Advances in Nitrogen Fertigation of Citrus

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ABSTRACT. Advances in micro-irrigation techniques, i.e., drip and under-the-tree sprinklers, have facilitated greater adoption of fertigation especially for perennial crops including citrus (*Citrus sinensis)*. Fertigation can improve nutrient uptake efficiency and minimize leaching of nutrients below the root zone, and thus can contribute to an increase in

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crop yield as well as crop quality as compared to those with conventional dry fertilizer broadcast application. In this paper, we summarized the recent fertigation studies on citrus. Long-term studies (over five to six years) have demonstrated that fertigation was beneficial as compared with broadcast of dry granular fertilizer for: (i) increased tree canopy area of young trees; (ii) increased fruit as well as juice yield of bearing orange and grapefruit (*Citrus paradisi*) trees; and (iii) decreased NO_3-N concentration in surficial aquifer. Citrus groves with drip or under-the-tree microsprinkler irrigation are ideal for fertigation with minimal or no extra cost for application of fertilizers. Soil area wetted by the sprinklers or drip emitters must be considered for success of fertigation. Fertigation must be avoided during heavy rainfall period to minimize leaching of nutrients and water below the rootzone.

KEYWORDS. Fruit quality, citrus, grapefruit, nutrient leaching into groundwater, nutrient uptake efficiency, partial rootzone wetting, water-soluble granular fertilizer broadcast

INTRODUCTION

Fertigation is a technique of applying fertilizers through an irrigation system. Advantages of fertigation identified by Burt et al. (1998) include: (i) reduced soil compaction by avoiding heavy equipment traffic through the field to apply fertilizers; (ii) less energy demand; (iii) less labor used; and (iv) application of nutrients in proper amounts within the soil area with maximum root distribution to supply plant nutrient requirements when they are needed.

Changing production practices, in some cases, has resulted in a shift towards more water-sensitive cultivars, which has led to greater dependence on irrigation/fertigation. For example, the citrus industry in Brazil has gradually shifted to rootstocks such as ‘Swingle’ citrumelo, ‘Sunki’, and ‘Cleopatra’ mandarins to replace the more traditional ‘Rangpur lime’ and ‘Volkamer lemon’ rootstocks. This was necessary to overcome the impact of devastating effects of citrus sudden death (CSD) syndrome. These newer rootstocks are more sensitive to water stress effects compared with the rootstocks they replaced. As a result, the overall need for irrigation of citrus in Brazil has increased in recent years (Román et al., 2004).

Depending on the crops and production regions, fertigation can be done through center-pivot, buried or surface driplines, or through sprinklers and microjets. Recent developments in drip and micro-irrigation methods have accelerated the adoption of fertigation for a wider range of crops, including fruit trees. Distribution uniformity of water by a given injection system is important for maximizing uniformity of nutrient distribution delivered through fertigation. Managing irrigation to minimize the leaching of water below the crop rooting depth is critical to minimize leaching of nutrients below the rootzone. Fertigation can result in greater yields and reduced nutrient losses with reduced total nutrient application rates compared with nutrient delivery by other conventional methods (Smith, 2001).

Fertigation offers the ability to deliver major nutrients, including nitrogen (N), phosphorus (P), and potassium (K); the secondary nutrients such as magnesium (Mg), calcium (Ca), and sulfur (S); and micronutrients including boron (B), copper (Cu), iron (Fe), manganese(Mn), molybdenum (Mo), and zinc (Zn). The main advantage of fertigation is that because the nutrients are applied in solution form, they are immediately available to the plants. Additionally, the quantity of nutrients delivered can be easily adjusted to match crop needs. The ability to precisely apply nutrients to match crop nutrient requirement and to apply nutrients to a localized area help maximize nutrient uptake efficiency. Scholberg et al. (2002) demonstrated that more frequent application of dilute N solution to citrus seedlings doubled nitrogen uptake efficiency (NUE) compared with less frequent application of a more concentrated nutrient solution. These authors also reported that increased residence time of N in the active rootzone enhanced NUE. Delivery of N through fertigation reduces N losses in the soil-plant system by ammonia volatilization and nitrate leaching (Smith, 2001).

Some common sources of nutrients used in fertigation and their concentrations of nutrients are shown in Table 1. This list is not comprehensive. Choice of sources of each nutrient depends on the availability and cost of the material in a given production region as well as its compatibility with other nutrient sources required for a given production condition. A clear understanding of compatibility among liquid fertilizers is important to avoid precipitation and clogging of the irrigation lines. These problems, which also are associated with poor water quality (i.e., excess iron and carbonate contents) and microbial growth (i.e., bacteria and algae), determine that irrigation lines need to be flushed after nutrients are delivered to clean the lines and emitters. Acid solution with either nitric, hydrochloric, phosphoric, or sulfuric acid may be used to dissolve certain compounds and precipitates that are insoluble under normal working conditions; bioactive copper might be used to reduce microbial growth (Boman, 2002).

TABLE 1. Common sources of nutrients used in solution.

Materials & formulation	Analysis of nutrients, %			Additional Elements
	N	P	K	%
Ammonium nitrate solution	21	0	0	
Ammonium sulfate solution	9	0	0	10 (S)
Ammonium polyphosphate	10	34	0	
Ammonium thiosulfate	12	0	0	26 (S)
Calcium nitrate solution	9	0	0	11 (Ca)
Urea ammonium nitrate solution	32	0	0	
Phosphoric acid	0	54	0	
Potassium nitrate solution	3	0	11	
Magnesium nitrate	7	0	0	6 (Mg)
Manganese nitrate	7	0	0	15 (Mn)
Zinc nitrate	7	0	0	17 (Zn)
Potassium chloride	0	0	62	
Potassium sulfate	0	0	52	
Potassium thiosulfate	0	0	25	17 (S)
Urea solution	23	0	0	

Note: Some of the above sources are specific to only some countries and for specific production systems.

Fertigation enhances crop quality and thus offers high value for the product leading to increased net revenue (Smith, 2001). The increased acceptance and adoption of fertigation across different crops and production systems have been possible due to: (i) improvements in formulation of macro- and micronutrient sources which are more soluble, readily obtainable, and convenient to use; and (ii) innovation in application technology including control systems for site specific application of nutrients as they are needed rather than as a blanket application.

In the case of tree crops, improvements in under-the-tree micro-irrigation technology offers an option to irrigate any desired area of coverage under the canopy. Fertigation in this case can deliver nutrients and water to an area of the soil under the tree canopy containing maximum concentration of roots. The fertigated area can be increased with growth of the trees by changing the micro-irrigation emitters to those covering larger soil area and the root distribution. To reduce emitter clogging by microbial growth or precipitations, the irrigation lines need to be flushed after nutrients are delivered to clean the lines. With under-the-tree fertigation, nutrient or water does not contact the foliage, thus there is no concern of foliage burn. Nutrients in soluble form are delivered with water directly into the rootzone, thus providing an ideal condition for rapid uptake of water and the nutrients. However, poor irrigation management, i.e., application of water in excess of crop requirement plus the storage capacity of the soil within the rooting depth, can contribute to leaching of water and nutrients below the rootzone. Therefore, optimal irrigation scheduling is important to maximize the uptake efficiencies of water as well as nutrients (Alva et al., 2005).

