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Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling

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ABSTRACT

Florida is the largest producer of fresh-market tomatoes in the United States. Production areas are typically intensively managed with high inputs of fertilizer and irrigation. The objectives of this 3-year field study were to evaluate the interaction between N-fertilizer rates and irrigation scheduling on yield, irrigation water use efficiency (iWUE) and root distribution of tomato cultivated in a plastic mulched/drip irrigated production systems. Experimental treatments included three irrigation scheduling regimes and three N-rates (176, 220 and 230 kg ha^{-1}). Irrigation treatments included were: (1) SUR (surface drip irrigation) both irrigation and fertigation line placed right underneath the plastic mulch; (2) SDI (subsurface drip irrigation) where the irrigation line was placed 0.15 m below the fertigation line which was located on top of the bed; and (3) TIME (conventional control) with irrigation and fertigation lines placed as in SUR and irrigation being applied once a day. Except for the "TIME" treatment all irrigation treatments were controlled by soil moisture sensor (SMS)-based irrigation set at 10% volumetric water content which was allotted five irrigation windows daily and bypassed events *if* the soil water content exceeded the established threshold. Average marketable fruit yields were 28, 56 and 79 Mg ha^{-1} for years 1–3, respectively. The SUR treatment required 15–51% less irrigation water when compared to TIME treatments, while the reductions in irrigation water use for SDI were 7–29%. Tomato yield was 11–80% higher for the SUR and SDI treatments than TIME where as N-rate did not affect yield. Root concentration was greatest in the vicinity of the irrigation and fertigation drip lines for all irrigation treatments. At the beginning of reproductive phase about 70–75% of the total root length density (RLD) was concentrated in the 0–15 cm soil layer while 15–20% of the roots were found in the 15–30 cm layer. Corresponding RLD distribution values during the reproductive phase were 68% and 22%, respectively. Root distribution in the soil profile thus appears to be mainly driven by development stage, soil moisture and nutrient availability. It is concluded that use of SDI and SMS-based systems consistently increased tomato yields while greatly improving irrigation water use efficiency and thereby reduced both irrigation water use and potential N leaching.

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Abbreviations: DAT, days after transplanting; SDI, subsurface drip irrigation; TIME, fixed time irrigation; SUR, surface drip irrigation; VWC, volumetric water content; iWUE, irrigation water use efficiency; SMS, soil moisture sensor.

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1. Introduction

Vegetables are a major component of Florida agriculture encompassing about 72,000 ha for production and presenting a crop value of 1.5 billion dollars. In 2004, Florida tomato production represented 42% of the 1.6 billion of tons of U.S. fresh-market field-grown tomato production (USDA, 2007). Most of the vegetable crops in Florida are irrigated and due to the coarse-textured soils and high temperatures, many of the soils have low water holding capacity and soil organic matter content (Carlisle et al., 1988). Since irrigation and fertilization are intrinsically linked, appropriate irrigation management is required for these soils in order to avoid nitrate leaching and groundwater pollution, especially in tomato production systems, which require substantial inputs of nitrogen fertilizer. Hochmuth and Cordasco (2000) summarized more than 15 fertilization trials under drip irrigated conditions in Florida, and they concluded that in 87% of these trials tomato yield did *not* increase with rates above 224 kg ha^{-1} of N and inefficient fertilizer use and excessive nitrate leaching may be the underlying cause for yield responses to excessively high N-application rates. Despite the N-fertilizer rate recommendation for mineral soils with drip irrigation in Florida being 224 kg N ha^{-1} (Olson et al., 2005), growers may opt to apply excessively high N rates to minimize risk of yield reductions due to nitrogen limitations. In addition, on sandy soils, proper irrigation management is decisive to maximize yield, fertilizer and irrigation water use efficiency (iWUE) for vegetable crop production.

On the other hand, significant reductions in water availability for irrigation use in southeast United States have increased the importance of implementation of water conservation practices in agriculture. Agricultural practices such as the use of plastic mulch, drip irrigation and quantitative irrigation scheduling are common in Florida, 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. Even with these advances, there remains a need for advancements in irrigation management by using real-time monitoring techniques combined with high frequency irrigation application methods based on actual plant water requirement. In practice, irrigation management and scheduling are commonly based on management skills (Fereres et al., 2003) but they may be further improved when factors such as plant evaporative demand, soil characteristics, root distribution are taken into account as well. The use of frequent but low volume irrigation applications via drip irrigation is superior to the more traditional scheduling of few but large applications (Locascio, 2005). In the past few years, sensor technology that permits continuous on-farm monitoring of soil water status has become increasingly accessible to commercial producers. Soil moisture sensors (SMS) measure volumetric soil water content (SWC), which can be used to more accurately balance specific crop water requirements. 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; Muñoz-Carpena et al., 2005). Recently, Zotarelli et al. (2008) reported that use of SMS-based irrigation allowed more efficient use of irrigation water resulting in a reduction in irrigation water use by 33–80% compared to a daily fixed time irrigation scheduling for zucchini squash in sandy soils.

Subsurface drip irrigation (SDI) is an adaptation of drip irrigation, where the irrigation drip tube is installed below the soil surface to reduce water losses due to soil evaporation thereby increasing water use efficiency (Ayars et al., 1999). A potential limitation to the use of subsurface drip irrigation in sandy soils is the establishment period when root systems are confined to the upper 5–10 cm and plant water supply depends on capillary rise which may be limited on sandy soils. In order to overcome this limitation, and to also reduce potential nitrate leaching, Zotarelli et al. (2008) combined surface applied fertigation via drip tape with subsurface drip irrigation controlled by soil moisture sensor irrigation. This combination resulted in a significant increase in water and nitrogen use efficiency and yield by zucchini squash, while it also increased N-retention in the top soil and thereby was also very effective in reducing N leaching. In fact, subsurface drip irrigation is an adaptation of a partial root zone drying technique, which requires wetting part of the root zone and leaving the other part dry, thereby utilizing reduced amount of irrigation water applied. It is expected that such a practice may increase irrigation-water-use efficiency (iWUE) leading to reduction in irrigation water requirement, while maintaining tomato yields (Kirda et al., 2004; Zegbe 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). Independent of the use of surface or subsurface drip irrigation, roots grow preferentially around the wetted emitter area and concentrate within the top 40 cm of the soil profile (Oliveira et al., 1996; Machado et al., 2003). In fact, maximum root growth has been shown to occur when adequate mineral nitrogen is present (Bloom, 1997), which indicates that lack of inorganic nitrogen in certain root zones may limit root growth. There is very little data on the effect of irrigation and fertigation management on tomato root distribution in sandy soil and its effect on water use efficiency and yields. The objective of this study was therefore to identify suitable irrigation scheduling methods, drip irrigation system design to reduce crop water use and to evaluate their effect on the optimal N-fertilizer rate, tomato yield and root distribution. We hypothesized that use of soil moisture sensor based irrigation systems will reduce irrigation water requirements of intensively managed tomato production systems.

