Estimation of Nitrate Leaching in an Entisol under Optimum Citrus Production

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ABSTRACT

Leaching of fertilizer nutrients and widespread NO_3-N contamination of drinking water wells in proximity to citrus growing regions of central Florida are a serious concern. We evaluated NO_3-N distribution in soil solution at various depths in the vadose zone, and N leaching below the root zone for two cropping seasons under the canopy of 21-yr-old Hamlin orange [*Citrus sinensis* (L.) Osbeck] trees on Cleopatra mandarin (*Citrus reticulata* Blanco) rootstock, on an entisol of central Florida. The treatments included 112, 168, 224, and 280 kg N ha^{-1} yr^{-1} as either dry granular fertilizer (DGF; broadcast, in 4 equal doses) or fertigation (FRT; 15 applications yr^{-1}), and 56, 112, and 168 N kg ha^{-1} yr^{-1} as controlled-release fertilizer (CRF; single application yr^{-1}). Irrigation was scheduled using recommended tensiometer set points as guidelines, with a target wetting depth of 90 cm. The NO_3-N was measured in soil solutions bi-weekly at 60-, 120-, and 240-cm depths using suction lysimeters (SLs) installed under the tree canopy. The 240-cm depth sample represented soil solution below the rooting depth of the trees, and the NO_3-N at this depth could contaminate groundwater. At the 60- or 120-cm depths, the NO_3-N concentrations occasionally peaked at 12 to 100 mg L^{-1}, but at 240 cm NO_3-N concentrations mostly remained below 10 mg L^{-1}. The careful irrigation management, split fertilizer application, and timing of application contributed to the low leaching of NO_3-N below the root zone. Calculated NO_3-N leaching losses below the rooting depth increased with increasing rate of N application and the amount of water drained, and accounted for 1 to 16% of applied fertilizer N.

Commercial citrus production in Florida occupies 342 200 ha, with a production of 11.0 and 2.08 million Mg of oranges and grapefruit, respectively (Florida Agricultural Statistics Service, 1999). This accounts for 75% of the total U.S. citrus production. Nearly 40% of Florida citrus acreage is on sandy Entisols along the Central Florida Ridge. Because of high sand content (>97%), low organic matter, lack of a confining soil horizon, poorly distributed high annual rainfall (mean annual rainfall of 1400 mm, with ≈60% of annual rainfall received during June to September) (National Oceanic and Atmospheric Administration, 1996), and occasional shallow water tables, these soils are vulnerable to rapid leaching of soil-applied chemicals and nutrients.

Historically, fruit bearing citrus trees have been fertilized predominantly using DGF, often broadcast over the entire grove. Irrigation was predominantly done with a sprinkler system that applied water over the top of the tree canopy. Recent technological advances in fertilizer formulations and irrigation designs have prompted renewed interest in improving the efficiency of fertilizer and water delivery in order to enhance N use efficiency. Freeze protection capability and increasing demand for water conservation has encouraged the citrus industry to choose microirrigation systems. This change in irrigation technique has also facilitated the application of liquid fertilizers through the irrigation system, i.e. FRT.

Current N fertilization recommendations (Tucker et al., 1995) are primarily based on tree response studies conducted in the 1950s and 1960s using trees with low fruit production potential (30–40 Mg ha^{-1}), on low-density plantings (usually <247 trees ha^{-1}, at 7.6 by 6.0 m spacing) with an overhead irrigation system and broadcast application of DGF. There has been almost no attempt to examine the fate of N applied either as DGF or FRT to bearing citrus trees. Controlled-release N fertilizers have also been developed that release N slowly over an extended period of time. The release of N can be better synchronized with crop uptake to minimize NO_3-N leaching losses. Results of several laboratory leaching studies conducted in citrus-growing soils of Florida with various controlled-release N fertilizers revealed low leaching (11–32%) losses of applied N compared with readily soluble NH_4NO_3 (Alva, 1992; Wang and Alva, 1996; Paramasivam and Alva, 1997).

The random drinking water quality survey in Highlands County in central Florida conducted by the Florida Department of Environmental Protection (FLDEP) revealed that 32% of total homeowner wells sampled (mostly into the surficial aquifer with poor construction) contained NO_3-N in excess of the USEPA maximum contaminant level of 10 mg NO_3-N L^{-1} (FLDEP, 1990, personal communication). This area is predominantly under citrus production; therefore, there is a need to investigate the fate of N applied to bearing citrus trees under current production practices, specifically with

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Abbreviations: CRF, controlled-release fertilizer; DGF, dry granular fertilizer; FRT, fertigation; FLDEP, Florida Department of Environmental Protection; IBDU, isobutylidene diurea; NBMP, N best management practices; PRCU, polyolefin resin-coated Urea; SL, suction lysimeter.

Table 1. Selected properties of Tavares fine sand (Typic Quartzipsamments).

