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Nitrogen and water use efficiency of zucchini squash for a plastic mulch bed system on a sandy soil

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Abstract

Zucchini squash (*Cucurbita pepo* L.) is an economically important vegetable crop in Florida. Typically, it is intensively managed with high inputs of fertiliser and irrigation water. Our objectives were to evaluate the interaction between fertilisation rates and irrigation treatments, and to quantify nitrate leaching in a plastic mulched/drip irrigated zucchini squash production systems. Three studies were carried out. The first study evaluated different depth placement of drip and fertigation lines on plant growth and fruit yield. Treatments included SUR (both irrigation and fertigation drip lines placed on the surface); S&S (both lines buried 0.15 m deep); and SDI (irrigation line placed 0.15 m below the fertigation line on the surface). The second and third studies compared three different N-rates and different soil moisture sensor-based irrigation strategies. Nitrate-N leaching was monitored by zero tension drainage lysimeters and soil samples. N leaching increased when irrigation and N-rates increased, with values ranging from 2 to 45 kg ha^{-1} of N. Use of SDI increased yields by 16% compared to the S&S treatment, and reduced nitrate leaching by 93% while increasing the water use efficiency by 75% compared to a fixed 2-h irrigation event per day treatment. Application of N above the standard recommended rate of 145 kg ha^{-1} did not increase yield, although yields were reduced at the lowest N-rate. The use of soil moisture sensors for automatic irrigation control reduced irrigation application and minimized nitrogen leaching. In addition, combining the soil moisture controlled SDI system that had surface applied fertigation resulted in similar or higher yields, while reducing both water use and potential N leaching because of improved nutrient retention in the root zone.

Keywords: Drainage; Soil moisture sensors; Drip irrigation; Irrigation scheduling; Fertigation; Nitrate leaching; Subsurface drip irrigation; *Cucurbita pepo*

1. Introduction

Squash (*Cucurbita pepo* L.) is an economically important vegetable with a U.S. crop value of $210 million (USDA, 2006). In 2006, Florida accounted for 15% of the total harvested U.S. squash acreage and 23% of the overall U.S. crop value (FASS, 2006; USDA, 2006). Squash production is typically intensely managed with high inputs of fertilisers and irrigation water, which increases the risk of groundwater nitrate contamination. Nitrate contamination in Florida areas is likely the result of a combination of factors such as N application in excess of crop demand, excessive irrigation and sandy soils.

To address N pollution concerns, various crop management practices have been suggested, such as the use of plastic mulch to improve irrigation water use efficiency (IWUE) and reduce rainfall-induced N leaching losses (Romic et al., 2003). Plastic mulching in combination with drip irrigation and frequent injection of nutrients can be used in the irrigation system (fertigation) to enhance water and nutrient use efficiency (Bowen and Frey, 2002). In particular, the use of subsurface drip irrigation (SDI) may be the best system for increasing yield, maximizing water and nitrogen use efficiencies and thereby minimizing nitrate leaching (Al-Omran et al., 2005; Lamm and Trooien, 2003). However, the use of plastic mulch and/or SDI as such, does not reduce the risk of groundwater contamination, unless environmentally sound irrigation and nitrogen application practices are also implemented.

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Irrigation management plays an important role on nitrogen use efficiency (NUE) and IWUE for vegetable crop production. The use of frequent but low water application volumes is superior to the more traditional scheduling of few applications of large irrigation volumes (Locascio, 2005). Because the former systems may be viewed as labour intensive and/or technically difficult to employ, automated irrigation systems which make use of soil moisture sensing devices may greatly facilitate the successful employment of low volume–high frequency irrigation systems for commercial vegetable crops (Muñoz-Carpena et al., 2005; Dukes et al., 2006). For example, Dukes and Scholberg (2005) reported a 11% reduction in water use when using a soil moisture sensor-based automated irrigation system for sweet corn as compared to sprinkler irrigation several times each week without affecting yield. Similarly, Sharmasarkar et al. (2001) reported that increased irrigation frequency reduced sugar beet crop water requirements and net drainage when using drip irrigation.

As critical as irrigation management, both the timing and amount of N applied to the crop must be managed in a way that supplies sufficient N for crop yield without leaching N to the groundwater. Several studies have reported that fertigation, applying fertiliser via the irrigation lines, may facilitate matching crop N needs with fertiliser applications so that any risk of N leaching is minimized (Mohammad, 2004a). For example, Mohammad (2004b) concluded that squash yield, NUE and IWUE increased with the use of fertigation compared to dry fertiliser being applied directly to a fine-loamy soil followed by irrigation. However, information is lacking about the interactive effects of water management on crop N utilization for drip irrigated squash production in Florida (Hochmuth and Cordasco, 2003). The objective of this study was to identify an appropriate irrigation scheduling method and N-rate to maintain or enhance zucchini squash yield and IWUE while reducing nitrate leaching. We hypothesized that alternative irrigation designs and improved irrigation management would reduce N leaching associated with intensive zucchini squash production systems.

2. Materials and methods

During the fall of 2004 and 2005 three studies were conducted at the University of Florida, Plant Science Research and Education Unit, near Citra, FL, USA. The research plot soils were classified as Candler sand and Tavares sand (Buster, 1979). These soils contain 97% sand-sized particles in the upper 1 m of the profile (Carlisle et al., 1978) with a field capacity range of 0.10–0.12 (v/v) in the 0–30 cm depth (Icerman, 2007). Two weeks before zucchini squash (*C. pepo* L. cultivar ‘‘wildcat’’) sowing, raised beds were constructed with 1.8 m between bed centres. Beds were fumigated (80% methyl bromide, 20% chloropicrin by volume) at a rate of 604 kg ha^{-1} before placement of both drip tape and silver plastic mulch in a single pass.