2. Materials and methods

Field experiments were carried out at the University of Florida, Plant Science Research and Education Unit, near Citra, FL, during the spring of 2005, 2006 and 2007. The soil has been classified as Candler sand and Tavares sand (Buster, 1979) containing 8.2 and 3.0 g kg^{-1} soil organic matter in the 0–30 and 30–90 cm soil layer. These soils contain 97% sand-sized particles in the upper 1 m of the profile (Carlisle et al., 1988) with a field capacity in the range of 0.10–0.12 (v/v) in the 0–30 cm depth (Icerman, 2007). Averaged initial soil nitrate content at beginning of the seasons was 1.8 ± 0.6, 2.6 ± 0.7 and

$2.7 \pm 0.7\ mg\ kg^{-1}$ for the 0–30, 30–60 and 60–90 cm soil depths, respectively. The average of nitrate content of the irrigation water was $0.4 \pm 0.3\ mg\ L^{-1}$.

The area was rototilled and raised beds (0.30 m height) were constructed with 1.8 m distance between bed centers. Granulated fertilizer was incorporated into the beds at a rate of $112\ kg\ ha^{-1}$ of P_2O_5. Beds were fumigated (80% methyl bromide, 20% chloropicrin by weight) at a rate of $604\ kg\ ha^{-1}$ after placement of both drip tapes 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, 0.25 mm thickness, $0.7\ L\ h^{-1}$ at 69 kPa, Chapin Watermatics, NY). Water applied by irrigation and fertigation was recorded by positive displacement flowmeters (V100 16 mm diameter bore with pulse output, AMCO Water Metering Systems Inc., Ocala, FL, USA). Weekly 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, MA, USA) 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.

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., 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, which occurred around 35–40 days after transplanting.

Tomato transplants (*Lycopersicon esculentum* Mill. var. "Florida 47") were set on 7 April 2005, 10 April 2006, and 10 April 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 as potassium chloride and $12\ kg\ ha^{-1}$ of Mg as magnesium sulphate. 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 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 irrigation treatments were differentiated by their arrangement of drip irrigation lines. The treatments were identified as surface drip irrigation (SUR), whereby both irrigation and fertigation drip lines were positioned on the soil surface (Fig. 1). The second treatment was identified as subsurface drip irrigation, with the irrigation drip line positioned at 0.15 m below soil surface while the fertigation drip line was positioned on the soil surface (Fig. 1). For both treatments irrigation events were controlled by a Quantified Irrigation Controller (QIC) system (Muñoz-Carpena et al., 2008), which included a 0.20 m long ECH_2O probe (Decagon Devices Inc. Pullman, WA) to monitor soil moisture. Probes were inserted vertically in order to integrate the soil water content in the upper 0.2 m at 0.05 m from the irrigation drip

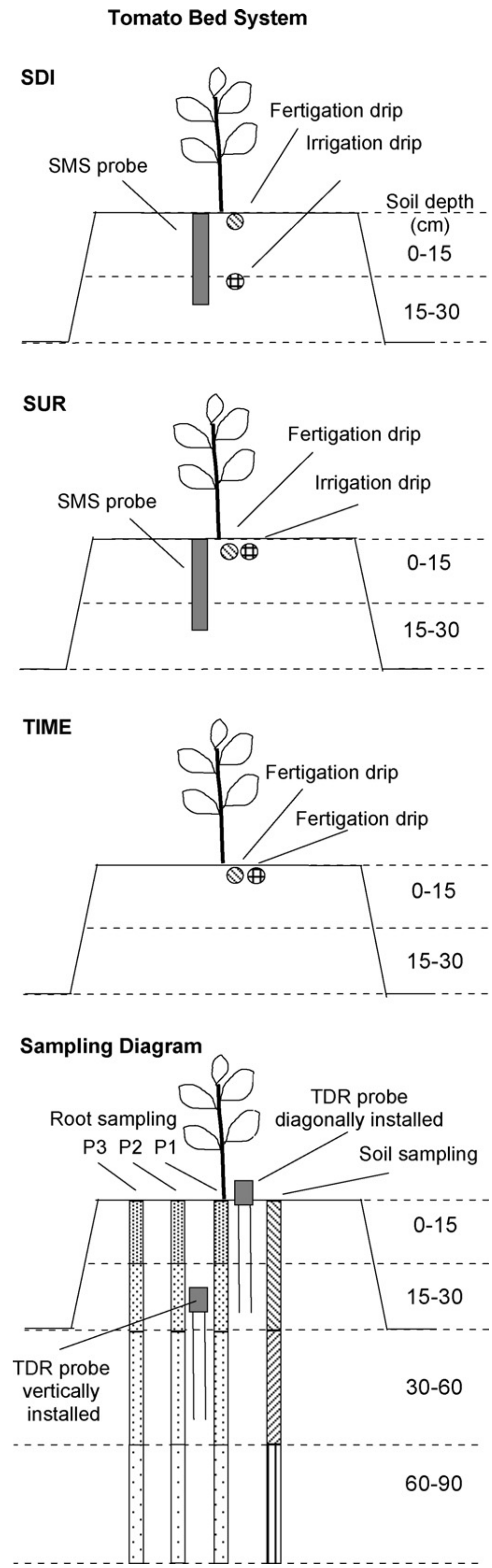

Fig. 1 – Overview of irrigation drip system, soil moisture sensor (SMS) placement and sampling scheme.

line. The QIC irrigation controllers allowed a pre-programmed timed irrigation event if measured soil water content was below a volumetric water content (VWC) value of 0.10 $m^3 m^{-3}$ (translating to a 510 mV reading) during one of five daily irrigation events, with each potential irrigation event lasting 24 min. Based on these readings up to a maximum of five irrigation events could occur per day totaling 2 h. A reference treatment employed a fixed time-based irrigation (TIME) featuring one fixed 2-h irrigation event per day. As well as SUR treatment, for TIME treatment it was used of twin line, one for irrigation and one for fertigation. This was due to the experimental convenience; however, the commercial grower would have one drip line for irrigation and fertigation (Fig. 1).

2.1. Plant growth, yield and irrigation water use efficiency

Plots were harvested on 70, 77 and 84 days after transplanting (DAT) in 2005; on 70, 77 and 86 DAT in 2006 and on 76, 83 and 90 DAT in 2007. The harvested area consisted of a central 10.5 m long region within each plot. Tomato fruits were graded into culls, U.S. Number 2 (medium), U.S. Number 1 (large), and Fancy (extra-large) according to USDA (1997) grading standards for fresh-market tomato. 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. Irrigation water use efficiency expressed in 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 ($m^3 ha^{-1}$).

