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Response of Young and Maturing Citrus Trees Grown on a Sandy Soil to Irrigation Scheduling, Nitrogen Fertilizer Rate, and Nitrogen Application Method

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***Abstract*. This study examined the effect of irrigation rates, nitrogen (N) fertilizer rates, and methods of applying N on growth and productivity of young (3 to 5 years old) and maturing (8 to 10 years old) citrus trees. A long-term study was conducted with the following objectives: 1) to measure the main effects of N rate, N application method, and irrigation on citrus tree growth and production from planting to maturity; 2) to establish growth and production relationships for long-term N rates and irrigation on well-drained sandy Entisols; and 3) to determine the effect of split fertilizer applications at two soil moisture regimes on citrus growth and production for two tree age classes as trees mature. Irrigation was applied using two selected ranges of soil moisture tensions and annual N rate varied by tree age as percentages of recommended. Methods of applying N included a dry granular fertilizer (DGF) containing soluble N applied four times annually or a controlled-release fertilizer (CRF) applied once per year and fertigation applied either four (FG04) or 30 (FG30) times annually. Canopy size and yield were higher with the moderate irrigation rate compared with the low rate for both young and maturing trees. Critical N rates for both canopy volume and yield were between 178 and 200 kg·ha^{-1}. The CRF and FG30 treatments produced larger trees and higher yields compared with FG04 and DGF in the young tree study, indicating that younger trees benefitted from frequent split fertilizer applications. As the trees matured and filled their allocated space, the two irrigation rates were continued and N was applied at six rates using either DGF or FG30. For these 8- to 10-year-old trees, critical values of N application rates were 210 and 204 kg·ha^{-1} for DGF and FG30, respectively. The absence of a significant interaction between N rate and application method indicated that N uptake efficiency was similar for all application methods tested. DGF and FG30 treatments resulted in similar maturing tree yields and fruit total soluble solids. Canopy volumes, for the same trees, were significantly greater all 3 years with the FG30 treatment compared with DGF. Thus, if increase in tree size is desired, increased number of split applications will likely promote tree growth; however, little increase in fruit yield may be obtained.**

Economic and environmental concerns require more precise management of irrigation and nutrition of citrus produced on the well-drained sandy Entisols of the central Florida ridge. Fertilizers are readily leached from these soils, and nitrate–N concentrations in groundwater above the allowed maximum contaminant limit have been attributed to application of nitrogen (N) fertilizers for citrus production (Alva et al., 2003). The N source, rate of uptake, irrigation management, duration and intensity of rain, depth of the rooting zone, and other factors influence leaching losses. Until recently, the method and frequency of N application on these well-drained soils were considered only in terms of horticultural response and economics (Davies, 1997). However, concerns about nitrates in groundwater, increasing fertilizer costs, and low fruit economic returns have renewed interest in improving N uptake efficiency by selecting the best source and method of application.

Dry granular fertilizer (DGF) is commonly applied three or four times per year to Florida citrus. Generally, ≈67% of the N is applied between January and May during the period of flowering and maximum N demand (Obreza and Morgan, 2008). The current best management practice restricts application of N to citrus orchards on soils considered vulnerable to leaching of nutrients during the summer rainy period (FDACS, 2002; Obreza and Morgan, 2008). Maximum yields have been obtained with annual application of less than 225 kg·ha^{-1} N for citrus grown on the well-drained soils of the central Florida ridge (Alva et al., 2003; Davies, 1997). Syvertsen and Jifon (2001) found no effect of fertigation frequency (12 or 80 times per year) on tree growth and production or on the amount of fertilizer N taken up or leached. However, seemingly contradictory results have been found in studies examining the effect of application method to improve N use efficiency and reduce leaching on sandy Entisols. Schumann et al. (2003) found that the highest yields were obtained by fertigation (FG) with lower N application rates compared with DGF and controlled-release fertilizers (CRF). Leaf N values were higher per unit of applied N in the FG plots, indicating more efficient uptake. The authors concluded FG was the most efficient method of N application in this study, probably as a result of optimal placement and multiple applications. Likewise, Alva et al. (1998) found yield was slightly greater and loading of groundwater nitrate–N was lower using FG compared with DGF. Leaf nutrient concentration and fruit quality were unaffected by application method. In a separate study, Alva and Paramasivam (1998) found that yield and leaf N concentration increased with increasing N application rate. In that study, there was no significant interaction between N rate and application method, indicating that DGF, CRF, and FG were equally effective.

