

Irrigation Scheduling for Green Bell Peppers Using Capacitance Soil Moisture Sensors

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Abstract: Vegetable production areas are intensively managed with high inputs of fertilizer and irrigation. The objectives of this study were to evaluate the interaction between N-fertilizer rates and irrigation scheduling using soil moisture sensor irrigation controllers (SMS) on yield, irrigation water use efficiency (IWUE) of bell pepper cultivated under plastic mulch and drip irrigation. Treatments included three irrigation scheduling and three N-rates (176, 220, and 330 kg/ha). Irrigation treatments were: SS₁₀, water application controlled by SMS-based irrigation set at 10% volumetric water content (VWC) which was allotted five irrigation windows daily and bypassed events if the soil VWC exceeded the established threshold; SS₁₂, threshold set at 12% VWC; and TIME, control with irrigation being applied once a day similar to grower irrigation management. Marketable yields ranged between 16 and 29 Mg/ha. The SMS treatments reduced the applied irrigation in 7 to 62% compared to TIME treatment without reducing yield. The treatments SS₁₀ and SS₁₂ reduced nitrate leaching by 25 to 73% compared to TIME treatment.

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Introduction

Florida is the most important center of production and distribution of vegetables in the southeastern United States with 73,500 ha planted in 2006 and a crop value greater than \$1.2 billion (USDA 2008). Green bell pepper (*Capsicum annuum*) represents almost 18% of the state vegetable value (FDACS 2007). Most of the pepper produced in Florida is cultivated in coarse-textured soils with low water holding capacity and soil organic matter content. Agricultural practices such as the use of polyethylene mulch and drip irrigation are common for pepper production and they provide growers with a viable option to reduce crop water requirements and thus conserve water resources, especially when

compared to traditional irrigation methods. As an additional advantage of use of drip irrigation, the scheduling application of soluble fertilizer through the irrigation system provides nutrient quantities that closely match short-term crop nutrient requirements (Hartz and Hochmuth 1996; Hochmuth 1992). Conversely, due to its highly localized water application, when not properly managed, drip irrigation may increase nutrient leaching beyond the rooting zone and pollute groundwater resources (Cook and Sanders 1991; Rajput and Patel 2006; Vazquez et al. 2006). A perceived negative consequence of using drip irrigation is that the wetted soil volume may be limited consequently reducing the crop root development (Mmolawa and Or 2000). Roots grow preferentially around the wetted emitter area and concentrate within the top 0.4 m of the soil profile (Machado et al. 2003; Oliveira et al. 1996). The root volume (also described as root intensity or density) of bell pepper has been found to be largely within 0–0.25 m depth in diverse environments (Goyal et al. 1988; Hulugalle and Willatt 1987). In fact, maximum root growth has been shown to occur when adequate mineral nitrogen is present (Bloom 1997; Lecompte et al. 2008), which indicates that lack of nitrogen in certain root zones may limit root growth, especially for fertilization injected in drip systems.

A substantial input of nitrogen fertilizer is required to maximize crop growth and profits of vegetable crops. Maximum crop N accumulation by pepper plants is on the order of 193–234 kg N ha⁻¹ (Locascio et al. 1985; Tei et al. 1999) and between 30 to 65% of the N is accumulated in the fruit (Santiago and Goyal 1985), therefore, high nitrogen rates can potentially increase nitrate leaching. High N application rates results in low nitrogen use efficiency (NUE) values as low as 24% (Tei et al. 1999) and NUE typically decreases as N-fertilizer application rates increase (Olsen et al. 1993; Tei et al. 1999). In addition, irrigation management plays an important role on NUE and irri-

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gation water use efficiency (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 in terms of IWUE (Dukes et al. 2010; Locascio 2005; Zotarelli et al. 2009). Excessive irrigation on vegetables may cause yield decreases relative to optimum irrigation amounts as determined by pan evaporation on fresh market tomato (Locascio et al. 1989), on field grown tomato (Ngouajio et al. 2007), on fresh market tomato in south Florida (Muñoz-Carpena et al. 2005a), on bell pepper (Sezen et al. 2006), and as determined by soil moisture sensor (SMS) control, on green bell pepper (Dukes et al. 2003). Recent technological advances on soil moisture sensing have provided growers real-time feedback on the effect of irrigation management on the actual soil water status. Therefore, such approaches provide a powerful tool for improving irrigation scheduling and can greatly enhance crop water use efficiency. The use of SMS-based irrigation systems can maintain soil water status within upper and lower limits determined by type of soil and crop preventing over irrigation and saving water (Dukes and Scholberg 2005).

Capacitance-based (e.g., time domain reflectometry and time domain transmission) soil moisture measurement devices have been shown to have relatively accurate soil moisture measurement in sandy soils common to Florida (Irmak and Irmak 2005), with low maintenance once installed (Muñoz-Carpena et al. 2005b). The potential of capacitance probes in automatic irrigation scheduling of vegetable crops has been reported in the literature. SMS irrigation control has been used on drip irrigated zucchini squash to increase yield by 35%, IWUE by 274%, and NUE by 40% relative to single daily timed irrigation representative of grower practices (Zotarelli et al. 2008). In general, this study found that a simple and inexpensive irrigation controller coupled with commercially available soil moisture probes (Muñoz-Carpena et al. 2008) was effective at reducing both irrigation water application and nitrogen leaching. Zotarelli et al. (2009), reported irrigation savings of 40 to 65% less than typical grower based time irrigation scheduling while increasing tomato yield by 11 to 45%.

