# IMPACT OF VARIABLE RATE FERTILIZATION ON NITRATE LEACHING IN A CITRUS ORCHARD

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## ABSTRACT

Non-point-source agricultural pollution from crop nutrients can be mitigated by improving fertilizer use efficiency. Florida citrus orchards grown on sandy soils are vulnerable to leaching excess nitrates into the groundwater. Site-specific variable rate application (VRA) fertilization based on the canopy size of citrus trees could improve horticultural profitability and fertilizer use efficiency, thereby reducing nitrate leaching. In this study, tree canopy sizes were measured with an ultrasonic sensor system in a 17-ha 'Valencia' orange orchard, and ranged from 0 to 240 $m^3$. Six nitrogen (N) rates (0, 134, 168, 202, 236 and 270 kg $ha^{-1}$ $y^{-1}$) were applied with a VRA fertilizer spreader according to a prescription map developed from tree canopy size information. For comparison, half of the orchard received the standard uniform N rate of 270 kg $ha^{-1}$ $y^{-1}$. Soil leachate samples were collected with vacuum lysimeters at 1.5-m depth from below the root zones of 36 trees in 18 paired plots. The leachate samples from 10 sampling dates in 2005 were analyzed for nitrate-N concentration, and leaf samples were analyzed for leaf nutrient concentrations under VRA and uniform fertilization. Trees with excess leaf N (>3%) under uniform fertilization had smaller canopy volumes (less than 100 $m^3$), and constituted 62% of the entire orchard. The VRA treatment significantly ($p \leq 0.05$) decreased nitrate loading from leachates leaving the root zone compared to the uniform treatment. Mean leachate nitrate-N concentrations for all VRA treatments ranged from 1.5 to 4.5 mg $L^{-1}$ and were below the maximum contaminant level for groundwater of 10 mg $L^{-1}$, while those under uniformly fertilized small and large trees were 28.5 and 14.0 mg $L^{-1}$, respectively. Most leaf nutrient concentrations were not significantly influenced by the VRA fertilization and were within the recommended optimal ranges. VRA used 40% less fertilizer than standard uniform fertilization and could improve orchard profitability.

**Keywords**: DGPS, fertilization, GIS, leaching, nitrate, tree canopy volume, ultrasonics, VRA

## INTRODUCTION

Most sandy citrus soils in Florida with low organic matter content require constant application of fertilizer, especially nitrogen (N). These soils are very vulnerable to nitrate-N leaching from fertilizer due to shallow root system of citrus, a low water and nutrient holding capacity, an excessively drained profile combined with a high (~1300 mm year$^{-1}$) annual rainfall (NRCS, 2001). Nitrate-N leached below the root zone inevitably enters the surficial groundwater of Florida's aquifers. Concentrations of nitrate-N above the maximum contaminant limit (MCL) for drinking water standards (10 mg L$^{-1}$; U.S. Department of Health, Education and Welfare, 1962) have been linked with major citrus production regions (Alva et al., 1998; Jones et al., 1990; Lamb et al., 1990).

Currently, best management practices (BMPs) for various growing areas are being implemented to address nitrate levels in groundwater (FDACS-OAWP, 2003). The uniform application of N based on tree ages and yield (FDACS, 2002; Tucker et al., 1995) in citrus orchards may not match with the requirement of individual trees and result in over– or under-application (Schumann et al., 2003). Local over-fertilization may pollute ground water and increase cost of production. Zaman et al. (2005) achieved a 40% reduction in fertilizer consumption in a 'Valencia' orchard, having substantial internal tree size variation, when using variable rate fertilization (VRA) on a single tree size basis as compared to the grower's uniform rate. Therefore, a long term approach to increase N uptake efficiency without increasing the cost of production and minimize nitrate-N contamination of ground water is to apply fertilizer site-specifically on each tree based on canopy size.