Depth	Horizon	Texture: Sand	Silt	Clay	Bulk density	Saturated hydraulic conductivity	Water content at 0.33 MPa	Organic C	CEC	pH in H_2O (1:1)
cm		g kg^{-1}			g cm^{-3}	cm h^{-1}	m^3 m^{-3}	g kg^{-1}	cmol kg^{-1}	
0–15	Ap	954	14	32	1.50	63.8	6.84	8.6	5.89	6.0
15–30	C_1	948	23	29	1.48	85.5	4.10	3.4	2.74	5.9
30–60	C_1	950	22	28	1.47	83.4	3.47	2.9	1.95	5.8
60–90	C_2	951	18	31	1.46	80.8	2.58	1.7	1.64	5.5
90–120	C_3	955	12	33	1.55	97.8	2.48	0.9	1.47	5.3
120–150	C_3	962	10	28	1.58	84.2	2.40	0.6	1.47	5.3

careful irrigation management. This study was conducted in a commercial grove of highly productive (with mean yield of 70–80 Mg ha^{-1}) citrus trees that received different N sources and rates with optimal irrigation scheduling.

This study was a part of a comprehensive project aimed to develop N best management practices (NBMP) for bearing citrus trees on vulnerable soils to attain optimum fruit yield and quality with minimal leaching of NO_3-N below the root zone. The tree response evaluation, in terms of leaf mineral concentrations, fruit yield, fruit quality, and concentration of NO_3 in soil solution collected within the rooting depth were reported earlier (Alva and Paramasivam, 1998). The major objectives of this study were to evaluate; (i) the effectiveness of irrigation and fertilizer NBMP to minimize leaching of NO_3-N below the root zone, (ii) the fate of applied N in soil and soil solution samples below the rooting depth, and (iii) the potential NO_3 leaching losses below the root zone.

MATERIALS AND METHODS

A field experiment was conducted using 21-yr-old ‘Hamlin’ orange trees on Cleopatra mandarin rootstock, planted (7.62 by 6.57 m; 286 trees ha^{-1}) in Tavares fine sand (hyperthermic, uncoated, Typic Quartzipsamments; moderately well drained). Under-tree microsprinklers (Maxijet Inc., Haines City, FL)[1] were used with one emitter per tree to deliver 0.083 m^3 h^{-1} at 0.276 MPa, to an area of 18.7 m^2, representing 48% of the grove area being irrigated. Each plot consisted of four uniform trees in a row, with the middle two trees used for response evaluation. At the beginning of the experiment, a bucket type soil auger (2.5-cm-diam. bucket auger with 15 cm height) was used to collect soil samples. Undisturbed soil cores were taken at 0- to 15-, 15- to 30-, 30- to 60-, 60- to 90-, 90- to 120-, and 120- to 150-cm depths, in five random locations within the experimental site, to construct the soil water characteristic curve, using a pressure plate apparatus (Klute, 1986). Subsamples of these cores were used to determine selected soil properties (Table 1).

Dry granular fertilizer, liquid fertilizer through FRT, and CRF were used as N sources. Nitrogen was derived from NH_4NO_3 for both DGF and FRT sources, and the CRF used was derived from polyolefin resin-coated urea. The DGF and FRT treatments were applied at 112, 168, 224, and 280 kg N ha^{-1} yr^{-1}, and the CRF was applied at 56, 112, and 168 kg N ha^{-1} yr^{-1}. A commercial applicator, calibrated for single-sided application, was used to apply the DGF in four equal doses, applied in February, April, May, and September, only on one side of the tree row. At each application, fertilizer was propelled under one-half of the canopy for the most part. The side of application was alternated for each subsequent application. The same equipment was used to apply the CRF, with the annual rate applied in one application in February to both sides of the row. The irrigation design was modified to simultaneously inject liquid fertilizer to all randomized replicate plots from a single injection point. We used an injection pump to introduce N fertilizer solution into the irrigation water mainline just downstream of an irrigation pump. This treated irrigation water was then pumped through the pipe to simultaneously irrigate all replicated treatment plots. The FRT was applied in 15 equally divided doses with three applied in February, three in March, three in April, three in May, two in September, and two in October. Fertilizer was not applied from June through August, during which 60% of the annual rainfall (1400 mm) occurs. The N rates described above were applied using an N, P, K blend with a ratio of 6.0:1.0:6.1. Standard production practices (such as herbicide and fungicide applications, hedging, and topping) as described by Tucker et al. (1995) were followed. The experimental design was a randomized complete block design, with five replications.

Suction Lysimeter, Tensiometer, and Rain Gauge Installation

Suction lysimeters, constructed using 2.5-cm-diam. (1-bar high-flow) porous ceramic cylinders (Soil Moisture Equipment Co., Santa Barbara, CA) connected to a polyvinyl chloride solution retainer cup at the bottom, were installed with ceramic cups placed at 60-, 120-, and 240-cm depths under the canopy. The SLs were installed 120 cm away from tree trunks. Suction lysimeters at these depths were installed in four of five replicates of all the treatment plots for a total of 180 SLs. Five clusters of tensiometers (Soil Measurement Systems, Tucson, AZ) were installed, one each at 15-, 30-, 90-, and 150-cm depths under the canopy along the dripline, to monitor soil water matric potential used as a basis for scheduling irrigation. After 5-cm-diam. holes were cored to desired depths, tensiometers were inserted into the holes. A sufficient quantity of soil from the bottom of the hole was poured back and tamped down slightly to ensure good soil contact with the porous ceramic cup. The remaining area around the tensiometer was back-filled with bentonite to completely seal the hole and guard against channeling water down the side of the tensiometers. A similar procedure was followed to install SLs. The tensiometers were read every 2 d, and irrigation was scheduled when the matric potential at the 15-cm depth attained −10 kPa for Jan to June and −15 kPa for July to December, (Smajstrala et al., 1987; Parsons, 1989). The 90- and 150-cm depth tensiometers were used to locate the depth of the wetting front for each irrigation and/or rain. Irrigation duration was calculated to replenish the water content of the uppermost 90-cm soil (a typical rooting depth in these sandy Entisols) back to field capacity. Two rain gauges were installed to record rainfall.

