SOIL MOISTURE-BASED IRRIGATION CONTROL TO CONSERVE WATER AND NUTRIENTS UNDER DRIP IRRIGATED VEGETABLE PRODUCTION

M.D. Dukes, R. Muñoz-Carpena, L. Zotarelli, J. Icerman, J.M. Scholberg

Agricultural and Biological Engineering Department, University of Florida, 107 Frazier Rogers Hall, PO Box 110570 Gainesville, FL 32611-0570. E-mail: mddukes@ufl.edu

ABSTRACT. Plastic mulch and drip irrigation are commonly used in high intensity vegetable production regions such as Florida. Drip irrigation can be much more efficient than sprinkler irrigation since only the root zone of the cropped area is irrigated. However, improper irrigation management can lead to wasted water and leaching of soluble chemicals such as nitrate. The objectives of this project were to optimize tomato and green bell pepper yield under varying levels of soil moisture controlled drip irrigation. Three nitrogen rates (80%, 100%, and 150% of the recommended rate) and several irrigation treatments were imposed on drip irrigated tomato and pepper. Irrigation treatments included soil water based automatic treatments set at 10% volumetric water content (VWC; field capacity) and 13% VWC. Both soil water based treatments were allotted five irrigation windows daily and bypassed events if the soil water content exceeded the established threshold. For comparison a treatment was established consisting of a single timed event each day in an attempt to mimic typical farmer practices. The lower irrigation set point tended to reduce irrigation and nitrate loss while maintaining and even increasing the crop yields, compared to the fixed time irrigation schedule. Soil moisture monitoring and modeling confirmed field results by showing that soil moisture based irrigation resulted in more stable soil moisture conditions (within the crop requirements) in the root zone and that this practice reduced percolation and leaching of nitrogen needed by the crop.

RESUMEN. El riego localizado bajo plástico se utiliza frecuentemente en regiones de horticultura intensiva como Florida. El riego localizado puede ser mucho más eficiente que el riego por aspersión puesto que la aplicación de agua se limita a la zona radicular del cultivo. Sin embargo el mal control del riego puede dar lugar a perdidas de agua y lixiviación de agroquímicos solubles como los nitratos. Los objetivos de este trabajo son la optimización de la producción de pimiento y tomate bajo diferentes regímenes de humedad del suelo. Para ello varios tratamientos de riego fueron combinados con dosis de fertirrigación nitrogenada (80%, 100% y 150% de la dosis recomendada en la zona). Los tratamientos de riego incluyeron el control automático de la humedad del suelo al 10% y 13% de humedad volumétrica. Ambos tratamientos basados en humedad del suelo fueron programados para dar un máximo de 5 aplicaciones diarias y saltarse el turno de riego automáticamente si el contenido de humedad del suelo al principio del turno superaba los niveles establecidos. Como control se estableció un sistema por calendario con una aplicación diaria siguiendo las prácticas comunes del regante en la zona. El tratamiento de riego basado en el punto de humedad del 10% redujo el riego aplicado mientras que aumentó la producción del cultivo con respecto al control. El seguimiento de la humedad del suelo y su simulación por ordenador confirmaron estos resultados al mostrar que el contenido de humedad se mantuvo más estable y adecuado al cultivo en este tratamiento, y se redujo el drenaje y las perdidas por lixiviación del nitrógeno necesario para el cultivo.

1.- Introduction

Vegetables are a major component of Florida agriculture encompassing about 72.000 ha for production and exhibiting a crop value of 1.5 billion dollars. In 2005, more than 24.6 Mha of tomato and green bell pepper were cultivated in Florida, which represented, respectively, about 30% and 32% of national area planted. In the same year, the value of these crops in Florida was about 213 million dollars which corresponded to 49% and 44% of the U.S. vegetable market, for each respective crop (USDA, 2006). Many of the soils where these vegetables are grown are very sandy with water holding capacity of 6-8% by volume or less. Thus, frequent irrigation and fertigation is required to minimize crop stress and to attain maximum production. While irrigation and fertigation practices vary widely among growers, irrigation typically occurs 1-2 times each day in fixed timed events with longer events during peak growth stages. Fertigation on the other hand commonly occurs 1-2 times each week. Although drip irrigation can be very efficient since water and nutrients are delivered to the crop root zone, mismanagement can lead to over-irrigation and excessive nutrient losses due to leaching.