Ultrasonic sensors can be used to quantify tree canopy volumes reliably and rapidly (Roper, 1988; Tumbo et al., 2002; Zaman and Salyani, 2004). An automated ultrasonic tree size measurement system (Durand-Wayland, Inc., Lagrange, Ga, USA) equipped with a Trimble AgGPS132 differential geographic positioning system (DGPS; Trimble Navigation Limited, Sunnyvale, Calif., USA) could be used for rapid real-time sensing, monitoring, calculation, storage and mapping of citrus tree canopy volume and height in commercial citrus orchards (Schumann and Zaman, 2005; Zaman and Schumann, 2005). Ultrasonically-sensed citrus tree size data is valuable to generate GPS-guided prescription maps for variable rate delivery of N and for estimating fruit yield in citrus orchards (Zaman et al., 2006).

A well-tuned VRA granular fertilizer spreader equipped with both GPS-guided prescription mapping and real-time measurement with photoelectric sensors is able to deliver fertilizer site-specifically on a single tree size basis in commercial Florida citrus orchards (Miller et al., 2005; Schumann et al., 2006a). However some commercial VRA fertilizer spreaders are not suitable for single tree fertilization as supplied, because they respond too slowly to rate change commands (Schumann et al., 2006b). Fortunately the performance of a slow fertilizer spreader can be significantly improved by replacing the hydraulic valves and VRA controller with faster components (Schumann et al., 2006a). The variable rate fertilization with a VRA fertilizer spreader based on ultrasonically-sensed tree volume may be useful to increase fertilizer use efficiency and avoid potential leaching problems associated with over-application of nitrogen. No published work in Florida citrus has addressed the impact of VRA fertilization on groundwater nitrate-N contamination. Therefore, this study was initiated to evaluate the impact of variable rate fertilization to mitigate potential groundwater nitrate-N pollution in the citrus orchards.

## METHODOLOGY

### Orchard History

A commercial citrus orchard (Gapway groves, Auburndale Fla.) near Fort Meade, Polk County, Florida (27.74789$^o$ N, 81.69509$^o$ W) was selected for a long-term experiment testing VRA of nitrogen (N) based on tree volume basis in 2003. The 17.0- ha orchard was planted with >40 year-old 'Valencia' sweet orange trees [*Citrus sinensis* (L.) Osb.] on Carrizo citrange (*Poncirus trifoliata* × *C. sinensis*) rootstock. Tree row orientation was N-S with a tree spacing of 10.7 m between rows and 5.3 m within the row. The tree canopies were not topped or hedged at the time of measurement. The soil type in the orchard was Candler sand (hyperthermic, coated Typic Quartzipsamments). These type of soils are deep, coarse-textured, excessively drained and low in nutrient reserves (NRCS, 2001). There was large spatial variability in tree canopy sizes because of a wide range of tree ages. Many original trees had been replaced due to tree loss from hurricanes, freezes and disease (Strang, 2004).

### Tree Volume Measurements

Each tree canopy volume was measured real-time in the orchard during June 2003 with a Durand Wayland ultrasonic system (Durand-Wayland, Inc., Lagrange, Ga, USA) and Trimble AgGPS132 DGPS (Trimble Navigation Limited, Sunnyvale, Calif., USA) using U.S. coast guard beacon correction and customized software developed at the University of Florida (Schumann and Zaman, 2005). The system consisted of a microprocessor controlling 10 ultrasonic sensors that were mounted every 0.6 m on a 6.7 m vertical mast. The mast was mounted on a custom trailer pulled behind a pickup truck. The system was moved at an average ground speed of 1.3 m $s^{-1}$ to get adequate vertical and horizontal samples per tree to quantify each tree canopy volume. Technical design of the system (hardware and software) and a detailed procedure for the real time measurement and mapping of tree volume in an orchard was reported earlier in Schumann and Zaman (2005). In September 2004 the trees were measured again with an improved 6-m tall ultrasonic array which was mounted on the towbar of a pickup truck and which could survey the orchard at 2.5 m $s^{-1}$ (Schumann and Hostler, 2006).

### Variable Rate Fertilization

Six N rates (0, 134, 168, 202, 236 and 270 kg $ha^{-1}$ $y^{-1}$) were applied with a variable rate fertilizer spreader according to a prescription map developed from ultrasonically measured tree canopy size information during 2003, 2004 and 2005.