In the fall of 2004, two studies were conducted (Studies 1 and 2) at the same time. Seeds were sown on 16 September 2004. During the second year all treatments were integrated in a single study (Study 3). The sowing date was 26 September 2005. Plots were 15 m long, and a tractor mounted hole puncher was used to make approximately 0.025 m wide square openings at 0.45 m intervals along the centre of the production bed. Plants were direct seeded by hand at a soil depth of 0.015 m. A weather station located within 500 m of the experimental site provided hourly temperature, relative humidity, solar radiation and wind speed data and this information was used to calculate reference evapotranspiration (ET_0) according to FAO-56 (Allen et al., 1998). Crop evapotranspiration (ET_c) was based on the product of ET_0 and the crop coefficient (K_c) for a given growth stage (Simonne et al., 2004) and values were reduced by 30% to account for the effect of plastic mulch on crop ET (Amayreh and Al-Abed, 2005) until the plant canopy was 80% full cover of raised bed area.

Irrigation was applied via drip tape (Turbulent Twin Wall, 0.2 m emitter spacing, 0.25 mm thickness, 0.7 L h^{-1} at 69 kPa, Chapin Watermatics, NY, USA). Water applied by irrigation and/or fertigation was recorded by positive displacement flowmeters (V100 16 mm diameter bore with pulse output, AMCO Water Metering Systems Inc., Ocala, FL, USA). Meter readings were recorded weekly and data from transducers that signalled a switch closure every 18.9 L were collected continuously by data loggers (HOBO event logger, Onset Computer Corp. Inc., Bourne, MA, USA) connected to each flow meter. Pressure was regulated by inline pressure regulators to maintain an average pressure in the field of 69 kPa during irrigation events. Drip tape was located within approximately 0.08 m of the plant row. The fertiliser applications were based on IFAS (Institute of Food and Agricultural Sciences, University of Florida) recommendations (Maynard et al., 2003). The fertigation consisted of injection of dissolved fertilisers into fertigation lines with a peristaltic pump. The experimental design consisted of a randomized complete block design with four replicates.

- *Study 1*: The aim of Study 1 was to test three different arrangements of drip irrigation and fertigation lines on squash growth and fruit yield. The drip position treatments included: (1) SUR, irrigation and fertigation drip lines positioned on the soil surface; (2) S&S, irrigation and fertigation drip lines both positioned 0.15 m below the soil surface; and (3) SDI, the irrigation drip line was positioned 0.15 m below soil surface and the fertigation drip line positioned on the soil surface (Table 1). Irrigation events were controlled by a Quantified Irrigation Controller (QIC) system (Muñoz-Carpena et al., 2007) which included a 0.20 m long ECH_2O probe (Decagon Devices Inc., Pullman, WA, USA) to measure soil moisture. Probes were inserted vertically for the SUR treatment in order to integrate the soil water content in the upper 0.2 m of the soil profile. The QIC irrigation controllers allowed irrigation if measured soil water content was below a soil volumetric water content (VWC) value of 0.15 m^3 m^{-3} (translating to a 525 mV reading) during one of five daily irrigation windows. This study received 164 kg ha^{-1} of N.
- *Study 2*: The second study was located next to first study and managed similarly. The objective of this study was to investigate irrigation water use and nitrogen use efficiency (NUE) by squash for soil moisture sensor-based production

Table 1
Outline and description of irrigation and fertilisation treatments along with threshold volumetric water content (VWC), cumulative irrigation application depth

Symbol	Volume of irrigation, irrigation drip tape position, fertigation drip tape position, irrigation schedule	Threshold VWC ($\text{m}^3\ \text{m}^{-3}$)	Irrigation applied (mm)
Study 1 (2004)			
SUR	QIC-based control system with a setting of 525 mV allowing for a maximum of 5 irrigation windows of surface applied irrigation per day	0.15	163
SDI	Same as SUR but with irrigation drip positioned 0.15 m below soil surface and surface fertigation.	0.15	163
S&S	Same as SUR but with both irrigation and fertigation drip placed 0.15 m below surface.	0.15	163
Study 2 (2004)			
SUR1	QIC-based control system with a setting of 475 mV allowing for a maximum of 5 irrigation windows of surface applied irrigation per day	0.13	66
SUR2	Same as SUR1 except for a 525 mV setting.	0.15	163
Study 3 (2005)			
SUR1	QIC-based control system with a setting of 475 mV allowing for a maximum of 5 irrigation windows per day, irrigation and fertigation drip positioned on the soil surface	0.13	172
SUR2	Same as SUR1 but with a 525 mV setting,	0.15	329
SDI	QIC-based system set at 475 mV allowing for a maximum of 5 irrigation windows per day, irrigation drip positioned 0.15 m below soil surface and surface fertigation	0.13	160
SUR_{time}	Once daily fixed duration surface applied irrigation treatment and surface fertigation	–	482

systems. The experimental design consisted of a complete factorial design including three N-rates and two soil moisture sensor-based systems. Treatments were replicated four times in completely randomized blocks. Nitrogen rates corresponded to 82, 164 and 246 kg ha^{-1} of N. The irrigation treatments were controlled via a QIC irrigation control system as described for the first study (Table 1). However, in this study two different target thresholds of VWC were tested, SUR1 with a VWC value of 0.13 $\text{m}^3\ \text{m}^{-3}$ (set at 475 mV, see Muñoz-Carpena et al., 2007 for details) and SUR2 with a VWC of 0.15 $\text{m}^3\ \text{m}^{-3}$ (set at 525 mV).