[1] Mention of product name does not suggest an endorsement of the product.

Sampling and Analysis of Soil and Soil Solution

To each SL, vacuum was applied at a constant rate (400 mm Hg) for ≈3 minutes with a vacuum pump and the hoses were sealed air-tight to facilitate collection of soil solution from the vadose zone. Soil solution was sampled every 2 wk using a vacuum pump. Between sampling each SL, the sampling line was rinsed in 1 *M* HCl and then in deionized water. The volume of soil solution collected from SLs varied depending on the wetness of soil. If the application of vacuum to soil solution samplers was incidently followed by an irrigation or rainfall event, that resulted in higher volume of soil solution in the samplers. On average, ≈50 mL of soil solution was collected from samplers installed at 60- and 120-cm depths, and as much as 200 mL at the 240-cm depth. About 20 mL of soil solution was stored in polyethylene vials, placed in an ice chest with dry ice, and transported to the laboratory for analysis. At each sampling, the SL was emptied, and vacuum was applied for collection of subsequent leachate. The remaining water in the SL was pumped out prior to applying vacuum for the next sample collection. There were some occasions when the application of vacuum to soil solution samplers coincided with dry soil (≈−10 KPa), and we collected less than 2 to 3 mL of soil solution from SLs at 60- and 120-cm depths. The concentration of NO_3-N in the soil solution was measured within 24 h of sample collection using an ion chromatograph (Dionex 100, Dionex Corporation, Sunnyvale, CA) following the procedure outlined by the USEPA (1991).

Soil samples were collected under the canopy using a 2.5-cm-diam. bucket auger 90 cm inside the tree drip line. Sampling was done during early spring prior to application of fertilizer, in summer, and in late fall after the last application of fertilizer during each year. Soil samples were taken at 15-cm increments for the first 30 cm, and then at 30-cm increments to a depth of 150 cm. Samples were air-dried, then ground to pass through a 2-mm sieve, and extracted with 2 *M* KCl. Rapid flow analyzer methods A303-S020 (Alpkem Corporation, 1989) and A303-S170 (Alpkem Corporation, 1986) were used to measure the concentrations of NH_4-N and NO_3-N, respectively.

Estimation of Nitrate Leaching Losses Below the Root Zone

The amount of NO_3 leached below the root zone was estimated using, in part, the concentration of NO_3-N in the soil solution collected at various sampling events at the 240-cm depth in the vadose zone under the citrus canopy. The mass of N leached below the root zone, (A_N), was calculated as the product of the mean NO_3-N concentration in the leachate sampled at 240 cm (C_{SL240}) multiplied by the volume of drainage water (Q) that passed through this depth between the successive sampling periods.

$$A_N = QC_{SL240} \quad [1]$$

Summation of these quantities over a period of 1 yr provided an estimate of total mass of N leached below the root zone.

Assuming steady state water flow, we calculated drainage (Q) as the product of Darcy's flux (q) and the time period (Δt) for which drainage was being calculated.

$$Q = q\Delta t \quad [2]$$

Using soil water potentials measured at 90 and 150 cm and saturated hydraulic conductivities, water flux below the root zone was calculated using the following Darcy's flux equation:

$$q = -k(h)\frac{\Delta H}{\Delta z} \quad [3]$$

where $k(h)$ (cm d^{-1}) is the effective unsaturated hydraulic conductivity represented by the geometric mean of the different hydraulic conductivities between 90 and 150 cm based on measured pressure heads, h (cm); ΔH is the total head gradient between 90 and 150 cm; Δz is the depth increment across which the head gradient was measured. The total hydraulic head (H; cm) at any depth in the profile is defined as:

$$H = h - z \quad [4]$$

where z is the depth (cm) below the soil surface at which h was measured.

The unsaturated hydraulic conductivity for different soil pressure heads was estimated using measured saturated hydraulic conductivity, the soil pressure head, and fitting parameters (α, n, and m) from van Genuchten (1980) (Eq. [5]). The k_s (cm d^{-1}) is the saturated hydraulic conductivity.

$$k(h) = k_s(1 + (\alpha h)^n)^{-m/2}\,(1 - (\alpha h)^{n-1}(1 + (\alpha h)^n)^{-m})^2 \quad [5]$$

The parameter α has unit of cm^{-1}, while n and m are unitless. Additional details of drainage calculations were given by Paramasivam et al. (2000).

Statistical Analysis

Since the mean tensiometer readings were used in the estimation of geometric mean of unsaturated hydraulic conductivity, and water flux in between two sampling periods, additional statistical procedures were not employed on estimated cumulative drainage water below the root zone. The estimated drainage was assumed to be same for all the treatments. Total quantities of 2 *M* KCl extractable NH_4-N and NO_3-N in the top 60 cm of the soil profile data and the estimated N leaching losses were analyzed for statistical significance using the Analysis of variance (ANOVA) procedure (SAS Institute, 1988), and mean separation was done using Duncan's multiple range test (DMRT) at a significance level of $P < 0.05$. Impact of N rates on estimated N leaching losses were evaluated by regression analysis for N sources separately using SAS (SAS Institute, 1988).