For comparison, half of the orchard received the standard uniform N rate of 270 kg $ha^{-1}$ $y^{-1}$ (Fig.1). Resets (one to two years age) received no fertilizer through VRA but were fertilized individually (25.6 kg $ha^{-1}$ $y^{-1}$) by hand (FDACS, 2002, Tucker et al., 1995). Fertilizer was applied in four equal splits during the dry part of the year using different fertilizer materials. The fertilizer materials and detailed procedure for VRA fertilization were described earlier in Zaman et al. (2005). Further details on the technical design and procedure for VRA fertilization using a GPS-based prescription map with the variable rate granular fertilizer spreader (M&D, Arcadia, Fla.) equipped with a control package (Chemical Containers, Lake Wales, Fla.) may be found in Miller et al. (2005).

**Soil Leachate Sample Analysis**

Vacuum lysimeters (Soilmoisture Equipment Corporation, Calif., USA) were installed under the canopies of 36 selected trees in 18 paired locations (Fig. 1) during the dry winter season of 2004. There were six trees in each of small (S), medium (M) and large (L) tree size classes located in each half of the grove (uniform and VRA fertilization). The canopy volumes of the three selected groups of tree sizes averaged 10.7 $m^3$ (range 1.3 - 30.5 $m^3$), 73.4 $m^3$ (range 34.8 - 126.7 $m^3$), and 184.7 $m^3$ (range 141.4 - 215.8 $m^3$), for the small, medium and large trees, respectively. The paired locations were arranged so that each tree in the VRA side of the field had a corresponding tree of similar size located as near as possible in the uniformly fertilized side of the field and each of those trees had a vacuum lysimeter installed under its canopy (Fig. 1). The ceramic cups of the lysimeters were installed at 1.5-m depth below the soil surface, which is below the root zones of the trees. A suitable 10-cm diameter access hole was augered in the soil for lysimeter insertion, and backfilled with sandy soil to set the lysimeters firmly in the ground. Each lysimeter consists of a porous ceramic cup to withdraw soil pore water using a vacuum; a body tube to act as a reservoir; and a simple stopper assembly with a single hole for applying a vacuum and retrieving the sample through tubes leading from the lysimeter to the ground surface. A 0.5 m long, 10-cm diameter PVC pipe was inserted in the soil over each lysimeter to protect the vacuum and suction tubes of the lysimeter and a PVC end-cap was placed over the top end of the pipe to prevent debris from entering the lysimeters. Lysimeters were located in the citrus tree lines between two tree trunks. Soil leachate samples were collected periodically (10 sampling dates of about 1-month interval) in 2005 with vacuum lysimeters using a customized 12VDC battery-operated vacuum pump (UNMP830 KNDC; KNF Neuberger Inc., Trenton, NJ). The nitrate concentration in the soil water samples was analyzed using an automated cadmium reduction method with a Flow Solution FS3000 instrument (OI Analytical Corporation, TX. USA).

**Leaf Nutrient Analysis**

Four-month old (mature) spring-flush leaf samples from non-bearing branches of 12 randomly selected trees with different sizes were collected during July 2003. The orchard was previously fertilized with a uniform N rate of 270 kg $ha^{-1}$ $year^{-1}$. Leaf N concentration measured in different tree sizes was analyzed according to procedures described by Obreza et al. (1992). Leaf samples were collected again during July 2005 from the 36 trees in 18 paired locations (six trees in each of small, medium and large size classes receiving VRA or uniform fertilization; Fig. 1). The samples were analyzed for leaf nutrients N, P, K, Ca, Mg, S, Mn, Fe, Zn, Cu, B, according to procedures of Obreza et al. (1992).

### Data Analysis

The linear regression method was used to find the relationship between N concentration and canopy volumes of 12 selected trees with Genstat statistical software (Genstat 6, Lawes Agricultural Trust, Rothamsted, UK). Tree volume data were analyzed to produce a histogram frequency distribution of different tree size classes in the entire orchard using Genstat software. Each tree canopy volume was mapped with ArcView GIS software (ESRI, Redlands, Calif., USA). Prescription maps were generated from ultrasonically scanned tree sizes on a single tree volume basis for variable rate application of N using ArcView GIS and Midtech Fieldware software (Midwest Technologies; Springfield, Ill., USA). The measured nitrate-N concentrations in soil leachate and leaf nutrients of the selected 36 trees were analysed with analysis of variance (ANOVA) using Genstat in order to compare the potential impacts that VRA or uniform fertilization have on the groundwater and to examine the leaf nutrient status under VRA and uniform fertilization. The soil solution nitrate data were not normally distributed, and were therefore logarithmically transformed before analysis of variance. Tests for significance of treatment factors were conducted by the F-test, and treatment means were separated by least significant differences (LSDs) using Genstat.

