PO_4. For the CRF, the sources of P and K were the same as for the dry water-soluble granular treatment, and N was derived from polymer-coated granulated urea. Treatments are summarized in Table 2.

Six-month-old spring flush leaves from nonfruiting terminals were sampled in July–August each year (Obreza et al., 1992). The leaf samples were thoroughly washed in detergent and dilute HCl, rinsed in distilled water, dried at 70°C for 48 h, ground to <0.4 mm, and ashed at 550°C for 5 h. The ash was cooled and 20 mL of 1 *M* HCl was added. The concentrations of P, Ca, Mg, and K were determined by inductively coupled plasma argon emission spectrometry (ICAPES; Plasma 40; Perkin Elmer Inc., Norwalk, CT), and the concentrations of N in leaf samples were analyzed by the Kjeldahl method (Bremner, 1996).

Shortly before fruit harvest, 25 to 30 fruit were sampled from each of the two middle trees in each plot. The fresh weight per fruit was based on the number and total fresh weight of fruit per plot. These fruit were taken to the University of Florida, Department of Citrus, Juice Quality Laboratory in Lake Alfred for analysis of juice quality, including juice content, soluble solid concentration (SSC), titratable acidity (TA), SSC/TA ratio, and amounts of total solids per unit fresh weight of the fruit, following standard procedures (Wardowski, 1990). The dates of fruit sample collection for quality analyses were 21 Dec., 1997, 15 Nov., 1998, and 3 Feb., 2000.

Fruit were harvested in January or February of each year. The fruit yields were recorded by manually picking the fruit from the two middle trees per plot into a standard 10-box bin (386 kg). The total weight of the fruit in each 10-box bin was measured by a calibrated stick, which is scaled from 1 to 10 corresponding to 1 to 10 boxes of fruit. The yield of the two trees per plot was used to calculate the per-hectare yield on the basis of tree density in the grove.

The response of fruit yield, quality, and leaf N concentration to N rates, sources, and irrigation was evaluated by analysis of variance and regression analysis with SAS (Release 6.12) (SAS Institute, 1996). There were no significant interactions between irrigation, fertilizer source, or fertilizer rate and year with respect to leaf N concentration, fruit yield, and quality. However, fruit yield varied significantly from year to year, as grapefruit production is of cyclic nature. Therefore, it may be more appropriate and meaningful to conduct a general statistical analysis of leaf N concentration, fruit yield, and quality response on the basis of the average data of 3 yr rather than year by year data.

Table 1. Selected properties of the Riviera fine sand from the experiment site.†

Depth	Organic matter	pH	Soil texture Clay	Sand	Silt
cm	g kg^{-1}		g kg^{-1}		
0–15	17.3	7.5	14	958	28
15–30	13.1	7.6	14	958	28
30–60	11.1	7.5	4	986	10
60–90	7.3	7.4	15	980	5
90–120	7.5	7.5	220	766	14
120–150	5.0	7.5	179	818	3

† Soil organic matter was measured with a CNS analyzer (NA 1500, Fisons Instruments Inc., Dearborn, MI); pH was measured at 1:1 soil/water ratio with a pH meter (Accumet Model 50, Fisher Scientific); and texture was measured by the micropipette method.

Table 2. Field trial treatments of irrigation and fertilization effects on yield and quality of white 'Marsh' grapefruit

Irrigation treatments	Fertilizers	N rates
kPa		kg ha^{-1}
15†	Dry water soluble granular	0 56, 112, 168, 224
	Fertigation	0 56, 112, 168, 224
	Controlled release fertilizer	0 56, 112, 168, 224
30	Dry water soluble granular	0 56, 112, 168, 224
	Fertigation	0 56, 112, 168, 224
	Controlled release fertilizer	0 56, 112, 168, 224

† Soil moisture tension value at which irrigation was initiated.

Table 3. ANOVA of irrigation and fertilization effects on leaf N concentration, fruit yield, and quality parameters of white 'Marsh' grapefruit (Data were means of the three years: 1997-1998, 1998-1999, and 1999-2000).

			Fruit quality parameters†					
Treatments	**Leaf N concentration**	**Fruit yield**	**Fruit weight**	**Juice**	**TA**	**SSC**	**SSC/TA**	**Solids**
Irrigation (I)	NS	NS	NS	NS	NS	NS	NS	NS
Fertilizer sources (S)	NS	NS	NS	NS	NS	NS	NS	NS
Fertilizer rates (R)	**	**	**	*	**	*	*	*
I × S	NS	NS	NS	NS	NS	NS	NS	NS
I × R	NS	NS	NS	NS	NS	NS	NS	NS
S × R	*	*	*	NS	*	*	*	NS
I × S × R	NS	NS	NS	NS	NS	NS	NS	NS

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
NS, not significant.
† TA, titratable acid and SSC, soluble solid concentration.