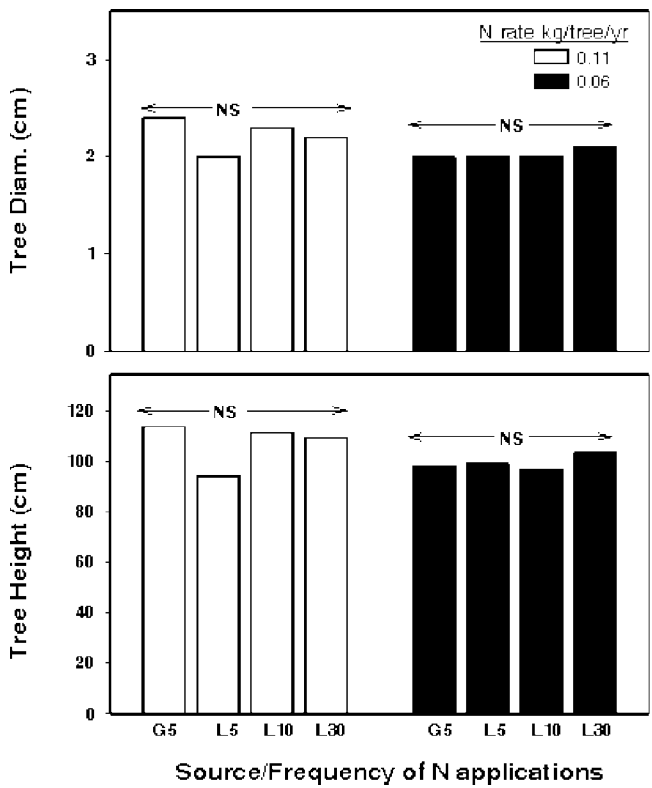
The objective of this paper is to summarize recent advances in application of N to citrus through fertigation. Evaluation of citrus-tree response to changes in nutrient management requires long-term studies because of the large storage of nutrients in the woody portion of the trees (Alva et al., 2006a; Mattos Jr., et al., 2003a, b; Morgan et al., 2006). The response of citrus trees to fertigation could vary depending on whether evaluations are based on tree growth parameters of young non-bearing trees, fruit yield response of bearing trees, leaf nutritional status of non-bearing vs. bearing trees, or soil conditions. Furthermore, the response could be different for orange (*Citrus sinensis*) vs. grapefruit (*Citrus paradisi*) trees. Despite the adoption of fertigation for citrus production a number of years ago, few long-term studies have been conducted to evaluate responses to fertigation of young tree growth, fruit yield and quality, as well as tree nutritional status of different age trees. In this paper, we summarized the available research results on evaluation of tree growth and fruit yield responses to fertigation compared with application of dry soluble granular fertilizers. The research gaps and the need for further investigations will be discussed. We recognize that this is one specific research area under the broad topic of fertigation. We also recognize research has been done in the other areas of fertigation, including optimal timing/frequency of application, optimal delivery systems to maximize nutrient uptake efficiency, optimal fertigation coverage of soil surface in relation to soil area of maximum root distribution, and an evaluation of drip vs. microsprinkler fertigation, etc. Coverage of these topics is outside the scope of this paper.

RESPONSE OF CITRUS TREES

Young Tree Growth

Willis et al. (1991) conducted a study in Florida using 1.5-year-old ‘Hamlin’ orange trees on ‘Sour Orange’ rootstock grown on a Kanapaha fine sand (loamy, siliceous, hyperthermic, Grossarenic Paleaquults). They evaluated two N rates (0.06 and 0.11 kg N/tree/year) as either broadcast application of dry granular fertilizer at five applications per year or as fertigation at 5, 10, or 30 applications per year. Trunk diameter or tree height was not significantly influenced by rate the method of N application or frequency of fertigation (Figure 1). The authors concluded that longer-term investigations were needed to evaluate the differences between

FIGURE 1. Growth response of 'Hamlin' orange trees on 'Sour Orange' rootstock at two N rates as broadcast application of dry granular fertilizer vs. fertigation (extracted from Willis et al., 1991). NS = Treatment means are not significantly different, at P = 0.05, by each response variable and each N rate; G5 = granular soluble fertilizer with five applications per growing season; L5, L10, L30 = Liquid form of N applied either 5, 10, or 30 applications per growing season, respectively.



fertigation and broadcast application (at lesser frequency) of dry granular fertilizers.

Bester et al. (1977) reported no significant difference in trunk diameter of newly planted 'Valencia' orange trees that received 0.05 kg of N per tree, per year fertigation at six applications per year or dry granular broadcast at four applications per year in the first two years. Rasmussen and Smith (1961) also reported lack of significant effects on growth of newly planted 'Valencia,' 'Hamlin,' and 'Pineapple' orange trees on 'Rough lemon' rootstock under different application frequency of granular fertilizer. Nitrogen rates applied during the first three years were 0.036, 0.072, and 0.162 kg of N per tree, per year.

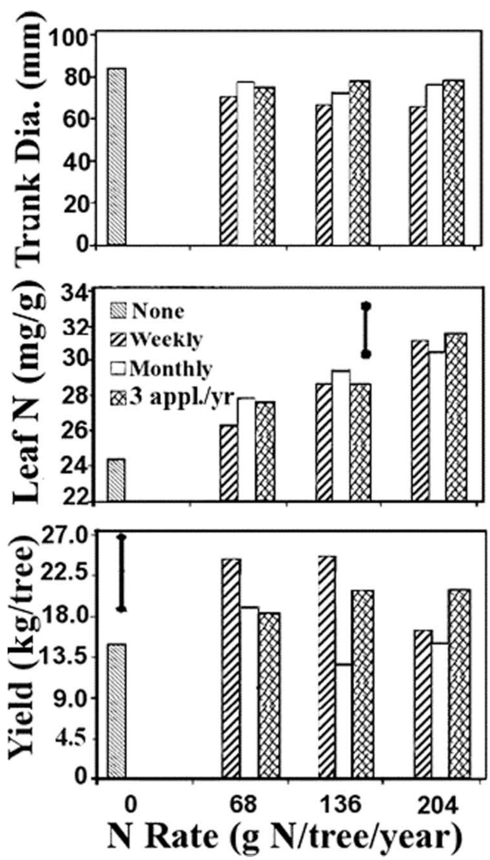
From the above studies, it is apparent that nutrient reserve in the young trees at the time of planting, depending on the nursery fertilization program, could contribute to nutrient requirement of the trees during the early years in the field. If so, then more than two-year evaluations of different nutrient management methods would be needed to evaluate nutrient management effects on growth or production.