Maximum biomass accumulation was evaluated by harvesting one representative plant per treatment replicate at 84, 86 and 90 DAT for 2005, 2006 and 2007 trials, respectively. For the 2005 and 2006 trials one representative plant was also harvested for each plot at bi-weekly intervals and used for growth analysis. Vegetative and reproductive plant parts were separated. Shoot and fruit tissues were dried at 65 °C for subsequent dry weight determination.

2.2. Root sampling and analysis

Roots were collected during the spring of 2006 at 24, 45 and 66 DAT for all irrigation treatments across the recommended N-rate (220 kg ha^{-1}) treatment combination. Using a 0.05 m diameter soil auger of known volume, soil cores were extracted at four different depths: 0–0.15, 0.15–0.30, 0.3–0.6 and 0.6–0.9 m and three different surface positions on a transversal line perpendicular to the plant line: underneath the irrigation/fertigation drip line (P1); in-row at 0.125 m distance from the drip line and immediately adjacent to a tomato plant (P2) and in-row at 0.25 m distance from the drip line close to the raised bed side, giving 12 unique sample locations (Fig. 1). After washing away the soil above a fine sieve, roots and organic debris were stored in plastic bags at 4 °C until further cleaning. Samples were then placed in a glass bowl placed above a light plate and roots were handpicked and placed in Petri dishes. Root length density (RLD) for each soil core was then determined with Winrhizo (Régent Instrument Inc., Quebec City, Canada) software and hardware. The RLD surface maps were plotted in Surfer 8 (Golden Software Inc., Golden, CO, USA).

Penetrometer resistance was measured in 0.05 m increments to a depth of 0.45 m using a hand-held digital cone penetrometer with a 30° conical probe and 12.8 mm diameter (Spectrum Technologies, Plainfield, IL, USA). Ten penetrometer measurements equidistant 0.08 m were taken across the bed on a transversal line perpendicular to the plant line.

2.3. Monitoring soil water and soil nitrate

The volumetric water content of the top soil of the production beds was monitored by coupling time domain reflectometry (TDR) probes (CS-615, Campbell Scientific Inc. Logan, UT, USA) with a datalogger (CR-10X, Campbell Scientific Inc., Logan, UT, USA). 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 at 0.05 m from the irrigation drip and the lower probe was inserted vertically below the upper probe recording soil moisture between 0.25 and 0.55 m (Fig. 1).

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. Composite samples were taken at the 0–0.3, 0.3–0.6, and 0.6–0.9 m soil depths. The center of the auger was placed at 0.10 m from the irrigation drip (Fig. 1). Collected soil samples were 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. 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, Jones and Case, 1990).

2.4. Statistical analysis

Statistical analyses were performed using PROC GLM procedure of SAS (SAS, 2002) to determine treatment effects for total plant biomass, fruit grade, yield and iWUE. When the *F* value was significant, a multiple means comparison was performed using Duncan Multiple Range Test at a *P* value of 0.05. For repeated measurements such as plant biomass N and P accumulation in 2005 and 2006, root length density, the PROC MIXED procedure of SAS with residual maximum likelihood estimation approach and least squares means of fixed effects were pair-wise compared.

3. Results and discussion

3.1. Soil water dynamics

The crop establishment period was characterized by application of similar irrigation volume to all irrigation treatments (Fig. 2). This period lasted 11, 14 and 13 DAT in 2005, 2006 and 2007, respectively and there were two fertigation events during the establishment period. Following this period, irrigation treatments were initiated. Each soil moisture sensor

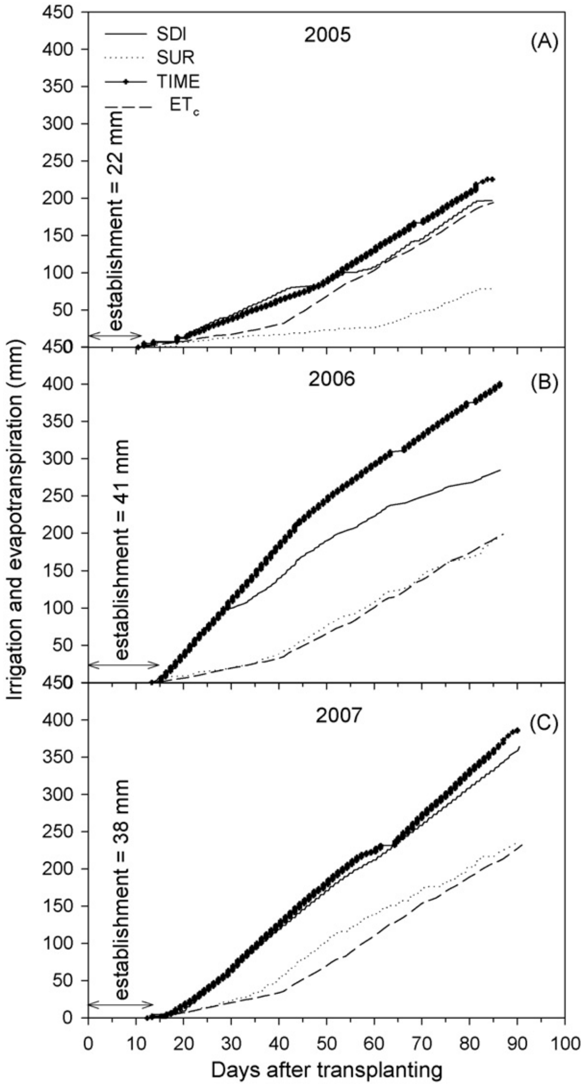

Fig. 2 – Cumulative irrigation and estimated evapotranspiration (ETc) after initial plant establishment as affected by different irrigation scheduling methods during the 2005, 2006, 2007 tomato growth season.

controller was programmed to bypass irrigation if the probe read soil moisture at or above the set threshold at the beginning of an irrigation window. During the crop season, programmed irrigation events were skipped which significantly reduced the amount of water applied to soil moisture sensor based treatments. The volume of irrigation increased in order SUR < SDI < TIME (Fig. 2). Calculated total ET_c for each year was 194 mm for 2005, 198 mm for 2006 and 232 mm for 2007 (Fig. 2).

The contribution of rainfall to crop 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. Still it was observed that high intensity precipitation events (>8 mm h^{-1}) increased the soil water content as measured by TDR. For example, precipitation events of 44, 48 and 45 mm occurring in 2005, 2006 and 2007, respectively (Fig. 3D–F), showed a slight increase (around 1%) in volumetric soil water content in the 0–25 cm depth layer (data not shown).