RESULTS AND DISCUSSION

Total Water Input and Drainage below the Rooting Depth

Total Water Input

Cumulative rainfall was greater in 1995 (1522 mm) than in 1994 (1255 mm) (Fig. 1). These values are, however, within the range of mean annual rainfall for this region (i.e. 1270 to 1575 mm, National Oceanic and Atmospheric Association, 1996). Although these totals exceed citrus tree water requirements, supplementary irrigation is required to optimize yield and quality due to the uneven distribution of rainfall over the year. The frequency of irrigation in the early part of the year was greater in early 1995 than 1994 to avoid moisture stress due to dry conditions in early 1995. Cumulative irrigation amount on a grove area basis was greater in 1995 (553 mm ha^{-1}) than in 1994 (478 mm ha^{-1}). More fre-

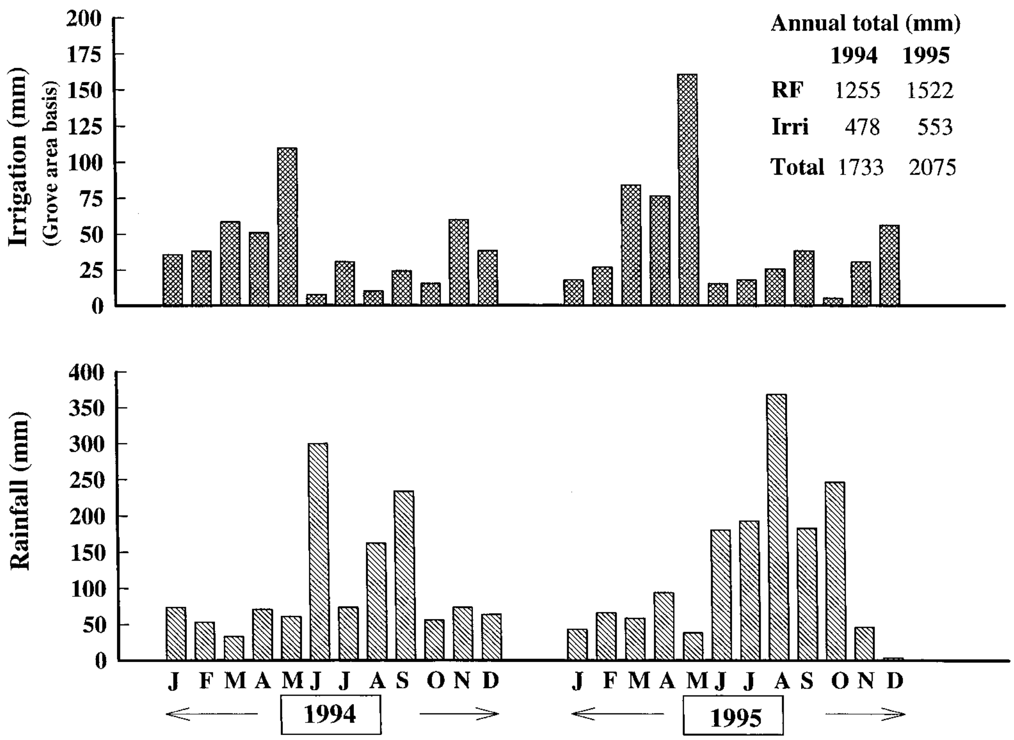

Fig. 1. Monthly summary of irrigation and rainfall data in 1994 and 1995.

quent precipitation occurred between July and October in 1995 than in 1994 (Fig. 1).

Drainage Water below the Rooting Depth

Three distinct increases (peaks) of drainage occurred during both cropping years. However, the timing of these peaks differed in these two years (Fig. 2a and 3a). Even though irrigation scheduling was done carefully by monitoring the soil moisture depletion using tensiometers and by applying only adequate water to replenish the deficit in the top 90-cm depth of soil, excessive rainfall and sometimes prolonged irrigation contributed to the drainage below the rooting depth (Fig. 1). Obviously, occurrence of peak drainage (≈60 mm) during April through June of 1994 (Fig. 2a) was due to a combination of prolonged irrigation and high incidence of rainfall. However, estimated peak drainage (80–120 mm) during 1995 (Fig. 3a) was purely due to high rainfall received during the months of August through October of 1995 (Fig. 1). Cumulative drainage below the rooting depth was 416 mm (Fig. 2b) in 1994 (24% of the total water input) and 615 mm (Fig. 3b) in 1995 (30% of the total water input).

Nitrate-Nitrogen Concentrations in Soil Solution

Under warm, humid conditions in Florida, nitrification of NH_4^+ is quite rapid (within 3 to 7 d of N application). Therefore, concentrations of NH_4-N in soil solution were quite low (<1 mg L^{-1}) during most of the sampling events (>99% of the sampling events). Accordingly, concentrations of NO_3-N in soil solution were used for estimation of N leaching losses. Since the major objective of this study was to estimate the potential leaching loss of NO_3^- below the rooting depth, concentration of NO_3-N in soil solution sampled at various sampling periods at 240-cm depth are presented.

