Monitoring of Nitrate Leaching in Sandy Soils: Comparison of Three Methods

Lincoln Zotarelli, Johannes M. Scholberg,* Michael D. Dukes, and Rafael Muñoz-Carpena

ABSTRACT

Proper N fertilizer and irrigation management can reduce nitrate leaching while maintaining crop yield, which is critical to enhance the sustainability of vegetable production on soils with poor water and nutrient-holding capacities. This study evaluated different methods to measure nitrate leaching in mulched drip-irrigated zucchini, pepper, and tomato production systems. Fertigation rates were 145 and 217 kg N ha^{-1} for zucchini; 192 and 288 kg N ha^{-1} for pepper; and 208 and 312 kg N ha^{-1} for tomato. Irrigation was either applied at a fixed daily rate or based on threshold values of soil moisture sensors placed in production beds. Ceramic suction cup lysimeters, subsurface drainage lysimeters and soil cores were used to access the interactive effects of N rate and irrigation management on N leaching. Irrigation treatments and N rate interaction effects on N leaching were significant for all crops. Applying N rates in excess of standard recommendations increased N leaching by 64, 59, and 32%, respectively, for pepper, tomato, and zucchini crops. Independent of the irrigation treatment or nitrogen rate, N leaching values measured from the ceramic cup lysimeter-based N leaching values were lower than the values from the drainage lysimeter and soil coring methods. However, overall nitrate concentration patterns were similar for all methods when the nitrate concentration and leached volume were relatively low.

NITROGEN is the most limiting crop nutrient for most non-legume production systems. Historically, excessive application of water and/or fertilizers was perceived to be "a cheap insurance premium" to minimize the risk of yield reductions associated with potentially unfavorable production conditions. However, more stringent environmental standards along with water use restrictions will require growers to increase both crop water and fertilizer efficiencies via implementation of improved irrigation and nutrient management practices (Bock and Hergert, 1991).

Under conditions that prevail in the southeastern USA, most soil N is rapidly converted to nitrate N (Jansson and Persson, 1982). Nitrate moves with the wetting front and N leaching on sandy soils is intrinsically linked with soil water dynamics. Actual N leaching losses depend on N source and application rates, crop removal capacity, and water displacement below the active root zone. Excessive irrigation and/or N application rate combined with intense rainfall on excessively drained sandy soils with low water-holding capacity greatly enhances the potential risk of N leaching (Knox and Moody, 1991; McNeal et al., 1995). Nitrate leaching from agricultural fields is considered to be one of the major contributors to groundwater contamination and 25% of surficial groundwater samples collected from agricultural areas of the Georgia-Florida coastal plain exceeded the USEPA nitrate standard for drinking water of 10 mg NO_3–N L^{-1} (USGS, 1998).

For vegetable crops, the introduction of plastic mulch, drip irrigation, and recently subsurface drip irrigation (Thompson et al., 2002; Lamm and Trooien, 2003) reduced soil water evaporation and potential nitrate leaching (Romic et al., 2003). The use of drip irrigation also facilitated fertilizer injection to irrigation systems (fertigation), which improved the synchronization between nutrient application and crop nutrient uptake (Bowen and Frey, 2002). On sandy soils, fertigation combined with plastic mulch may reduce nutrient leaching (Romic et al., 2003; Vázquez et al., 2006). Improved irrigation management will be a key requirement for enhancing fertilizer use efficiency which is critical for reducing nitrate loading of groundwater resources. A key criterion for assessing the effectiveness of best management practices (BMPs) to enhance water quality will be their effectiveness in reducing nitrate leaching.

Different methods have been employed to assess N leaching in unsaturated soils (Barbee and Brown, 1986; Lord and Shepherd, 1993; Webster et al., 1993; Pampolino et al., 2000). Soil coring is simple, relatively cheap, widely used, and applicable to most soils. However, soil coring can be time-consuming, it is destructive, and it only provides a "snapshot" of N distribution. In comparison with other methods, soil sampling provides an indirect measurement of inorganic N in the soil solution (Webster et al., 1993). Repeated soil coring may also introduce errors associated with inherent spatial variability in soil nitrate concentration, which may be an issue for drip-irrigated vegetable systems on coarse sandy soils that may have fairly pronounced lateral water and nutrient gradients (Simonne et al., 2004b). Although soil coring will provide information on N distribution within the soil profile and N balances at a single point in time, this method is not suitable to calculate N leaching unless it is combined with modeling approaches and/or by linking soil N distribution with water flow dynamics below the rhizosphere (Willian and Nielsen, 1989).

Ceramic suction cup lysimeters are considered to be a suitable technique to monitor N leaching in non-structured soils (Webster et al., 1993). They are easy to install and allow repeated measurements from the exact same location, but they do not allow development of mass balances at a single point in time unless potential soil water flux is determined at the same time. More-

L. Zotarelli and J.M. Scholberg, Univ. of Florida, IFAS, Agronomy Dep., 304 Newell Hall, Gainesville, FL 32611. M.D. Dukes and R. Muñoz-Carpena, Univ. of Florida, IFAS, Agricultural and Biological Engineering Dep., 120 Frazier Rogers Hall, Gainesville, FL 32611. Received 26 July 2006. *Corresponding author (jmscholberg@ifas.ufl.edu).

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Abbreviations: DAT, days after transplanting; ET_c, actual crop evapotranspiration; SE, standard error; VWC, volumetric water content.

over, under low soil water availability and dry conditions that often prevail in coarse sandy soils, it is often not possible to obtain adequate sample volumes, which may induce large uncertainties in calculating N losses (Barbee and Brown, 1986; Lord and Shepherd, 1993).

Drainage lysimeters are commonly used to monitor N leaching dynamics. They capture the entire leachate volume and N concentration, which can then be used to calculate N load passing below a specific soil depth. However, installation may result in appreciable soil disturbance. Also, they must be sized to represent a production unit. Finally, lysimeters need to be placed deep enough so that soil water conditions in the crop root zone represent overall field conditions, yet shallow enough to ensure adequate drainage and to ensure that time trends match actual N displacement below the effective root zone. Similar to the use of ceramic suction cups, the use of drainage lysimeters allows for direct and relatively consistent and precise measurement of nitrate concentrations (Webster et al., 1993). An additional advantage of this method is that it provides an "integrative approach" (both in space and time) which may be a more realistic way of assessing total N loads compared with other approaches that represent a relatively small spatial dimension (<5 cm) and only provide a "snapshot" of N leaching patterns.