Although in most cases nutrient reserves in nursery grown trees contribute to nutrient requirement of the trees during the early years, nursery practices have changed during recent years to produce container nursery trees with a single stem. These container-grown nursery trees contain lower amounts of nutrient reserves compared with in the field-nursery trees (Castle and Rouse, 1990). In such cases, the currently recommended fertilizer rates for young trees (Ferguson et al., 1995; Mattos Jr. et al., 2006) may not be adequate to support optimal tree growth and development. Adequate growth of trees in their early stages of development in the field promotes higher fruit yields because there is a close relationship between canopy volume and number of fruits per tree in the subsequent years (Quaggio et al., 2004).

Young Bearing Trees

Weinert et al. (2002) conducted a field study on five-year-old 'Newhall' navel orange trees on 'Carrizo' citrange rootstock on a calcareous Gilman loam soil (coarse, loamy, mixed hyperthermic Typic Torrifluvent) in Maricopa County, Arizona. The trees were planted in 1997 and the second year treatments included a factorial combination of four N rates (0, 0.068, 0.136, and 0.204 kg of N per tree, per year) and three application frequencies for the growing season, i.e. 27, 7, and 3 applications per year. Trees were irrigated using under-the-tree microsprinklers with one emitter per tree (300 degree coverage, delivery rate of 37.8 $L{\cdot}h^{-1}$). Irrigation was scheduled when the available soil water content depleted about 33% throughout the growing period. Urea ammonium nitrate (UAN-32) solution was used for fertigation. Increasing N rates significantly increased the leaf N concentration, particularly at the 0.136 and 0.204 kg N per tree rates compared with no fertilizer (Figure 2). The weekly application of either 0.068 or 0.136 kg of N per tree, per year significantly increased the fruit yield compared with that of the trees that were unfertilized. The trunk diameter response was nonsignificant across

FIGURE 2. Trunk diameter, leaf N, and fruit yield of two-year old 'Newhall' navel orange trees on 'Carrizo' citrange rootstock as influenced by different rates of N and fertigation frequencies (extracted from Weinert et al., 2002).



the range of frequencies (3 to 27 applications per year) of N fertigation. Fruit quality parameters, including Brix, and fruit mass were not significantly influenced by N rate or frequency of fertigation.

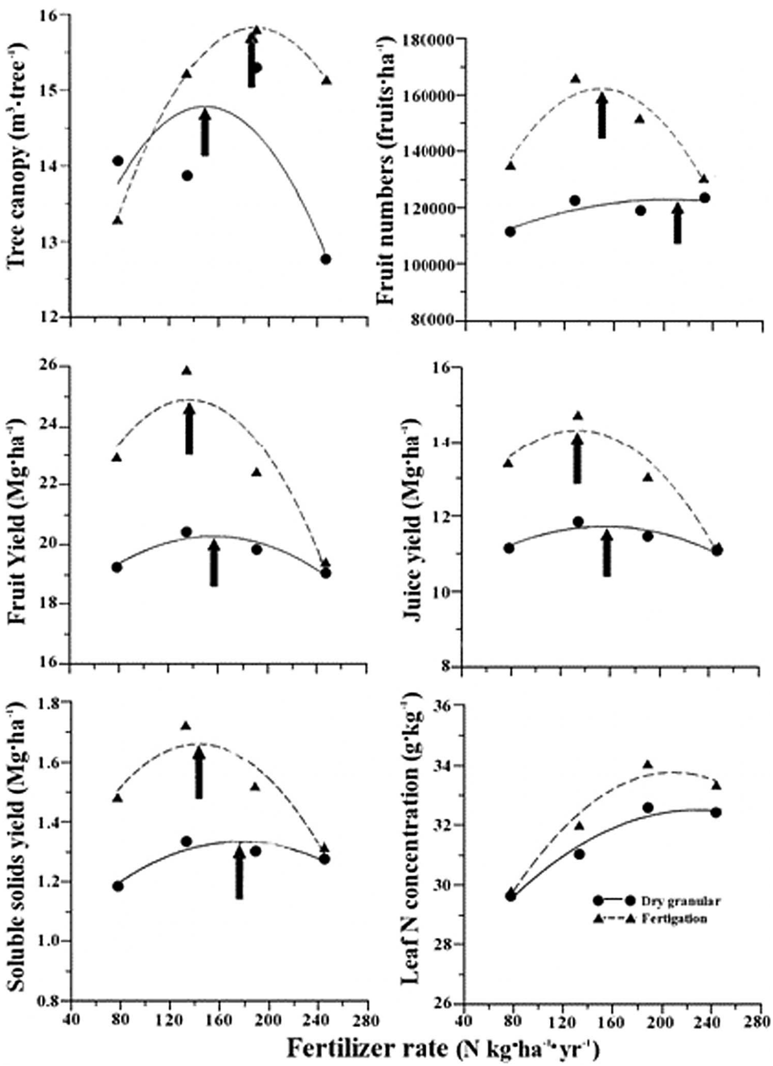
For tree crops, understanding N uptake efficiency as well as partitioning of N into different parts of the tree on an annual basis from the fertilizer N applied during a given year is complicated due to a large N reserve in the woody portion of the trees. Stored N represents a considerably large quantity in mature trees (Mattos Jr. et al., 2003a). Stored N in the nursery trees provides a portion of the N requirement of the one- to two-year-old trees in the field. This is, in part, responsible for a poor response of young trees to annual N applications (Boman, 1993; Castle and Rouse, 1990; Marler and Davies, 1990; Swietlik, 1992). Accordingly, the N rate/frequency evaluation should be carried out for several years to derive valid conclusions.

On the basis of the studies described above and those of Duenhas et al. (2002), Ferguson et al. (1990), and Rasmussen and Smith (1961), it appears that within the given duration of the respective studies, both fertilizer delivery methods (fertigation vs. dry granular-broadcast) and frequency of fertigation did not demonstrate significant effects on the tree growth. The lack of response was probably related to the short duration of the study and complications of stored nutrients in the woody portion of the trees, which was, in turn, redistributed to satisfy the nutrient requirement for the new growth.

Schumann et al. (2003) reported two years of responses of seven and eight-year-old Hamlin orange trees on 'Swingle' citrumelo rootstock grown (286 trees ha^{-1}) on a Candler fine sand (hyperthermic, coated Typic Quartzipsamments) in central Florida. Water-soluble granular (WSG; four equal split dose applications per year), fertigation (FRT; 15 appl/year), and controlled-release fertilizer (CRF; single application per year) were evaluated in this study at four rates (adjusted for tree age) for each fertilizer source. The trees were irrigated using under-the-tree, low-volume microsprinklers, one emitter per tree with a delivery rate of 38 $L \cdot h^{-1}$ and wetting area of 7.1 m^2 per tree. Trees were exposed to the different N source/rate treatments from planting until the yield evaluations seven to eight years later. The N rates evaluated during the seventh and eighth year were either 78, 134, 190, or 246 $kg \cdot ha^{-1} \cdot yr^{-1}$.