## RESULTS AND DISCUSSION

The tree canopy volumes in this orchard during 2003 ranged from 0 (missing) to 240 $m^3$ (Fig. 1), due to the age of the orchard (>40 years), and the practice of continuous replanting (resetting) of dead, damaged or diseased trees (Strang, 2004).

The previous results of this study demonstrated that trees with excess leaf N (>3%; Tucker et al., 1995) under uniform fertilization had canopy volumes less than 100 $m^3$, and constituted 62% of the entire orchard (Zaman et al., 2005). Therefore, variable N rates were implemented in the western half of the orchard on a per-tree size basis (Fig. 1). The VRA of N on a per-tree basis reduced granular fertilizer consumption by 38% (Zaman et al., 2005). More than 50% of the trees in this orchard were also damaged by the hurricanes in 2004 (Zaman et al., 2006). Each tree volume was measured and mapped again in September, 2004 after the hurricanes and a new prescription map was generated using the ultrasonically-sensed tree size information for accurate fertilization. Fertilizer consumption was subsequently reduced by 40% with VRA of fertilizer in the same orchard after the hurricanes. Further details on previous results of this study can be found in Zaman et al. (2005). In general, loss of N occurs when mineral N

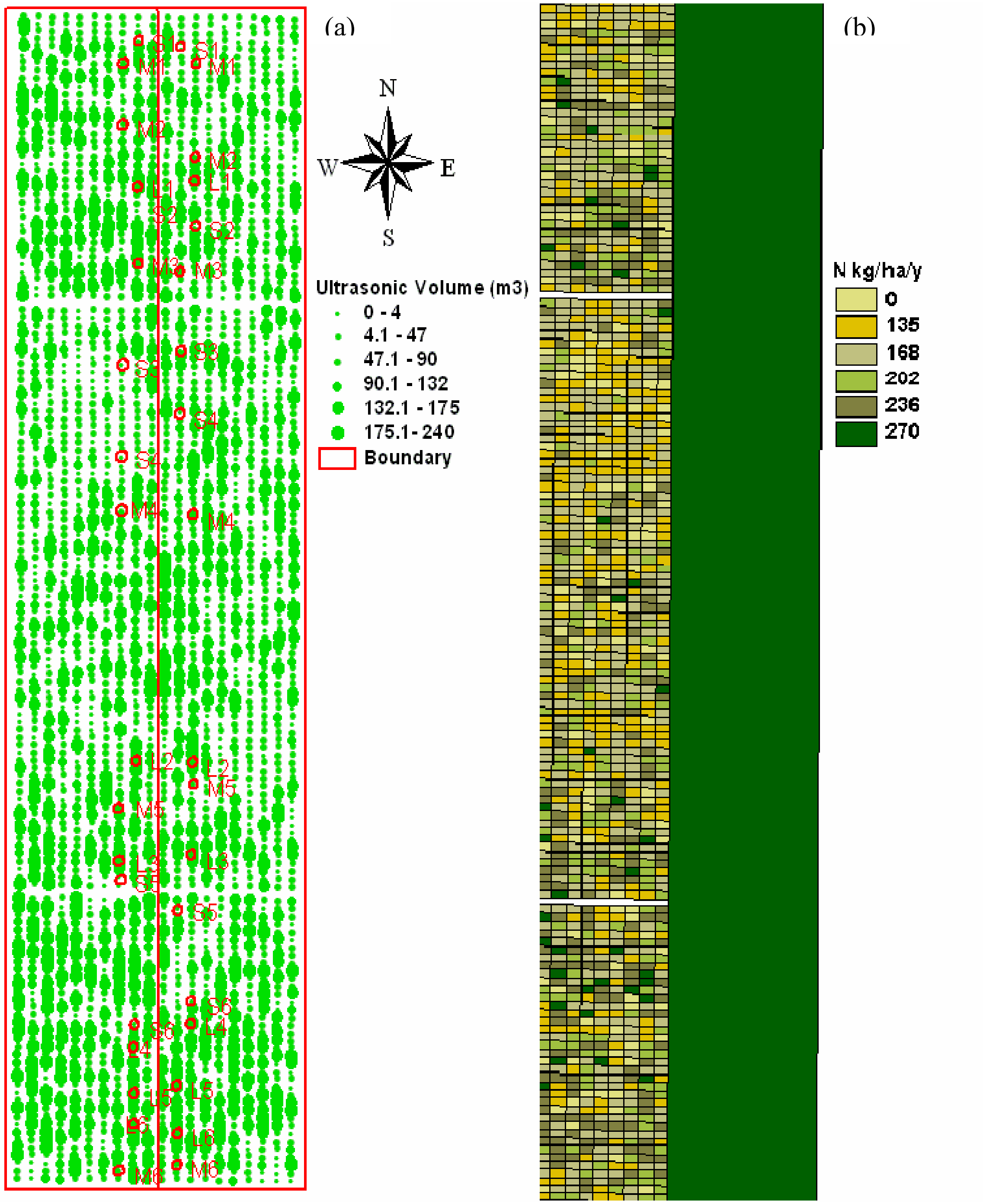


**Fig 1.** (a) Ultrasonic tree volume map showing locations of lysimeters (O) under the selected trees [small (S), medium (M), large (L)] on both sides of the field (uniform = east, VRA = west) (b) prescription map of the orchard showing variable N rates developed for different tree sizes in the western half of the experimental area.

($NH_4$ and $NO_3$) is present in excess of plant needs (Johnson and Raun, 1995). The previous results of this study indicated that excess nutrients which could be leached below the root system constitute a direct financial loss of wasted fertilizer.

The VRA treatment significantly ($p \leq 0.05$) decreased nitrate-N concentration in leachates measured below the root zone of trees, when compared to the uniform treatment (Table 1). The leachates would continue moving downwards through the porous sand until they reach the surficial groundwater. Thus the leachates leaving the root zone indicate the potential impact of nitrate-N pollutants on groundwater. Mean leachate nitrate-N concentrations for all VRA treatments ranged from 1.5 to 4.5 mg $L^{-1}$ and were below the maximum contaminant level (MCL) for groundwater of 10 mg $L^{-1}$ (U.S. Department of Health, Education and Welfare, 1962), while those under