The objective of this study was to compare the effectiveness of three different methods for monitoring and quantifying N leaching below mulched vegetable production beds as affected by the volume of irrigation and N rate.

We hypothesized that the use of different methods to monitor N leaching will result in similar estimates of overall cumulative N leaching rates independent of the volume of irrigation or N rate applied.

MATERIALS AND METHODS

Site Description

Experiments were conducted at the University of Florida Plant Science Research and Education Unit, near Citra, FL. The soil at the research site was Tavares sand (Buster, 1979). This soil contains >97% sand-sized particles and has a field capacity of 0.074 ± 0.014 (soil water content reported as percent by volume). Permanent wilting point water content was 0.04 ± 0.01 by volume in the upper 0.2 m of the profile. Soil carbon concentration was 6.8 g C kg^{-1} of soil in the upper 0.2 m and <2.8 g C kg^{-1} of soil for the 0.2- to 0.9-m soil depth (Carlisle et al., 1978).

Two weeks before vegetable transplanting, raised beds of approximately 32-cm height were constructed. Beds were fumigated (80% methyl bromide, 20% chloropicrin by weight) at a rate of 604 kg ha^{-1} concomitant to placement of both drip tape and plastic mulch in a single pass. Raised beds were 15 m long and 0.9 m wide with the bed centers spaced 1.8 m apart.

Vegetable crops grown were pepper (*Capsicum annuum* L., 'Brigadier'), tomato (*Lycopersicon esculentum* Mill., 'Florida 47'), and zucchini (*Cucurbita pepo* L. 'Wild Cat'). Tomato and bell pepper were transplanted on 7 Apr. 2005. Peppers were planted in staggered twin rows at 0.3-m spacing both between and within the row. Tomato was planted in a single row at 0.45-m plant spacing. Zucchini seed was sown on 26 Sept. 2005 in a single row per plot, with 0.45-m spacing between plants.

The experiment compared the nitrate leaching for different irrigation rates and three methods of measuring nitrate leaching. The experimental design consisted of factorial irrigation rates (two for tomato and zucchini and three irrigation rates for pepper) assigned at random to the whole plots within each block. The methods were assigned to the subplots within each whole plot. The plot design was a randomized complete block design with four replicates (blocks).

Fertilizer was applied as weekly fertigation schedules based on IFAS (Institute of Food and Agricultural Science–University of Florida) recommendations (Maynard et al., 2003a, 2003b, 2003c). Nitrogen fertilizer application rates corresponded with either 100% (1.0 IFAS) or 150% (1.5 IFAS) of the recommendation for each crop. Weekly fertigation rates and cumulative amount of N applied are outlined in Fig. 1 and Table 1. The leaching potential of sandy soils is very high (McNeal et al., 1995). To reduce N leaching, N application rates were relatively low during initial growth, greatest during the linear growth phase, and gradually reduced toward the end of the growing season (Fig. 1). For pepper and tomato, N application rates were 11.7 kg N ha^{-1} wk^{-1} (wk 1–2) and 15.6 kg N ha^{-1} wk^{-1} (wk 3–4). Rates increased during the linear growth phase to 19.6 kg N ha^{-1} wk^{-1} (wk 5–11) before being reduced to 15.6 kg N ha^{-1} toward the end of the growing season. For zucchini, application rates of 11.7 kg N ha^{-1} wk^{-1} (wk 1–2) were increased to 19.6 kg N ha^{-1} wk^{-1} (wk 3–7) before being reduced to 11.7 kg N ha^{-1} wk^{-1} (wk 8–9) before final harvesting (Fig. 1). All other nutrients were applied at recommended rates. All phosphorus (112 kg P_2O_5 ha^{-1}) and micronutrients were applied before applying plastic mulch to beds.

A weather station located within 500 m of the experimental site provided temperature, relative humidity, solar radiation, and wind speed data. This station also provided the weather

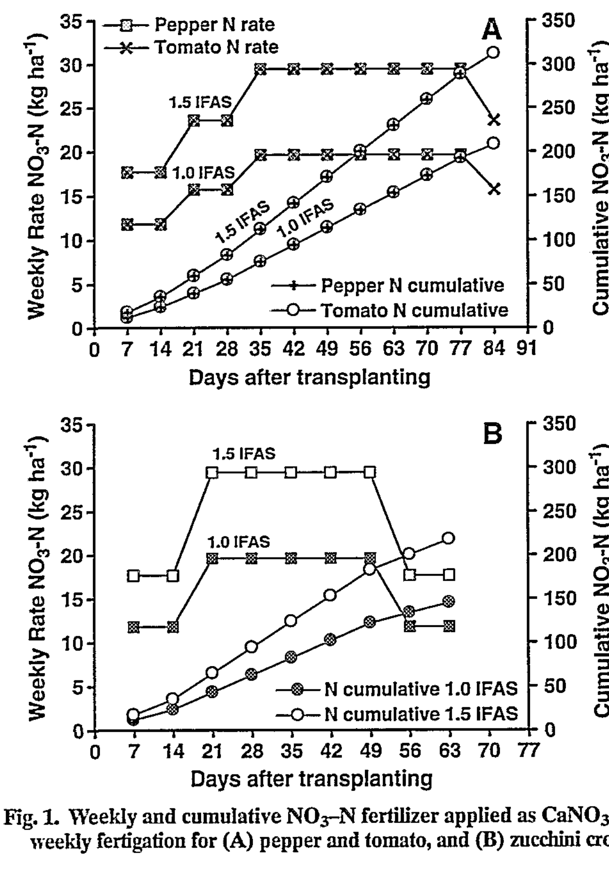

Fig. 1. Weekly and cumulative NO_3–N fertilizer applied as $CaNO_3$ by weekly fertigation for (A) pepper and tomato, and (B) zucchini crops.

Table 1. Overview of irrigation and fertilization treatments.