Fertilizer rate and method experiments on sandy Spodosols or Alfisols with confining layers at 1-m depth or less have had neutral or positive responses to application method (Obreza and Rouse, 1993; Rouse et al., 1999). The soil types in those studies were finer textured sandy soils with higher organic matter content, available water, and cation exchange capacities compared with the Entisols in the studies cited. Obreza and Rouse (1993) and Ferguson and Davies (1995) found that fertilizer source (CRF and DGF) had no effect on growth, yield, or fruit quality and the rate–by-source interaction was not significant. In a later study, Rouse et al. (1999) reported significantly increased yield of 3- to 5 year-old trees with CRF compared with DGF. However, there was no interaction of N rate and N source in this experiment. Reported yield of trees fertilized with DGF was similar to that of CRF when both were applied at a low rate. Similar yields among the two application methods would suggest similar uptake efficiency for both sources at the lowest rate. Greater yield with higher rates of CRF may suggest increased uptake efficiency compared with equal rates of DGF.

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Several field studies have determined the importance of proper irrigation scheduling on citrus growth and production on the low water and nutrient-retaining soils of central Florida (Boman, 1994; Morgan et al., 2006; Parsons et al., 2001; Scholberg et al., 2002). Field-scale fertilizer rate and method studies to date have been performed at a single irrigation schedule that varied from study to study. To determine the interaction of irrigation schedule, N application rate, and application method, a long-term study was conducted with the following objectives: 1) to measure the main effects and interactions of N rate, N application method, and irrigation on citrus tree growth and production from planting to maturity; 2) to establish growth and production relationships for long-term N rates and irrigation on well-drained sandy Entisols; and 3) to determine the effect of split fertilizer applications at two soil moisture regimes on citrus growth and production for two tree age classes as trees mature. To accomplish these goals, an experiment was conducted for a period of 10 years that provides additional information regarding the effects of irrigation and nutrient management on the growth and production of citrus trees on Entisols. Combining N rate and application method with irrigation schedule in a long-term experiment provided new insight into some of the contradictory results reviewed. Understanding the importance of irrigation rate, fertilizer N rate, and method of supplying N provides the basis for improved management of citrus and its environment on well-drained sandy soils.

Materials and Methods

'Ambersweet' orange trees [*Citrus reticulata* Blanco × (*C. paradisi* Macf. × *C. reticulata*) × midseason orange *C. sinensis* (L.) Osb.] on Swingle citrumelo rootstock [*C. paradisi* Macf. × *Poncirus trifoliata* (L.) Raf.] grown in a commercial nursery were planted in Apr. 1992 at a spacing of 3 m in the row and 6 m between rows. The planting was located in western Orange County, FL, at latitude 28°28′20″ north and longitude 81°28′38″ west on a Candler fine sand soil (hyperthermic, uncoated, Typic Quartzipsamment). An automated irrigation system was installed before planting and reclaimed municipal wastewater was used for irrigation. Water was supplied to each tree by a microsprinkler that wetted a circular area with a diameter of 3.3 m, or 53% of the total orchard floor area. Water application rates are reported on a total land area, not on a wetted area basis. Plots consisted of 12 adjacent trees in one row and were arranged in a randomized complete block experimental design with four replicates. Trees in all plots were grown for 1 year after recommended commercial practices before experimental treatments were applied.

This 10-year study was conducted in two phases. Treatments in the young tree phase (1- to 5-year-old trees) were factorial combinations of two irrigation rates, three N application rates, and four application methods (Table 1). Treatments were modified in the maturing tree phase (6 to 10 years old) to provide better resolution of the N rate response. Two application methods were omitted and three additional N rates were included for each of the remaining two application methods. The experiment then consisted of two irrigation rates, six N rates, and two methods of application.