uniformly fertilized small and large trees were 28.5 and 14.0 mg $L^{-1}$, respectively (Table 1). The difference in mean leachate nitrate-N concentrations between both methods in small and large size trees was particularly striking. The uniformly fertilized (270 kg N $ha^{-1}$ $y^{-1}$) side of the orchard having small trees showed the highest potential pollutant impact, with an average nitrate-N concentration in leachates of 28.5 mg $L^{-1}$. In contrast, the nitrate-N concentration was extremely low (1.5 mg $L^{-1}$) in small trees under VRA fertilization, due to the reduced rate of fertilizer (135 kg N $ha^{-1}$ $y^{-1}$; Table 1 and Fig. 1), thus demonstrating the benefits of site-specific fertilization according to tree size. The mean leachate nitrate-N concentrations under large trees which were uniformly fertilized were significantly higher (14.0 mg $L^{-1}$) than those under large trees with VRA fertilization (4.5 mg $L^{-1}$; Table 1). Thus the large class of trees also benefited from the choice of 236 or 270 kg $ha^{-1}$ $y^{-1}$ as VRA rates, compared to the uniformly fertilized 270 kg $ha^{-1}$ $y^{-1}$ rate. The nitrate-N concentrations in medium size trees under both VRA and uniform fertilization methods were not significantly different and were below the MCL. Ground-truth inspections revealed that very well developed canopy skirts (lower branches) on these medium size trees were hanging on the ground and deflected much of the banded granular fertilizer away from the lysimeters under the canopy. The large and small trees did not have well developed canopy skirt branches, so the fertilizer applied by the fertilizer spreader would have reached the lysimeters under the canopy unimpeded. The risk of nitrate leaching from rain is increased at the dripline of the canopy because soil water content and flux are greater there than closer to tree trunk (Alva et al., 1999). It may therefore be beneficial to prune the tree skirts well off the ground when banding granular fertilizer from a spreader. Whitney et al. (2003) reported that average yields of 3-m-tall Valencia trees were not significantly affected by skirting (lower limb removal) at 0.6 and 0.9 m. They also found that fruits from the bottom of the unskirted trees showed significantly increased rind blemishes, were generally smaller in size, but had juice qualities at least equivalent to other fruit on the tree. Therefore, it is suggested that trees should be skirted just after harvesting the fruit and before fertilizer application for accurate delivery of granular fertilizer under the tree canopy.