Appropriate irrigation scheduling and matching irrigation amounts with the effective water holding capacity of the effective rootzone thus may provide ways to minimize the incidence of excess N leaching associated with overirrigation. The objective of this study was therefore to identify suitable irrigation scheduling methods to reduce irrigation water application as well as to evaluate the effect on optimal N-fertilizer rate and pepper yield, plant biomass, and N accumulation. We hypothesize that use of SMS-based irrigation systems will reduce pepper irrigation water requirements and consequently reduce $\text{NO}_3\text{-N}$ leaching below the root zone while maintaining or increasing marketable yield.

Materials and Methods

During the spring of 2005, 2006, and 2007, field experiments were carried out at the University of Florida, Plant Science Research and Education Unit, near Citra, Florida. The soil has been classified as Candler sand (Buster 1979) with 97% sand-sized particles in the upper 1 m of the profile (Carlisle et al. 1988). The field capacity was in the range of 0.10–0.12 ($\text{m}^3 \text{m}^{-3}$) in the 0–0.3 m depth (Iceman 2007). The average of initial soil nitrate content at beginning of the seasons was 1.84 ± 0.84 , 1.22 ± 0.61 , and $0.91 \pm 0.39 \text{ mg kg}^{-1}$ at 0–0.3, 0.3–0.6, and 0.6–0.9 m depth,

respectively. The average of nitrate content of the irrigation water weekly measured was $0.64 \pm 0.25 \text{ mg L}^{-1}$.

Three weeks before transplanting, the area was rototilled and raised beds were constructed with 1.8-m distance between bed centers. Granular fertilizer was incorporated into the beds at a rate of 112 kg ha^{-1} of P_2O_5 . Beds were fumigated (80% methyl bromide and 20% chloropicrin by weight) at a rate of 340 kg ha^{-1} after placement of both drip tapes in the center of the bed and plastic mulch in a single pass 13 days before transplanting. Irrigation was applied via drip tape (turbulent twin wall, 0.20-m emitter spacing, and 0.25-mm thickness, $0.75 \text{ L h}^{-1} \text{ emitter}^{-1}$ at 69 kPa, Chaplin Watermatics, N.Y.). 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, Fla.). Weekly manual meter measurements were manually recorded while data from transducers that signaled a switch closure every 18.9 L were collected continuously by data loggers (HOBO event logger, Onset Computer Corp., Inc., Bourne, Mass.) connected to each flow meter. Pressure was regulated by inline pressure regulators designed to maintain an average pressure in the field of 69 kPa during irrigation events.

Plots were 15 m long, and a tractor mounted hole puncher was used to make 50 mm wide openings at 0.30-m intervals along the production bed. Green bell pepper transplants (*Capsicum annuum* L., var. "Brigadier") were set on April 7, 2005, April 10, 2006, and April 10, 2007. Weekly fertigation consisted of injecting dissolved fertilizer salts into fertigation lines according to Maynard et al. (2003). All plots received 247 kg ha^{-1} of K_2O as potassium chloride and 12 kg ha^{-1} of Mg as magnesium sulfate. The experimental design consisted of a complete factorial arrangement of three N-rates and three irrigation treatments randomized within blocks. The N-rate treatments corresponded to 176, 220, and 330 kg ha^{-1} of N applied as calcium nitrate. Weekly N application rates, expressed as a percentage of the total N application, corresponded to 5.5% at weeks 1, 2, and 13; 7.1% at weeks 3, 4, and 12; and 8.9% at weeks 5–11 (Maynard et al. 2003).

The crop establishment period was characterized by application of similar irrigation volume to all irrigation treatments. This period lasted 14, 14, and 12 DAT in 2005, 2006, and 2007, respectively. In the same year order above, the volume of water applied via irrigation corresponded to 50, 72, and 64 mm (Fig. 1). Following this period, irrigation treatments were initiated. Two irrigation treatments were regulated by the commercial RS500 SMS controller manufactured by Acclima, Inc. (Meridian, Id.). The RS500 unit controls irrigation application by bypassing time clock initiated irrigation events if soil moisture was at or above a preset threshold of volumetric water content (VWC) at 0.10 or $0.12 \text{ m}^3 \text{m}^{-3}$, respectively, SS_{10} and SS_{12} , according to the factory calibration. The SMS probes were installed at a 45° angle between two plants that measured the soil moisture in the top 0.15 m of the bed. Timed irrigation windows were specified as five possible events per day, starting at 8:00 a.m., 10:00 a.m., 12:00 p.m., 2:00 p.m., and 4:00 p.m. for 24 min each (2 h day^{-1} total). A reference treatments (TIME) were established, a time-based irrigation treatment with one fixed 2 h irrigation event per day.

A weather station located within 500 m of the experimental site provided temperature, relative humidity, solar radiation, and wind speed data and this information was used to calculate daily 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. 2007).

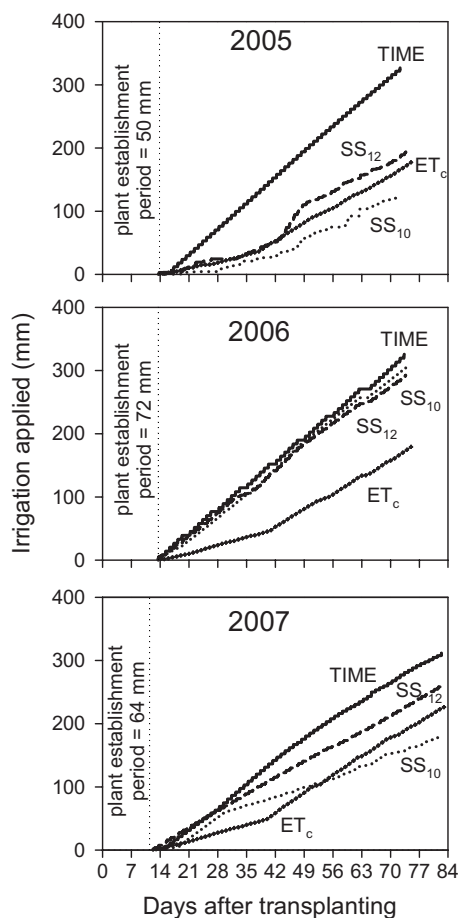


Fig. 1. Cumulative irrigation and estimated evapotranspiration (ET_c) after initial green bell pepper establishment as affected by different irrigation scheduling methods during the spring of 2005, 2006, and 2007