Irrigation treatments. Irrigation was automatically controlled by four transducer tensiometers at a 150-mm depth in each irrigation treatment. Scheduling started in 1993 (Year 1) and remained the same through the end of the study (2002, Year 10). The moderate rate irrigation was scheduled when two of the four tensiometers reached 8 kPa in the spring and 12 kPa during the rest of the year. Low-rate irrigation was scheduled at 10 kPa (spring) and 15 kPa (rest of the year). Soil water potential values for the low irrigation rate were selected to increase intervals between irrigation events compared with soil water potentials of the moderate rate that would provide irrigation at current soil water depletion recommendations (Obreza and Morgan, 2008). Irrigation volume varied but averaged 300 mm annually for the low irrigation rated and 560 mm for the moderate rate. Each tree was irrigated by one microsprinkler emitter (Tornado; Plastro Irrigation Systems, Ltd., Ha'Amakim, Israel) with an output of 57 $L \cdot hr^{-1}$ distributed in a circular pattern ≈3.3 m in diameter. The reclaimed water met drinking water standards for most elements and contained a low concentration of N (≈7 $mg \cdot kg^{-1}$). Previous work indicated the N at this concentration in reclaimed water did not contribute to the N requirements of citrus (Scholberg et al., 2002). Irrigation at the low and moderate rates with this water provided ≈11 and 22 $kg \cdot ha^{-1}$ N, respectively, for the two irrigation treatments.

Table 1. Factorial design[z] of irrigation scheduling and nitrogen (N) fertilization treatments applied to young citrus trees (1993 to 1997) and maturing trees (1998 to 2002).

Treatment	1993–1994	1995–1997	1998–2002
Irrigation rate—Soil water potential set points by month (kPa)			
Low		February–May (10) June–January (15)	
Moderate		February–May (8) June–January (12)	
Annual N rate—Percentage of recommended annual N rate ($kg \cdot ha^{-1}$)			
Low	50 (48)	60 (135)	60 (135)
	—	—	75 (170)
Moderate	100 (97)	90 (200)	90 (200)
	—	—	105 (235)
High	200 (195)	120 (270)	120 (270)
	—	—	135 (300)
Application method (applications per year)			
Controlled release	1	1	—
Dry soluble	4	4	4
Low-frequency fertigation	4	4	—
High-frequency fertigation	30	30	30

[z]Experimental design was randomized complete block replicated four times. Each plot was treated with one irrigation rate, one annual N rate applied using one application method. The N rates and methods were changed over time to reflect increasing N rates with tree growth and the need to determine better resolution on interaction of the number of split applications and N rate on yield of maturing citrus trees. Data from the final 2 years of 1994 to 1997 and 1998 to 2002 were analyzed statistically with the beginning 2 years of each time period used as transition time from the previous treatments.

Fertilizer Rates and Application Methods

Young tree study. Fertilizer rates were expressed on the basis of N rate because N is the primary limiting nutrient for citrus production in Florida (Mattos et al., 2003). The initial experiment included four equal split applications of DGF in February, March, May, and September and CRF applied once annually in February. These dry materials were applied by hand to a circle with a diameter of ≈0.5 m centered at the trunk of the young tree. The same rates of nutrient were also applied by fertigation either weekly from February to September [30 applications per year (FG30)] or four times per year at the same time the DGF was applied (FG04), but the area of application was much larger as a result of the distribution provided by the irrigation system. These placements of fertilizer are typical of commercial application methods. They result in concentration of the entire DGF and CRF nutrient loads over a relatively small area compared with FG30 or FG04 treatments. Beginning in 1995 (Year 3), all dry fertilizers were applied by a mechanical spreader in a band ≈2.5 m wide along the trunk row as is the common commercial practice for trees older than 3 years old.