A citrus tree's root system is a relatively shallow, well-branched framework of woody laterals and fine fibrous roots (Schneider, 1968; Castle, 1980a). The fibrous root density decreases substantially below the 60-cm depth, with very few roots at 120 cm (Castle, 1980b). Nitrate in solution at the 60- and 120-cm depths, thus, represents N available for root uptake. However, the 240-cm depth represents the vadose zone below the major rooting depth of citrus. Nitrate at this depth is not available to the trees, nor can it be readily transformed (denitrified or assimilated) because of the limited microbial population and available C at that depth (Paramasivam et al., 1999), and thus, can be subject to leaching into groundwater.

Concentrations of NO_3-N in soil solution sampled at 240-cm depth during the 1994 and 1995 cropping seasons are shown in Fig. 2 and 3. Few occasional rapid increases in concentration (peaks) of NO_3-N in the soil solution were evident for DGF source in early 1994 (Fig. 2a) but not in 1995. Similar peaks in concentration of NO_3-N in soil solution were evident for FRT source in both 1994 and 1995 (Fig. 2c and 3c). For CRF, NO_3-N concentration in soil solution did not exceed 10 mg L^{-1} in 1994 (Fig. 2e) or in 1995 (Fig. 3e). In a very few instances, increases in concentrations of NO_3-N were observed with DGF and FRT N sources in both years and were in the range of 17 to 33 mg L^{-1} at the 240-cm depth. Overall, this resulted in collection of twofold higher

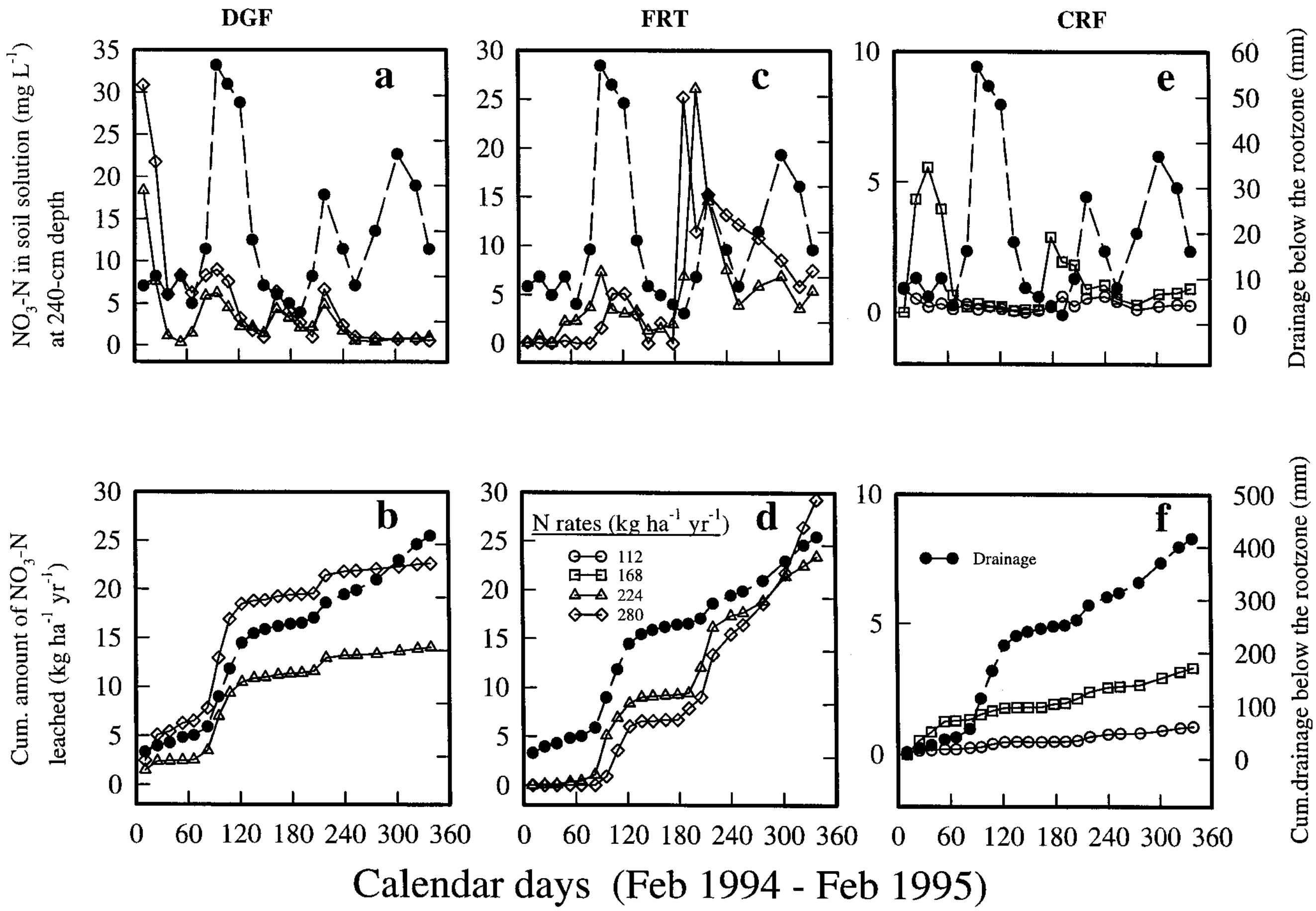

Fig. 2. Concentrations of NO_3-N in soil solution sampled at 240 cm depth, calculated amount of drainage below this depth, and estimates of cumulative amount of water and NO_3-N leached below 240 cm, i.e. root zone depth of mature citrus trees—February 1994 through February 1995.