Fruit Yield, Plant Biomass, and Water Use Efficiency

Plots were harvested on 60, 74, and 77 days after transplanting (DAT) in 2005; on 58, 70, and 74 DAT in 2006 and on 69 and 83 DAT in 2007. The harvested area consisted of a central 10.5-m long region within each plot. Pepper fruits were graded into culls, U.S. Number 2 (medium), U.S. Number 1 (large), and Fancy (extralarge) according to USDA (2005) grading standards for fresh market sweet peppers. Marketable weight was calculated as total harvested weight minus the weight of culls. The number and weight of fruits per grading class were recorded for individual plots. IWUE expressed in $\text{kg of fruits m}^{-3}$ was calculated by taking the quotient of the marketable yields (kg ha^{-1}) and the total applied seasonal irrigation depth ($\text{m}^3 \text{ha}^{-1}$).

Plant N Accumulation and Nitrogen Use Efficiency

Maximum biomass accumulation was evaluated by harvesting two representative plants per treatment replicate at 74, 70, and 78 DAT for 2005, 2006, and 2007 trials, respectively. Vegetative and reproductive plant parts were separated. Shoot and fruit tissues were dried at 65°C for subsequent dry weight determination.

Shoot and fruit 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 an aluminum block digestion procedure of Gallaher et al. (1975) and

analyzed for total Kjeldahl N at the Analytical Research Laboratory (University of Florida, Gainesville) using U.S. 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. NUE was defined as N uptake by the plants divided by the total amount of N supplied from weekly fertigation plus initial soil nitrate. In 2005, leaf samples were also taken at 47 DAT. The 12 most recently matured leaves were collected between 9 and 11 a.m. from each treatment plot. The petiole base was cut at 15 mm from the stem attachment and crushed in a stainless steel garlic crusher. Sap $\text{NO}_3\text{-N}$ concentration in the sap was determined by an ion electrode method using C-141 Cardy Nitrate Meter (Horiba, Spectrum Technologies, Inc., Plainfield, Ill.)

Monitoring Soil Water Percolation and Nitrate Leaching

The VWC of the top soil of the production beds was monitored by coupling time domain reflectometry (TDR) probes (CS-616, Campbell Scientific, Inc. Logan, Utah) with a data logger (CR-10X, Campbell Scientific, Inc., Logan, Utah). Soil moisture probes were placed in the beds at two subsequent soil layers which recorded soil moisture values. The upper probe was inserted at an angle in order to capture soil moisture in the top 0.25 m of the profile and the lower probe was inserted vertically below the upper probe recording soil moisture between 0.25 and 0.55 m.

Zero tension drainage lysimeters were located 0.75 m below the surface of the bed (Zotarelli et al. 2007). The drainage lysimeters were constructed out of 208-L capacity drums that were cut in half lengthwise with a length of 0.85 m, a diameter of 0.55 m, and a height of 0.27 m. A total of 24 lysimeters were used to evaluate percolated volume and nitrate leaching in all irrigation treatments under N-rate treatments of 220 and 330 kg ha^{-1} (four replicates for each treatment). 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. 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. Total leachate volume was determined gravimetrically and subsamples collected from each bottle were analyzed for $\text{NO}_3\text{-N}$ and thus total N loading rates could be calculated. Nitrate samples were analyzed using an air-segmented automated spectrophotometer (Flow Solution IV, OI Analytical, College Station, Tex.) coupled with a Cd reduction approach [modified U.S. EPA Method 353.2 (Jones and Case 1991)].

Statistical Analysis

Statistical analyses were performed using PROC GLM procedure of SAS (SAS 2002) to determine treatment effects for total plant biomass and N accumulation, yield, IWUE, and NUE. When the F value was significant, a multiple means comparison was performed using Duncan's multiple range test at a P value of 0.05. For repeated measurements such as percolated volume and nitrate