The DGF and liquid FG formulations contained 8N–0P–6.6K with ammonium nitrate sources provided by local vendors. The CRF was a Meister® product (Helena Chemical Company, Fresno, CA) with a 9-month release time. It contained 18N–2.6P–9.9K, and the N form was urea. Annual fertilizer N rates applied to individual trees in 1993 (Year 1) and 1994 (Year 2) were half, one, and two times recommended rates for Florida citrus (Koo, 1984) resulting in 0.09, 0.18, and 0.36 kg N per tree (50, 97, and 195 $kg \cdot ha^{-1}$). At the time of this study, the recommended annual N rate changed from the rates stated previously to a flat N rate of 224 $kg \cdot ha^{-1}$ for both maturing and mature citrus trees (Tucker et al., 1995). Thus, fertilizer N rates were increased in Years 3 to 5 to 60%, 90%, and 120% of the recommended 224 kg·ha^{-1} annual N rate (Table 1).

Maturing tree study. It was determined that little information existed about how N rate affected tree growth and early fruit yields as a young orchard developed; therefore, the main focus of the study from Years 6 to 10 was to determine the interaction of N application rate, irrigation scheduling, and number of split fertilizer applications on production. In the sixth year of this study, some treatments were modified to allow better resolution of the N rate effect. Irrigation treatments remained the same, but the number of N rates increased from three to six and application methods were reduced from four to two (Table 1). Treatments originally receiving FG30 or DGF applications were continued without modification. Plots receiving CRF or FG04 were maintained with the same irrigation treatments but were converted to the N rate closest to their previous value and to either DGF or FG30. Plots formerly receiving FG04 received DGF and plots that received CRF in the young tree study received FG30 in the mature tree study. Annual N rates were set at 60%, 75%, 90%, 105%, 120%, and 135% of the recommended 224 kg·ha^{-1} (Table 1). For example, the CRF and FG04 treatments receiving 200 kg·ha^{-1} annually were converted to 170 or 235 kg·ha^{-1} annually applied as FG30 or DGF. These modified treatments were maintained for 2 years (Years 6 and 7) before data from the final 3 years (Years 8 to 10) of the experiment were collected. These changes provided six N rates and two methods of application along with the continuing two irrigation rates.

Data collection and sample analysis. Average canopy volume of the middle four trees was measured annually using a spheroid canopy shape model described by Whitney et al. (1991). To determine canopy volume, in-row and cross-row canopy diameters, tree height, and the highest point of canopy interception are used to estimate the volume of a truncated sphere. Fruit yield was measured by harvesting the middle 10 trees of each plot; the weight of fruit harvested from each plot was determined using commercial scales. Mean fruit diameter and fruit weights were measured for ≈20 representative fruits per plot. Degrees Brix and total titratable acidity in the juice from the sample fruits were determined according to hygrometer and base titration methods approved for Florida citrus quality tests (Wardowski et al., 1995). Samples of spring growth leaves (20 leaves from 10 trees) were taken in June or August of each year. Leaf samples were analyzed for N, phosphorus, and potassium. Leaf samples were dried at 70 °C to a constant weight and ground using a Cyclotec mill (Tecator Manufacturing, Tecator, Sweden). Ground tissue was analyzed for N by Kjeldahl methods (method 351.2; USEPA, 1993) using steam distillation (Buchi Analytical, Inc., New Castle, DE).

Statistical analysis. Treatments for both the young tree and maturing tree portions of the study were maintained for 5 years, but reported results are based on the last 3 years of each study. Data from the intervening 2 years were omitted as a transition from the young (3 to 5 years) to the maturing (8 to 10 years) trees. The general linear model procedure of SAS Version 9.1 (SAS, Inc., Cary, NC) was used to determine statistical significance of treatment main effects and interactions on canopy volume, yield, fruit size, juice content, juice quality, and leaf mineral content means. Generally, the effects of treatments were analyzed each year to allow yearly changes in the importance of individual factors in time to be more apparent. The critical point defined by a linear rise to plateau model was used to determine the minimum N rate for plots with significant N rate × N application method interactions using the nonlinear regression procedure in SAS.