Recently, it has been hypothesized that nitrogen and irrigation water use efficiency (IWUE) for vegetable crop production may be improved through better irrigation management. The use of frequent but low water application volumes has proven superior to the more traditional scheduling of few applications of a large irrigation volumes (Locascio, 2005). Because the former systems may be viewed as labor 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). For example, Dukes et al. (2003) reported a 50% reduction in water use when using a soil moisture sensor-based automated irrigation system for bell pepper as compared to a once daily manually irrigated system without affecting yield.

To accurately predict environmental impacts associated with human practices such as irrigation management, a quantitative description of both water and solute movement through the vadose zone is required. For drip irrigation, it is essential to account for the two dimensional nature of the system. As such, the HYDRUS-2D mathematical simulation model has been used to simulate drip irrigation systems and proven to be a viable predictor of both water and solute dynamics (Mmolawa and Or, 2003; Skaggs et al., 2004; Gardenas et al., 2005). The HYDRUS-2D program numerically solves the Richards' equation for saturated-unsaturated water flow and the convection-dispersion equation for solute transport. The flow equation also incorporates a sink term to account for water uptake by plant roots (Simunek et al., 1999).

The objective of this study was to quantify nitrate leaching and yield response of tomato and pepper in North Florida to irrigation scheduling methods. In addition, the study aimed to measure and reproduce through numerical simulations using HYDRUS-2D a detailed representation of the unique two dimensional water and salinity distributions for surface drip irrigated, raised bed systems.

2.- Materials and Methods

The field experiments were carried out at the University of Florida, Plant Science Research and Education Unit, near Citra, FL, during the spring of 2005 and 2006, and fall 2006. The soil at the research site has been classified as a Tavares sand (Buster, 1979). This soil contains >97% sand-sized particles and has a field capacity of 0.074 ± 0.014 (soil water content reported as percent by volume). Permanent wilting point water content was 0.04 ± 0.01 by volume in the upper 0.2 m of the profile (Carlisle et al., 1978). The area was roto-tilled and raised beds were constructed at 1.8 m apart on center. The raised beds were fumigated (80% methyl bromide, 20% chloropicrin by weight) at a rate of 604 kg ha^{-1} after placement of both drip tape and plastic mulch in a single pass and the tomato (*Lycopersicon esculentum Mill.* var. “Florida 47”) and pepper (*Capsicum annuum* L., ‘Brigadier’) transplanting occurred 10 days after fumigation.

Spring tomato and pepper were transplanted on April 7, 2005 and April 10, 2006, and September 10, 2006 for fall pepper. Tomato plants were transplanted in a single row in the middle of the bed at 0.45 m spacing. Pepper plants were planted 0.3 m apart in twin staggered rows spaced at 0.3 m. Weekly fertigation schedules were used for N (Maynard et al., 2003a; Maynard et al., 2003b) and the total N applied was 208 and 220 kg N ha^{-1} for pepper and tomato, respectively. Fertilizer sources and rates used were potassium chloride at 207 kg ha^{-1} of K_2O and magnesium sulfate at 10 kg ha^{-1} of Mg. Fertigation was performed by injection of dissolved fertilizer salts into fertigation lines with a peristaltic pump. In the fall, 220 kg ha^{-1} of 10-10-10 fertilizer was banded and mixed into soil during the bed formation. This application represented 22 kg ha^{-1} of N, P_2O_5 and K_2O applied, respectively. In the spring, the same pre-planting fertilization was mixed into soil during the bed formation, except for N.

A weather station located within 500 m of the experimental site provided hourly temperature, relative humidity, solar radiation and wind speed data. Irrigation was applied via drip tape (Turbulent Twin Wall, 0.20 m emitter spacing, 0.25 mm thickness, 3.8 L hr-1 at 69 kPa, Chaplin Watermatics, NY). And, 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). Weekly meter measurements were manually recorded and 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) 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.