The SUR treatment received an average of 1.1, 2.6 and 2.9 mm day^{-1} of irrigation water in 2005, 2006 and 2007, respectively. Even with similar ET_c between 2005 and 2006, SUR applied lower irrigation volume in 2005 compared to 2006, due to unfavorable growth conditions and disease occurrence which lowered the crop water requirements. This result was confirmed by the lower biomass accumulation in 2005 compared to 2006 (Table 2).

The corresponding average irrigation rates for the SDI treatment were 2.6, 3.8 and 4.6 mm day^{-1}, for 2005, 2006 and 2007, respectively. Use of SDI system resulted in higher water application, even though soil moisture content thresholds were the same for both the SUR and SDI treatments. The water savings for SDI compared to TIME treatments ranged from 7 to 29% (Fig. 2). These values are very low when compared to the potential water savings of SUR treatment (40–51%) achieved in 2006 and 2007. Higher water application for SDI may be attributed to the position of the soil moisture probe with respect to the irrigation line. The irrigation drip line for this treatment was buried at a depth of 15 cm under the surface. The probe was however positioned the same as SUR so that it averaged the soil moisture from the surface down to a depth of 20 cm. Due to the lower placement of the drip tape the top 15 cm of soil would be relatively dry due since capillary rise in sandy soils is limited and therefore fewer irrigation events were bypassed due to high soil moisture readings.

The soil moisture content as measured by TDR probes had a noticeable increase in soil moisture after each irrigation event throughout the growing season for SUR and TIME (Fig. 4A–I). However, due to the TDR position (0–25 cm) in relation to the irrigation drip position (15 cm below surface) for the SDI treatment, variations in soil moisture during each irrigation event were not as distinct as for the other treatments. Soil moisture sensor based irrigation treatments irrigated for short periods of time which resulted in a relatively small increase in soil moisture, consequently decreasing the volume of percolate. This was true for both the SUR and SDI treatment, which received a higher volume of water than SUR (Fig. 4). On the other hand, the TIME treatment was irrigated for a longer time period which resulted in very pronounced soil moisture fluctuations (Fig. 4G–I). These spikes in soil moisture were only temporary, as excess soil moisture that rapidly drained in this sandy soil. 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 other treatments (Fig. 4A–F). In fact, similar spikes in soil water content were observed at 25–55 cm showing appreciable soil water percolation though the soil profile throughout the entire production cycle (Fig. 4G–I). 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 reducing N retention and crop N supply and thereby reduce yield for tomato (Table 2).

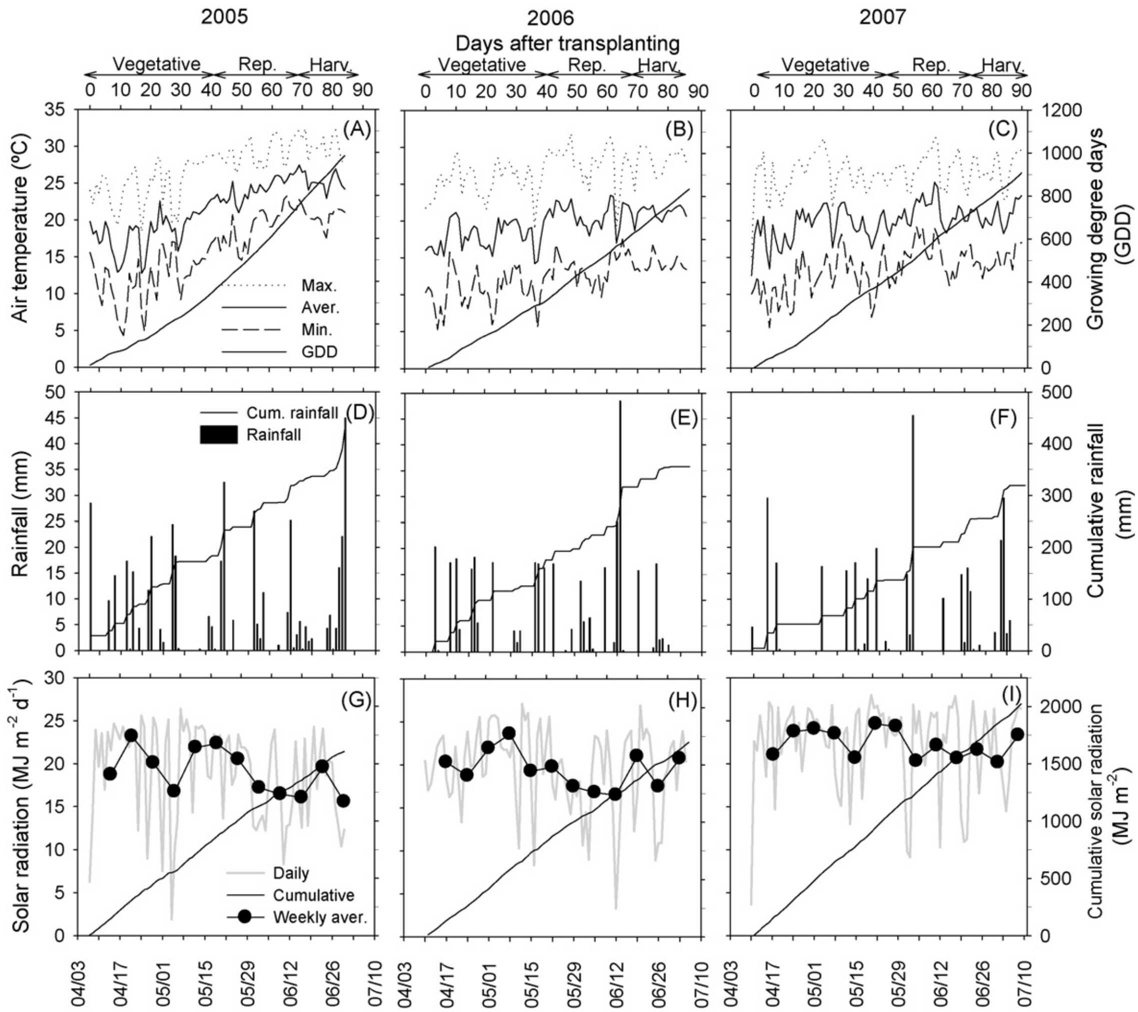

Fig. 3 – Minimum, maximum, average daily temperatures and cumulative daily growing degree days (GDD, temperature base of 10 °C), daily and cumulative rainfall and daily and cumulative solar radiation during the 2005, 2006 and 2007 tomato-growing season.

By comparison, irrigation water from the SUR and SDI treatments produced relatively constant soil moisture values over time, as irrigation water was distributed across multiple irrigation events according to the soil moisture threshold and thus crop water demand. In addition, almost no spikes in soil moisture were registered by TDR probes at 25–55 cm soil depth layer, indicating that the volume of water applied at the soil surface did not exceed root water extraction. Vazquez et al. (2006) compared high and low irrigation frequencies for tomato crop and concluded that high irrigation frequency (8 events of 15 min day^{-1}) increased water use efficiency and resulted in almost no leaching.