Crop/symbol		Relative volume of irrigation, drip tape position, irrigation schedule	Rate of irrigation	Irrigation volume	N applied rate†	
					1.0 IFAS	1.5 IFAS
			mm d^{-1}	mm	kg ha^{-1}	
Pepper	P1	Low volume, soil moisture sensor with five possible events per day.	0.8	70	192‡	288
	P2	Medium volume, soil moisture sensor with five possible events per day.	2.0	170	192	288
	P3	High volume, fixed time irrigation schedule, irrigation applied at fixed daily duration of 2 h.	3.3	280	192	288
Tomato	T1	Low volume, quantified irrigation controller system, time-based irrigation, five possible events per day.	1.4	120	208§	312
	T2	Time-fixed irrigation schedule, irrigation applied at fixed daily durations of 1 or 2 h, depending on growth stage.	2.9	245	208	312
Zucchini	Z1	Medium volume, soil moisture sensor with five possible events per day.	4.6	329	145¶	217
	Z2	Fixed time irrigation schedule, irrigation applied at fixed daily durations of 2 h per day.	6.7	482	145	217

† Multiplier coefficient.
‡ Nitrogen rate according to Maynard et al. 2003b.
§ Nitrogen rate according to Maynard et al. 2003a.
¶ Nitrogen rate according to Maynard et al. 2003c.

parameters required to calculate reference evapotranspiration (ET_0) according to FAO-56 (Allen et al., 1998). Crop evapotranspiration (ET_c) was calculated based on the product of ET_0 and the crop coefficient (K_c) for a given crop growth stage (Simonne et al., 2004a) and values were reduced by 30% to account for the effect of plastic mulched vegetable beds on overall ET values (Amayreh and Al-Abed, 2005).

Irrigation

Irrigation was applied via drip tape (Turbulent Twin Wall, 0.2-m emitter spacing, 0.25-mm thickness, 3.8 L h^{-1} at 69 kPa, Chapin Watermatics, Watertown, NY). Two drip tapes were used, one for irrigation and one for fertigation. Irrigation treatments consisted of three different management and/or scheduling approaches; two sensor-controlled, and one fixed-time irrigation, resulting in different volumes of water applied to the crops. Two control sensors were used, a University of Florida designed quantified irrigation controller (QIC) system (Muñoz-Carpena et al., 2007) that allowed time-based irrigation (five potential irrigation events per day) if soil volumetric water content (VWC) dropped below a threshold value previously established. The commercially available Acclima RS500 soil moisture sensor (Median, ID) with a VWC threshold value that allowed time-based irrigation events similar to QIC was also used for selected treatments. The third irrigation approach, included as a control treatment, was a fixed time irrigation schedule (grower practice) in which water was applied 1 or 2 h per day depending on crop growth stage.

Water applied by irrigation or by fertigation was recorded by positive displacement flow meters (V100 1.6-cm diam. bore with pulse output, AMCO Water Metering Systems, Inc., Ocala, FL). Weekly manual meter measurements were taken and data from transducers that signaled a switch closure every 18.9 L were collected continuously by data loggers on each meter (HOBO event logger, Onset Computer Corp., Inc., Bourne, MA). Pressure was regulated by inline pressure regulators to maintain operating pressures of 83 kPa at the irrigation source and an average pressure in the field of 69 kPa during irrigation events.

Monitoring Nitrogen Methods

For monitoring N the following methods were evaluated: (i) soil coring at 0.3-m increments to a soil depth of 0.9 m; (ii) use of ceramic suction cups placed vertically in the center of the plots 0.9 m below the drip tape; and (iii) subsurface drainage lysimeters installed 0.75 m beneath the top of the beds. Samples were collected in each block for all methods. Ceramic suction cups and drainage lysimeters were placed next to each other and the soil samples were taken adjacent to other devices. Each collection method was replicated four times in corresponding field plots for each treatment.

Soil samples were collected biweekly using a 50-mm diam. soil auger. Samples were obtained 6 d after the previous fertigation and 1 d before the next one. A 10-g subsample was extracted with 50 mL of 2 *M* KCl and filtered by gravity (Q8, Fisher Scientific Inc., Pittsburgh, PA) within 1 d of soil sampling (Mulvaney, 1996). The gravimetric water content was determined for each depth interval and was used (by multiplying by the bulk density) to give the VWC.

Ceramic suction cups with an outside diameter of 48 mm and a height of 51 mm (Soilmoisture Equipment Corp., Santa Barbara, CA) were connected to a 1.0 m long PVC pipe closed at the top with a two-hole rubber stopper. Soil solution samples were collected weekly by applying approximately 70 kPa vacuum to the cups 6 d after the previous fertigation and 1 d before the next one. Samples were collected 24 h after the vacuum was applied just before the next fertigation.

Subsurface drainage lysimeters were installed in September 2004 in such a manner that they collected leachate for a representative transect of the production bed. The 0.75-m installation depth was selected since it was shallow enough to facilitate burial and sampling yet was below the effective root zone of tomato (Oliveira et al., 1996, Machado et al., 2003), pepper, and zucchini. Lysimeters were constructed out of 208-L capacity drums that were cut in half lengthwise. They were 0.85 m long, 0.27 m high, and had a diameter of 0.55 m. A 0.80 m long slotted pipe (well screen, slot size = 0.3 mm) with a diameter of 32 mm was capped at both ends and placed in the bottom of each lysimeter. One end of the slotted pipe was fitted with a 6.4-mm i.d. butyl rubber suction tube (Fisher Scientific Inc., Pittsburgh, PA) that was routed to the bottom of the raised bed to allow extraction of the leachate collected at the bottom of the lysimeter by a vacuum pump. The leachate was removed weekly, a day before the next fertigation by applying a partial vacuum (35–40 kPa) using 20-L high vacuum bottles (Nalge Nunc International, Rochester, NY) placed in the vacuum line for each drainage lysimeter (Fig. 2). Leachate volume was determined gravimetrically and subsamples were collected from each bottle for NO_3–N analysis. Samples were extracted on weekly intervals as more frequent extraction would result in erratic sampling results and biweekly sampling would increase the excessive water accumulation, increasing the potential for denitrification.