RESULTS AND DISCUSSION

Fruit Yield

Fruit yield across the three seasons averaged 60.7 Mg ha^{-1} yr^{-1} for the low irrigation rate and 59.5 Mg ha^{-1} yr^{-1} for the high irrigation rate and no significant difference was observed between the two irrigation treatments (Table 3). This could be attributed to the fact that the Indian River area has obvious rainy and dry seasons and the difference in moisture tensions between the high and the low treatment (15 kPa) was too narrow to cause any significant effect on the growth of mature grapefruit trees. The mean fruit yields across the three years were 47.4, 54.7, and 55.4 Mg ha^{-1} yr^{-1}, respectively, for the WSG, CRF, and FRT treatment. Nitrogen source had no significant effect on fruit yield (Table 3). Therefore, the data of all three N sources were combined to discuss yield response to N rates.

Fruit yield was significantly affected by N rate (Table 3). Increasing N rate consistently and markedly increased fruit number per tree (data not shown) and subsequently fruit yield. The response of fruit yield to N rate was not significantly affected by irrigation treatment or fertilizer source (Table 3). The relationship between fruit yield and fertilizer rate was described by a linear model (Fig. 1). A quadratic relationship of fruit yield to N rate was reported by Smith (1966) and Obreza and Rouse (1993). The relationship of fruit yield to leaf N concentration also fitted a linear model (Fig. 2). Fruit yield increased with increasing leaf N concentration. However, it must be pointed out that the increase in fruit yield might diminish when the leaf N concentration approached higher levels at higher N rates (He et al., 2000).

Fruit Quality

Fruit quality was not significantly affected by irrigation treatment or fertilizer source (Table 3). However, N rate significantly affected fruit quality. Fruit size was small at N rates below 50 kg ha^{-1} and leaf N concentration <21 g kg^{-1}, probably because of nutrient deficiency (Fig. 3). Fruit weight initially increased with increasing N rates, but decreased quadratically with N rates >100 kg ha^{-1} or leaf N concentration >22 g kg^{-1} (Fig. 3). Titratable acid concentrations (TA) in fruit were positively correlated with N application rates ($r = 0.94$ at $P < 0.01$), and soluble solid concentration (SSC) also increased with N rate (data not shown). However, the effect of N rate or leaf N concentration on TA was greater than on SSC. Consequently, the SSC/TA ratio decreased with N rate or leaf N concentration (Fig. 4). Increasing N rate generally increased juice and solids contents (Calvert et al., 2000) and the effect was significant (Table 3). These results indicate that fruit quality attributes such as juice volume, total solids, and SSC may be improved by increasing fertilizer rates. How-

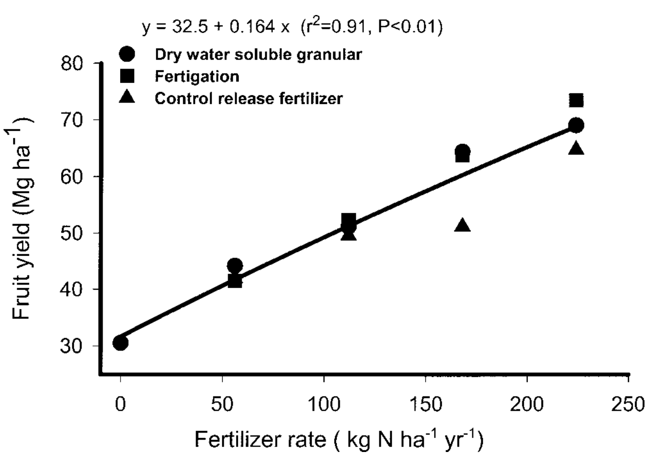

Fig. 1. Effect of fertilizer rates on fruit yield of white Marsh grapefruit, 1997–2000.

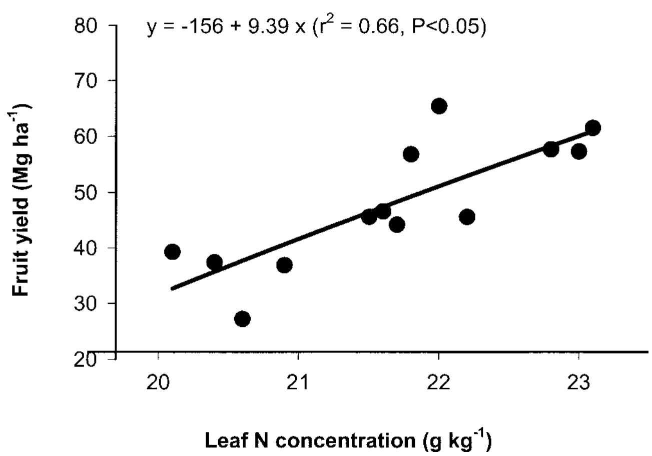

Fig. 2. Fruit yield in relation to leaf N concentration in 6-mo-old spring flush, 1997–2000.