- *Study 3*: The third study was conducted during the fall of 2005, which integrated treatments from the first two studies. The objective of this study was to evaluate the interactive effect of three N-rates, 73, 145 and 217 kg ha^{-1} of N and five different irrigation scheduling regimes on zucchini squash yields, NUE and IWUE. The irrigation treatments were: SUR1 and SUR2 (as described under Study 2); SDI where this system featured subsurface drip tape positioned 0.15 m below the surface placed fertigation line controlled by a QIC system using a 525 mV (0.15 $\text{m}^3\ \text{m}^{-3}$ VWC) target threshold; and 4 SUR_{time} a time-based irrigation treatment with one fixed 2-h irrigation event per day, similar to producer irrigation management (Table 1).

2.1. Plant growth and yield

Harvest occurred weekly between 15 November and 1 December 2004 for Studies 1 and 2, and 17 November and 12 December 2005 for Study 3. The harvested area was the central 10.5 m region within each plot and plots were harvested two times a week. Total weight and number of squash fruits were recorded. IWUE expressed in kg of fruits per m^3 of irrigation applied was calculated by the quotient of marketable yields (kg ha^{-1}) and the total seasonal irrigation applied ($\text{m}^3\ \text{ha}^{-1}$). For all studies two representative squash plants were harvested from each plot at 2-week intervals and used for growth analysis. Vegetative and reproductive (fruit) plant parts were separated. Shoot and fruit tissues were dried at 65 °C for subsequent dry weight determination. Afterwards, tissue samples were ground in a Wiley mill to pass through a 2 mm screen, and a thoroughly mixed 5 g portion of each sample was stored. Tissue material was digested using a modification of the aluminium block digestion procedure of Gallaher et al. (1975) and analysed for total Kjeldahl N at the Analytical Research Lab (University of Florida, Gainesville, FL, USA) using EPA method 351.2 (Jones and Case, 1991). Nitrogen accumulation by the plant was calculated by multiplying weights of stems plus leaves, and fruit tissue by the corresponding N concentrations. Nitrogen use efficiency (NUE) was defined as N uptake by the plants divided by the total amount of N supplied from weekly fertigation plus initial soil nitrate.

2.2. Monitoring soil water and N leaching

The volumetric water content on the top soil of the bed was monitored by coupling time domain reflectometry (TDR) probes CS-615 with a datalogger CR-10X (Campbell Scientific

Inc., Logan, UT, USA). The TDR probes were installed vertically to measure the soil moisture in the 0–0.3 m range across all irrigation treatments.

In 2005 (Study 3), to monitor the soil nitrate which was not taken up by plants, soil samples were collected with a 0.05 m diameter soil auger every 2 weeks in each plot 6 days after the previous fertigation event and 1 day prior to the following fertigation event. Treatments sampled included the two higher rates of N for the SUR2, SDI and SUR$_{time}$ irrigation treatments and the first soil sampling was taken before the first fertigation event. Composite samples were taken at the 0–0.3, 0.3–0.6, and 0.6–0.9 m soil depths and placed on ice and refrigerated until further analysis. A 10 g subsample was extracted with 50 mL of 2 M KCl and filtered within 1 day of soil sampling.

Zero tension drainage lysimeters were installed 0.75 m below the surface of the bed (Zotarelli et al., 2007). Briefly, drainage lysimeters were constructed out of 208 L capacity drums that were cut in half lengthwise and had a length of 0.85 m, a diameter of 0.55 m, and a height of 0.27 m. A vacuum pump was used to extract the leachate accumulated at the bottom of the lysimeter. The leachate was removed weekly one day prior to the next fertigation event by applying a partial vacuum (35–40 kPa) using 20 L vacuum bottles for each drainage lysimeter. Total leachate volume was determined gravimetrically and subsamples collected from each bottle were analysed for NO_3-N and thus total N loading rates could be calculated. Soil solution and soil core extracts were stored at −18 °C until nitrate and nitrite analyses were conducted. Samples were analysed using an air-segmented automated spectrophotometer (Flow Solution IV, OI Analytical, College Station, TX, USA) coupled with a Cd reduction approach (modified US EPA Method 353.2).

Statistical analyses were performed using PROC GLM of SAS (SAS Inst. Inc., 1996) to determine treatment effects. When F value was significant, a multiple means comparison was performed using Duncan's multiple range test at a P value of 0.05. For nitrate concentration in the soil profile, a multiple means comparison was performed using Tukey's studentized range test.

3. Results and discussion

3.1. Climatic conditions and evapotranspiration patterns

The cumulative rainfall at the final harvest was 173 and 228 mm for 2004 and 2005, respectively. In the presence of plastic mulch and the absence of a perched water table, the contribution of rainfall to crop water requirements and drainage measurements was considered to be negligible. Plastic mulched systems on coarse sandy soils have very limited lateral flow. In addition, water was not observed in the drainage lysimeters after a rainfall event (Fig. 1B) and TDR measurements showed no significant contribution of rainfall to the soil moisture at the 0–30 cm depth (Fig. 2). The fall growing season of 2005 was cooler than 2004. In both years, overall temperatures decreased over time and temperature fluctuations increased as the season progressed. During 2004, temperatures dropped below 10 °C on several occasions, while in 2005 three frost events occurred during the harvesting period. Since the crop was not protected, in 2005 the frosts reduced the number of harvesting events, plant growth and yield, compared to the 2004 season. Calculated total ET$_c$ for each year was 108 mm for 2004, and 171 mm for 2005 (Fig. 1A). For all treatments, irrigation rates during the season exceeded cumulative ET$_c$ curve, except for SUR1 in 2004 which accumulated a water deficit of about 43 mm.