2.1. Irrigation treatments

For tomato, the irrigation treatments were as follows: 1) SMS1 – commercial RS500 soil moisture sensor controller manufactured by Acclima, Inc. (Meridian, ID), installed at a 30 degree angle between two plants that measured the soil moisture in the upper 0 to 0.15 m of the bed. This control system bypassed scheduled timed events if the soil moisture level was above 0.10 m^3 m^{-3} VWC (Dukes and Muñoz-Carpena, 2006), 2) SDI – irrigation events were controlled by a Quantified Irrigation Controller (QIC) system (Muñoz-Carpena et al., 2006) which included a 0.20 m long ECH_2O probe (Decagon Devices, Inc. Pullman, WA) to measure soil moisture. This treatment featured subsurface drip irrigation (SDI) tape positioned 0.15 m below the surface fertigation line. Probes were inserted vertically in order to integrate the soil water content in the upper 0.2 m of the soil profile. The QIC irrigation controllers allowed events if measured soil water content was below a volumetric water content (VWC) value of 0.10 m^3 m^{-3} (510 mV probe output) during one of five possible 24 min irrigation windows each day. Depending on the VWC readings, up to a maximum of five irrigation events with a 2 hr total could occur per day, equivalent to the FT – fixed time irrigation of one 2 hr event each day established to mimic typical farmer practices.

Pepper irrigation treatments were as follows: 1) SMS1 – commercial RS500 soil moisture sensor controller, installed at a 30 degree angle between two plants that measured the soil moisture in the upper 0 to 0.15 m of the bed. Again, this control system bypassed scheduled timed events if the soil moisture level was above 0.10 m^3 m^{-3} VWC, 2) SMS2 – commercial RS500 soil moisture sensor controller manufactured by Acclima set to bypass scheduled timed events if the soil moisture level was above 0.13 m^3 m^{-3} VWC, 3) FT – a time-based irrigation treatment with one fixed 2 hr irrigation event per day.

2.2. Measurements and monitoring

The harvest area was the central 10.5 m region within each 15 m long plot. Weight of fruits per grading class was recorded for individual plots and marketable weight was calculated as total harvested weight minus culls. Irrigation water use efficiency (IWUE) expressed in kg of fruits m^{-3} was calculated dividing marketable yields (kg ha^{-1}) by the total seasonal irrigation applied (m^3 ha^{-1}).

The volumetric water content on the top soil of the bed was monitored by coupling time domain reflectometry (TDR) probes (CS-615, Campbell Scientific, Inc. Logan, Utah) with a datalogger (CR-10X, Campbell Scientific, Inc., Logan, Utah). Soil moisture probes recorded soil moisture values hourly during 2005 and every 15 min during 2006. For tomato, the upper probe was inserted at an angle in order to capture soil moisture of 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 m and 0.55 m. For pepper, only the upper 0.15 m soil layer was monitored by TDR.

Drainage lysimeters were installed 0.75 m below the surface of the bed (Zotarelli et al. 2007). Leachate extraction occurred weekly one day prior to fertigation. Total leachate volume was determined gravimetrically and subsamples collected from each bottle were analyzed for nitrate plus nitrite nitrogen, allowing for total N loss determination. Composite soil samples were taken at the 0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m soil depths. A 10 g subsample was extracted with 50 mL of 2 M KCl and filtered within one day of soil sampling. Soil solution and soil core extracts were stored at –18 ºC until analysis. Samples were analyzed using an air-segmented automated spectrophotometer (Flow Solution IV, OI Analytical, College Station, TX) coupled with a Cd reduction approach (modified US EPA Method 353.2).

Statistical analyses on the randomized complete block designs were performed using PROC GLM of SAS (SAS Inst. Inc., 1996) to determine irrigation treatment effects. When the F value was significant, a multiple means comparison was performed using Duncan Multiple Range Test at a P value of 0.05.

2.3. Modeling

In 2006, soil moisture was measured at 15 minute intervals by CS616 (Campbell Scientific Inc., Logan, UT) time domain reflectometers. A matrix containing eight TDRs was installed in one of the FT treatment rows. An approximately 40 cm long section centered under an emitter of the entire bed width was removed from the installation location. This section provided enough space for horizontal TDR installation parallel to the surface. Tomato plants were located near the start of the 30 cm long probes. After installation the section was repacked with the original soil. The matrix was configured in a 2 X 4 (depth X width) formation, with the top row buried at 8 cm and a bottom row at 23 cm below the surface of the bed. The four columns were spaced 16 cm apart centered directly under the drip tape. The purpose of the matrix configuration was to capture the hypothesized wet-bulb shape of water redistribution under the emitter. A similar matrix of Hydra Probe II (Stevens Water Monitoring Systems, Inc., Portland, Oregon) probes was installed on the opposite side of the bed to measure moisture content and salinity. For measurement comparisons, an identical group of two matrices was installed in a representative SMS treatment. For model calibration purposes, symmetrical probe locations were averaged to match the half-bed geometry used in model simulations.