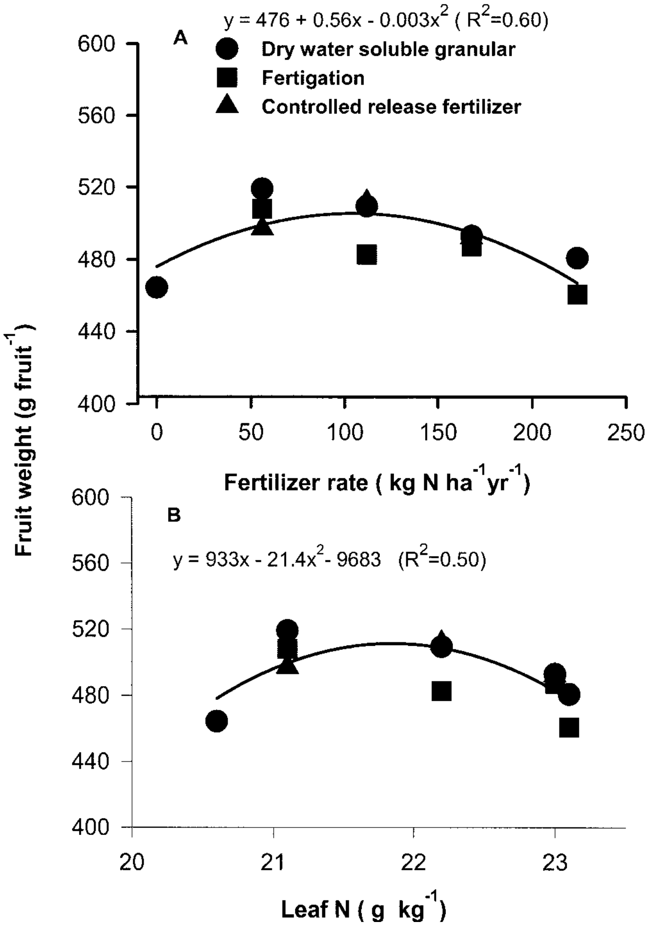

Fig. 3. Fruit weight of white Marsh grapefruit in relation to fertilizer rates and sources (A) or leaf N concentration (B), 1997–2000.

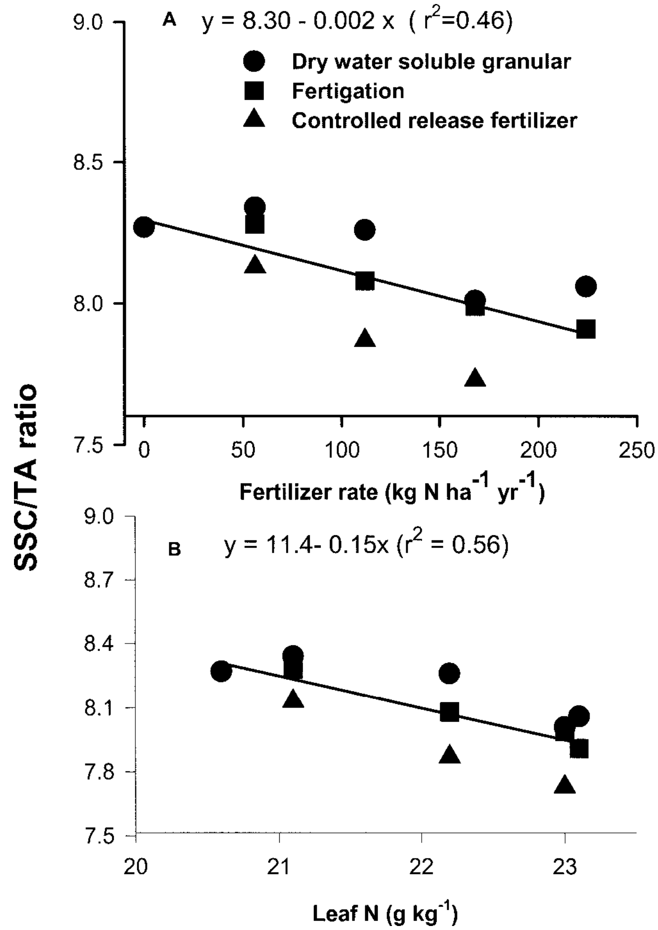

Fig. 4. Relationship between SSC/TA ratio and N rates and sources (A) and leaf N concentration (B), 1997– 2000 (SSC = soluble solid concentration and TA = titratable acid).

ever, apart from yield, some negative effects of increasing N rates on fruit quality components such as decreased fruit size and increased acid concentration need to be carefully considered in the development of best management practices for grapefruit.