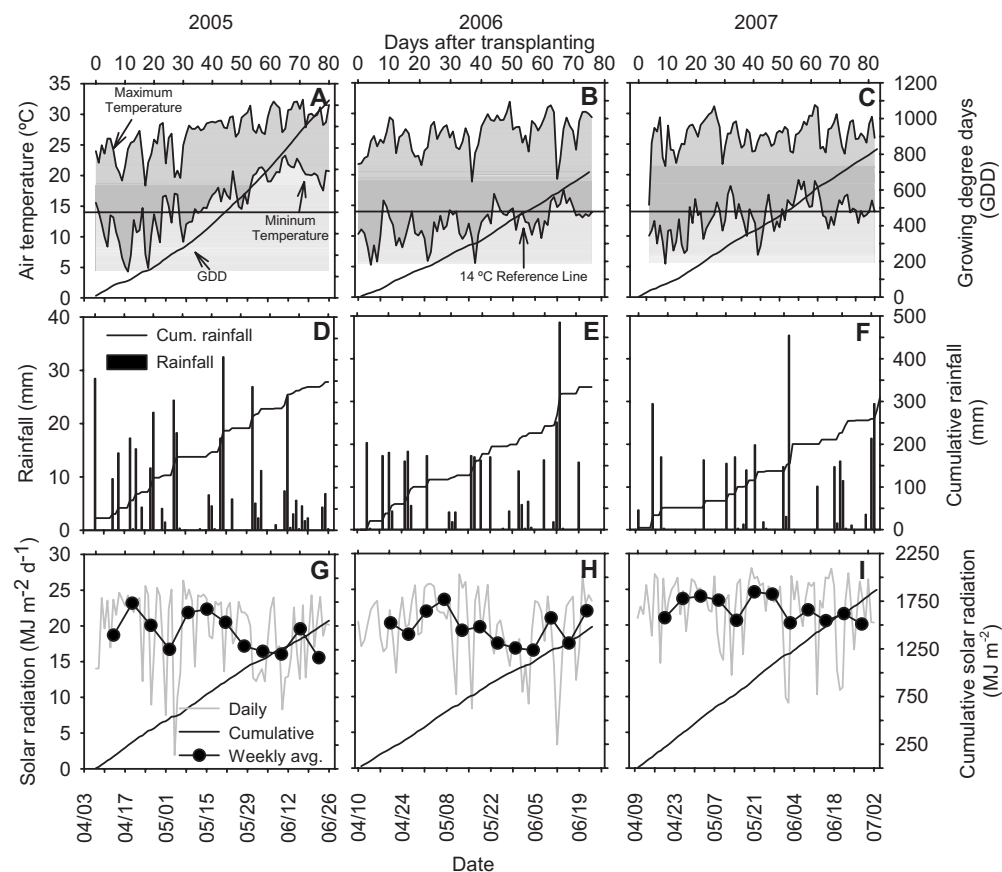


Fig. 2. Minimum, maximum, average daily temperatures and cumulative daily growing degree days (GDD), daily and cumulative rainfall and daily and cumulative solar radiation during the spring of 2005, 2006, and 2007 pepper growing season

leaching, the PROC MIXED procedure of SAS with residual maximum likelihood estimation approach and least-squares means of fixed effects were pairwise compared.

Results and Discussion

Irrigation and Soil Water

During the crop season, programmed irrigation events were skipped, which significantly reduced the amount of water applied to SMS based treatments. The overall volume of irrigation increased in order $SS_{10} < SS_{12} < TIME$, except in 2006 when SS_{10} received similar volume of irrigation water as SS_{12} (Fig. 1). It was observed that both SMS treatments failed to bypass irrigation events in the beginning of the season. The locations of both treatment sensors were assessed 35 DAT and reburied in a different location in the bed. The location of the sensor relative to drip line and plant plays an important role in the sensing irrigation systems. Regardless that the treatments were set at different thresholds, if the SS_{10} soil moisture probe was placed in a drier spot, it could result in higher irrigation volume applied than the SS_{12} . However, after 35 DAT, both treatments were bypassing and irrigating the same scheduled events and applying same irrigation amounts. The problem was attributed to cross communication between the capacitance sensors, causing each of the irrigation controllers to receive signals from only one of the two wired sensors. Several adjustments were made, but the problem was not solved until each controller was wired to a separate individual irrigation

timer, which occurred at 58 DAT, when the SMS treatments began to irrigate independently of each other (Fig. 1).

The contribution of rainfall to pepper water requirements was not considered in the calculations, due to the presence of plastic mulch and the absence of a perched water table, while coarse sandy soils also typically demonstrate very limited lateral flow. Although, it was observed that high intensity precipitation events ($>8 \text{ mm h}^{-1}$) increased the soil water content as measured by TDR. For both SMS treatments, there was no increase in number of skipped events after rainfall. For example, precipitation events of 44, 48, and 45 mm occurring in 2005, 2006, and 2007, respectively [Figs. 2(d–f)], showed a slight increase (around 1%) in VWC in the 0 to 0.25-m depth layer (data not shown). The SS_{10} treatment received an average of 1.0, 4.7, and 2.6 mm day^{-1} of irrigation water in 2005, 2006, and 2007, respectively. For the same respective year order, the corresponding average irrigation rates for the SS_{12} treatment were 2.2, 4.5, and 3.7 mm day^{-1} and for the TIME treatment were 4.3, 5.1, and 4.4 mm day^{-1} .

The soil moisture had a noticeable increase after each irrigation event for SMS treatments and TIME (Fig. 3). However, due to the reduced number of irrigation events for the SS_{10} treatment, variations in soil moisture at 0–0.25 m soil depth layer were not as distinct as the SS_{12} and TIME treatments. SMS-based irrigation treatments irrigated for short periods of time, in this case, 24 min, which resulted in a relatively small increase in soil moisture in the upper soil layer, consequently decreasing the volume of percolate [Figs. 3(b–d)]. In fact, slight oscillations in soil moisture were during the irrigation events observed in the deep monitored layer