Results and Discussion

Young trees. Irrigation rate was not consistently linked with either N rate or N application method, but not in all 3 years. Irrigation rate × N rate interactions were significant for yield in 2 of 3 years and total soluble solids (TSS) concentrations in all 3 years (Table 2). However, no significant effect of N rate or irrigation rate on fruit titratable acidity was found. Canopy size and yield of young trees generally increased as irrigation rate increased. Conversely, leaf N and TSS decreased with increased irrigation rate. Similar decreases in leaf P or potassium were not observed. The reduction in juice TSS was not a surprise, because dilution of juice from increased irrigation has been commonly observed (Koo and Smajstrla, 1984). However, TSS production per hectare was higher for the moderate irrigation rate as a result of the increased yield (data not shown). The N rate × application method interaction was significant for fruit yield in all 3 years and canopy volume in 2 of 3 years (Table 2). Method of nutrient application also influenced tree size and yield, but the effects changed with time. At the higher N rates, yield and tree size for the DGF method were considerably lower than for the other methods. Trees receiving the high rate of DGF were stunted and exhibited symptoms of high salt concentration in the root zone. Fertilizer salts can accumulate in the soil under Florida's dry spring conditions unless periodically leached (Syvertsen and Levy, 2005). The

Table 2. The effects of irrigation scheduling, nitrogen (N) rate, and N application method on fruit yield, canopy volume, leaf N concentration, and juice quality of young citrus trees 3 to 5 years old.

	Yield (mg·ha^{-1})			Canopy volume (m^3/tree)			Leaf N (g·kg^{-1})			Juice total soluble solids (°Brix)		
Treatment	1995	1996	1997	1995	1996	1997	1995	1996	1997	1995	1996	1997
Irrigation												
Low	2.1	17.7	34.4	3.4	6.9	10.3	25.7	24.9	23.0	9.11	11.60	10.49
Moderate	9.4	13.9	40.7	3.7	9.0	12.9	25.1	24.8	22.1	8.48	11.48	10.36
N rate (kg·ha^{-1})												
135	3.7	12.7	29.7	3.4	7.3	10.8	24.9	24.2	21.8	8.65	11.46	10.30
200	6.8	16.7	40.4	3.7	8.0	11.8	25.1	24.7	22.0	8.87	11.51	10.49
270	6.9	18.4	42.5	3.7	8.3	12.1	26.3	25.3	23.2	8.87	11.66	10.56
N method[z]												
CRF	6.5	16.9	39.6	3.5	7.8	11.3	25.5	25.8	22.7	8.89	11.78	10.57
DGF	5.6	13.4	36.7	3.3	7.6	11.5	25.7	24.8	22.3	8.85	11.31	10.40
FG04	5.2	16.3	35.4	3.6	7.9	11.4	24.9	23.5	22.1	8.76	11.70	10.39
FG30	5.8	16.6	38.6	4.1	8.4	12.2	25.6	25.3	23.2	8.68	11.37	10.34
					Statistics[y]							
Irrigation	**	**	**	**	**	**	NS	NS	**	**	NS	**
N rate	**	**	**	NS	**	**	**	**	**	**	NS	**
N method	**	*	*	**	*	*	**	**	**	*	**	*
Irrigation by N rate	**	NS	**	NS	NS	**	NS	NS	NS	**	*	*
Irrigation. by N method	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
N rate by N method	**	*	*	**	*	NS	NS	NS	NS	NS	NS	NS

[z]Fertilizer application methods; controlled-release (CRF), dry soluble (DSF), fertigation four times per year (FG04), and fertigation 30 times per year (FG30).
[y]Statistical significances: NS = nonsignificant; *, ** = significant at $P < 0.05$ and 0.01, respectively.

method of application for dry products (DGF and CRF) was changed in 1995 (Year 3) from hand application to a circle ≈0.5 m in diameter to a band ≈2.5 m wide as is typical of commercial practice. Changing the application method in Year 3 (1995) increased the surface area to which fertilizer was applied and reduced the effect of the high fertilizer application rate on a relatively small area. However, trees receiving DGF remained smaller compared with the other application methods until Year 5 (1997).