These seven and eight-year-old trees showed quadratic responses to N rates for canopy volume, fruit yield, fruit numbers, juice yield, and soluble solids yield (Figure 3). The peak fruit yield of the trees under fertigation was greater by 6 $Mg \cdot ha^{-1}$ compared with trees under dry granular fertilizer treatment. The optimal N rate was lower by 20 $kg \cdot ha^{-1}$ for fertigation (140 $kg \cdot ha^{-1}$) than for granular fertilizer (160 $kg \cdot ha^{-1}$). Net return is based on maximum soluble

FIGURE 3. Effects of fertilizer sources and rates on tree growth, fruit yield, soluble solids, juice yield, and leaf N concentration responses of seven- and eight-year-old 'Hamlin' orange trees on 'Swingle' citrumelo rootstock grown on a Candler fine sand in Florida (extracted from Schumann et al., 2003). Yield data are means for the years 7 and 8.



solids and Brix yields. The optimal N rates for Brix were 145 and 180 kg·ha^{-1} for the fertigation and dry granular broadcast treatments, respectively. Tree canopy, fruit number, and leaf N concentration were also greater with fertigation compared with dry granular fertilizer. This study was the first to report increased yield at lower optimal N rates of fertigation by conditioning the trees to different source/rates of fertilization over a long time.

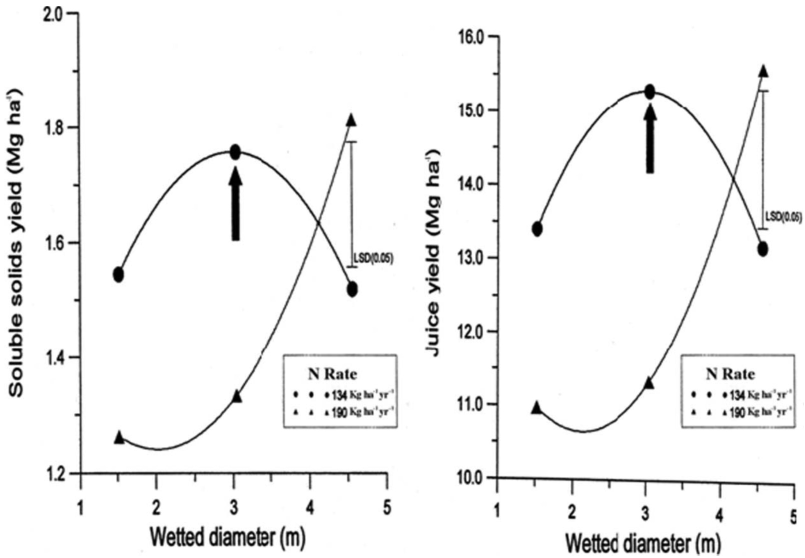
Cantarella et al. (1992; 2003) concluded, based on field experiments conducted in the State of São Paulo, Brazil, that there were two to three years lag time before trees show response to different N rates, applied as dry granular fertilizers, particularly when experiments began with adequately fertilized citrus trees. These studies demonstrated that maximum fruit yield was attained at 150 to 200 kg·ha^{-1} N.

Schumann et al. (2003) conducted a parallel study to compare three sprinkler coverage circles of 1.5, 3.0, and 4.5 m diameter per tree. All sprinklers delivered 37.8 L·h^{-1} water regardless of coverage area, thus, the rate of water application per unit area decreased with an increase in wetting area per tree. They evaluated two N rates of 134 and 190 kg·ha^{-1} as fertigation (15 applications per year). At the 190 kg·ha^{-1} N rate treatment, soluble solids and juice yields increased with an increase in area of sprinkler coverage over the full range of wetting area (Figure 4). At the 134 kg·ha^{-1} N rate treatment, responses were quadratic with decreases in soluble solids and juice yields at a higher sprinkler coverage areas. Increasing the sprinkler wetted area decreases the amount of nutrient applied per unit area during each fertigation. At the 4.5 m diameter, some portion of the nutrients was applied outside the area of root distribution, thus resulting in losses. This could explain the quadratic response found at the low N rate. At the high N rate, however, although some fraction of the total N may be unavailable to the tree roots at the high wetted area, the total amount of N that was available to the tree roots was high enough to show a positive response to this wetted area treatment. This study demonstrated that by conditioning the root distribution by different sprinkler coverage areas over the entire growth of the trees for eight years, the soluble solid yield responded to sprinkler coverage area differently with different N rates.

Mature Bearing Trees

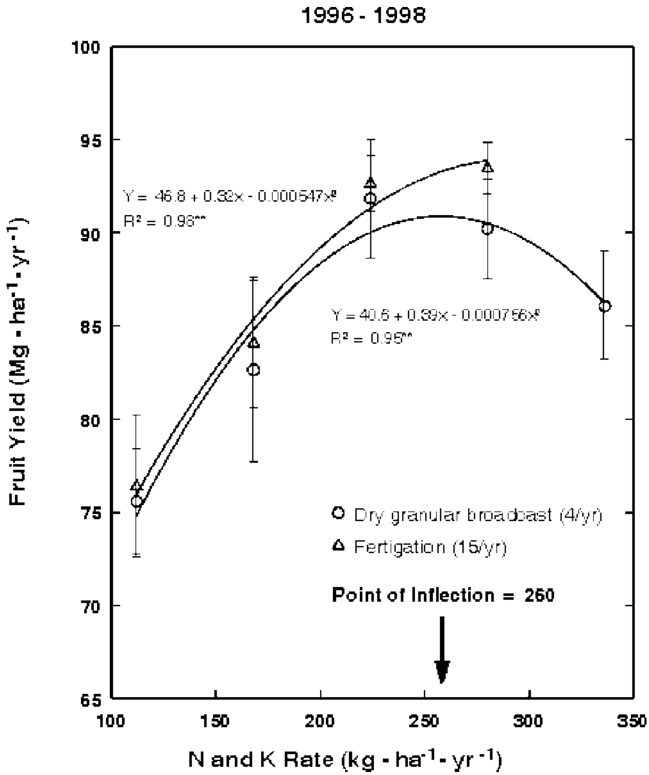
A six-year field experiment (1993–1998) was conducted in a Tavares fine sand (hyperthermic, uncoated Typic Quartzipsamments) in central Florida using 25-plus-year-old Hamlin orange trees on ‘Cleopatra’ mandarin rootstock (286 trees per hectare) to evaluate the effects of various rates

FIGURE 4. Mean soluble solids and juice yield (seven- and -year-old trees) of 'Hamlin' orange trees on 'Swingle citrumelo' rootstock that received two N rates as fertigation over a range of wetting areas. The arrow points to the peak yield for a quadratic relationship with wetting area of the emitters at the low N rate. The value of the vertical line represents the least significant difference (LSD) for mean comparison between two N rates at P = 0.05 (extracted from Schumann et al., 2003).