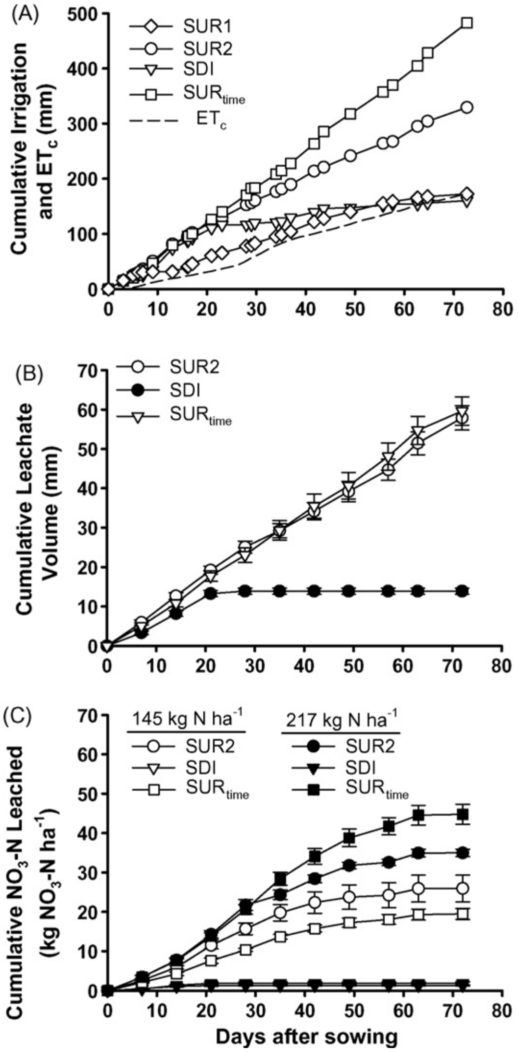

Fig. 1. (A) Cumulative irrigation, calculated cumulative crop evapotranspiration (ET$_c$) in fall 2005, (B) cumulative leachate volume (note SUR1 drainage not monitored) and (C) cumulative NO_3-N leaching for irrigation treatments under N-rate of 145 and 217 kg ha^{-1} during fall 2005, Study 3. Bars represent ±1 S.E. from the mean.

3.2. Study 1—effect of drip position

In Study 1 the use of different drip position arrangements significantly affected the IWUE and yield (Table 2). The cumulative irrigation volume applied to Study 1 was 163 mm for all treatments. The treatment ranking for marketable yields and IWUE was as follows: SDI $\geq$ SUR $\geq$ S&S with SDI resulting in significantly ($P < 0.05$) higher yields compared to

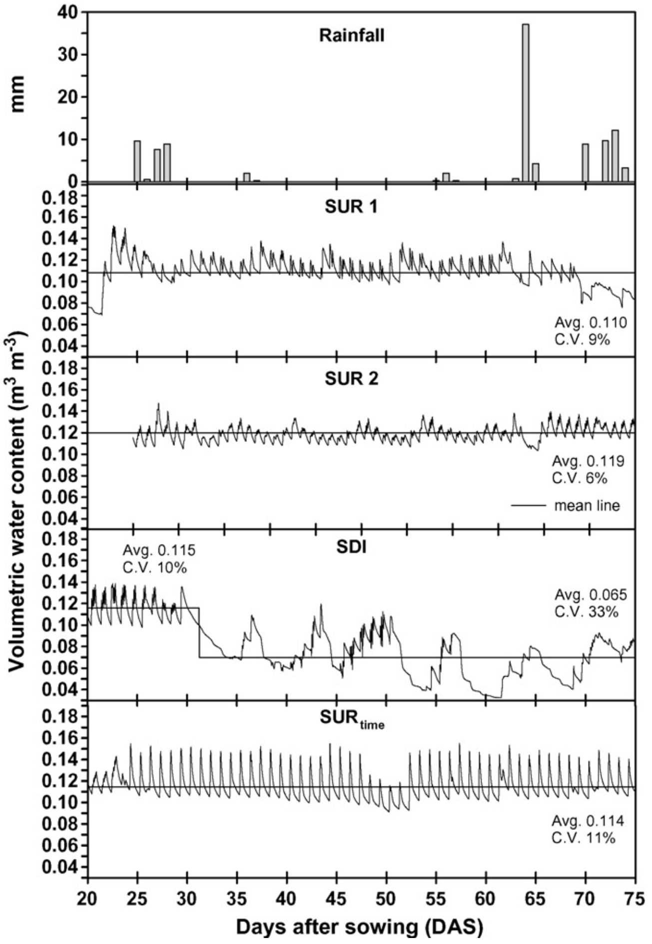

Fig. 2. Rainfall events and volumetric soil moisture content at the 0–0.3 m depth, as affected by irrigation treatments, after the establishment period in 2005.

S&S (Table 2). The SDI treatment increased yield by 16% (7.1 Mg ha^{-1}) compared to S&S treatment. There was no difference between SUR and SDI yield, similar to the results reported by Camp et al. (1993). The S&S treatment had a lower IWUE value (22.2 kg m^{-3}) compared to the SDI treatment, which produced 26.6 kg fruit m^{-3} of water applied (Table 2). Average fruit size and above ground dry matter accumulation were not significantly affected by drip position (data not shown). However, not only plant and fruit N accumulation but also overall NUE was significantly higher for SUR and SDI treatments compared to S&S irrigation system (Table 2). According to Ells et al. (1994), more than 60% of *C. pepo* roots were located in the top 15 cm of soil throughout the season, and for this reason S&S may have reduced IWUE and NUE. Conversely, the use of buried drip irrigation (SDI) resulted in an increase of 45% on NUE due to improved nutrient retention in the upper soil layer where most of the roots were located. Overall, SDI had numerically higher values for most production parameters, but differences were not significant compared to the SUR treatment at the $P < 0.05$ level.