The Nitrogen Best Management Practices (N-BMPs) have been implemented throughout the state of Florida for judicious N fertilizer application aimed at reducing contamination of the soil and groundwater through nitrate leaching and to optimize the fruit production. The current fertilizer guidelines are calendar-

**Table 1.** Effect of uniform (270 kg N $ha^{-1}$ $y^{-1}$) and variable rate application (VRA; based on tree sizes) fertilization on soil water $NO_3$-N concentration and leaf nutrients in a citrus orchard

| Tree size | Fertilizer method | $NO_3$-N (mg $L^{-1}$) | N (g $kg^{-1}$) | P (g $kg^{-1}$) | K (g $kg^{-1}$) | Ca (g $kg^{-1}$) | Mg (g $kg^{-1}$) | S (g $kg^{-1}$) | Cu (mg $kg^{-1}$) | Fe (mg $kg^{-1}$) | Mn (mg $kg^{-1}$) | Zn (mg $kg^{-1}$) | B (mg $kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Small | Uniform | 28.5 | 27.9 | 1.32 | 12.3 | 39.3 | 5.08 | 3.53 | 13.42 | 94.8 | 57.8 | 112 | 52.8 |
| | VRA | 1.50 | 27.7 | 1.42 | 15.4 | 35.6 | 4.63 | 3.25 | 15.14 | 86.8 | 49.5 | 119 | 53.0 |
| Medium | Uniform | 1.30 | 26.4 | 1.17 | 9.2 | 40.5 | 4.33 | 3.53 | 12.71 | 81.1 | 79.7 | 196 | 67.3 |
| | VRA | 2.50 | 27.0 | 1.38 | 13.0 | 35.2 | 4.35 | 3.08 | 16.40 | 70.7 | 75.6 | 164 | 59.5 |
| Large | Uniform | 14.0 | 27.8 | 1.23 | 12.4 | 35.8 | 3.55 | 3.05 | 8.30 | 73.4 | 78.2 | 139 | 79.5 |
| | VRA | 4.50 | 29.6 | 1.18 | 13.8 | 33.8 | 3.92 | 3.25 | 9.09 | 70.1 | 59.2 | 96.0 | 80.5 |
| **LSD (p<0.05)** | | 3.20 | 2.25 | 0.178 | 3.84 | 5.23 | 0.610 | 0.352 | 4.70 | 11.3 | 28.7 | 78.0 | 14.3 |
| **Treatment factor** | | | | | | | **Analysis of Variance** | | | | | | |
| Fertilizer Method (F) | | ** | NS | NS | * | * | NS | NS | NS | * | NS | NS | NS |
| Tree Size (T) | | ** | * | * | NS | NS | *** | NS | *** | *** | NS | * | *** |
| F x T | | ** | NS | NS | NS | NS | NS | * | NS | NS | NS | NS | NS |

*Significant at the 0.05 probability level

** Significant at the 0.01 probability level

*** Significant at the 0.001 probability level based, indicating upper N limits for generalized average tree ages only (FDACS, 2002; Tucker et al., 1995). The results of this study demonstrated that reduced amount of N used with VRA fertilization (Fig. 1) reduced leaching of nitrate-N below the rooting depth, therefore protecting the groundwater (Table 1). It is proposed that N rates should be calculated considering the tree sizes because many extraneous factors (rootstock, soil series) can modify tree size and therefore N consumption is only partially dependent on tree age. For example, an invigorating rootstock may outgrow a standard rootstock by 100% at age 5 y, and by 25% at age 10 y (Castle, 2005). Growers should be encouraged not to simply default to the highest allowed BMP N rate for a given orchard. The importance of this N-conservation strategy was demonstrated convincingly by the large-scale citrus N-BMPs experiments of the Ridge Quality Project in the 1990s (Lamb et al., 1999) and small plot experiments (Alva et al., 1998).