The modeling of different irrigation scenarios was conducted using the computer simulation model HYDRUS-2D. The program numerically solves Richards' equation for saturated-unsaturated water flow and the convection-dispersion equation for solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The modified form of Richard’s equation used in HYDRUS-2D is seen in Equation 1, where θ is the volumetric water content [L^3L^{-3}], h is the pressure head [L], S is a sink term [T^{-1}], x_i are the spatial coordinates [L], t is time [T], are components of a dimensionless anisotropy tensor KA, and K is the unsaturated hydraulic conductivity function [LT^{-1}],

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^{A}\frac{\partial h}{\partial x_j} + K_{iz}^{A}\right)\right] - S \tag{1}$$

To correctly model the described system great importance is placed on an accurate quantification of the soil water retention curve. Accordingly, the van Genuchten-Mualem model (Eqns. 2-3) for unsaturated hydraulic conductivity was inversely calibrated to the system. The van Genuchten-Mualem equations are defined where θ_r is residual water content [L^3L^{-3}], θ_s is saturated water content [L^3L^{-3}], h is pressure head [L], α is soil water retention coefficient [L^{-1}], n and m are scaling factors [-], S_e is degree of saturation [-], and K_s is saturated hydraulic conductivity [LT^{-1}],

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} & h > 0 \\ \theta_r & h \le 0 \end{cases} \tag{2}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (3)$$

where m = 1 – 1/n, n > 1. The van Genuchten-Mualem model within HYDRUS-2D contains five independent input parameters (θ_r, θ_s, α, n, and K_s), which were optimized to the field site. HYDRUS-2D also requires a pore-connectivity parameter l that was estimated to be 0.5 for all scenarios. The water content tolerance was lowered to 0.005 [L^3L^{-3}] representing the absolute magnitude of change allowed for unsaturated nodes between two iterations within a time step (Simunek et al., 1999). For all model runs only half of the bed area was considered with calibration performed under the assumption that water flow is symmetrical across the vertical plane directly beneath the emitter (Wooding, 1968; Warrick, 1974). A wetted radius of 2.5 cm was assumed for the cross section and held constant throughout irrigation events. It should be noted that the wetted radius under a drip emitter is in fact dynamic, expanding as the irrigation event progresses (Goldberg et al., 1971), but the variable flux boundary condition in HYDRUS-2D is static in length (Simunek et al., 1999). The lower boundary of the profile was assumed to have free drainage and all other boundaries were assumed to undergo no flux. No flux was assumed since the bed is covered in plastic mulch, eliminating surface evaporation and with no vegetation between rows. ET in the inner-row area was assumed to be negligible. The optimization process included within HYDRUS-2D follows the Levenberg-Marquardt nonlinear minimization method, which is a combination of the Newton and steepest descend methods (Simunek et al., 1999). The five soil water retention curve parameters (θ_r, θ_s, α, n, and K_s) were included in the optimization function.

The system was calibrated using collected soil moisture data from the FT irrigation treatment. After calibration, week long scenarios for high frequency irrigation and single event irrigation were simulated, representing the SMS1 and FT irrigation treatments respectively. The resulting soil moisture distributions are compared.