NO_3-N concentrations in soil solutions from SLs installed in fertigated plots compared with DGF plots at the 240-cm depth (Fig. 2c and 3c).

Nitrate-N concentrations were the lowest at all depths and across all rates for CRF compared with DGF and FRT, probably due to the controlled release property of this source. The CRF material used in this study was polyolefin resin-coated urea. A 29-d leaching study by Wang and Alva (1996) with readily soluble NH_4NO_3 and slow-release fertilizers [isobutylidene diurea (IBDU) and a polyolefin resin-coated Urea (PRCU)] in Wabasso (sandy, siliceous, hyperthermic Alfic Haplaquod) and Candler (hyperthermic, uncoated, Typic Quartzipsamments) soils revealed that leaching of N represented 27 to 32% for IBDU, 11 to 12% for PRCU, and 88 to 100% for NH_4NO_3. Results of another 120-d column leaching study in Candler soil with urea-based CRF [such as Poly-S (Scotts Sierra Company, Marysville, OH), Osmocote (Scotts Sierra Company, Marysville, OH), and Meister (Helena Chemical Company, Tampa, FL)] revealed leaching losses of 30 to 59% of total N applied (Paramasivam and Alva, 1997). However, under careful irrigation and N management conditions employed in the current study, NO_3-N concentrations were normally below 10 mg L^{-1} at a 240-cm depth during the 2-yr monitoring period.

Cumulative Nitrate-Nitrogen Leaching Losses

Estimated cumulative NO_3-N leaching losses for various N sources and rates are presented in Table 2 for both cropping years. Since N leaching losses can be affected by both the availability of N and the amount of drainage water for leaching, the relationship between N rates and leaching losses were further explored by regression analysis and presented separately for various N sources by year (Table 2). In all cases, the relationship between N rates and N leaching losses was significant at the 0.05 probability level. The estimated cumulative amounts of NO_3-N leached below the rooting depth from the DGF source accounted for 6.1 to 8.0% of applied N at 224 and 280 kg ha^{-1} yr^{-1}, respectively. The corresponding values for the FRT source were 10.4 to 14.0%. For the CRF source, cumulative leaching losses of NO_3-N accounted for 1.0 to 4.7% of the applied N at 112 and 168 kg ha^{-1} yr^{-1}. Across all N rates, estimates of N leached below the rooting depth of mature citrus trees as percentage of N applied varied from 5 to 12% for DGF, 10 to 16% for FRT, and 1 to 5% for the CRF source.

Results of percentage N leached in relation to applied N clearly indicated the influence of N source and rate applied. However, the amount of N available at any particular time and the amount of water available as