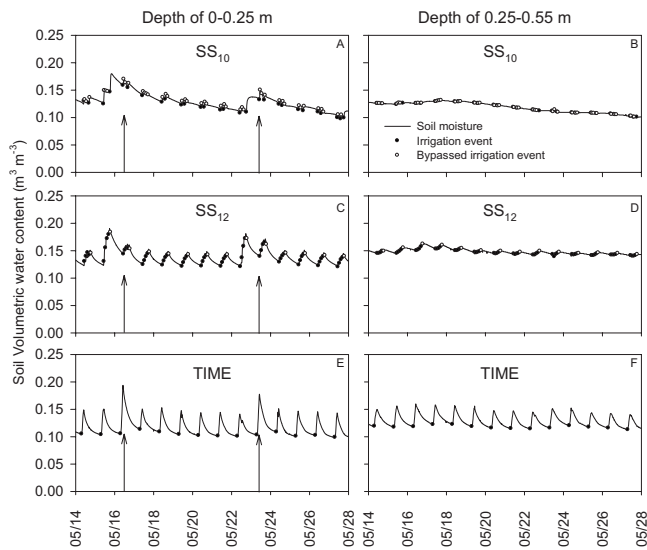


Fig. 3. Example of daily irrigation events and volumetric soil moisture content (0–25, left column and 15–55-cm depth right column) for pepper at flowering stage during the spring of 2007 for [(a) and (b)] SS₁₀; [(c) and (d)] SS₁₂; and [(e) and (f)] TIME treatment. The close circles indicate irrigation event, the open circles indicate bypassed irrigation events, and arrows indicate fertigation events.

for SS₁₀ and SS₁₂ treatment. On the other hand, the TIME treatment was irrigated for a longer time period (2 h), which resulted in very pronounced soil moisture fluctuations [Figs. 3(e and f)]. For TIME treatment, after each irrigation event, the soil moisture content from 0.10 to 0.15 m³ m⁻³. Soil moisture content returned to field capacity within 12 h. The spikes also indicate that the soil water content as measured by the TDR probes rapidly reaches a point above the soil water holding capacity in the soil upper layer, inducing percolation to deeper soil layers and explaining the higher percolate values for the TIME treatment compared to the SMS treatments. In fact, similar spikes in soil water content were observed at 0.25–0.55 m showing appreciable soil water percolation though the soil profile throughout the entire production cycle. In terms of soil water availability to plants, the TIME treatment initially may provide more favorable growth conditions since the soil remains wetter, thus reducing potential water stress. However, excessive water percolation also may reduce N retention and crop N supply and thereby reduce yield for green bell pepper (Table 1).

Plant Biomass, Yield, and Irrigation Water Use Efficiency

There were no interactions between irrigation and N-rate treatments for total and marketable yield, maximum plant biomass accumulation, or IWUE (Table 1). The overall total yield for green bell pepper ranged between 26.7 to 32.0 Mg ha⁻¹ in 2005; 18.2 to 19.4 Mg ha⁻¹ in 2006; and 24.7 and 28.2 Mg ha⁻¹ in 2007. Except in 2006, when unfavorable environmental conditions occurred, bell pepper yield obtained in these experiments were in the range of those reported in the literature for sandy soils in Florida (Dukes et al. 2003; Maynard and Santos 2007; Simonne et al. 2006). The lower yield in 2006 compared to 2005 and 2007 was attributed to the effect air temperature on plant development and flowering. Low night temperatures were shown to have a considerable effect on flower morphology and function-

ing, larger flowers, with swollen ovaries and shorter styles in comparison with flowers grown under higher temperature conditions. This effect of low temperatures has a direct effect on pepper production by decreasing the total number of pollen grains formed and by reducing their viability and germination capacity (Aloni et al. 1999; Polowick and Sawhney 1985; Pressman et al. 2006; Shaked et al. 2004). According to Polowick and Sawhney (1985), nonextreme conditions such as 18°C day and 15°C night caused stamen deformation with abnormal, nonviable pollen, which resulted in functionally male-sterile flowers. A detailed analysis of measured air temperature during the entire crop cycle revealed that in 2006, pepper plants were exposed to temperatures below 14°C during 311 h, while in 2005 and 2007, the cumulative hours with low temperatures (<14°C) were 181 and 185 h, respectively. In addition, temperatures below 14°C occurred during the entire plant development and reproduction stages in 2006 (Fig. 2), while in 2005, the low temperatures occurred exclusively during the beginning of the season (until 35 DAT). In 2007, low temperatures occurred throughout the season for short periods of time, however, between 49 and 63 DAT (peak of flowering stage) there was no occurrence of low temperatures. Air temperature may have affected the relation of marketable and total yield. In 2006, the weight of fruits classified as culls (total yield minus marketable yield) reached 3.4 Mg ha⁻¹, which corresponded to 18% of total yield. Reduced proportion of culls was reported in 2005 and 2007, 10 and 3%, respectively (Table 1).

Differences in pepper yield between seasons also can be attributed to substantial differences in solar radiation. The cumulative solar radiation measured was 1,535, 1,482, and 1,849 MJ m⁻² for 2005, 2006, and 2007, respectively [Fig. 2(g–i)]. During the period between the end of May and beginning of June in 2005 and 2006, there was a reduction in solar radiation availability due to elevated number of cloudy/rainy days. Conversely, in 2007 the reduced number of rain events resulted in higher solar radiation availability compared to 2005 and 2006. The higher cumulative solar radiation in 2007 may have benefited pepper yield in response to the low temperatures occurred during reproductive phase compared to 2005, since both years yielded similarly.

There was no significant effect ($P \leq 0.05$) of N-rates on pepper yield. Only for 2007 conditions, a linear response of application of N-rates was observed (Table 1). The increase of N-rate from 176 to 220 kg ha⁻¹ and from 220 to 330 kg ha⁻¹ resulted in an increase of 6% (nonsignificant) of marketable yield. Complementarily, the only statistical difference was observed between N-rates of 176 and 330 kg ha⁻¹ for that particular year. The lack of yield response to N-rates above 220 kg ha⁻¹ has been reported for other vegetable crops for drip irrigated production systems in Florida (Hochmuth and Cordasco 2000; Zotarelli et al. 2008; Zotarelli et al. 2009).