Reduced yield and tree size at the higher DGF rates suggests improved nutrient use efficiency of trees fertilized with CRF and FG30 or root injury as a result of salt burn from excessive fertilizer distributed to a small area. Accumulation of salts from fertilizer applications during dry spring seasons without adequate flushing of the root zone has been documented (Levy and Syvertsen, 2004; Syvertsen and Levy, 2005). The same annual N rate per tree was applied by all four methods. However, DGF and CRF were applied to a circle ≈0.5 m in diameter centered at the base of the tree. By contrast, the nutrients applied by the FG30 and FG04 methods were distributed with irrigation water to a circle ≈3.3 m in diameter. The application of the high rate of DGF immediately over the root zone resulted in injury and smaller tree size. The CRF was applied to the same small area as the DGF but did not cause injury as a result of its slow release characteristic. Note that the DGF applied at the lowest N rate was similar in size to FG30 and larger compared with the other two application methods (Fig. 1). Larger tree size with lower rates of DGF compared with the FG04 method may indicate that FG04 distributed

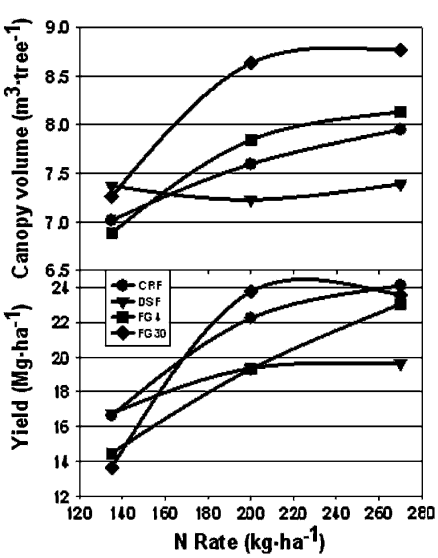

Fig. 1. Canopy volume and yield as a function of nitrogen (N) rate by application method for the young trees (age, 3 to 5 years). The interaction of N rate with application method resulted from reduced canopy size and yield at higher rates of dry soluble fertigation. All values were similar at the lowest N rate indicating similar uptake efficiency among methods.

fertilizer over an area larger than the existing root zone.

The largest trees at the higher N rates received the FG04 and FG30 treatments. Linear plateau analysis of the N rate by application method data indicates that the critical values or minimum N rates required to reach the canopy volume plateau were 182, 198, and 199 $kg \cdot ha^{-1}$ for FG30, CRF, and FG04, respectively, representing canopy volumes of 8.4, 7.6, and 7.9 m^3. The FG30 treatment produced larger trees with lower annual N rates compared with both CRF and FG4. Thus, the importance of application method to young trees was clearly demonstrated. The results also illustrate the problem of applying N as a fluid through an irrigation system that was designed for mature citrus trees, i.e., the wetting pattern extends beyond the root zone of younger trees. Applying optimum N rates before the root system expands to the entire irrigated area results in high potential loss of N and reduced N use efficiency.

The University of Florida-recommended N rates for young citrus trees at the time these applications were being made were excessive (Koo, 1984) and were reduced in subsequent recommendations (Tucker et al., 1995). The combination of an excessive recommended rate and DGF application by hand to a small area immediately over the small root zone of young trees probably resulted in root injury resulting from the salt content of the fertilizer, although this was not determined. The FG04 and DGF trees received the same amount of N per application, but the microsprinkler distributed the fertilizer to a larger area, much of which was beyond the root zone. Based on this interaction between N rate and method, recommendations for young tree fertilization have been reduced and the method of N application has been changed to avoid salt damage (Obreza and Morgan, 2008).

Leaf N and juice quality were also impacted by all three main factors (Table 2). Leaf N concentrations were generally within the recommended ranges for young trees, but they increased with increasing N rate and decreased with increased irrigation rate. Leaf nutrient status was significantly lower in FG04 plots compared with the other three methods.

With the exception of FG30, fruit yield of the young trees did not increase as N rate increased from 200 to 270 $kg \cdot ha^{-1}$ (Fig. 1). The linear plateau analysis indicates that the critical value for fruit yield was in the range of 177 to 188 $kg \cdot ha^{-1}$. Fruit yield for the FG30 method increased at the 270 $kg \cdot ha^{-1}$ N rate compared with the 200 $kg \cdot ha^{-1}$ rate, indicating that a plateau had not been reached for this application method.