Soil solution and soil core extracts were stored at −18°C until they were analyzed for nitrate using an air-segmented

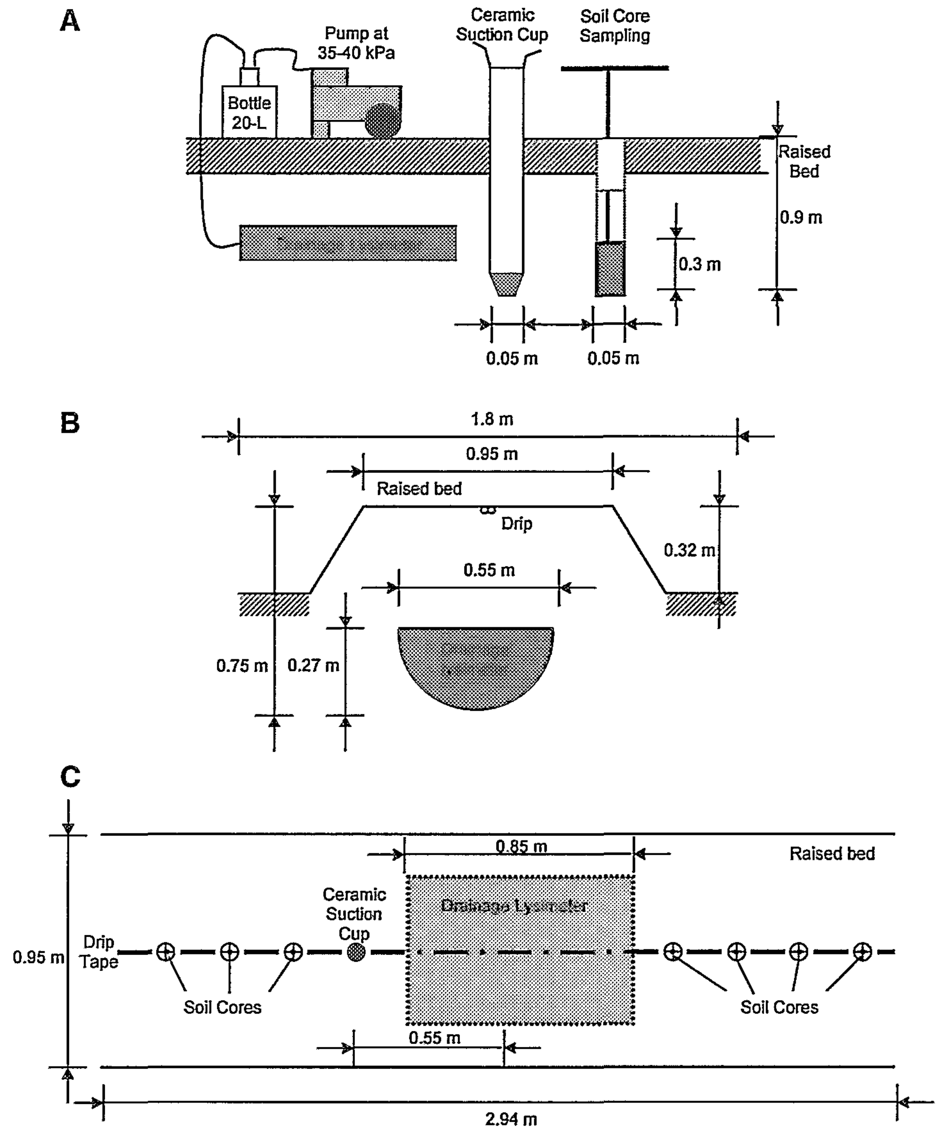

Fig. 2. (A) Overview of instrumentation used for collecting leaching samples, (B) drainage lysimeter layout, and (C) top view of instrumentation distribution.

automated spectrophotometer (Flow Solution IV, OI Analytical, College Station, TX) coupled with a Cd reduction approach (USEPA Method 353.2; USEPA, 1983). Total N loading rates from each method were calculated using the trapezoidal approximated integration rule (Lord and Shepherd, 1993), where the total amount of NO_3–N leached (kg ha^{-1}) is the integrated area under the plot of NO_3–N concentration against cumulative drainage (mm) obtained from drainage lysimeters.

Statistical Analysis

Statistical analyses were performed using Proc GLM of SAS (SAS Institute, Inc., 1996) to evaluate the capacity of each method for each cropping system. Means were compared using Duncan's Multiple Range test ($P < 0.05$). PROC GLM was used to correlate overall seasonal N leaching for the N monitoring methods across cropping systems, irrigation treatments, and N rates.

Since irrigation and fertigation patterns affect N leaching, assessment of the effectiveness of different methods to monitor N leaching requires a basic understanding of leaching dynamics. Therefore, drainage and N leaching dynamics for the three systems as affected by irrigation and N management practices are outlined before comparing and discussing the performance of N leaching assessment methods.

RESULTS AND DISCUSSION

Leaching Dynamics

Leaching patterns reflected irrigation application practices (Fig. 3). For treatments receiving the greatest irrigation volume (P3, T2, and Z2) cumulative drainage below the root zone as measured by leachate recovery from drainage lysimeters ranged from 44 to 68 mm (Fig. 3). Corresponding drainage values for P1 and T1 ranged from 5 to 15 mm compared with 30 mm for P2 and 58 to 68 mm for T2, Z1, and Z2. Two distinct leaching phases were observed. The first one occurred during the initial crop establishment (0–18 days after treatment [DAT]), when drainage was similar for all treatments. During this phase, irrigation application rates in excess of crop demand are commonly used to reduce transplant