Leaf Nitrogen Concentration

Except for the 1997-1998 growing season, during which FRT resulted in a lower average leaf N concentration (19.3 g kg^{-1}) than the WSG (20.5 g kg^{-1}) or CRF (20.3 g kg^{-1}), no significant differences in leaf N concentration were observed among the three fertilizer sources or the two irrigation treatments (Table 3). Therefore, all the data from different N sources and irrigation treatments were combined to develop leaf N concentration standards from a single response curve. Nitrogen concentration in the 6-mo-old spring flush leaves of the grapefruit increased with increasing N rates regardless of fertilizer source (Fig. 5). On the basis of a linear regression of the pooled data across the three years, leaf N concentration increased by 0.01 g kg^{-1} per kg N increment.

The concentrations of leaf P (11–13 g kg^{-1}), Ca (35–47 g kg^{-1}), or Mg (3.5–4.8 g kg^{-1}) did not respond to fertilizer rates or sources (Data not shown). Increasing fertilization rates slightly decreased leaf K concentrations (6–11 g kg^{-1}), which probably resulted from enhanced soil acidification at higher N rates (pH decreased by 1–3 units, depending on N rates) that decreased K availability in the sandy soil (He et al., 1999). On the basis of leaf nutrient guidelines for citrus trees (Tucker et al., 1995), leaf P, Ca, or Mg concentrations were within the optimum ranges, and leaf K concentration was slightly lower than the optimal levels.

The relationships shown in Fig. 2 through 4 provide a basis for establishing a critical leaf N concentration range. To develop leaf N concentration standards, maximum yield needs to be identified. Maximum yield is defined as the highest possible yield under a given set of conditions, when the factor under consideration is not limiting. This does not mean the greatest potential yield under all conditions. Since the absolute yields vary with different conditions, yield is expressed as percent of a maximum for each year, i.e., relative yield, in Fig. 6. Grapefruit production has a cyclic nature, i.e., a high yield year followed by a low yield year and vice versa (He, Z. L., David V. Calvert, A. K. Alva, and Y. C. Li, unpublished data). On the basis of the relative yield, yield in each year approaches its maximum (100%) in the same way when controllable limiting factors are relieved. The relative yields of grapefruit for all the three years were quadratically related to leaf N concen-

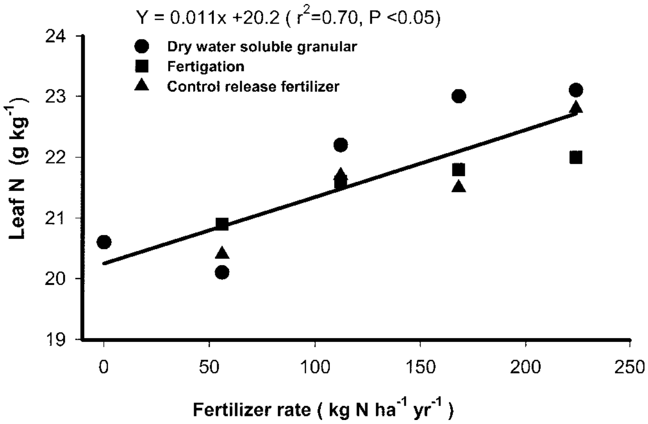

Fig. 5. Effect of fertilizer rates and sources on leaf N concentration in 6-mo-old spring flush, 1997–2000.

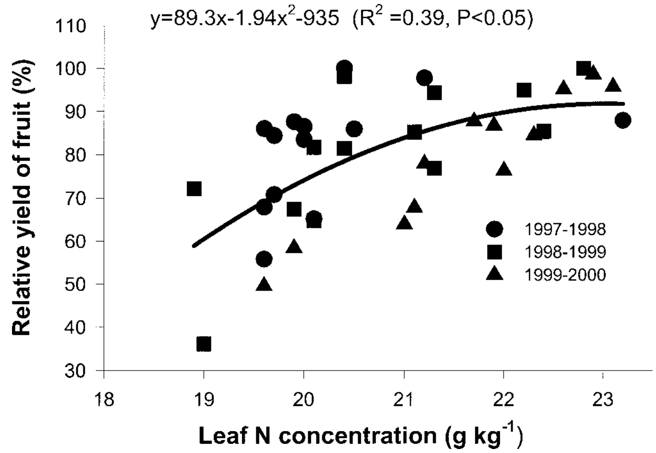

Fig. 6. Relative fruit yield in relation to leaf N concentration in 6-mo-old spring flush, 1997–2000.