3.3. Study 2—effect of nitrogen rate under two different irrigation threshold of VWC

The crop establishment period was characterized by application of similar irrigation volume to all treatments during the first 15 days after sowing (DAS). After this phase, the irrigation treatments were initiated. Use of a higher set point (SUR2 vs. SUR1) with the QIC sensor control system resulted in a slightly wetter top soil of 0.010–0.015 m^3 m^{-3} increase in VWC. The dry treatment (SUR1) received 0.9 mm day^{-1} and corresponding values for the wetter treatment (SUR2) were 2.1 mm day^{-1}. At the end of the season, SUR2 resulted in application of 97 mm more water compared to SUR1 (Table 1). The leachate collected in the drainage lysimeters on SUR2 was 31 mm. Cumulative NO$_3$-N leaching values for SUR2 at end of the season were 6, 8 and 13 kg ha^{-1} of N for rates of 82, 164 and 246 kg ha^{-1}of N, respectively. However, no differences at the $P < 0.05$ level between the N-rates were observed.

There were no interactions between irrigation and N-rate treatments, but soil water availability had an important effect on IWUE and yield. Overall yield for SUR2 was 12.4% higher compared to SUR1 (Table 3). The lower yield of SUR1 may be attributed to the water stress due to the reduced amount of water applied throughout the entire season, which was below the calculated crop evapotranspiration demand 60 DAS (data not shown). The final dry matter accumulation (shoots and dry fruits) was similar across N and irrigation treatments. The effect of N-rate in yield response was $246 \geq 164 \geq 82$ kg ha^{-1}. The increase of N-rate from 82 to 246 kg ha^{-1} resulted in a significant increase of 9% on marketable yield and promoted an accumulation of 32% more N in the plant above ground.

A detailed analysis of plant N influx showed the relationship between soil water availability and N-rate application (Fig. 3), and the effects on the total N accumulation by plants. As no interaction between N rates and irrigation treatments were

Table 2
Drip position effect on marketable yield; total dry matter accumulation (DM) of shoot and fruits excluding roots; N accumulation in the shoot and fruit; irrigation water use efficiency (IWUE); and nitrogen use efficiency (NUE) for zucchini squash in Study 1 (2004)

Irrigation treatment	Marketable yield (Mg ha^{-1})	Dry matter (Mg ha^{-1})	Nitrogen (kg ha^{-1})		IWUE (kg fruit m^{-3})	NUE (%)
			Shoot	Fruit		
SUR	38.6 ab[a]	4.83 a	32.4 ab	80.0 ab	23.8 ab	55.5 a
SDI	43.1 a	5.38 a	37.4 a	87.7 a	26.6 a	62.8 a
S&S	36.0 b	4.63 a	26.1 b	73.4 b	22.2 b	43.3 b
C.V. (%)	7.2	7.7	15.2	13.2	7.2	10.8

C.V.: coefficient of variation.

[a] Means within columns followed by the same lowercase letter are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test.

Table 3
Irrigation and N-rate treatment effects on marketable yield; total dry matter accumulation (DM) of shoot and fruits excluding roots; N accumulation in the shoot and fruit; irrigation water use efficiency (IWUE); and nitrogen use efficiency (NUE) for zucchini squash in Studies 2 and 3

	Marketable yield (Mg ha^{-1})	Dry matter (Mg ha^{-1})	Nitrogen (kg ha^{-1})		IWUE (kg fruit m^{-3})	NUE (%)
			Shoot	Fruit		
Study 2 (2004)						
Irrigation scheduling						
SUR1	38.0 b[a]	4.74 a	44.2 a	77.9 a	57.5 a	53.7 a
SUR2	42.7 a	5.20 a	40.1 a	78.4 a	26.3 b	51.5 a
Nitrogen (kg ha^{-1})						
82	38.8 B[b]	4.78 A	35.1 B	67.4 B	40.8 A	64.3 A
164	39.8 AB	5.00 A	41.1 A	82.8 A	40.8 A	51.2 B
246	42.3 A	5.13 A	50.3 A	85.0 A	44.2 A	42.0 C
Irrigation × N	ns	ns	ns	ns	ns	ns
C.V. (%)	6.0	13.6	14.6	13.3	7.3	15.1
Study 3 (2005)						
Irrigation scheduling						
SUR1	27.6 a[a]	3.65 a	77.4 b	35.9 a	16.1 b	37.1 a
SUR2	22.0 b	3.01 b	59.5 c	27.1 b	6.7 d	29.4 bc
SDI	26.9 a	3.82 a	92.1 a	37.4 a	16.8 a	39.9 a
SUR$_{time}$	20.5 b	2.94 b	54.0 c	24.7 b	4.3 e	26.5 c
Nitrogen (kg ha^{-1})						
73	21.9 B[b]	2.94 B	54.5 B	25.8 C	9.7 B	37.6 A
145	24.6 A	3.44 A	73.8 A	31.6 B	11.1 B	32.4 B
217	27.2 A	3.67 A	89.9 A	36.5 A	12.1 A	29.6 B
Irrigation × N	ns	ns	ns	ns	ns	ns
C.V. (%)	13.6	13.2	19.3	15.9	15.3	19.6

ns: non-significant.

[a] Means within columns followed by the same lowercase letters are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test.

[b] Means within columns followed by the same uppercase letters are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test.

observed, both factors were analysed separately. From germination until 28 DAS, the cumulative irrigation was 29 and 62 mm for SUR1 and SUR2, respectively. The irrigation scheduling slightly affected the N-uptake rate. At 28 DAS the N-uptake rate was 1.6 and 1.2 kg ha^{-1} of N day^{-1} for SUR1 and SUR2, respectively; but no effect of N-rates within each irrigation schedule was observed. Between 25 and 50 DAS, the plant vegetative growth was characterised by the exponential increase of N-uptake rates. The maximum N-uptake rate occurred earlier for SUR1, between 42 and 46 DAS for SUR2, which may be a physiological indication of water stress under SUR1. In fact, at 46 DAS, SUR2 had received 52% more water than SUR1 (54 mm), which resulted in slightly higher total above ground N accumulation (49 and 39 kg ha^{-1} of N for SUR1 and SUR2, respectively). However, at end of the season, both irrigation treatments accumulated about 104 kg ha^{-1} of N above ground.