and sources of fertilizers on fruit yield, quality, and fate and transport of N in the soil (Alva and Paramasivam, 1998; Alva et al., 2006b; 2006c). Trees were irrigated using under-the-tree microsprinklers with one emitter per tree (83 L·h^{-1} delivery rate; 18.7 m^2 wetting area per tree). The wetting area represented 53% of the grove area. Irrigation was scheduled using recommended tensiometer set points of 10×10^{-3} and 15×10^{-3} MPa (in the top 30 cm depth soil) during the January–June and July–December time periods, respectively (Smajstrla et al., 1985; 1987; Parsons, 1989). Figure 5 shows three years (1996–1998) mean fruit yield response to N and K rates in the range of 112 to 336 kg·ha^{-1} as a water-soluble granular source (broadcast under the tree canopy; four applications per year) or in the range of 112 to 280 kg·ha^{-1} applied by fertigation (18 appl/year). Across the full range of N rates, fruit yield response was quadratic with optimal N rate at about 260 kg·ha^{-1}. Across the range of N rates, 112 to 280 kg·ha^{-1}, mean fruit

FIGURE 5. Fruit yield response of 25-plus-year-old 'Hamlin' orange trees on 'Cleopatra' mandarin rootstock (grown on a Tavares fine sand in Florida) to various rates of fertilizer as broadcast application (4 applications per year) of water soluble granular (WSG) or fertigation (FRT, 18 applications per year). Data shown are mean of years 4 through 6 of the study (extracted from Alva et al., 2006c).



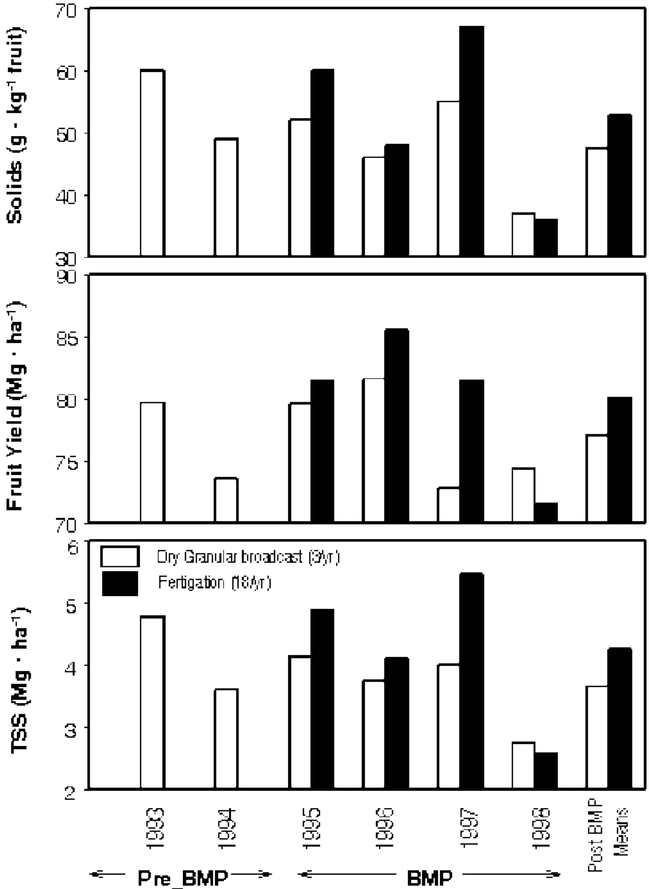
yields were not significantly different between fertigation and broadcast of water-soluble granular fertilizer. This study demonstrated that under careful irrigation scheduling, fertigation supports fruit yields equal to those with similar rates of broadcast granular fertilizer. Since fertigation was done during scheduled irrigation events, it did not require additional labor and/or energy costs unlike the broadcast application. The mean fruit yield at the optimal N rate was about 90 Mg·ha^{-1}, which was similar to yields from granular application but was almost two-fold greater yield than the industry average fruit yield for Florida (40–45 Mg·ha^{-1}). This study also confirmed the need to improve irrigation management to develop best management practices of N fertilization to minimize leaching losses, particularly in sandy soils.

Alva et al. (1998; 2003) and Alva, Paramasivam, and Graham (1998) conducted a nitrogen best management practice demonstration study (1993–1998) using two identical blocks (32 ha each) of 34-plus-years-old Valencia orange trees on 'Rough lemon' rootstock planted (286 trees ha^{-1}) in an Astatula fine sand (hyperthermic, uncoated, Typic Quartzipsamments) in Highlands County, Florida. Large blocks of groves were used in this study to facilitate application of commercial, industry-scale management practices. Both blocks were irrigated by one low-volume sprinkler per tree with a delivery rate of 96 L·h^{-1} and wetted area of 28 m^2 per tree. During 1993 and 1994, both blocks were on similar management practices including fertilizer application of 197 and 209 kg·ha^{-1} N, respectively. The fertilizer blend contained dry granular sources of N, P, and K. The annual fertilizer requirement was equally divided into three broadcast applications, i.e., January/February, May/June, and September/October. Soil water content was not monitored.

Subsequently, for four years the two blocks received different fertilizer management combined with improved irrigation management, while keeping all other tree management practices similar across the two blocks. The annual nitrogen rate was 180 kg·ha^{-1} for both blocks. For one block, dry granular product along with P and K sources (in a NPK blend of 1:0.5:1) was broadcast three times a year with 90, 45, and 45 kg·ha^{-1} N applied during January/February, May, and September, respectively. The second block received the same annual N rate, except that the NPK blend was applied in 18 fertigations per year, i.e., January–May (14 applications) and September–October (4 applications). Due to heavy rainfall during June through August (60% of annual total precipitation of about 1500 mm), no fertilizer was applied during this period. Irrigation was scheduled using tensiometer readings (at 15 and 30 cm depth), following the recommended set points of 10×10^{-3} and 15×10^{-3} MPa during January–June and July–December, respectively. Thus, this commercial-scale demonstration project incorporated precision scheduling of irrigation along with improved N management to evaluate the fruit yield and quality response, as well as leaching of NO_3-N below the tree rootzone.