The use of SMS to control irrigation significantly affected the IWUE in 2005 and 2007 (Table 1). The treatment ranking for IWUE was as follows: SS₁₀ > SS₁₂ > TIME. The TIME treatment had a lowest IWUE values (<8 kg m⁻³) due to the high irrigation rates applied. In 2006, reduced yields associated to the high volume of irrigation applied for all treatments were responsible for the lower IWUE values (<5.7 kg m⁻³, Table 1). It is important to point out that high irrigation rates as applied for TIME did not increased yield, conversely, the use of scheduling irrigation by using SMS allowed application of less water, divided in five possible irrigation events per day (low volume, high frequency), which resulted in higher IWUE values. While TIME treatment had a single irrigation event (high volume, low frequency), which promotes excessive water percolation (Fig. 4).

Table 1. Pepper Yield, Irrigation Water Use Efficiency (IWUE), Shoot and Fruit Dry Biomass, N Accumulation and N-Fertilizer Use Efficiency (NUE) as Affected by N-Rate (kg ha^{-1}) and Irrigation Treatment during Spring of 2005, 2006, and 2007

Season	Main effect	Yield		IWUE (kg m ⁻³)	Dry weight		N accumulation			NUE (%)
		Total (mg ha ⁻¹)	Marketable (mg ha ⁻¹)		Shoot (kg ha ⁻¹)	Fruit (kg ha ⁻¹)	Shoot (kg ha ⁻¹)	Fruit (kg ha ⁻¹)	Total (kg ha ⁻¹)	
2005 spring	Irrigation ^a	b								
	SS ₁₀	26.7 b	24.1 b	20.5 a	1.58 a	1.29 a	58.5 a	39.6 b	98.2 ab	40.5 a
	SS ₁₂	32.0 a	29.6 a	14.6 b	1.63 a	1.49 a	55.6 a	45.6 a	101.3 a	41.8 a
	TIME	27.8 b	24.6 b	8.1 c	1.30 a	1.39 a	41.6 b	39.7 b	80.2 b	33.5 b
	N-rate									
	176	29.8 a	27.2 a	13.8 a	1.39 a	1.31 a	43.5 b	37.1 b	80.5 b	45.7 a
	220	28.7 a	26.0 a	14.3 a	1.45 a	1.33 a	49.9 ab	39.3 ab	89.2 b	40.6 ab
	330	27.9 a	24.6 a	14.8 a	1.67 a	1.51 a	61.8 a	48.1 a	109.9 a	33.1 b
	Contrast ^c	ns	ns	ns	ns	ns	L*Q ^{ns}	L*Q ^{ns}	L*Q ^{ns}	L*Q ^{ns}
	2006 spring	Irrigation								
SS ₁₀		19.4 a	16.1 a	5.2 a	0.84 a	0.72 a	22.6 b	14.1 b	37.4 b	15.4 b
SS ₁₂		19.3 a	16.7 a	5.7 a	0.81 a	0.74 a	20.4 b	14.7 b	34.5 b	14.2 b
TIME		18.2 a	16.1 a	4.9 a	0.91 a	0.83 a	29.9 a	19.0 a	48.9 a	20.0 a
N-rate										
176		17.8 a	14.6 a	4.7 a	0.75 a	0.69 a	21.4 a	14.1 a	35.4 a	20.1 a
220		18.3 a	15.1 a	4.9 a	0.86 a	0.72 a	25.4 a	16.1 a	41.5 a	18.8 a
330		20.8 a	17.3 a	6.7 a	0.84 a	0.78 a	26.1 a	17.8 a	43.9 a	13.3 b
Contrast ^c		ns	ns	ns	ns	ns	ns	ns	ns	L*Q ^{ns}
2007 spring		Irrigation								
	SS ₁₀	28.2 a	27.5 a	15.1 a	1.30 a	1.24 a	41.5 a	31.2 a	72.7 a	30.0 a
	SS ₁₂	24.7 b	24.6 b	9.1 b	1.16 a	1.11 b	36.4 a	29.7 b	66.2 b	27.3 b
	TIME	25.3 b	23.8 b	7.9 b	1.08 a	1.07 b	35.0 a	27.6 b	62.6 b	25.7 b
	N-rate									
	176	24.4 b	23.7 b	10.1 a	1.00 b	1.07 b	29.9 b	26.0 b	55.9 b	31.8 a
	220	26.2 ab	25.3 ab	10.7 a	1.26 a	1.14 ab	40.2 a	29.6 ab	69.8 ab	31.7 a
	330	27.6 a	26.8 a	11.3 a	1.32 a	1.21 a	44.9 a	33.1 a	78.0 a	23.6 a
	Contrast ^c	L*Q ^{ns}	L*Q ^{ns}	ns	L*Q ^{ns}	L*Q ^{ns}	L**Q ^{ns}	L*Q ^{ns}	L*Q ^{ns}	L*Q ^{ns}

^aIrrigation treatments: SS₁₀ and SS₁₂=Acclima Digital TDT RS-500 based control system allowing for a maximum of five irrigation windows per day set at 0.10 and 0.12 $\text{m}^3 \text{m}^{-3}$ VWC and TIME=once daily fixed duration irrigation treatment.

^bMeans within columns followed by the same lowercase letters are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test for irrigation and N-rate treatments within same season.

^cOrthogonal polynomial contrast for the effect of N-rates (ns=not significant; L=linear; Q=quadratic; and * $P \leq 0.05$).