3.2. *Plant growth, yield and irrigation water use efficiency*

There were no interactions between irrigation and N-rate treatments for yield, biomass accumulation or irrigation water use efficiency, but irrigation treatments had an important impact on iWUE and tomato yield (Table 1). The use of soil moisture sensors increased marketable tomato yield 69–80% in 2005; 20–26% in 2006 and 11–21% in 2007 when compared to the TIME treatment (Table 2). There was no significant difference on tomato marketable yield for SDI and SUR treatments, averaging 32 Mg ha^{-1} in 2005 and 59 Mg ha^{-1} and in 2006. However, in 2007, SUR treatments out-yielded SDI treatments (85.7 Mg ha^{-1} vs. 78.9 Mg ha^{-1}). Except in 2005, when unfavorable growth conditions hampered plant growth, tomato yield obtained in these experiments were in the range of those reported in the literature for sandy soils in Florida (Doss et al., 1975; Everett, 1978; Rhoads et al., 1988, 1996; Scholberg et al., 2000b). The increase in tomato yield in 2006 and 2007 compared to 2005 was attributed to several factors. First, the overall volume of irrigation applied was higher in the two last years compared to 2005, allowing for more water uptake. Also higher temperatures and the occurrence of disease in 2005, increased stress on the crop. Appreciable differences in temperature, rainfall and solar radiation were registered in each of the 3 years of experiment. The spring of 2005 was characterized by wetter and hotter season compared to the subsequent seasons which interfered with effective disease control and also resulted in premature blooming. The cumulative rainfall at the final harvest was 472, 357 and

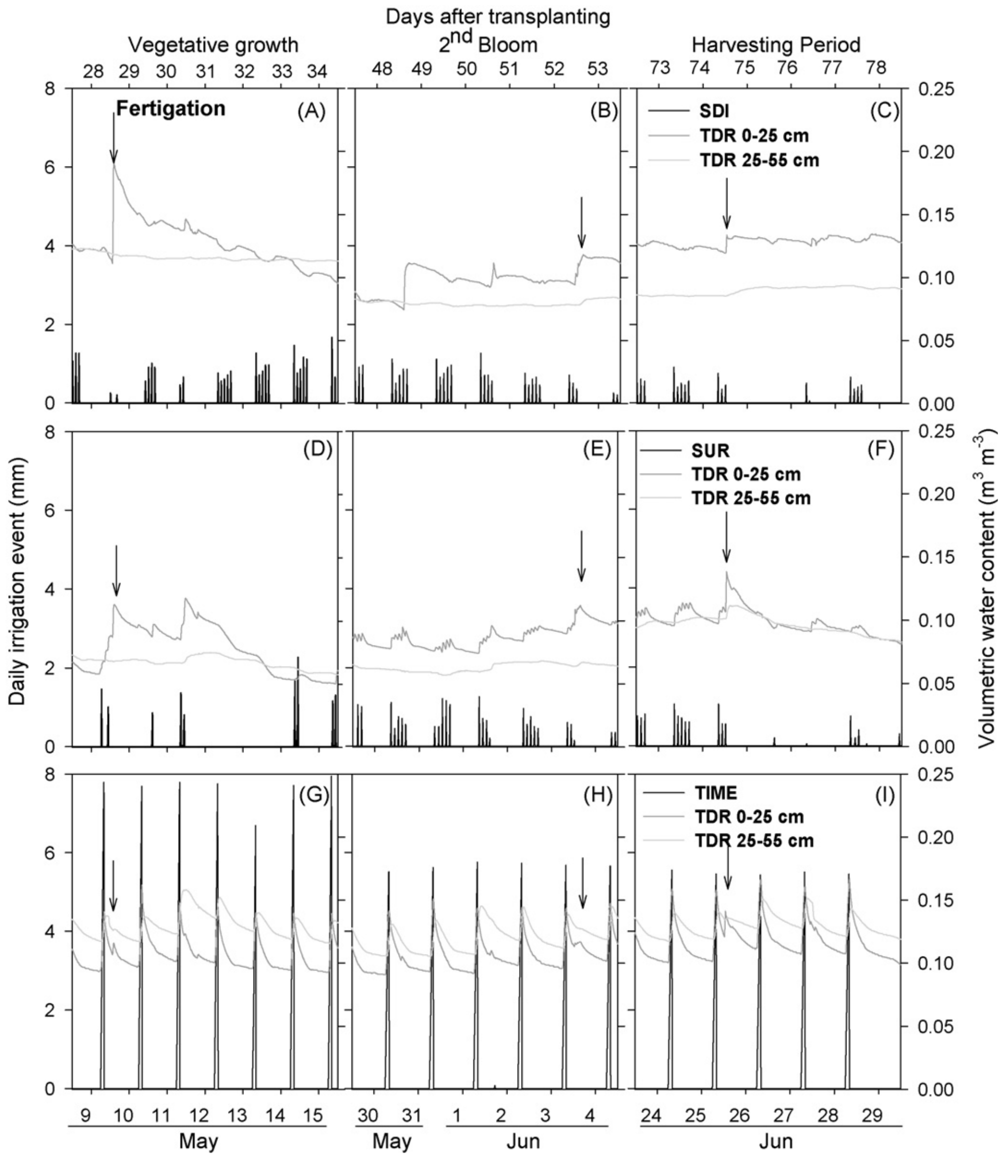

Fig. 4 – Daily irrigation events and volumetric soil water content (0–25 and 25–55 cm depth) for tomato during three crop development stages (vegetative growth, 2nd bloom and harvesting period) during the spring of 2006 for SDI (A–C), SUR (D–F), and TIME (G–I) treatment. The arrows indicate fertigation events.