Over a four-year period the mean fruit yield of fertigation treatment increased by 11%, while total soluble solids (TSS) increased by 16% compared with dry granular fertilizer application (Figure 6). Fruit yield showed an alternate bearing habit as evident from alternate years of high and low fruit yields. The magnitude of increased fruit yield with fertigation

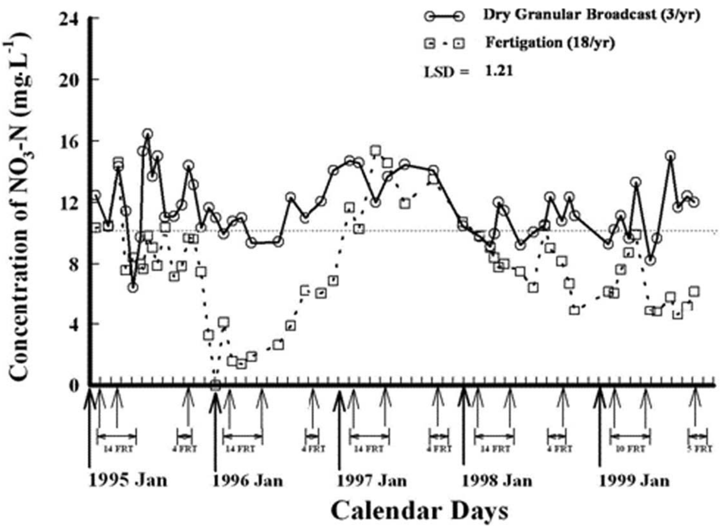
FIGURE 6. Fruit yield and total soluble solid (TSS) response of ‘Valencia’ orange trees on ‘Rough lemon’ rootstock with dry granular broadcast vs. fertigation at similar N rate (extracted from Alva et al., 2003).



compared with the dry granular fertilizer broadcast treatment was particularly greater during the ‘on years’ (high fruit yields) compared with ‘off years’ (low fruit yields). The success of fertigation also depends on the optimal scheduling of irrigation.

The NO_3-N concentration in the surficial aquifer was monitored during the study by sampling four monitoring wells in each block (Figure 7). When the study began, the surficial aquifer NO_3-N concentration was above the U.S. Environmental Protection Agency (EPA) recommended

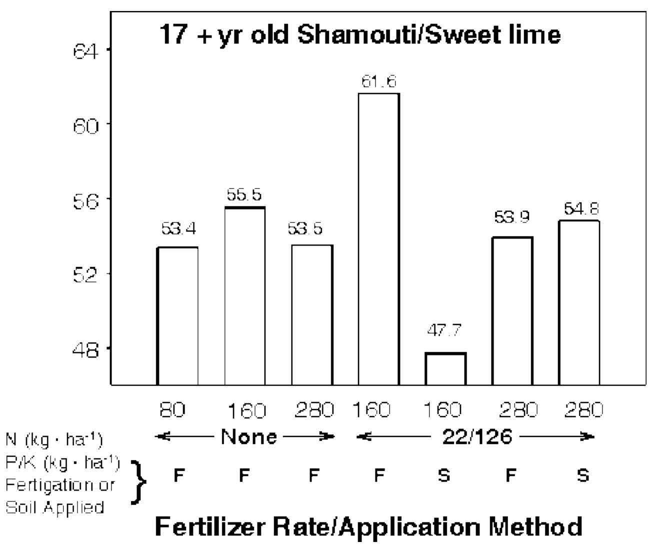
FIGURE 7. Concentration of NO_3-N in the surficial aquifer underneath citrus groves with 34-plus-year-old 'Valencia' orange trees on 'Rough lemon' rootstock grown in Astatula fine sand in central Florida. Each data point is mean of four monitoring well samples (A.K. Alva, 2005; extracted from Delgado et al., 2005).



critical concentration for drinking water of 10 mg·L^{-1}, which is defined as the maximum contaminant limit (MCL) of NO_3-N for drinking water . As the study progressed, the NO_3-N concentration in the surficial groundwater decreased in the block that was under fertigation; these concentrations were often below 10 mg·L^{-1} MCL and were also significantly lower than those in the groundwater underneath the block that received broadcast application of dry granular fertilizer. In the latter block, the surficial aquifer NO_3-N concentrations generally remained above the 10 mg·L^{-1} MCL. This long-term study was the first to demonstrate the fertigation benefit of decreasing NO_3-N loading into the surficial aquifer underneath citrus groves in sandy soils under high summer rainfall.

Dasberg et al. (1988) conducted a five-years study using 17-plus-year-old 'Shamouti' orange trees (416 trees ha^{-1}) on 'Sweet lime' rootstock. Fertigation was evaluated at 80, 160, and 280 kg·ha^{-1} N rates (mean rates across five years; with no P and K). The 160 and 280 kg·ha^{-1} N rates were also evaluated with P and K at 22 and 126 kg·ha^{-1} rates, respectively (mean across five years), and as either soil application of granular fertilizer (applied below the tree canopy in one or two applications per year) or as fertigations (March–August). The trees were irrigated using one under-the-tree microsprinkler per tree with a delivery rate of 70 L·h^{-1}. The wetting area of the trees accounted for 70% of the total grove area. Five-year average fruit yield varied from 47.7 to 61.6 Mg·ha^{-1} across different fertilizer treatments (Figure 8). With no P or K applied, increasing N rates from 80 to 280 kg·ha^{-1} resulted in no significant differences in the fruit yield. Among the treatments that received P and K along with N at 160 kg·ha^{-1} rate, fruit yield was greater by 29% with fertigation than that with soil application of granular fertilizer. At the 280 kg·ha^{-1} N rate, fruit yield differences were nonsignificant regardless of soil application or fertigation (Figure 8). Dasberg et al. (1988) concluded that 160 kg·ha^{-1} N applied all in one or two doses as granular product (applied under the tree canopy) was inefficient compared with application of the similar N rate as fertigation. Indeed the fruit yield was 16% greater with fertigation of 160 kg·ha^{-1} N alone (with no P or K) compared with that of soil application of the same N rate with P and K rates. In the case of the 280 kg·ha^{-1} N rate, fruit yield was largely similar

FIGURE 8. Five-year mean fruit yield of 17-plus-year-old 'Shamouti' orange trees on 'Sweet lime' rootstock with different rates of N as fertigation (F) without P and K, or two N rates with P and K as single application of granular fertilizer to the soil (S) or as fertigation during March through August (extracted from Dasberg et al., 1988).



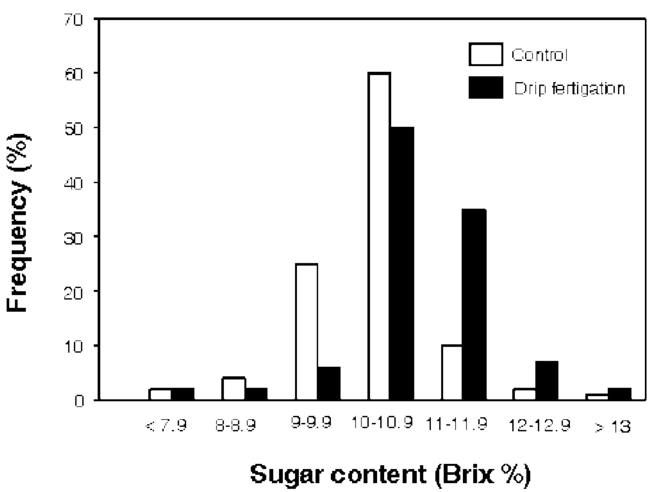
(53.5 to 54.8 Mg·ha^{-1}), regardless of either granular source or fertigation with P and K, or only N fertigation without P and K.