Yield measurements showed that reduced irrigation volume application and proper irrigation scheduling showed potential to produced more pepper fruits with less irrigation water. In 2006, even with different irrigation scheduling (one single application for TIME versus five irrigation windows for SS₁₀ and SS₁₂), the volume of irrigation was very similar between treatments, therefore the pepper yield was identical. Differences between SS₁₀ and SS₁₂ in 2005 and 2007 can be also explained based on the estimated cumulative crop evapotranspiration and the cumulative irrigation water application for each treatment. When comparing pepper yield of treatments SS₁₀ and SS₁₂ in 2005, it is important to point out that after the establishment period (14 DAT), the cumulative irrigation volume for SS₁₀ was below the cumulative ET_c (Fig. 1), while, the cumulative irrigation volume for SS₁₂ was always on or slightly above the ET_c curve during the entire plant cycle including flowering (Fig. 1). Thus, yields for SS₁₂ were higher than SS₁₀ due to reduced irrigation water application for SS₁₀, but no statistical differences in biomass accumulation were observed. However, in 2007, the cumulative irrigation for SS₁₀ was above the ET_c curve until 50 DAT and slightly below after 50 DAT. On the other hand, SS₁₂ cumulative irrigation volume was always above the ET_c curve. Thus, SS₁₀ had adequate water most

of the season which optimized yields, whereas, yield on SS₁₂ was reduced due to excessive watering (and N leaching) which was observed on TIME in all years and SS₁₀ and SS₁₂ in 2006.

Shoot biomass accumulation ranged between 1.30 to 1.58 Mg ha^{-1} in 2005, 0.81 to 0.84 Mg ha^{-1} in 2006 and 1.08 to 1.30 Mg ha^{-1} in 2007. There was no significant ($P \leq 0.05$) difference between SMS-based treatments and TIME treatments, neither between N-rates. However, in 2007 the fruit biomass accumulation was superior under SS₁₀ treatment (Table 1), following the same pattern for marketable yield. In the same year, the N-rates of 220 and 330 kg ha^{-1} resulted in higher fruit and shoot biomass accumulation, however they did not differed between each other.

Plant N Accumulation and Nitrogen Use Efficiency

Pepper plant N nutrition was slightly enhanced by SMS-based irrigation systems and N accumulation in fruits and shoots were significant ($P \leq 0.05$) greater in 2005 and 2007 compared to TIME treatment (Table 1). The corresponding increase in shoot N uptake for SMS-based systems occurred for SS₁₂ in 2005 and SS₁₀ in 2007 in the order of 20 and 14%, respectively. Moreover,

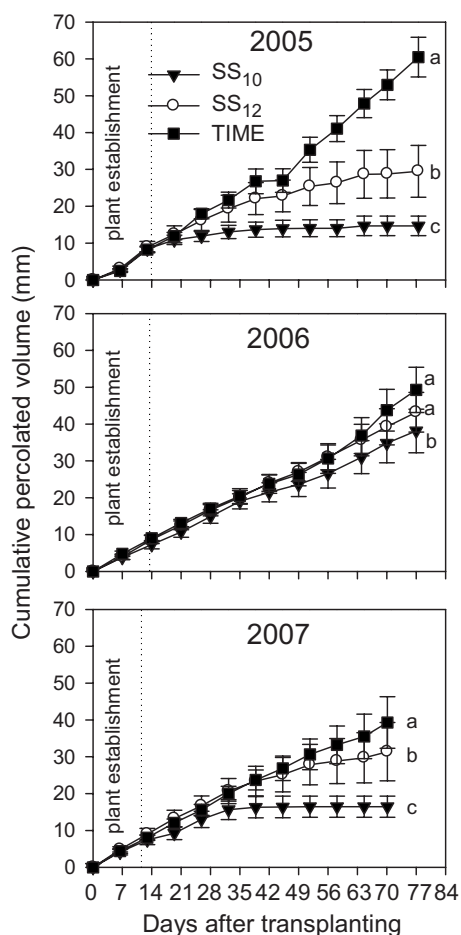


Fig. 4. Cumulative leachate volume of drainage lysimeters in the spring of 2005, 2006, and 2007 and fall of 2006 and 2007. Different letters indicate differences at the 95% confidence level. Error bars represent $\pm$ standard error from the mean, $n=4$.

the overall N accumulation increased in the order of 2005 > 2007 > 2006, thus mirroring the overall plant dry weight accumulation and yield trends. Complementary measurements of plant N levels using petiole sap $\text{NO}_3\text{-N}$ status were taken at 46 DAT. Petiole sap $\text{NO}_3\text{-N}$ concentration of SS₁₀ (1,648 mg L⁻¹) and SS₁₂ (1,353 mg L⁻¹) were significantly ($P \leq 0.05$) higher than TIME (1,061 mg L⁻¹) treatment. The petiole sap $\text{NO}_3\text{-N}$ concentration found was within the range of optimum concentration reported Hochmuth (1994), except for TIME treatment, which showed a $\text{NO}_3\text{-N}$ sap concentration 20% below the lower limit. These differences $\text{NO}_3\text{-N}$ sap concentration among irrigation treatments corroborated with nitrate leaching patterns and NUE, in general, higher nitrate leaching resulted in lower nitrate sap concentration in the plant.