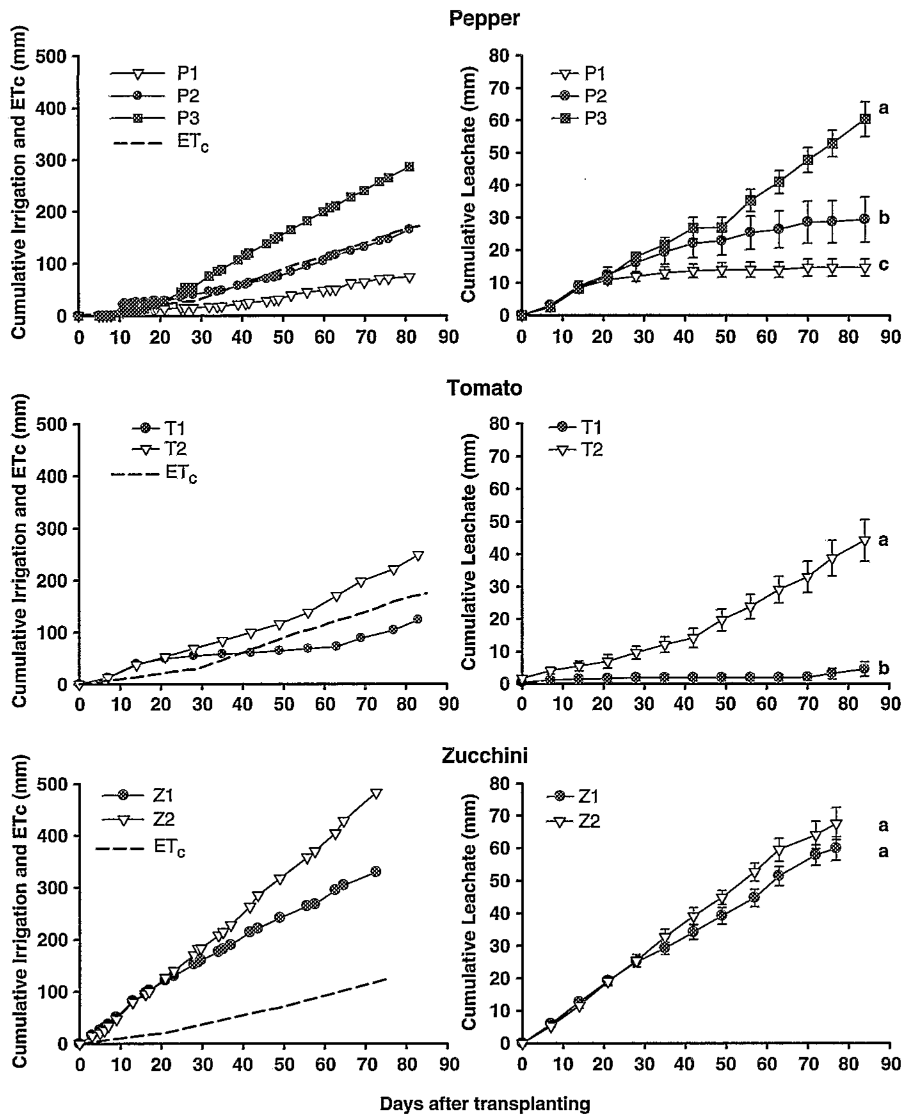

Fig. 3. Cumulative irrigation, calculated cumulative crop evapotranspiration (ET_c), and cumulative leaching of drainage lysimeters. Different letters indicate differences at the 95% confidence level for cumulative leachate (error bars represent ± 1 SE from the mean, n = 4).

shock and promote a rapid increase in root volume (Simonne et al., 2004a). However, water and nutrient assimilation rates by crops are limited, which increases the potential risk of nitrate leaching below the root zone (Vázquez et al., 2005). In this study, during the establishment phase irrigation rates typically exceeded ET_c, resulting in high drainage (Fig. 3).

After this time period treatments differentiated according to irrigation treatment. Drainage for the low volume treatments was low for pepper (P1) while no drainage occurred for tomato (T1). For these treatments, the cumulative volume leached in the drainage lysimeters for the pepper and tomato ranged between 5 and 15 mm, representing 4 to 20% of the water applied by irrigation. Most leaching occurred during initial crop establishment when high irrigation application rates were used for all treatments.

In contrast to the low irrigation volume treatments, measured leachate for the greater volume treatments increased throughout the growing season (Fig. 3). The irrigation volume applied to P2 and T2 treatments was 170 to 329 mm, respectively, resulting in 29 and 43 mm of leaching below the effective root zone, which translated to about 18% of total irrigation water. In P3 and Z2, the leaching fraction was much higher and respective values were 60 and 67 mm. Applying irrigation below ET_c (P1 and T1) resulted in a reduction of more than 50% of the leachate volume (Fig. 3). Irrigation rates for P3, Z1, and Z2 treatments, on the other hand, typically exceeded ET_c (by 60%) throughout the entire growth period, resulting in a continuous increase in cumulative leaching. In contrast, weekly increments in drainage volumes decreased significantly for P1, P2, and T1 treatments after initial crop establishment (Fig. 3) because of higher plant ET_c and lower rates of irrigation applied to these treatments.

Nitrogen Leaching Dynamics

The volume of irrigation had a significant effect on N leaching for all cropping systems (Table 2), except for

Table 2. Nitrate leached measured by drainage lysimeters, soil core, and ceramic suction cups under different irrigation and N rates at end of pepper, tomato, and zucchini crop cycle.

	Irrigation							
	1.0 IFAS				1.5 IFAS			
Parameter	Drainage lysimeter	Soil core	Ceramic suc. cup	Mean	Drainage lysimeter	Soil core	Ceramic suc. cup	Mean
				Pepper				
N applied (kg N ha^{-1})			192				288	
P1	6.0ABb	9.0Ac	2.3Bb	5.8	18.8	18.4	6.6	14.6c†
P2	26.7Aa	25.8Ab	20.7Ba	24.4	39.7	27.7	17.3	28.2b
P3	36.5Aa	37.6Aa	9.4Bb	27.8	58.8	53.9	48.9	53.9a
Mean	23.0	24.1	10.8	–	39.1A	33.3A	24.3 B	–
Coef. variation (%)				35.9				26.3
F value								
Irrigation (I)				35.2***				66.2***
Method (M)				13.7***				9.3***
I × M				4.7**				0.8ns§
				Tomato				
N applied (kg N ha^{-1})			208				312	
T1	5.2Ab	5.1Ab	2.7Aa	4.3	6.8Ab†‡	6.4Ab	2.7Ab	5.3
T3	37.1Aa	30.4Aa	4.0Ba	23.8	62.1Aa	36.4Ba	33.8Ba	44.1
Mean	21.1	17.5	3.3	–	34.4	21.4	18.2	–
Coef. variation (%)				31.5				15.8
F value								
Irrigation (I)				67.1***				596.5***
Method (M)				21.0***				38.8***
I × M				15.3***				26.8***
				Zucchini				
N applied (kg N ha^{-1})			145				217	
Z2	25.9ABa	34.1Aa	11.4Ba	23.8	35.0Aa†‡	40.6Aa	11.9Ba	29.2
Z3	19.5Aa	21.4Ab	14.5Ba	18.4	44.8Aa	28.1Bb	16.4Ba	29.8
Mean	22.7‡	27.8	12.4	–	39.9	34.4	14.1	–
Coef. variation (%)				30.0				19.6
F value								
Irrigation (I)				2.4ns				0.1ns
Method (M)				6.3*				44.2***
I × M				4.7ns				8.2**

*, **, *** Significant $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively.