Fruit Quality

Morinaga (2004) conducted studies on 'Satsuma' mandarin in southwestern Japan. This premium quality fruit that contributes to high net returns requires maintaining 12–14% sugar and about 1% acid contents. To achieve this, Morinaga (2004) developed a system of drip fertigation with year-round plastic mulch. With the conventional practice, Brix content usually was in the range of 9.0–10.9% (Figure 9). In contrast, in the alternate system of drip fertigation with year-round plastic mulch Brix was usually in the range of 10–12.9%. Beneficial effects of the alternate system included: (i) reduced labor cost of plastic mulch removal annually; (ii) improved fruit quality and vigor; and (iii) facilitated application of fertilizers underneath the plastic mulch. On the basis of this study, Morinaga (2004) concluded that the alternate (drip irrigation) system improved fruit color, and contents of vitamin A, β-carotene, and β-cryptoxanthine.

Work conducted with Valencia sweet orange on a clayey Oxisol in Brazil demonstrated that fruit quality traits were affected by irrigation treatments (Villas-Bôas et al., 2002). Irrigated plots used either microsprinklers or drippers with two water delivery rates adjusted to

FIGURE 9. Effects of fertigation vs. broadcast application of dry fertilizer on sugar content of 'Satsuma' mandarin (extracted from Morinaga, 2004).



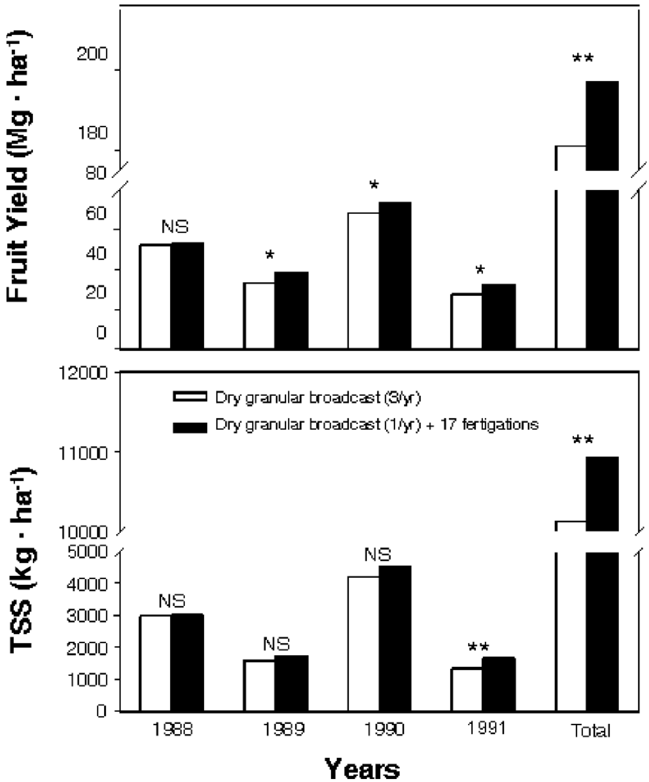
supply 50% and 100% of evapotranspiration (ET) obtained from a class A pan. Fruit size increased in the irrigated compared with the unirrigated treatment. However, Brix content of fruits decreased from 10.4 to 8.7%, and juice acidity decreased from 1.24 to 0.47%. The fruits in the 100% ET irrigation treatment showed an average for height and width of 7.9 cm, whereas those from the unirrigated treatment were 7.3 cm.

Grapefruit Yield Response

Boman (1996) conducted a four-year field experiment using 13-plus-year-old 'Ruby Red' grapefruit trees on 'Sour orange' rootstock planted (215 trees·ha^{-1}) in a Pineda fine sand (loamy, siliceous, hyperthermic, Arenic Glossaqualfs) in St. Lucie County, Florida. Two methods of fertilizer applications were compared at approximately 180 kg·ha^{-1} N and 150 kgha^{-1} K: (i) dry granular fertilizer with annual rates of N and K applied in three equally split broadcast applications (during February/March, May/June, and October/November); and (ii) 1/3 annual rates of N and K applied as granular material broadcast in February, with the remainder of the N and K sources applied as fertigation at two-week intervals during April through early November (i.e., 17–18 fertigations per year). Across the four years, the leaf nutrient concentrations were not significantly influenced by the method of fertilizer applications. However, as shown in Figure 10, the fruit yield (three out of four years) and total soluble solids (one out of four years) were significantly greater for the trees with dry fertilizer broadcast+fertigation treatment compared with trees with dry broadcast (three applications per year) of full N and K rates (Figure 10). In this study, however, fruit weight and juice quality parameters were not significantly different between the two fertilizer management techniques.

A six-year-study (1994 to 1999; A.K. Alva et al., 2008; unpublished data) on 30-plus-year-old 'White Marsh' grapefruit trees on 'Sour orange' rootstock (268 trees ha^{-1}) was conducted on a Riviera fine sand (loamy, siliceous, hyperthermic, Arenic Glossaqualf) in Martin County, Florida. The trees were irrigated using under-the-tree microsprinklers with one emitter per tree (delivery rate of 37.8 L·h^{-1}). Irrigation was scheduled when the soil water tensiometers reading at 15 cm depth dropped below 15×10^{-3} MPa. Water-soluble granular fertilizer (N:P:K blend at 1.0:0.17:1.02 ratio) was compared with a total fertigation using liquid fertilizer sources with similar N:P:K ratio as that in the dry fertilizer blend. Nitrogen rates at 56, 112, 168, and 224 kg·ha^{-1} were evaluated. The granular fertilizer source was applied in three doses (February, May, October), while fertigation was applied in

FIGURE 10. Fruit yield and soluble solid (TSS) response of 'Ruby Red' grapefruit trees on 'Sour orange' rootstock (extracted from Boman, 1996).

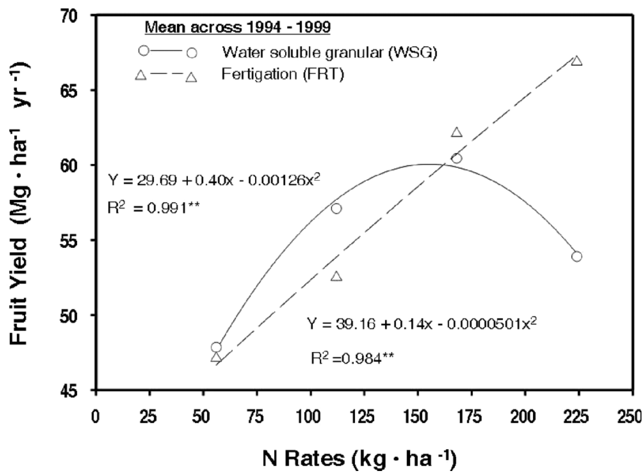


15 doses (February–May and September–October). With dry granular fertilizer, the mean fruit yield showed a quadratic response (47 to 60 Mg·ha^{-1}) to N rate (Figure 11); while in the case of fertigation, fruit yield response (47–67 Mg·ha^{-1}) was nearly linear across the same range of N rates. Thus, at the high N rate, mean fruit yield was 26% greater in the trees that received fertigation compared with trees that received the broadcast application of dry granular fertilizer.