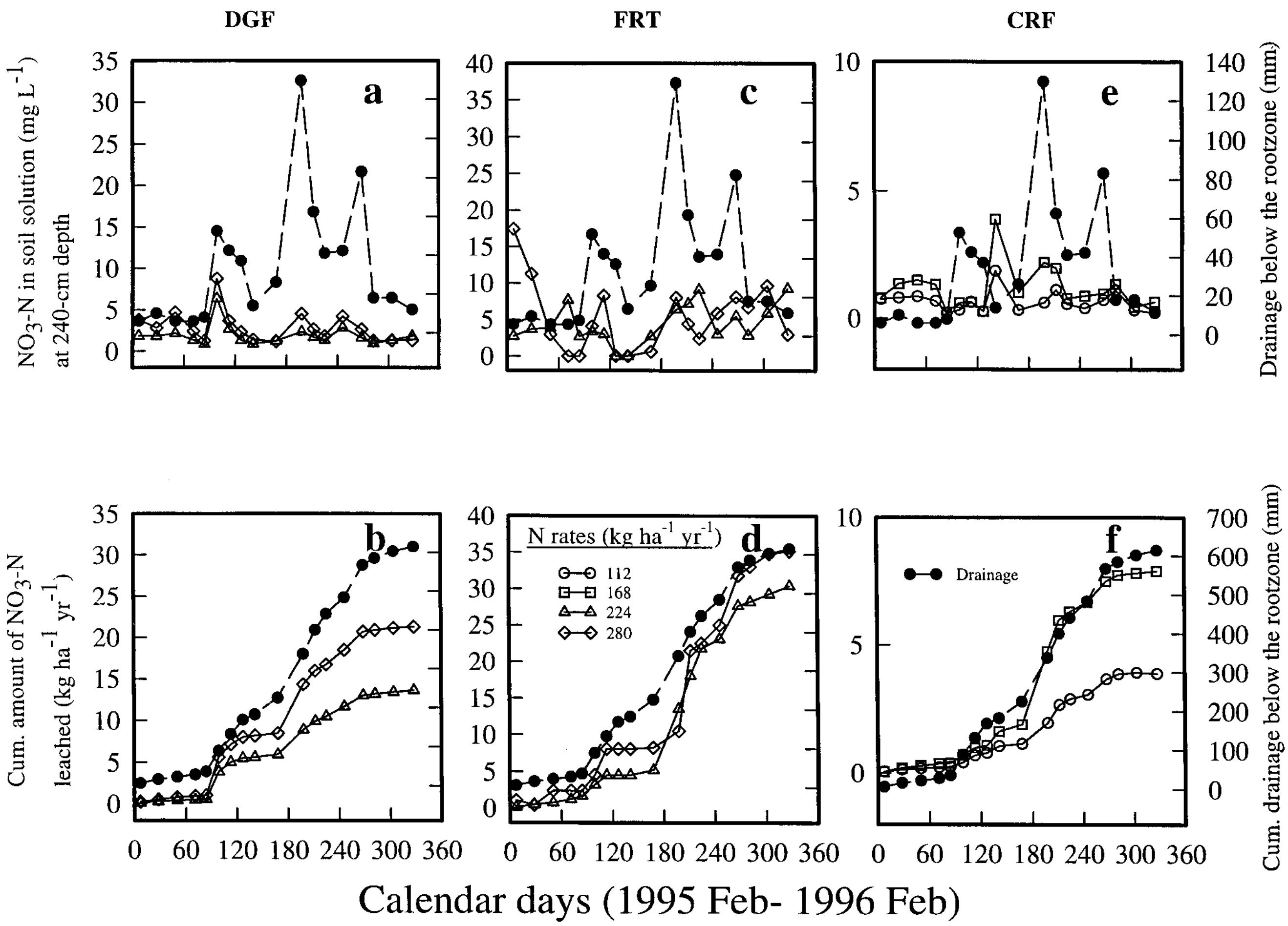

Fig. 3. Concentrations of NO_3-N in soil solution sampled at 240 cm depth, calculated amount of drainage below this depth, and estimates of cumulative amount of water and NO_3-N leached below 240 cm, i.e. root zone depth of mature citrus trees—1995 through February 1996.

drainage for leaching are important determining factors of leaching losses of applied N fertilizer. High N applications generally showed high NO_3-N concentration in soil solution, which coincidently happened to be with certain FRT events. This observation is in contrast to the observation of Dasberg et al. (1988), and also to the general

Table 2. Effects of N source and rates on the estimated NO_3-N leached below the rooting depth of mature citrus trees in an Entisol with optimal irrigation scheduling.

Treatments		Year	
N Source†	N rate	1994	1995
	kg ha^{-1} yr^{-1}	kg NO_3-N	
DGF	112	10.3	12.4
	168	11.5	13.2
	224	14.0	13.7
	280	22.6	21.3
Regression		‡$y = 25.2 - 0.22x + 0.0008x^2$ $r^2 = 0.97$*	$y = 27.2 - 0.20x + 0.0007x^2$ $r^2 = 0.91$*
FRT	112	16.3	18.2
	168	18.4	24.1
	224	23.4	30.4
	280	29.3	35.1
Regression		$y = 20.9 - 0.09x + 0.0005x^2$ $r^2 = 0.99$*	$y = 6.4 + 0.10x + 0.0001x^2$ $r^2 = 0.99$*
CRF	56	0.6	0.9
	112	1.1	3.3
	168	3.3	7.9
Regression		$y = 1.8 - 0.04x + 0.0003x^2$ $r^2 = 0.99$*	$y = 1.1 + 0.03x + 0.0002x^2$ $r^2 = 0.99$*

* Significant at $P = 0.05$.

† Four rates (DGF and FRT) and three rates (CRF) of N sources were analyzed separately for each cropping year for statistical significance and for further regression analysis.

‡ Regression equations showing relationship between estimated NO_3-N leached (y) Vs. N rates (x).

Table 3. Effects of N sources and rates on 2 *M* KCl extractable nitrate-N in the top 60 cm soil profile during 1995.

Treatments		Mean NO_3-N in soil profile (0–60 cm)		
N Source†	N rate	March	June	October
	kg ha^{-1} yr^{-1}	kg ha^{-1}		
DGF	112	62.7a‡	8.2a	33.7a
	168	63.3a	12.6b	34.4a
	224	65.3a	18.3c	36.4a
	280	67.6a	17.2c	35.9a
Mean§		64.7**	14.1	35.1*
FRT	112	28.9b	10.2a	9.3b
	168	29.6b	14.2b	9.9b
	224	30.1b	21.9d	10.9b
	280	32.2b	24.3d	10.6b
Mean		30.2**	17.1	10.2*
CRF	56	14.9a	3.9a	5.8a
	112	16.8a	4.3a	6.2a
	168	42.3b	4.7a	6.9a
Mean		24.7	4.3	6.3

*, **: Significant at $P = 0.05$ and 0.001, respectively.
† Four rates (DGF and FRT) and three rates (CRF) of N sources were analyzed separately for each sampling period for statistical significance and for further mean separation.
‡ Values reported are mean of five replicate analyses. Values within a column followed by the same letter are not significantly different according to Duncan multiple range test (DMRT) at $P = 0.05$.
§ Values reported are mean across all N rates within a source and sampling time, irrespective of statistical significance.

expectation of FRT practice. However, as indicated above, the estimated higher leaching of NO_3-N with FRT was purely because of unexpected prolonged irrigation or unexpected high rainfall (Fig. 1) following certain FRT events in both cropping years. Further improved N uptake efficiency by citrus with FRT compared with DGF was reported earlier by Dasberg et al. (1988), Alva and Paramasivam (1998), and Alva et al. (1998).