Nitrogen uptake patterns and N accumulation were similar for N-rates of 163 and 246 kg ha^{-1}, with a N uptake peak at 3.0

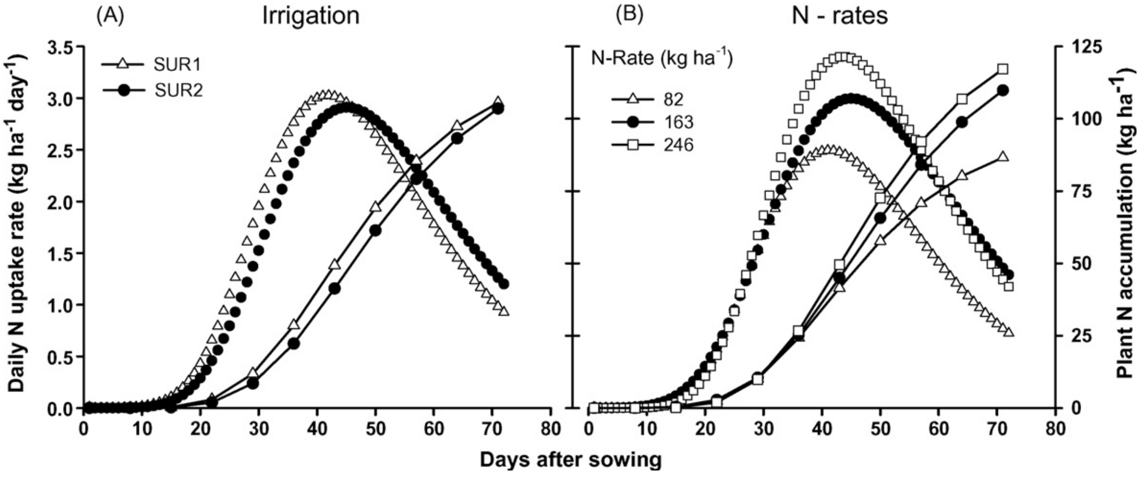

Fig. 3. Calculated daily N uptake rate (kg ha^{-1} day^{-1}) (symbols) and plant N accumulation (kg ha^{-1}) (symbol and line) under two irrigation schedules (A) and three N-rates (B) for Study 2.

and 3.4 kg ha^{-1} day^{-1}, respectively. However, the lowest N-rate (82 kg ha^{-1}) attained a plant N-uptake of 2.5 kg ha^{-1} day^{-1}, resulting in 27–36% less N accumulated in the plant above ground at end of the season (Fig. 3 and Table 3).

The average of NO_3-N concentration in the soil solution at 0–30 cm depth at 30, 37, 44 and 51 DAS was 43 ± 5; 113 ± 38 and 274 ± 143 mg L^{-1} for N-rates of 82, 163 and 246 kg ha^{-1}, respectively. However, these differences in soil nitrate concentration between N-rates of 163 and 246 kg ha^{-1} did not result in a yield increase, but increased the NO_3-N leached by 73% (data not shown). The irrigation treatments did not affect N uptake rates and plant N accumulation but significantly affected marketable yield. The reduction in yield under SUR1 was due to the increase in water demand by the plants during fruit development, which is a very critical time period for water stress. For zucchini squash yield, soil water availability was a primal component of the plant production, even under higher soil N concentration conditions. This hypothesis was confirmed by comparing the NO_3-N concentration in the soil solution at the 0–30 cm depth between 44 and 65 DAS. The soil nitrate concentration under SUR1 was 277 ± 56 mg L^{-1}, while under SUR2 it was 56 ± 10 mg L^{-1}, which clearly showed the dilution effect under higher irrigation rates.

3.4. Study 3—effect of nitrogen rate, drip position and irrigation scheduling

Similar to Study 2, the establishment period lasted until 20 DAS. After this period, the average irrigation rates for SUR1 and SUR2 treatments were 2.2 and 4.3 mm day^{-1}, respectively (Table 1). Corresponding values for SDI and SUR$_{time}$ treatments were 2.1 and 6.3 mm day^{-1} (Fig. 1). Use of a higher soil moisture set point of SUR2, compared to SUR1 with the QIC sensor, showed a slightly wetter top soil (Fig. 2). Treatments SUR2 and SUR$_{time}$ had similar overall average VWC values (Fig. 2). However, SUR$_{time}$ and SDI had higher oscillation of VWC compared to SUR treatments. The fluctuations in VWC for the SUR$_{time}$ treatment were associated with a high volume of water applied during a single irrigation application, which also resulted in substantial drainage below the rootzone (Fig. 1B). However, on soil moisture sensor-based treatments, the water was applied only when the VWC dropped below the set point during one of the five daily irrigation windows, reducing the amount of water being applied, and decreasing VWC fluctuations and potential water percolation considerably. In particular, the average VWC in the SDI treatment (the irrigation drip positioned at 15 cm below the soil surface) decreased by 60%, from 0.115 m^3 m^{-3} at the beginning of the season to 0.068 m^3 m^{-3}, on average, 30 DAS (Fig. 2). The oscillations of VWC in SDI were related to spikes in the mV read by the dielectric capacitance probes (QIC) after the weekly fertigation events, caused by salt concentrations on the top soil (Hagin et al., 2002; Schroder, 2006).