Maturing trees. No consistent irrigation rate, N rate, or N application method interactions were found with the exception of a significant irrigation rate × N rate interaction for TSS and N rate × N application method interaction for canopy volume in 2 of 3 years (Table 3). Canopy size and yield were higher at the moderate irrigation rate compared with the low rate (Fig. 2). Like with the young tree study, TSS significantly decreased with increased irrigation, but TSS per hectare was greater with the higher irrigation rate (data not shown).

Equal yield, leaf N, and juice TSS were produced by the DGF and FG30 methods, but canopy volumes were significantly greater for FG30. Linear plateau analysis indicated that the critical N rates for yield were 210 and 204 $kg \cdot ha^{-1}$ for DGF and FG30, respectively. This result indicated little effect of greater number of fertilizer applications on yield (Fig. 2). The absence of significant N application rate interactions with application method for the maturing trees indicates that N uptake efficiency did not vary for split applications of N. Instead, it suggests that citrus root systems are equally effective in capturing available N from frequent small fertilizer applications or from four much larger applications. Efficient uptake of N from very dilute soil solutions has been demonstrated (Scholberg et al., 2002). Syvertsen and Jifon (2001) found no benefit of frequent fertigation on tree growth, fruit yield, N uptake, or leaching losses in sandy soils. However, Quinous et al. (2003, 2005) found greater N use efficiency (NUE) with 66 split applications from a drip irrigation system compared with five applications with flood irrigation in a clay loam soil.

Effective uptake of N from more concentrated sources has also been observed. Mattos et al. (2003) estimated NUE for 6-year-old 'Valencia' trees grown in a sandy soil to be 40% and 26% for ammonium nitrate and urea, respectively. Feigenbaum et al. (1987) reported that the NUE for a ^{15}N-labeled KNO_3 applied to 22-year-old 'Shamouti' orange was 40%. Syvertsen and Smith (1996) estimated NUE to be 61% to 83% for 4-year-old grapefruit trees grown in lysimeters. Nitrogen uptake efficiency decreased with increased N application rates. Lea-Cox and Syvertsen (1996) reported a similar finding of lower NUE with higher N application rate for greenhouse grown seedlings. The NUE reported ranged from 47% to 60% after an uptake period of 31 d. Indirect evidence for efficient uptake of N from three to four annual applications comes from the common and successful commercial practice of providing the annual N requirement by this method.

It is not surprising that there was little effect of application method, assuming proper irrigation scheduling after application, because the methods have much in common. Ammonium nitrate is a common soluble source of N used in formulating DGFs and fluid fertilizers. Irrigation of DGF immediately after application is recommended to dissolve the ammonium nitrate and move it into the root zone to reduce losses resulting from ammonia volatilization. Irrigation immediately after DGF application thus differs little from applying fluid ammonium nitrate with irrigation water. Similarly, use of CRF may mimic multiple fertigations because both methods maintain low concentrations

Table 3. The effects of irrigation scheduling, nitrogen (N) rate, and N application method on fruit yield, canopy volume, leaf N concentration, and juice quality of maturing citrus trees 8 to 10 years old.