323 mm for 2005, 2006 and 2007, respectively (Fig. 3). The cumulative precipitation during May of 2005 in the experimental site was 111 mm, which was around 20% higher than the historical 29-year average (NOAA, 2007) and about 40% higher compared to 2006 and 2007. The exceptional high rain intensity and wetter condition in 2005 promoted favorable condition to appearance of bacterial spot disease (*Xanthomonascampestris*) at beginning of the crop season. Frequent applications of fungicide were used to prevent disease spread but warm and wet conditions hampered complete disease suppression. During 2006 and 2007, favorable weather conditions characterized by lower temperatures, humidity, and precipitation occurred during the reproductive phase (Fig. 3) resulting in low disease pressure. During the reproductive and harvest period (after 41 DAT), the average maximum temperatures were 29.6, 28.1 and 27.0 °C for 2005, 2006 and 2007, respectively. The number of days with temperatures above 28 °C (which adversely affects fruit production) was also greatest in 2005, followed by 2006 then 2007. Significant decreases in fruit weight and number was observed by Peet et al. (1997) when daily mean temperatures increased from 25 to 29 °C attributed to ovule development and post-pollen production processes. A similar trend was observed during this experiment as tomato yield and dry biomass increased when cooler temperatures occurred. The percentage of culls also decreased under cooler temperatures (total yield minus marketable yield, Table 2). Another effect of temperature was reflected in the duration of the crop cycle, which in 2007 was 4–6 days longer than 2005 or 2006. Differences in tomato yield also can be attributed to substantial differences in solar radiation during the three crop seasons. The cumulative solar radiation measured was 1606, 1699 and 2022 MJ m^{-2} for 2005,

Table 1 – Analysis of variance summary for plant dry biomass, tomato grades, total and marketable yields and irrigation water use efficiency (iWUE) as affected by N-rate (N) and irrigation treatment (I)

Season	Source	d.f.	Yield		Above ground biomass	iWUE
			Total	Marketable		
2005	Replication	3	NS	NS	NS	NS
	Irrigation (I)	2	***	***	*	***
	N	2	NS	NS	NS	NS
	I × N	4	NS	NS	NS	NS
	Error	24				
	CV %	18.9	20.3	27.8	21.6	
2006	Replication	3	NS	NS	NS	NS
	Irrigation (I)	2	*	*	*	***
	N	2	NS	NS	NS	NS
	I × N	4	NS	NS	NS	NS
	Error	24				
	CV %	18.5	20.9	15.3	20.13	
2007	Replication	3	NS	NS	NS	NS
	Irrigation (I)	2	*	*	*	***
	N	2	NS	NS	NS	NS
	I × N	4	NS	NS	NS	NS
	Error	24				
	CV %	14.4	14.7	14.1	16.8	

*Significant at $P \leq 0.05$; **significant at $P \leq 0.01$; ***significant at $P \leq 0.001$. NS: not significant; CV %: coefficient of variation; d.f.: degrees of freedom.

Table 2 – Tomato total and marketable yield, above-ground dry biomass above and irrigation water use efficiency (iWUE) as affected by N-rate (kg ha^{-1}) and irrigation treatment

Season	Main effect	Yield (Mg ha^{-1})		Above ground biomass (Mg ha^{-1})	iWUE (kg m^{-3})
		Total	Marketable		
2005	Irrigation				
	SUR	37.4 a	33.3 a	2.79 a	42.7 a
	SDI	36.3 a[†]	31.3 a	3.18 a	15.9 b
	TIME	24.8 b	18.5 b	2.00 b	8.7 c
	N-rate				
	176	31.6	26.9	2.59	22.4
	220	32.3	27.5	2.62	22.0
	330	34.6	29.7	2.57	23.0
2006	Irrigation				
	SUR	68.0 a	60.1 a	5.02 a	30.8 a
	SDI	64.2 ab	57.5 a	4.74 a	20.2 b
	TIME	55.0 b	47.8 b	3.38 b	12.0 c
	N-rate				
	176	60.7	53.6	4.04	20.4
	220	59.8	52.6	4.37	20.8
	330	67.5	59.3	4.70	21.8
2007	Irrigation				
	SUR	87.4 a	85.7 a	5.54 a	36.7 a
	SDI	80.5 b	78.9 b	5.04 ab	21.8 b
	TIME	72.0 c	70.9 c	4.64 b	18.4 b
	N-rate				
	176	73.8	72.9	4.72	24.0
	220	84.4	82.7	5.15	27.1
	330	81.6	79.9	5.35	25.9

SDI: subsurface drip irrigation controlled by soil moisture sensor; SUR: surface drip irrigation controlled by soil moisture sensor; TIME: time-fixed irrigation.

[†] Means 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 same season. The absence of letters indicates no significant difference between treatments.

2006 and 2007, respectively (Fig. 3G–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. In 2007, there was a reduced number of rain events, resulting in higher solar radiation availability than 2005 and 2006. Moreover, due to unfavorable growth conditions crop canopies in 2005 were sparser and plant height was also lower, thus also reducing radiation interception as well, which results in reduced potential production (Scholberg et al., 2000a). In fact, the association of all stress factors cited above indicated that the plants were not transpiring at maximum levels which resulted in water application lower than the ET_c for SUR treatment in 2005 (Fig. 2).

There was no significant effect ($P \leq 0.05$) of N-rates on tomato yield. Above ground biomass at the end of the crop cycle was significantly ($P \leq 0.05$) greater for soil moisture sensor treatments compared to the TIME treatment. Shoot biomass accumulation for TIME ranged between 1.28 and 1.61 Mg ha^{-1}, which was significantly ($P \leq 0.05$) lower than SMS-based treatments in 2005 and 2006. However, in 2007 the shoot biomass accumulation also differed between SMS-based treatments as well (Table 2). The maximum daily biomass accumulation rate was 148, 151 and 119 kg of dry matter per accumulated degree day, for SDI, SUR and TIME, respectively (data not shown). For the TIME treatment, the peak in dry matter accumulation occurred at 50 DAT, corresponding to 10 and 14 days earlier than SDI and SUR. Higher rates of biomass accumulation for SMS-based treatments may be associated to the higher nitrate availability in the soil profile (Zotarelli et al., 2008).

The use of different drip position arrangements significantly affected the iWUE and yield (Table 2). The treatment ranking for iWUE was as follows: SUR > SDI > TIME. The TIME treatment had a lowest iWUE values (8.7–18.4 kg m^{-3}) due to the high irrigation rates applied, and also due to the lower marketable yield (Table 2). In this case, two relevant aspects played an important role in the iWUE results. First the use of SMS allowed application of water in five possible irrigation events per day (low volume and high frequency), while TIME treatment had a single irrigation event (high volume and low frequency), which promotes excessive water percolation due to the very limited soil water holding capacity of the sandy soil (Fig. 4).

Table 3 – Significance of date, irrigation, position and depth and sub-effects when constituting linear models on sampled root length density of tomato during the 2006 cropping season

Model term	d.f.	F-Value	Probability (P)
Main effects			
Date	2	48.45	<0.0001
Irrigation	2	9.53	<0.0001
Position	2	39.22	<0.0001
Depth	3	163.19	<0.0001
Two-way interactions			
Irrigation × Depth	6	8.35	<0.0001[a]
Position × Depth	6	17.99	<0.0001[a]
Date × Irrigation	4	3.37	0.0102[b]
Date × Position	4	2.62	0.0349[b]
Date × Depth	6	11.47	<0.0001[b]
Irrigation × Position	4	1.61	NS
Three-way interactions			
Date × Irrigation × Position	8	1.14	NS
Date × Irrigation × Depth	12	3.65	<0.0001[c]
Date × Position × Depth	12	1.61	NS
Irrigation × Position × Depth	12	3.42	<0.0001[c]
Four-way interaction			
Date × Irrigation × Position × Depth	24	1.35	NS

[a] See Table 4.
[b] See Table 5.
[c] See Fig. 5.