Different irrigation schedules used for SUR2 and SUR$_{time}$ resulted in similar volume leached, about 62 mm. The volume leached on the SDI treatment was 14 mm, which occurred until 27 DAS (Fig. 1B). The combination of reduced irrigation rate and drip irrigation position in the SDI treatment directly affected the volume leached and increased the residual soil nitrate concentration in the 0–0.3 m depth layer. In this treatment, at the end of the season, the total cumulative NO_3-N leached was 1.7 and 2.4 kg ha^{-1} of N for N-rates of 145 and 217 kg ha^{-1}, respectively (Fig. 1C). Conversely, SUR2 and SUR$_{time}$ resulted in higher nitrate leaching: 20–26 and 35–45 kg ha^{-1} of NO_3-N for applied N-rates of 145 and 217 kg ha^{-1}, respectively. A high volume of irrigation induced dilution and/or displacement of N-fertiliser (SUR$_{time}$ and SUR 2) and reduced NUE by plants. Increasing N fertiliser rates from 145 to 217 kg ha^{-1}, increased residual soil N values by 100–350% (data not shown). Although this increase did not result in additional yield benefits, it did increase N leaching for the SUR2 and SUR$_{time}$ treatments by 36 and 126%, respectively.

Regardless of the fact that there was no interaction between irrigation and N-rate treatments, lower irrigation rates showed higher IWUE and NUE. In terms of yields, SUR1 and SDI were similar, while SUR2 and SUR$_{time}$ were 21% lower than other irrigation treatments. Reduction in fruit yield was related to the volume of water applied and the irrigation method used. Treatments SUR$_{time}$ and SUR2 received approximately two to three times more irrigation water compared to SUR1, increasing N displacement in the soil profile (Fig. 4) and decreasing dry matter and N accumulation (Table 3).

The plants showed a positive response in fruit yield, NUE, and plant N accumulation with increasing N-rates (Table 3). The fertilisation with N-rates of 145 and 217 kg ha^{-1} resulted in similar fruit yield, plant N accumulation and NUE, but N

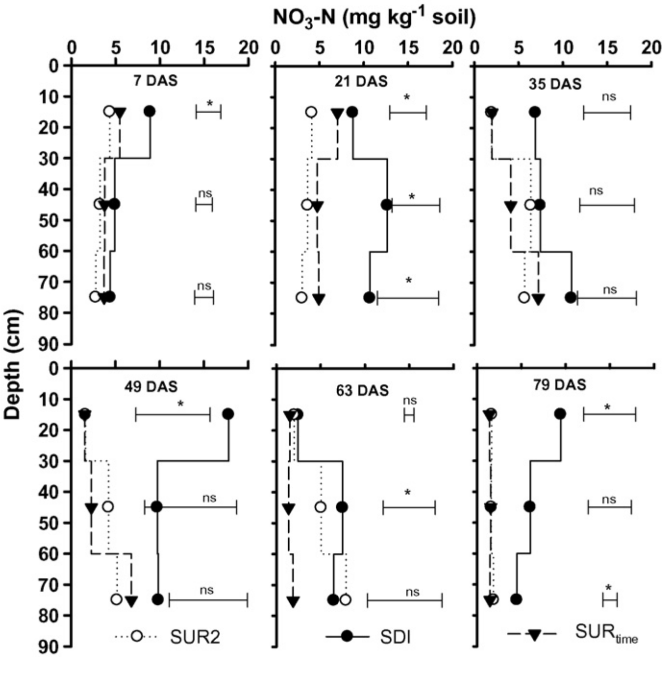

Fig. 4. Soil nitrate concentration as measured by soil coring for the SUR2, SDI and SUR$_{time}$ irrigation treatments fertilised with 217 kg ha^{-1} of N at 7, 21, 35, 49, 63 and 79 days after sowing (DAS) for three soil depth layers in Study 3 (2005). Bars represent minimum significant difference according to Tukey's test; ns = non-significant; *significant at $P = 0.1$.

accumulation in the fruits was higher for the highest N-rate (Table 3). Appreciable reduction of yields, dry matter and N accumulation occurred due to the application of 73 kg ha^{-1} of N. The crop N uptake decreased with increasing N-rate following the ''law of the diminishing returns''. Although higher N-rates increased tissue-N concentrations (Huett and White, 1991), overall NUE values decreased with higher N-rates. Similar trends were noted by Mohammad (2004a), who reported that under N-limiting conditions squash plants extracted more mineralized nitrogen in order to sustain crop N demand.

4. Conclusions

The use of soil moisture sensor-based irrigation allowed more efficient use of irrigation water resulting in a reduction in irrigation water use by 33–80% compared to a SUR_{time} treatment which mimicked typical grower irrigation practices. A soil moisture sensor-based subsurface drip irrigation (SDI) system combined with surface applied fertigation in zucchini squash, resulted in a reduction in water applied and N leaching, an increase in the nitrogen uptake efficiency, and similar or higher yields compared to other treatments.

Combining subsurface drip irrigation (SDI) with surface applied fertigation greatly reduced N leaching, and resulted in higher NUE by zucchini squash. The use of soil moisture sensor-based irrigation may contribute to a consistent reduction of leaching when the soil volumetric water content is maintained within the field capacity threshold. There were no yield benefits with N-rates over 145 kg ha^{-1}. It was concluded that appropriate use of SDI and/or sensor-based irrigation systems can allow growers to sustain profitable yield while it can greatly save irrigation water and reduce the potential nitrate leaching in susceptible soils.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56, Rome.

Al-Omran, A.M., Sheta, A.S., Falatah, A.M., Al-Harbi, A.R., 2005. Effect of drip irrigation on squash (*Cucurbita pepo*) yield and water-use efficiency in sandy calcareous soils amended with clay deposits. Agric. Water Manage. 73, 43–55.

Amayreh, J., Al-Abed, N., 2005. Developing crop coefficients for field-grown tomato (*Lycopersicon esculentum* Mill) under drip irrigation with black plastic mulch. Agric. Water Manage. 73, 247–254.

Bowen, P., Frey, B., 2002. Response of plasticultured bell pepper to staking, irrigation frequency, and fertigated nitrogen rate. HortScience 37, 95–100.

Buster, T.P., 1979. Soil Survey of Marion County, Florida. Soil Conservation Service, Washington, DC.