† The values followed by the same lowercase letter in the column indicate that the means of irrigation treatments are not significantly different (at $P \leq 0.05$ according Duncan's test) between treatments within N rates and nitrate leaching methods.

‡ The values followed by the same uppercase letter in the row indicate that the means of nitrate leaching method are not significantly different (at $P \leq 0.05$ according Duncan's test) between treatments within N rates and irrigation treatments.

§ ns, not significant.

zucchini due to the higher volume of irrigation applied compared with pepper and tomato crops. Because of weekly fertigation with calcium nitrate, solubilization, nitrification, soil N retention, and volatilization did not affect nor delay N leaching patterns, so they were directly linked to fertigation events. Due to the very low soil organic matter content of the top soil (<6.8 g C kg^{-1}) and the 60- to 90-cm soil layer (<2 g C kg^{-1}), N mineralization/immobilization was too low to affect leaching results either.

The monitoring method (M) main effect was significant for both crops and N rate (Table 2). Nitrate concentration in the water samples obtained from drainage lysimeters during the initial establishment phase was similar for all irrigation treatments within N rate. Values were typically between 70 and 100 mg NO_3–N L^{-1} for the 1.0 and 1.5 N rates (data not shown). Solution nitrate concentration increased to 240 and 280 mg NO_3–N L^{-1} for P2 at 56 DAT for the 1.0 and 1.5 IFAS N rates, respectively. The use of high irrigation application rates for the P3 treatment (Table 1) resulted in a dilution effect. As a result, nitrate concentration for this treatment remained at 70 and 100 mg NO_3–N L^{-1} for the respective 1.0 and 1.5 IFAS N rates treatments throughout the entire season. A similar dilution effect was observed for tomato and zucchini when the irrigation rate was increased.

In general, nitrate leaching followed similar trends as overall drainage (Fig. 3). However, the application of N rates above IFAS recommendations increased N leaching by 66% (19 vs. 32 kg N ha^{-1}), 63% (12 vs. 19 kg N ha^{-1}), and 32% (17 vs. 22 kg N ha^{-1}) for pepper, tomato, and zucchini, respectively. For pepper, nitrate leaching was also significantly lower for the P1 treatments (low volume of water applied) compared with all other irrigation treatments. With the use of high irrigation rates (e.g., P3 and T2 treatments), on the other hand, N leaching increased with N rate (Table 2).

Comparison between Methods of Nitrate Leaching Measurements

Multiplying net drainage volumes obtained from drainage lysimeters by nitrate solution concentration values below the effective root zone (60 cm) via soil coring and/or ceramic cups allowed us to calculate N loading rates for these methods as well. Nitrate leaching for all three methods were calculated as a function of cumulative drainage depth for each irrigation treatment.

In most cases there was a significant effect of volume of irrigation on the total amount of N that was being leached. Applying fertilizer in excess of IFAS recommendations tended to greatly increase N loss. For all crops there were discrepancies in measured concentrations between methods. Considering overall nitrate loads (kg NO_3–N ha^{-1}) regardless of irrigation treatments or nitrogen rate, ceramic suction cups had significantly lower nitrate load means compared with the drainage lysimeter and soil core methods for pepper and zucchini (Table 2; Fig. 4, 5, and 6). For tomato these effects were only significant for the T3 irrigation treatment.

The lower value of nitrate leaching obtained with ceramic suction cups was related to our inability to obtain samples when soil conditions were relatively dry before sampling. However, for irrigation treatments receiving less water (T1) it was observed that N leaching based on ceramic cup values resulted in similar calculated N loading rates obtained with the two other methods tested in this study (Table 2 and Fig. 5). In this case, most of the N leaching occurred during the establishment phase, when relatively high irrigation rates were applied. As a result, since moisture was typically adequate to obtain samples from suction cups during this period and only limited N leaching occurred afterward, use of the soil coring and ceramic suction cups methods gave similar results.

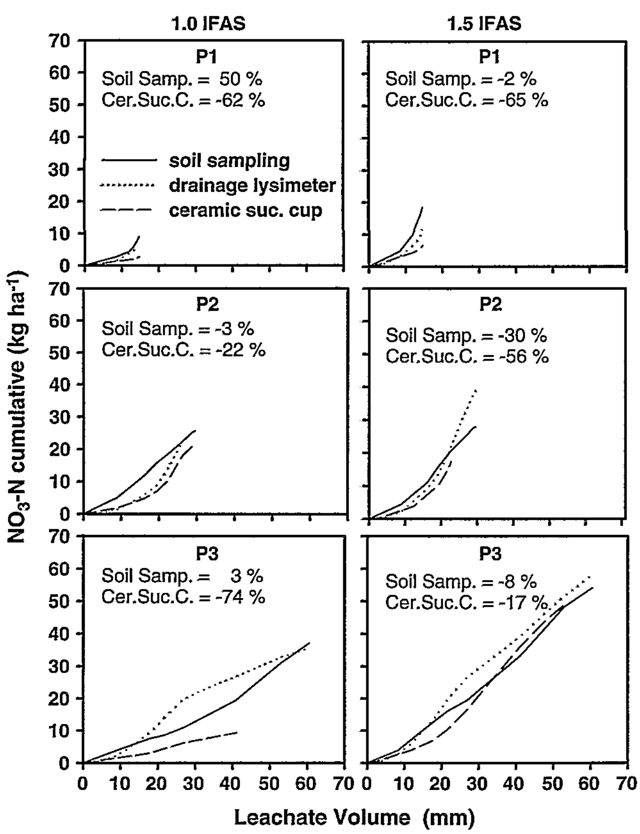

Fig. 4. Cumulative NO_3–N leaching for pepper (P) for different volumes of irrigation and two N rates measured by soil samples (60–90 cm), drainage lysimeters (75 cm), and ceramic suction cups (90 cm). Percentage values indicate the percentage difference in cumulative nitrate leached compared with values obtained by drainage lysimeter method.