3.3. Root length density distribution

The values of RLD observed in 2006 revealed different rooting patterns among irrigation treatments, but consistently larger concentrations of roots found in the upper soil layers. There were interactive effects between the date of sampling, irrigation treatment, sampling position and depth (Table 3). During the reproductive phase (66 DAT), about 51–78% of root length density was found between 0 and 15 cm of the soil profile. Below 15 cm, the root length density decreased greatly with 15–28% being present at 15–30 cm; 5–11% at 30–60 cm soil depth; and 4–10% at the lowest (60–90 cm) soil layer (Table 4). In addition to crop specific root distribution pattern dynamics, differences in soil bulk density provide some explanation of

Table 4 – Root length density (cm cm^{-3}) interaction effects between irrigation and soil depth (left); and sampling position of sampling and soil depth (right) during the 2006 cropping season

Depth (cm)	Irrigation			Depth (cm)	Position		
	SUR	SDI	TIME		P1	P2	P3
0–15	1.27 Ba	2.83 Aa	1.24 Ba	0–15	3.11 Aa	1.56 Ba	0.67 Ca
15–30	0.50 Ab	0.53 Ab	0.52 Ab	15–30	0.64 Ab	0.54 Ab	0.38 Bb
30–60	0.10 Ac	0.17 Ac	0.19 Ac	30–60	0.20 Ac	0.18 Ac	0.08 Ac
60–90	0.07 Ac	0.10 Ac	0.19 Ac	60–90	0.21 Ac	0.09 Ac	0.07 Ac

P1: on the irrigation/fertigation drip; P2: in-row at 0.125 m distance from the drip line and immediately adjacent to a tomato plant; P3: in-row at 0.25 m distance from the drip; DAT: days after transplanting. Means within rows having same uppercase letters and means within columns having same lowercase letters do not differ at the $P \leq 0.05$ level according least square means differences. SDI: subsurface drip irrigation controlled by soil moisture sensor; SUR: surface drip irrigation controlled by soil moisture sensor; TIME: time-fixed irrigation.

tomato root proliferation in the soil profile. The lower bulk density (1.45 g cm^{-3}) of the upper soil layer (0–30 cm) due to the soil cultivation during the raised bed formation and slightly higher content of soil organic matter, soil moisture and nutrients may promote root growth. Conversely, lower soil layers (below 30 cm) which had bulk density of 1.7 g cm^{-3}, certainly created some impedance to root growth. In fact, soil resistance measured with a cone penetrometer in the upper soil layer (0–20 cm) ranged between 0 and 0.1 MPa (data not shown). Soil resistance increased with depth. In the 20–30 cm depth layer, the resistance increased in depth from 0.1 to 0.5 MPa and in the 30–50 cm depth, the soil resistance also increased with depth from 0.5 to 3.0 MPa (data not shown).

Considering the equivalent impact of bulk densities across irrigation treatments, the three-way interaction between sampling position across the bed, irrigation treatment and sampling depth implies that the use of SDI systems increased the RLD in the upper soil layer after 45 DAT compared to the SUR and TIME treatments (Table 3 and Fig. 5). Root length density decreased exponentially with soil depth and at greater soil depths it was similar for all irrigation treatments (Bryla et al., 2003; Machado and Oliveira, 2005). However, based on the visual presentation in Fig. 5, it appears that there was a tendency for TIME treatments to have greater root concentrations at greater soil depth, whereas the SMS-based systems root length densities > 0.25 cm cm^{-3} was clearly confined to the upper 20–30 cm of the soil profile. Higher root colonization at greater soil depth for TIME seems to mimic wetting and leaching patterns observed with this treatment and may be related to higher nitrate availability (Bloom et al., 2003) below 60 cm due to the higher nitrate leaching (Zotarelli et al., 2008).

Across all positions and depths, the total RLD increased significantly from 24 to 66 DAT for all irrigation treatments. While there were no statistical differences between TIME and SUR, at 45 and 66 DAT, SDI showed 48–54% higher RLD than SUR and TIME, respectively. Root length density significantly ($P \leq 0.05$) increased in the position P1 (underneath the drip irrigation/fertigation) and P2 (0.125 m from drip and adjacent to the tomato plant) from 24 to 66 DAT. No similar pattern was observed in the position P3 (0.25 m distance from the drip line). Independent of the sampling date, there was a 41% reduction in RLD from P1 to P2 and 70% from P1 to P3 (Table 5). In general, the SDI treatment showed a wider distribution of roots across the bed. The RLD at P2 and P3 in this particular depth layer for SDI was significantly ($P \leq 0.05$) higher than SUR and TIME.

The root distribution patterns showed that independently of the irrigation treatment, the RLD concentrated preferentially around the fertigation emitters. These results are in agreement with Machado et al. (2003) and Oliveira et al. (1996), which irrigation and fertigation were applied through the same drip tape at different depths. At 66 DAT, the RLD at P1 for SDI treatment at 0–15 cm reached 10.5 ± 3.9 cm cm^{-3} compared to 2.6 ± 1.7 and 2.5 ± 0.9 cm cm^{-3} for SUR and TIME, respectively. At the same sampling position in the 15–30 cm depth layer, RLD decreased significantly ($P \leq 0.05$) for SUR (0.6 cm cm^{-3}) and SDI (0.4 cm cm^{-3}) treatments compared to TIME (1.1 cm cm^{-3}). Between 30 and 90 cm depth, RLD values were <0.2 cm cm^{-3} for SDI and SUR, however, RLD for TIME was significantly higher 0.7 and 0.9 cm cm^{-3} for 30–60 and