Camp, C.R., Garrett, J.T., Sadler, E.J., Busscher, W.J., 1993. Microirrigation management for double-cropped vegetables in a humid area. Trans. ASAE 36, 1639–1644.

Carlisle, V.W., Caldwell, R.E., Sodek, F., Hammond, L.C., Calhoun, F.G., Granger, M.A., Breland, H.L., Characterization Data for Selected Florida soils. Soil Science Research Report 78-1. University of Florida, Institute of Food and Agricultural Sciences. Gainesville, FL. 1978.

Dukes, M.D., Scholberg, J.M., 2005. Soil moisture controlled subsurface drip irrigation on sandy soils. Appl. Eng. Agric. 21, 89–101.

Dukes, M.D., Zotarelli, L., Scholberg, J.M., Muñoz-Carpena, R., 2006. Irrigation and nitrogen best management practices under drip irrigated vegetable production. In: Proceedings of the World Environmental & Water Resources Congress. Omaha, Nebraska, May 21–25, 2006. ASCE, Reston, VA.

Ells, J.E., McSay, A.E., Kruse, E.G., Larson, G., 1994. Root distribution and proliferation of field-grown acorn squash as influenced by plastic mulch and water. HortTechnology 4, 248–252.

FASS 2006. Florida Agricultural Statistics Service: Vegetables Acreage Production and Value. Online: http://www.nass.usda.gov/ (last accessed March 14, 2006).

Gallaher, R.N., Weldon, C.O., Futral, J.G., 1975. An aluminum block digester for plant and soil analysis. Soil Sci. Soc. Am. Proc. 39, 803–806.

Hagin, J., Sneh, M., Lowengart, A., 2002. Fertigation: Fertilization through Irrigation Research Topic No. 23. International Potash Institute, Basel, Switzerland.

Hochmuth G.J., Cordasco, K., 2003. A summary of N research with squash in Florida. HS 750, Hortic. Sci. Dept., Florida Coop. Ext. Serv., Inst. Food Agric. Sci., University of Florida, August 1999 (Reviewed May 2003).

Huett, D.O., White, E., 1991. Determination of critical nitrogen concentration of zucchini squash (*Cucurbita pepo* L.) cv. Blackjack grown in sand culture. Aust. J. Exp. Agric. 31, 835–842.

Iceman, J., 2007. Approaches for two-dimensional monitoring and numerical modeling of drip systems. M.Sc. Thesis. Agricultural and Biological Engineering Department, University of Florida, Gainesville, p. 148.

Jones Jr., J.B., Case, V.W., 1991. Sampling, handling and analyzing plant tissue samples. In: Westerman, R.L. (Ed.), Soil Testing and Plant Analysis, 3rd ed. Book Series No. 3. Soil Sci. Soc. Am., Madison, WI, pp. 389–415.

Lamm, F.R., Trooien, T.P., 2003. Subsurface drip irrigation for corn productivity: a review of 10 years of research in Kansas. Irrig. Sci. 22 (3–4), 195–200.

Locascio, S.J., 2005. Management of irrigation for vegetables: Past, present, and future. HortTechnology 15, 482–485.

Maynard, D.N., Hochmuth, G.J., Vavrina, C.S., Stall, W.M., Kucharek, T.A., Webb, S.E., Taylor, T.G., Smith, S.A., Simonne, E.H., Olson, S.M., 2003. Cucurbit production in Florida. In: Olsen, Simonne, (Eds.), Vegetable Production Guide for Florida. University of Florida, Gainesville, FL, pp. 159–182.

Mohammad, M.J., 2004a. Squash yield, nutrient content and soil fertility parameters in response to methods of fertilizer application and rates of nitrogen fertigation. Nutr. Cycl. Agroecosyst. 68, 99–108.

Mohammad, M.J., 2004b. Utilization of applied nitrogen and irrigation water by drip-fertigated squash as determined by nuclear and traditional techniques. Nutr. Cycl. Agroecosyst. 69, 1–11.

Muñoz-Carpena, R., Dukes, M.D., Li, Y.C., Klassen, W., 2005. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. HortTechnology 15 (3), 584–590.

Muñoz-Carpena, R., Dukes, M.D., Li, Y.C., Klassen, W., 2007. Design and evaluation of a new controller for soil water-based irrigation control. Appl. Eng. Agric. (in review).

Romic, D., Romic, M., Borosic, J., Poljak, M., 2003. Mulching decreases nitrate leaching in bell pepper (*Capsicum annuum* L.) cultivation. Agric. Water Manage. 60, 87–97.

SAS Inst. Inc., 1996. SAS Statistics User's Guide Release Version 6. SAS Inst. Inc., Cary, NC.

Schroder, J.H., 2006. Soil moisture-based drip irrigation for efficient use of water and nutrients and sustainability of vegetables cropped on coarse soils. M.Sc. Dissertation. University of Florida, Gainesville.

Sharmasarkar, F.C., Sharmasarkar, S., Miller, S.D., Vance, G.F., Zhang, R., 2001. Assessment of drip and flood irrigation on water and fertilizer use efficiencies for sugarbeets. Agric. Water Manage. 46, 214–251.

Simonne, E.H., Dukes, M.D., Haman, D.Z., 2004. Principles and practices of irrigation management for vegetables. In: Olsen, Simonne, (Eds.), Vegetable Production Guide for Florida. University of Florida, Gainesville, FL, pp. 33–39.

USDA 2006. Census, US – State Data Table, 35. Vegetables and Melons Harvested for Sale: 2002. http://www.nass.usda.gov:8080/Census/Pull_Data_Census (last accessed March 14, 2006).

Zotarelli, L., Scholberg, J.M., Dukes, M.D., Muñoz-Carpena, R., 2007. Monitoring of nitrate leaching in sandy soils: comparison of three methods. J. Environ. Qual. 36 (4), 953–962.