trations (Fig. 6). At 90% of the maximum relative yield, the leaf N concentrations ranged from 22 to 23 g kg^{-1} under the experimental conditions. The 90% of maximum yield has been widely considered to be the optimal yield because of two reasons: (i) increase in yield is generally insignificant after this point; (ii) economic return (output/input ratio) progressively diminishes with higher yield targets (Mitcherlish, 1954). This is particularly true for grapefruit, as higher yield targets require more N fertilizer, which adversely affects fruit quality properties such as fruit size, acid content, and SSC/TA ratio (Fig. 3–4). These properties are important for fresh fruit marketing.

The data in Fig. 4 indicate that fruit weight and SSC/TA ratio were negatively related to leaf N concentrations, whereas the TA, SSC, juice volume, and total solids were positively related with leaf N concentrations, although the significance varied in quality properties and between the production years. However, it was observed that at leaf N concentrations of 22 to 23 g kg^{-1}, the fruit weight was around 490 to 500 g (Fig. 3) and the SSC/TA ratios were 7.9 to 8.0 (Fig. 4), which usually are considered the appropriate size and ratios for fresh fruit packing (Florida Cooperative Extension Service, 1979). Therefore, the leaf N concentrations of 22 to 23 g kg^{-1} should support optimal fruit yield with acceptable fruit quality for grapefruit.

The critical leaf N concentration of 22 to 23 g kg^{-1} proposed from this study for optimal grapefruit production is comparable with those previously reported for maximum yield for grapefruit. Reitz and Hunziker (1961) observed that maximum yield for Marsh grapefruit was obtained at 160 kg N ha^{-1} with a leaf N concentration of 21.3 g kg^{-1}. Smith et al. (1969) reported that full yield potential and thrifty tree condition resulted when 170 kg N ha^{-1} yr^{-1} was applied. This N rate maintained a leaf N level of about 24.5 g kg^{-1} in 4- to 5-mo-old leaves. Futch and Alva (1994) found that leaf N concentration in mature spring flush foliage over the three years varied from 22 to 24 g kg^{-1} when 168 to 275 kg N ha^{-1}yr^{-1} was applied. The relatively higher leaf N concentrations from the study of Smith et al. (1969) could be attributed to (i) deeper soil which allows a deeper rooting zone, thus increasing N use efficiency, (ii) low planting density (only 125 trees ha kg^{-1}), and (iii) use of younger leaves (4–5 mo old instead of 6-mo-old leaves).

On the basis of this study, 130 to 208 kg N ha^{-1} yr^{-1} is needed to maintain the concentration of N in the 6-mo-old spring flush foliage at 22 to 23 g kg^{-1} with average fruit yield about 65 to 70 Mg ha^{-1} yr^{-1}. The increased amount of N applied compared with previously reported maximum N rate (100–170 kg N ha^{-1} yr^{-1}) could be due to the increased planting density (from 150–270 trees ha^{-1}) and yield (from 45–50 to 65–70 Mg ha^{-1} yr^{-1}). As a matter of fact, this N rate, if calculated as kilograms N per tree (0.5–0.8) was lower than those (0.9–1.2 kg N per tree) applied for grapefruit trees in the 1960s (Reitz and Hunziker, 1961; Smith et al., 1969). The increased N utilization efficiency (higher yield with the same N rate) was attributed to improved irrigation and other management practices (Alva and Paramasivam, 1998). It must be pointed out that rootstock affects fruit yield and quality (Fallahi et al., 1989) and therefore, caution needs to be taken when the leaf N concentration standards or optimal N rate, which is developed on the basis of sour orange rootstock, are applied to other rootstocks. In addition, the effect of N rate on fruit weight or size was reported to be related with K availability (Du Plessis and Koen, 1988). When K availability is low, increasing N rate alone significantly reduced fruit size and yield, thus resulting in lower net income (Du Plessis and Koen, 1988). In our study, we fixed the N:P:K ratio at 1:0.17:1.02. Potassium and N were actually raised at similar levels when fertilizer rate increased. This might cause some effect of N rate on reduced fruit size. Therefore, a balanced N and K fertilization should be also considered in applying leaf N concentration standards proposed from this study.

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