	Yield (mg·ha^{-1})			Canopy volume (m^{3}/tree)			Leaf N (g·kg^{-1})			Juice total soluble solids (°Brix)		
Treatments	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
Irrigation												
Low	52.1	40.6	55.0	19.5	22.2	25.2	24.4	24.1	24.6	10.77	9.02	8.42
Moderate	58.3	50.0	61.8	22.2	27.1	28.4	25.7	24.2	24.4	9.26	8.78	8.56
N rate (kg·ha^{-1})												
135	50.5	33.2	50.9	20.8	24.7	27.0	23.8	22.7	22.2	9.84	8.76	8.48
170	54.9	39.9	51.3	20.2	24.2	26.4	24.0	23.1	24.6	9.96	8.77	8.58
200	55.7	46.4	59.7	21.6	25.3	27.2	25.0	23.4	24.6	10.11	8.82	8.40
235	55.7	48.5	64.9	21.0	24.5	26.5	25.5	25.1	25.7	10.03	8.86	8.62
270	56.8	55.2	63.0	21.5	25.4	27.7	25.6	24.7	25.3	9.84	9.13	8.47
300	57.7	48.8	60.5	20.1	23.9	26.2	26.4	25.0	24.7	10.31	9.10	8.54
N method[z]												
DGF	51.9	45.9	58.3	19.9	23.5	26.1	24.4	24.4	24.1	10.06	8.86	8.50
FG30	58.3	44.8	58.5	21.8	25.8	27.5	25.7	24.0	24.8	9.97	8.94	8.54
					Statistics[y]							
Irrigation	**	**	**	**	**	**	**	NS	NS	**	**	*
N rate	NS	**	**	NS	NS	NS	**	**	NS	**	**	*
N method	**	NS	NS	**	**	**	**	NS	NS	*	*	NS
Irrigation by N rate	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
Irrigation by N method	NS	NS	NS	NS	NS	NS	**	NS	NS	*	*	NS
N rate by N method	**	NS	NS	NS	*	*	NS	*	NS	**	NS	NS

[z]Fertilizer application methods; dry soluble (DGF) and fertigation 30 times per year (FG30).
[y]Statistical significances: NS = nonsignificant; *, ** = significant at $P < 0.05$ and 0.01, respectively.

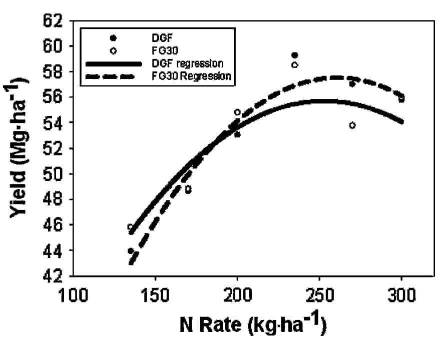

Fig. 2. Yield as a function of nitrogen (N) rate by application method for maturing trees (age, 8 to 10 years). No consistent interaction between N rate and method indicates little effect of multiple applications on mature tree yields.

of N in the root zone for extended periods of time.

Conclusions

Canopy size and yield were higher with the moderate irrigation rate compared with the low rate for both young and maturing tree studies. Leaf N concentrations were within the optimum range for both irrigation rates indicating little adverse effect of increased irrigation amount on tree nutrient status with increased irrigation rate. The CRF and FG30 treatments produced larger trees and higher yields compared with FG04 and DGF in the young tree study, indicating that younger trees benefitted from frequent split fertilizer applications because it avoided potential root damage resulting from salt loading by DGF in relatively small application zones. However, DGF and FG30 treatments resulted in similar maturing tree yields and fruit TSS. Canopy volumes, for the same trees, were significantly greater all 3 years with the FG30 treatment compared with DGF. These results support previous work showing little or no yield increase of splitting N into numerous small applications on the well-drained sandy soils of the central Florida ridge. However, tree size for maturing trees increases with increased split applications. Thus, if increase in tree size is desired, increased number of split applications will likely promote tree growth; however, little increase in fruit yield may be obtained. Optimum citrus production is possible from 8- to 10-year-old trees with a maximum annual N rate of 200 to 235 kg·ha^{-1} or less.

It appears that the ability of citrus to store substantial quantities of N and to efficiently absorb it from both dilute and concentrated soil solutions makes application frequency unimportant in mature trees. The apparent salt damage from application of high rates to young trees, however, suggests that it is wise to avoid applying the entire annual N requirement to trees of small size using a soluble source applied infrequently over the relatively small root zone. The decline in yield frequently observed with fertilizer rates greater than 200 kg·ha^{-1} may be partially the result of excessive salt, particularly in areas where the salt content of irrigation water is a problem. One important aspect of more frequent applications of fertilizer is that less fertilizer nutrients are available for leaching if a rain event occurs after fertilizer application.

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