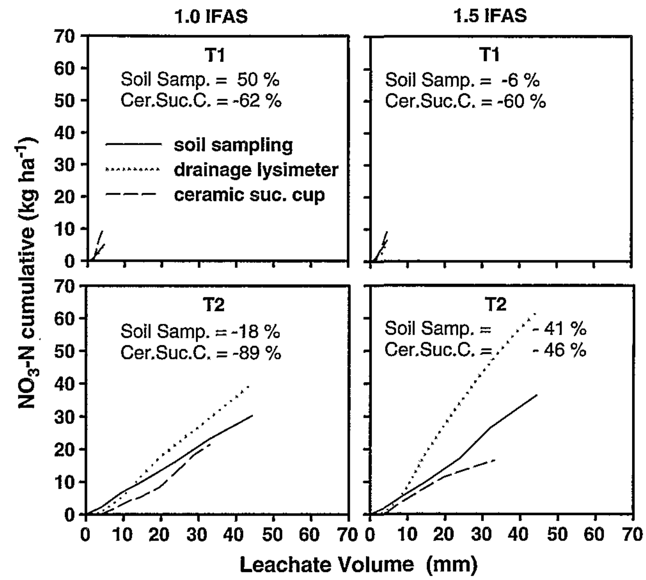

Fig. 5. Cumulative NO_3–N leaching for tomato (T) for different volumes of irrigation and two N rates measured by soil samples (60–90 cm), drainage lysimeters (75 cm), and ceramic suction cups (90 cm). Percentage values indicate the percentage difference in cumulative nitrate leached compared with values obtained by drainage lysimeter method.

On the other hand, for treatments that received greater irrigation volume, such as T2 and Z1 and Z2, N loads measured by ceramic suction cups were typically lower than those based on drainage lysimeter measurements (Table 2; Fig. 5 and 6). Overall nitrate concentrations from ceramic suction cups were slightly lower than the nitrate concentration measured in the drainage lysimeters. Similar results were reported by Webster et al. (1993). Barbee and Brown (1986) proposed that

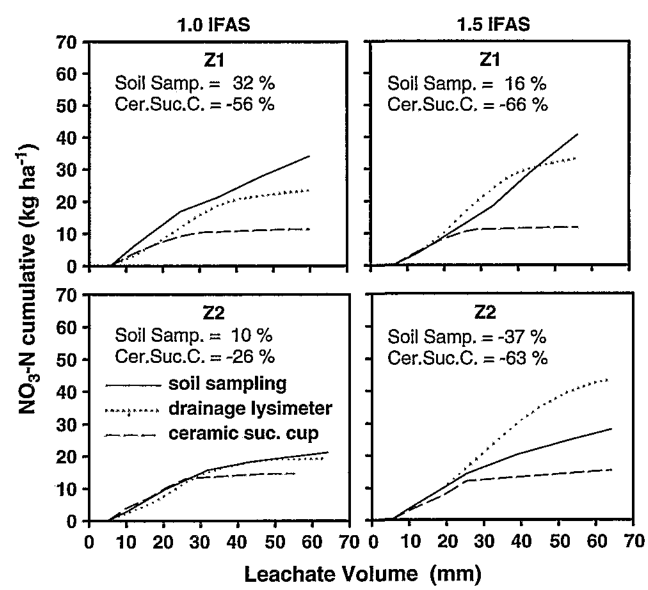

Fig. 6. Cumulative NO_3–N leaching for zucchini (Z) for different volumes of irrigation and two N rates measured by soil samples (60–90 cm), drainage lysimeters (75 cm), and ceramic suction cups (90 cm). Percentage values indicate the percentage difference in cumulative nitrate leached compared with values obtained by drainage lysimeter method.

ceramic suction cups were not suitable for monitoring water percolation through the soil profile under excessively wet conditions and/or for soils with high hydraulic conductivities.

When comparing soil cores and drainage lysimeter results for tomato (T2) and zucchini (Z2) with the 1.5 IFAS N rate, the opposite trend occurred. Soil core- and suction cup-based measures were relatively low compared with drainage lysimeters. This result may be related to N displacement below the sampling depth. Similar trends were observed by Barbee and Brown (1986) and Lord and Shepherd (1993). Soil extraction procedures can also affect nitrogen concentration and may impact solubility and calculation of solution concentrations. However, in our case the soil was a relatively inert medium. Due to the very low percentage organic matter (OM%) and cation exchange capacity (CEC) values of sandy soils and in the absence of NH_4, these interferences in our system were minimized.

To make an overall assessment of the different methods across time and production systems sample, sets were integrated into a single data set. There was a close correlation (r^2 = 0.86) between use of soil cores and drainage lysimeter (Fig. 7A). However, for the low N range, calculated N loading rates based on soil coring were slightly higher compared with those based on drainage lysimeters (Fig. 7A). However, at higher N loading values the reverse was true; soil coring-based values were 28% lower compared with drainage lysimeter-based estimates. There was also a close correlation (r^2 = 0.86) between ceramic suction cup lysimeter-based N loading estimates and those based on drainage lysimeters (Fig. 7B). However, in this case N loading values based on suction cup lysimeters were up to 42% lower compared with those derived from subsurface drainage lysimeters. Although ceramic suction cup lysimeter- and soil core-based N loading estimates were closely correlated (r^2 = 0.67), suction cup lysimeter-based N loading estimates were up to 28% lower compared with soil coring-based estimates (Fig. 7C).