Except in 2006 when shoot and fruit N accumulation were not affected by the N-rate (Table 1), the N-rate of 176 kg ha⁻¹ showed reduced N shoot and fruit accumulation. In 2007, with more favorable climatic conditions, a linear response of biomass and N accumulation to the N-rate treatments was detected (Table 1). In other words, more favorable growth conditions resulted in higher N uptake capacity, increasing the N-rate from 176 to 220 kg ha⁻¹ and from 220 to 330 kg ha⁻¹ resulted in an overall increase of 10 to 20% in total N accumulation. The effect of N-rate treatments on petiole sap $\text{NO}_3\text{-N}$ concentration evaluated at flowering stage showed values of 1,141, 1,419, and

Table 2. Cumulative $\text{NO}_3\text{-N}$ Leached Measured by Drainage Lysimeters under Irrigation Treatments and N-Rates at End of Pepper Crop Cycle

Season main effect	$\text{NO}_3\text{-N}$ leached (kg ha ⁻¹)		
	2005	2006	2007
Irrigation			
SS ₁₀	12.4 c ^a	23.1 b	15.2 c
SS ₁₂	34.4 b	23.3 b	30.1 b
TIME	47.6 a	40.1 a	40.3 a
N-rate (kg ha ⁻¹ of N)			
220	23.8 B ^b	19.9 B	27.7 A
330	39.1 A	37.9 A	35.6 A

^aThe values within columns followed by the same lowercase letters are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test for irrigation treatments within season.

^bThe values within columns followed by the same uppercase letters are not significantly different ($P \leq 0.05$) according to Duncan's multiple range test for N-rate treatments within season.

1,342 mg L⁻¹ for N-rates of 176, 220, and 330 kg ha⁻¹, respectively, with no significant differences between N-rates of 220 and 330 kg ha⁻¹. It is also important to note that there were no differences in fresh marketable yield between those three N-rates in 2005 and 2006 seasons and between N-rates of 220 and 330 kg ha⁻¹ in 2007. Results of petiole sap $\text{NO}_3\text{-N}$ concentration indicated that the N-rate of 330 kg ha⁻¹ may be exceeding the N of a pepper plant needs and possibly inducing N luxury consumption. Though, the extra consumption did not result in higher yields, in fact, for TIME treatment this N-rate showed higher $\text{NO}_3\text{-N}$ leaching.

NUE was significantly ($P \leq 0.05$) higher when lower N-rates were applied (Tables 2). The use of SMS resulted in higher NUE in 2005 for SS₁₀ and SS₁₂, and SS₁₀ in 2007. Again, there was no interaction between N-rate and irrigation treatment on NUE. The NUE increased with the increase in yield level. The NUE values ranged between 33 and 42% in 2005, 14 and 20% in 2006, and 25% and 30% in 2007. Linear NUE values decreased with increasing N-rates (Table 1) may be related to limitation in uptake and sink capacities resulting in a saturation response (e.g., "law of the diminishing returns"). In other words, as N supply continues to increase, factors other than N limit growth and yield. In 2005 and 2007, the TIME treatment showed consistently lower values of NUE, which was related to the higher irrigation volumes being applied resulting in increased N dilution and displacement thus reducing N uptake efficiency (Scholberg et al. 2002). In addition, a significant increase in nitrate leaching was observed with the increase of N-rate.

Drainage and Nitrate Leaching

Water percolation during crop establishment was identical for all treatments; 8, 10, and 8 mm for 2005, 2006, and 2007, respectively. According to the statistical analysis for the postestablishment period, an overall decrease ($P \leq 0.05$) in soil water percolation was obtained when SMS-based irrigation controlled the water application. The TIME treatment resulted in the highest volume of water percolated below the effective root zone and captured in the lysimeters (Fig. 4). The volume percolated ranged between 32 and 52 mm (Fig. 4), which corresponded to 10 to 16% of the applied irrigation water. Excluding 2006 season, the volume percolated under SS₁₀ treatment was 6 and 10 mm, in

2005 and 2007, respectively, which corresponded to only 5% of the total irrigation water applied. Similar comparison showed that SS₁₂ treatment percolated 21 and 24 mm in 2005 and 2007, respectively, which was translated to 9 and 11% of the total irrigation water applied, respectively.

There was no interaction between irrigation and N-rate treatments for cumulative nitrate loads below root zone. The TIME treatment resulted in the most NO₃-N leaching. Cumulative NO₃-N leaching values were ranged between 40 and 47 kg ha⁻¹ for TIME treatment (Table 2). The single high volume daily application of the TIME treatment is likely the cause of the appreciable drainage and NO₃-N leaching below the rootzone compared to the irrigation scheduling. A consistent reduction in NO₃-N leaching was observed when scheduling irrigation associated to the use of SMS was adopted. These reductions were on the order of 25 to 74%, which can be translated to range of 10 to 35 kg ha⁻¹ of N. Independently of the irrigation treatment, the increase in N-rate from 220 to 330 kg ha⁻¹, significantly ($P \leq 0.05$) increased the NO₃-N leaching in 2005 and 2006 (Table 2).

Conclusions

The initial premise that sound irrigation management can enhance N retention greatly in the active root zone, resulting in improved NUE was confirmed in this study. It is concluded that better irrigation practices enhanced overall pepper yield, and NUE, while reducing water percolation and NO₃-N leaching. It is proposed that the relatively inefficient N use typically observed in commercial vegetable operations is related mainly to excessive irrigation, resulting in premature N displacement below the root zone. For our experimental conditions, soil-moisture sensor based irrigation systems in bell pepper significantly reduced the applied irrigation resulting in 7 to 62% less irrigation water applied compared to fixed time irrigation (TIME) treatment without compromising marketable yield. The TIME treatment resulted in excessive N leaching and dilution thereby further hampering N uptake and further compounding the low fertilizer use efficiency. The treatments SS₁₀ and SS₁₂ successfully reduced NO₃-N leaching by 25 to 73%. In addition, excessively high N application rates (>220 kg ha⁻¹) may increase the NO₃-N leaching below the active root zone. It is concluded that appropriate use of SMS and/or sensor-based irrigation controllers can allow growers to sustain yield while reducing irrigation application and reducing NO₃-N leaching in low water holding capacity soils.

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