A study in a large southern California watershed planted with citrus reported 67 kg N ha^{-1} leaching losses (Bingham et al., 1971) that accounted for 45% of the annual applied N. Avnimelech and Raveh (1976) reported average leaching losses of 50 and 130 kg NO_3-N ha^{-1} yr^{-1} (i.e., ≈21 and 47% of applied N) with mature 'Shamouti' orange grown in a clay loam and sandy loam soil, respectively, in Israel. Another N FRT study (Dasberg et al., 1984) over a 4-yr period, with mature Shamouti orange in the coastal plain of Israel, showed ≈8 to 48% N leaching loss with varying irrigation (580–880 mm) and N rates (87–393 kg N ha^{-1} yr^{-1}). In the above studies, N leaching was estimated using the mean NO_3-N concentration in the soil solution in the subsoil and annual volume of water that passed through the soil profile. The estimate of N leached in our study was lower than that reported in the above studies. The lower quantities of NO_3-N leaching estimates in this study, compared with those reported in the other studies, may have been a consequence of improved management of N and irrigation.

Soil solution samples obtained using ceramic-cup SLs only provide information on soil solution chemical characteristics at the time of sampling, and not the flux passed the sampling zone. Therefore, the estimates of N leached using NO_3-N concentrations in the SL samples only approximate the amount of N leached. Frequent sampling of soil solution is necessary to adequately characterize the changes in leachate concentrations with time.

Nitrogen in the Soil Profile

Nitrogen source or rate did not significantly affect 2 *M* KCl extractable NO_3-N in 1994 (data not shown). The mean residual amount of NO_3-N varied from 8 to 39 kg ha^{-1} in 1994. The mean residual amount of NH_4-N in the top 60 cm of the soil profile varied from 35 to 93, and 48 to 119 kg ha^{-1} for 1994 and 1995, respectively. The concentration of NH_4-N was much greater than that of NO_3-N in the soil profile whenever samples were taken.

Since N rates were similar for the DGF and FRT sources only, mean comparisons of mean residual NO_3-N was evaluated between these two sources (Table 3). Significant differences were evident in March and October only (Table 3). During all three sampling periods of 1995, residual NO_3-N in the top 60 cm of the soil profile of the DGF treatment plot was numerically greater than in FRT plots (Table 3). The lower values for FRT treatment were expected because the annual amount of FRT N was applied in 15 split applications, while DGF was split into four applications.

Soil sampling and extraction of N available to growing crops, although more laborious, gives a better and more rapid estimate of N status in the soil profile than does short-term incubations or actual plant uptake in the greenhouse or the field (Broadbent, 1981). However, soil sampling with interpretations of the N profile cannot be used to compare N sources and rates across different cropping seasons. This is because N profile distribution is affected by N fertilizer sources, rates, crop uptake, and other environmental factors that promote downward N movement in the sandy soil profile. In addition, widely varying frequencies and application timing were used among the N sources in this study. This is further complicated by the fact that citrus exhibits an alternate bearing pattern, which will create differences in nutrient removal by harvested fruit (a major component of N removal) from year to year that ultimately affect the N in the soil profile (Alva and Paramasivam, 1998).

The nutrition program for bearing citrus trees should be aimed primarily at supporting the current crop of fruit and new growth. New vegetative growth is important for fruit yield during the subsequent year. The nutrient requirement is maximum from early spring through early summer (Tucker et al., 1995). Thus, citrus trees will take up most N during this period, while N may accumulate in the profile during the rest of the year excluding the losses due to leaching, and other associated N transformation processes.

In a mature Shamouti Orange tree study in a Hamra sandy loam with sandy subsoil on the coastal plain of Israel, with applications of 100 to 310 kg N ha^{-1} yr^{-1} as liquid NH_4NO_3, the NO_3-N soil profile increased from 14 to 69, 8 to 27, and 6 to 22 mg kg^{-1} at 0- to 30-, 30- to 120-, and 120- to 300- cm depths, respectively, with increasing rate of N application (Dasberg et al., 1983). These results represented only a one-time sampling during July of 1982. Even though we sampled three times a year (March, June, and August of 1994, and March, June, and October of 1995), NO_3-N soil profile distribution was neither significantly influenced by N source nor by rate, with the exception in 1995.

CONCLUSIONS

Concentrations of NO_3-N in soil solution at 240-cm sampling depth (below the rooting depth of mature citrus trees) mostly remained below 10 mg L^{-1} NO_3-N during the 2-yr monitoring period. Using soil solution NO_3-N concentrations and estimates of quantity of water drained below this depth, the amounts of N leached below the rooting depth were estimated for various N sources: 5 to 12% for DGF, 10 to 16% for FRT, and 1 to 5% for CRF. Therefore, with highly productive trees and with careful timing of fertilizer applications and irrigation, the leaching of NO_3^- below the root zone of the trees was minimal compared with previously reported studies. Results of this leaching estimation study, along with previously published fruit yield and quality information, will be used to further fine-tune irrigation and N management, and to develop best management practices for fertilizing bearing citrus trees in Florida.

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