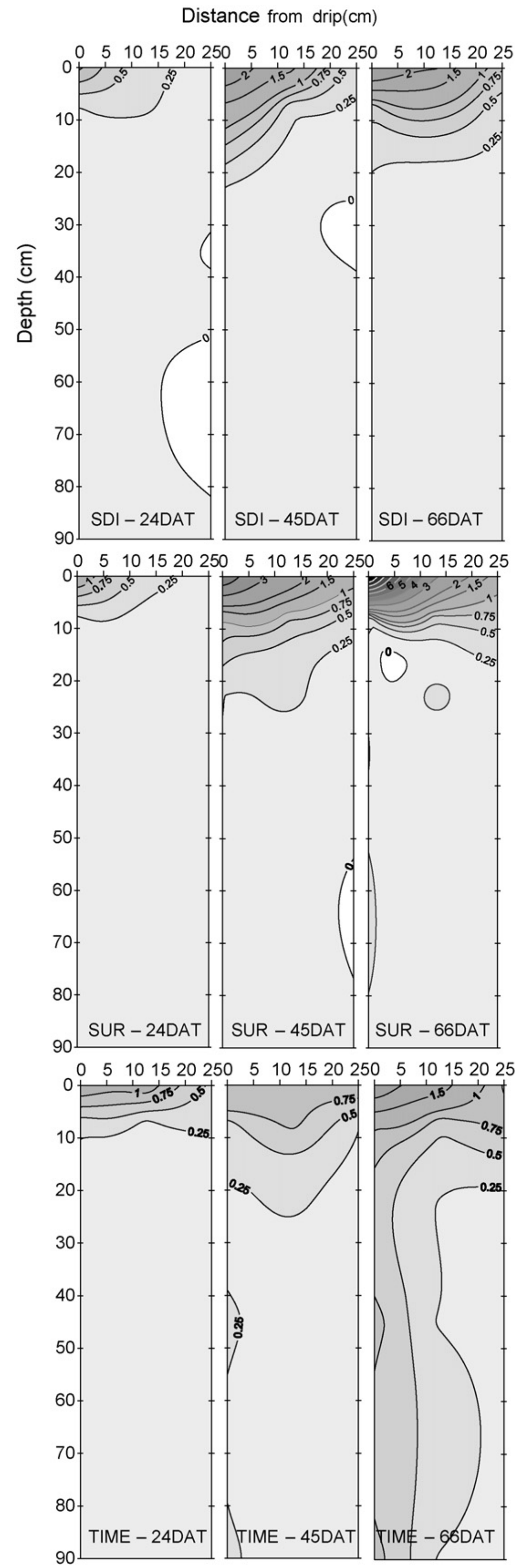

Fig. 5 – Tomato root length distribution (cm cm^{-3}) as affected by soil depth and distance to the bed center at 24, 45 and 66 days after transplanting (DAT). Note that darker shades indicate higher root densities.

Table 5 – Root length density (cm cm^{-3}) by interactions between irrigation and sampling date (top); sampling position and sampling date (center); and soil depth and sampling date (bottom) during the 2006 cropping season

	Date		
	24 DAT	45 DAT	66 DAT
Irrigation			
SUR	0.20 Ba	0.59 Ab	0.68 Ab
SDI	0.23 Ca	1.00 Ba	1.50 Aa
TIME	0.32 Ba	0.48 Bb	0.81 Ab
Position			
P1	0.39 Ca	1.08 Ba	1.65 Aa
P2	0.23 Cab	0.67 Bb	0.88 Ab
P3	0.13 Ab	0.31 Ac	0.46 Ac
Depth (cm)			
0–15	0.70 Ca	1.83 Ba	2.79 Aa
15–30	0.22 Bb	0.63 Ab	0.70 Ab
30–60	0.05 Ab	0.18 Ab	0.26 Ac
60–90	0.03 Bb	0.11 ABc	0.23 Ac

P1: on the irrigation/fertigation drip; P2: in-row at 0.125 m distance from the drip line and immediately adjacent to a tomato plant; P3: in-row at 0.25 m distance from the drip; DAT: days after transplanting. Means within rows having same uppercase letters and means within columns having same lowercase letters do not differ at the $P \leq 0.05$ level according least square means differences. SDI: subsurface drip irrigation controlled by soil moisture sensor; SUR: surface drip irrigation controlled by soil moisture sensor; TIME: time-fixed irrigation.

60–90 cm depth layer, respectively. There were no differences in RLD across irrigation treatments for 30–60 and 60–90 cm depth layer and the values ranged between 0.07 and 0.36 cm cm^{-3}.

The combination of reduced irrigation rate and drip irrigation position in the SDI treatment directly affected the soil water movement dynamics, and increased the residual soil nitrate concentration in the 0–0.3 m depth layer. Average soil nitrate concentration at 74 DAT (6 days after the fertigation event) for SDI was 32 mg of N-NO_3^- kg^{-1} of soil, while respective values for SUR and TIME were 12 and 2 mg of N-NO_3^- kg^{-1} of soil in the 0–30 cm depth. In the 30–60 cm depth, TIME showed the lowest value of nitrate concentration (1.5 mg kg^{-1}), followed by SDI (7 mg kg^{-1}) and SUR (10 mg kg^{-1}). The frequent application of small volumes of water tended to result in the wetting front being closer to the surface and center and thereby also in a reduction of N displacement/leaching. As a result, this greatly enhanced root proliferation in the moist and N enriched zone close to the surface. Therefore root length densities were relatively high compared to systems where the wetting volume and displacement depth is much greater. Low frequency high volume irrigation systems tended to induce dilution and/or displacement of N-fertilizer in TIME treatment, which resulted in higher root proliferation (Bloom, 1997) below 0.3 m at the bed center underneath the fertigation drip compared to root density values observed for SDI and SUR. However, the total RLD for SUR and TIME was similar (Fig. 5). Relatively high root concentrations at greater soil depths for TIME did not result in relative yield benefits. In contrast, despite that roots may have proliferated at greater soil depth, the overall resource utilization may have been reduced for the TIME treatment. For the SMS-based treatments both water and nutrient retention near the surface appears to mimic the genetic tendency of the crop to form, especially during initial growth, most of its roots near the surface. The increase in root density for SUR and SDI, could not overcome the much faster displacement of labile nutrients and thus did not result in additional yield or biomass accumulation benefits. In the case of TIME leaching was often very intense (Fig. 4) resulting in soil N values invariably low despite high N application rates.

4. Conclusions

Soil-moisture sensor based irrigation systems in tomato significantly reduced the applied irrigation on tomato, with the surface drip irrigation controlled by soil moisture sensor treatment resulting in 15–51% less irrigation water applied compared to fixed time irrigation (TIME) treatments. Corresponding reductions in irrigation water application for subsurface drip irrigation controlled by soil moisture sensor were 7–29%. However, due to the soil moisture sensor positioning as related to the location of the irrigation drip, higher irrigation water application occurred. Tomato yield was also increased 11–26% for SMS-based treatments compared to the TIME treatment, in 2006 and 2007, when weather was not a yield-limiting factor. Tomato roots were most concentrated in the vicinity of the irrigation/fertigation drip line and significantly higher concentration of roots were found in the upper 15 cm for the SDI treatment, which may be related to lower nitrogen leaching in the soil profile. Use of N application rates above 176 kg ha^{-1} of N did not result in yield benefits. It is concluded that appropriate use of SDI and/or sensor-based irrigation systems can allow growers to sustain profitable yield while reducing irrigation application in low water holding capacity soils.

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