RECOMMENDATIONS

Some practical guidelines for fertigation of citrus in Florida production conditions are reported by Koo (1980), and Boman and Obreza (2002).

FIGURE 11. Fruit yield response (six years mean) of 25-plus-year-old 'White Marsh' grapefruit trees on sour orange rootstock to different rates of N applied as water-soluble granular source broadcast (3 appl/yr) or fertigation (15 appl/yr). (A.K. Alva et al., 2007; unpublished data).



The combination of some nutrient sources can result in precipitation in the water lines and, in turn, cause problems of water and nutrient delivery. High calcium concentrations in the irrigation water (in excess of 100 $mg{\cdot}L^{-1}$) can precipitate phosphate if injected. Injecting fertilizer to irrigation water containing high salt content can result in excessive salt accumulation on the plant, as well as on the soil, if overhead irrigation was practiced. Salt build-up in the soil can be avoided by either excess rainfall or excess irrigation water application to leach the salts below the root zone. Fertigation, particularly through the drip system, requires high quality water. Suspended solids and microorganisms can plug the emitters. Among the N sources, anhydrous ammonia or any other N source that has free ammonia should not be used for fertigation. Potassium chloride can be used as a source of K for fertigation for most crops even when applied on the foliage. This is due to the ease of distribution of this product in large quantities with irrigation water. Potassium chloride has high K content (62% K) and is relatively cheaper than other K sources such as potassium nitrate or potassium sulfate. The latter sources should be used if crop in question is sensitive to chloride.

Backflow prevention devices should be installed in the water lines upstream of fertilizer injection to prevent the potential of contaminating the irrigation water source by the injected fertilizers. Optimum irrigation scheduling, to supply adequate water as needed for the plants and to maintain the depth of wetting within the rooting depth to minimize water and nutrients leaching below the rootzone, is important for successful fertigation. Injection of fertilizers to irrigation water when irrigation is scheduled in excess of water needs by the crop result in leaching of both water and nutrients below the rootzone.

Fertigation should be scheduled to deliver the amount of nutrients to match the crop nutrient requirement. Nutrient demand by the crop is dependent on the crop growth stage. Adequate knowledge of differences in crop nutritional demands over the crop growth stages is important to adjust the portion of nutrients delivered at various growth stages. Distribution uniformity of irrigation water is important for fertigation, particularly with overhead systems such as pivot fertigation. Flushing the irrigation system after injecting fertilizer solution is important to clean fertilizer residue in the injection pump, irrigation lines, and check valve. Irrigation systems should be carefully monitored during fertigation for possible leak and potential blockage of emitters.

Continuous evaluation of soil fertility is highly recommended. Chemical analyses of soil and soil solution samples are necessary for monitoring short-term and long-term changes in soil nutrient and associated properties that will assist management decisions for optimizing crop growth and yield.

The current recommendation for nutrient management for irrigated citrus groves in Brazil is similar to that for non-irrigated citrus. However with fertigation, N and K rates are recommended to be reduced by 20% because uptake efficiency of these nutrients are greater with fertigation compared with using dry fertilizer broadcast application. Recommended nutrient rates are adjusted depending on the crop load expectation, leaf nitrogen content, and resin extractable P and exchangeable K in the soil at 0–20 cm depth layer (Table 2). For example, a grove yielding 50 $Mg \cdot ha^{-1}$ of fruits, leaf N content of 27 $g \cdot kg^{-1}$, and resin extractable P in the soil of = 20 $mg \cdot dm^{-3}$ and exchangeable K concentration of 2 $mmol_c \cdot dm^{-3}$ at 0–20 cm depth soil; the recommended annual rates of N, P, and K for fertigation are 160, 30, and 65 $kg \cdot ha^{-1}$, respectively.

To minimize the risk of soil acidification associated with fertigation (as discussed above), P can be applied as dry granular form in a single dose in winter or early spring. However, a small portion of P can be applied through the drip lines as phosphoric acid in order to clean the irrigation lines to prevent clogging. Nitrogen and potassium are applied two to three

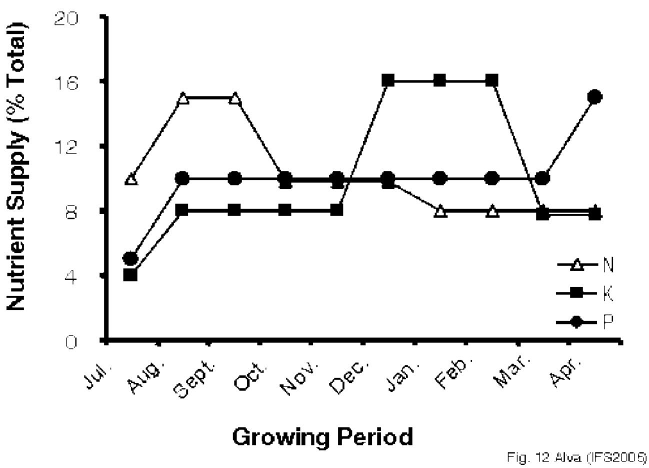
TABLE 2. Guidelines for fertilization of ‘Sweet orange’ groves in Brazil for different fruit yield targets and depending on the leaf N concentration and soil P and K status.

Fruit yield	Leaf N (g kg^{-1})			Soil P-resin (mg dm^{-3})				Soil exch-K ($mmol_c$ dm^{-3})			
	<23	23–27	>27	<5	6–12	13–30	>30	<0.7	0.8–1.5	1.6–3.0	>3.0
Mg ha^{-1}	----N (kg ha^{-1})------			------P_2O_5 (kg ha^{-1})------				----------K_2O (kg ha^{-1})--------			
<15	100	70	60	50	40	20	0	60	40	20	0
16–20	120	80	70	70	50	30	0	80	60	40	0
21–30	140	120	90	90	70	40	0	120	80	60	0
31–40	200	160	130	130	100	50	0	140	120	80	40
41–50	220	200	160	160	120	60	0	180	140	100	50
>50	240	220	180	180	140	70	0	200	160	120	60

Source: with basis on Quaggio et al., (1998; 2005; 2006).

times a week, from early spring to late summer, as described in Figure 12. In some areas with high and frequent summer rainfall, fertigation may not be practical. In such cases, one-third of the annual nutrient rates should be delivered as fertigation commencing at the end of summer. Ammonium nitrate and potassium chloride are the preferred N and K sources for

FIGURE 12. Recommend distribution of nutrients delivered as fertigation for citrus through the growing season in Brazil (J.A. Quaggio et al., 2006; unpublished data).



fertigation. Even though other more expensive fertilizers such as calcium nitrate, potassium nitrate, and monoammonium phosphate can be used. Potential additional benefits of using these expensive N, P, K sources are not being investigated.

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