The VRA fertilization treatment did not significantly ($p>0.05$) influence the leaf N concentration during the 2005 sampling date (Table 1). The leaf N concentrations were within the optimal or slightly above the optimal range of 25 to 27 g kg$^{-1}$ (Table 2) despite the lower N rates applied to small and medium size trees in VRA fertilization treatments in the west side of the orchard. The concentrations of leaf P, K Ca, Mg, S, Cu, Fe, Mn, and B were within the optimal concentration range in all sizes of trees under VRA fertilization (Tables 1 and 2). The mean concentrations of Zn were slightly above the optimal concentration range in all sizes of trees with the uniform treatment and in medium and small tree sizes with VRA treatments. The leaf analysis results in 2005 confirmed that, with the exception of Zn concentration, the trees under VRA fertilization were within the recommended optimal nutrition status (Tables 1 and 2). Therefore, site-specific fertilization based on the canopy size of citrus trees could improve horticultural profitability, increase fertilizer use efficiency, and thereby reduce nitrate leaching without adverse nutritional effects to the trees.

**Table 2.** Citrus leaf nutrient concentrations in 4-6 month old spring leaf flush (Tucker et al.,1995).

| Element | Deficient less than | Low | Optimum | High | Excessive more than |
|---|---|---|---|---|---|
| N (g kg$^{-1}$) | 22 | 22-24 | 25-28 | 29-32 | 32 |
| P (g kg$^{-1}$) | 0.9 | 0.9-1.1 | 1.2-1.7 | 1.8-3.0 | 3.0 |
| K (g kg$^{-1}$) | 7.0 | 7.0-11 | 12-17 | 18-24 | 24 |
| Ca (g kg$^{-1}$) | 15 | 15-29 | 30-50 | 51-70 | 70 |
| Mg (g kg$^{-1}$) | 2.0 | 2.0-2.9 | 3.0-5.0 | 5.1-7.0 | 70 |
| S (g kg$^{-1}$) | 1.4 | 1.4-1.9 | 2.0-4.0 | 4.1-6.0 | 6.0 |
| Cu (mg kg$^{-1}$) | 4.0 | 4.0-5.0 | 6-16 | 17-20 | 20 |
| Fe (mg kg$^{-1}$) | 35 | 35-59 | 60-120 | 121-200 | 200 |
| Mn (mg kg$^{-1}$) | 18 | 18-24 | 25-100 | 101-300 | 300 |
| Zn (mg kg$^{-1}$) | 18 | 18-24 | 25-100 | 101-300 | 300 |
| B (mg kg$^{-1}$) | 20 | 20-35 | 36-100 | 101-200 | 200 |

## CONCLUSIONS

- The VRA treatment significantly ($p \leq 0.05$) decreased nitrate loading from leachates into ground water compared to the uniform treatment.
- Mean leachate nitrate-N concentrations for all VRA treatments ranged from 1.5 to 4.5 mg $L^{-1}$ and were below the maximum contaminant level for groundwater of 10 mg $L^{-1}$, while those under uniformly fertilized small and large trees were 28.5 and 14.0 mg $L^{-1}$, respectively.
- Most leaf nutrient concentrations were not significantly influenced by the VRA fertilization and were within the recommended optimal ranges.
- Based on the results of this study, it is recommended that fertilizer rates should be calculated considering the tree sizes and not necessarily only the age in order to increase nutrient uptake efficiency, reduce cost of production and eliminate prolonged nitrate excesses in the root zone, which can potentially leach to groundwater.

This study is continuing and harvest data is being collected. Fruit samples from selected trees can be analyzed for N content and standard juice quality analysis. However, similar studies in other commercial orchards are needed to develop general recommendations for optimal N rates per tree size basis, not only by tree age. In addition, a range of measured and calculated tree size variables (canopy height, maximum diameter, canopy volume, bearing canopy volume, canopy ground area, and cross-sectional canopy area) can be established and their ability to predict the correct fertilizer rate according to tree size will be tested by regression analysis.

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