The relatively low N leaching estimates with the use of suction cups for monitoring N leaching compared with other approaches may be related to a number of factors. First, use of high irrigation rates may have resulted in a dilution effect. Second, on (coarse) sandy soils performance of suction cup lysimeters may be erratic unless the soil is close to or above field capacity, and in some cases no sample could be obtained. Alternatively higher irrigation rates may also have resulted in greater displacement depth. According Lord and Shepherd (1993), variations of vacuum applied to the ceramic suction cups has no detectable effect on nitrate concentration in the samples. However, it should be noted that the poor nitrate extraction efficiency of ceramic suction cups may be related to the smaller effective soil volume being extracted. For suction lysimeters this would be on the order of 150 to 300 cm^3 due to the limited lateral water movement in coarse sandy soils compared with soil coring (590 cm^3) or drainage lysimeters (140000 cm^3). As a result, soil coring and suction lysimeters sampling from smaller areas may greatly increase spatial variability and/or potential fluctuations between measurements. To solve this problem, Barbee and Brown (1986) recommended the installation of greater number of ceramic cups and/or more frequent sampling. Second, for exces-

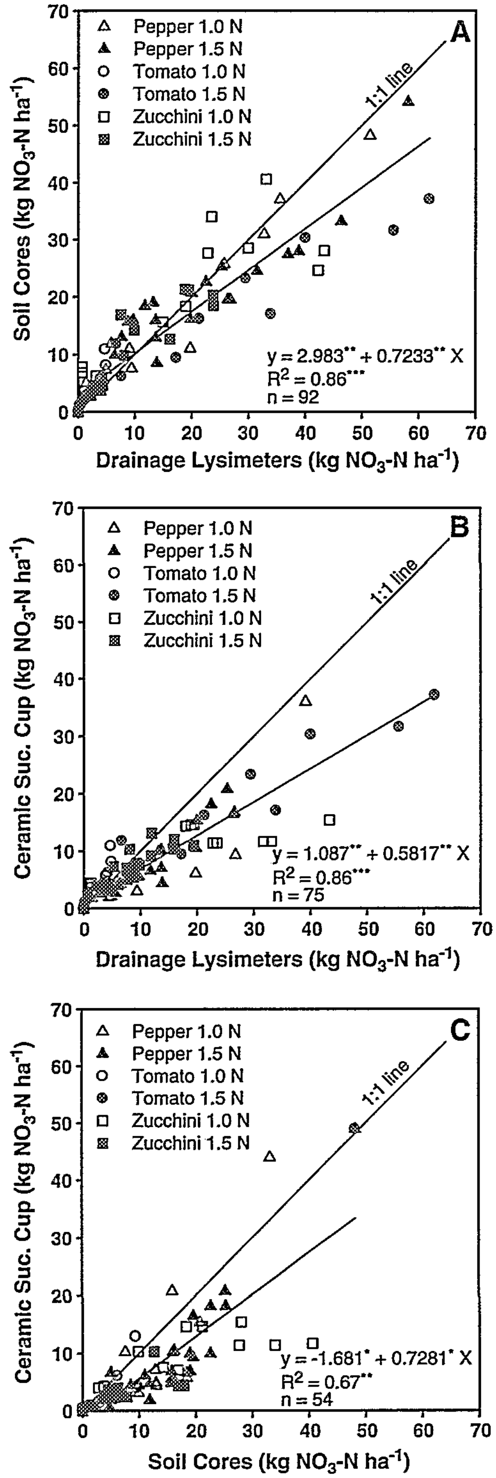

Fig. 7. Correlation between calculated cumulative nitrate leaching across cropping systems as calculated by (A) soil core sampling vs. drainage lysimeters; (B) ceramic suction cups vs. drainage lysimeters; and (C) ceramic suction cups vs. soil core sampling. **, * Significant at $P \leq 0.01$ and $P \leq 0.001$, respectively.**

sively drained sandy soil typical of our field site, ceramic cups may not collect the nitrate moving in the soil fast enough (Barbee and Brown, 1986).

With the use of subsurface drainage lysimeters, all of the N that was displaced below the effective root zone was retained since it accumulated at the bottom of the barrel. In this case, employing a partial vacuum allowed us to extract the entire intercepted leachate volume associated with a 0.84 m wide section of the production beds within 6 d after a specific fertigation event. With the use of ceramic suction cup lysimeter and soil core methods, sampling appeared to be more of a "snapshot" approach at biweekly intervals. Some of the nitrate leaching through the soil profile may have passed below the sampling point between sampling events. In this case, weekly sampling may be required to capture the complete N spike before it is displaced below the suction cup. On the other hand, according to Lord and Shepherd (1993), high sampling frequency is not recommended (shorter than bi-weekly) for suction cup lysimeters, since the applied vacuum may affect overall solution flow and/or drainage (Van der Ploeg and Beese, 1977).

In the case of the drainage lysimeters, we used weekly sampling and the drainage was typically less than 5 mm wk^{-1}. Although we also used a partial vacuum to pump the drainage lysimeters, this vacuum was not applied via a porous cup and therefore soil tension within the drainage lysimeter was limited to the air entry value of the soil (<40 kPa) and was not assumed to affect water flow within the effective root zone.

Although the drainage lysimeters were used as a reference method to measure the volume drainage and N loads, some factors may still interfere with nitrate measurements even with this approach. Accumulation of water in the bottom of the drainage lysimeters between sampling dates may enhance denitrification loss that would result in an underestimation of potential N leaching. However, in the absence of anaerobic conditions (which we verified in a follow-up study), denitrification rates for sandy soils in Florida are typically low due to the low soil carbon content (Espinoza, 1997). The use of weekly samplings combined with a partial vacuum allowed for an effective extraction of leachate at the bottom of the drainage lysimeter and the absence of anaerobic conditions. After sampling, soil water in the bottom of the barrel dropped to 15 to 20% VWC and the soil system remained oxygenated between samplings, thereby minimizing denitrification potential.

A second point of concern is roots reaching the bottom of the lysimeter and taking up nitrate accumulating there that would otherwise have bypassed the root system. However, root growth studies have shown that the majority of the root system is concentrated in the upper 0.25 to 0.3 m of the production bed (Goyal et al., 1988). Since the drainage lysimeters were installed at 0.75-m soil depth, root concentrations in the bottom of the drainage lysimeter, even at the end of the growing season, would have been minute (<5% of total root length), and should not significantly interfere with the N leaching assessment (Zotarelli et al., unpublished data, 2006).

CONCLUSIONS

A comparison of different methods of monitoring soil N leaching showed consistent patterns between drainage lysimeters and soil cores across three different mulched vegetable systems. Estimated N loading rates based on the use of ceramic suction cup samplers were lower compared with the other methods. Although each method of measurement of nitrate leaching may have certain limitations, they enhance our understanding of the processes that control and/or can reduce nonpoint-source pollution associated with commercial vegetable production systems.

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