3.- Results and discussion

3.1. Crop yield, nitrogen leaching and water use efficiency

The use of soil moisture sensors increased tomato yield between 21% and 43% compared to FT irrigation treatment (Table 1). In 2005, tomato marketable yield was similar for SDI and SMS reaching about 32 Mg ha^{-1}; however, in 2006 the same treatments yielded 52 and 64 Mg ha^{-1}, respectively. The increase in tomato yield in 2006 compared to 2005 was attributed to several combined factors. First, the overall volume of irrigation applied was higher in 2006 compared to 2005, allowing for more water uptake. Second, in 2005 some tomato plants were infected by bacterial spot caused by *Xanthomonas campestris* and due to the occurrence of frequent rainfall events (Fig.1) the disease spread rapidly, although it was chemically controlled a few days after the diagnostic. Meanwhile, in 2006 favorable weather conditions such as lower temperatures, lower humidity, and little precipitation during the reproductive phase (Fig. 1), resulted in no disease occurrence. In terms of tomato fruit quality, SDI and SMS1 treatments showed lower weight classified as cull compared to the FT treatment. The FT treatment rendered about 16 to 24% of the total harvested fruits as culls, while for the SMS1 treatments only 9 to 13% of the fruits were classified as culls.

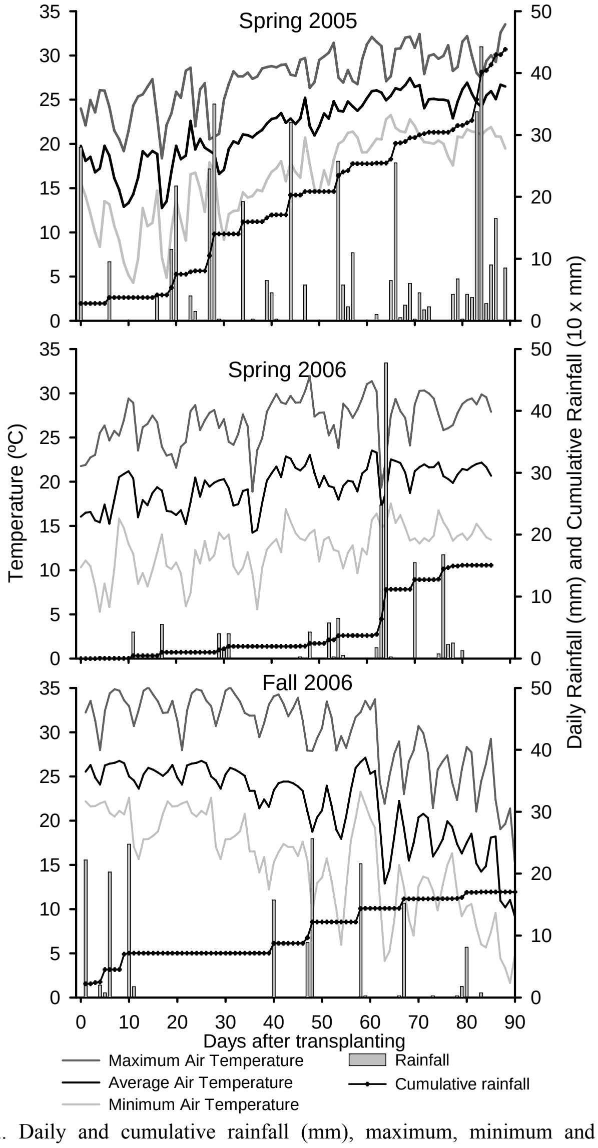

Fig. 1. Daily and cumulative rainfall (mm), maximum, minimum and average of daily temperature (ºC) during the spring growing seasons of 2005 and 2006 and fall season 2006.

Water use efficiency (IWUE) was significantly higher for the SMS treatment in both seasons, followed by SDI, and then FT. In fact, the use of SMS not only reduced the volume of water applied by irrigation, but also increased the yield compared to FT. The low yield levels observed for the FT treatment may be related to excessive N leaching below the root zone (Figs. 2 and 3).

In the spring pepper season, marketable yields ranged between 13.0 to 29.6 Mg ha^{-1}, but no differences were observed for irrigation treatments. The use of a soil moisture sensor at the higher soil moisture threshold did not increase pepper yield or quality. About 9 and 17% of the total yield were classified as culls, in 2005 and 2006 respectively. The use of SMS with a lower irrigation threshold increased the IWUE of peppers without reducing yield. The treatment SMS1 resulted in at least 49% higher irrigation water use efficiency than the other irrigation treatments, again while maintaining statistically similar yields.

Table 1. Irrigation depth, irrigation water use efficiency (IWUE), marketable (Mkt.) yield for pepper and tomato cultivated in 2005/2006.

Irrigation Treat.	Irrigation mm	Irrigation mm d^{-1}	Mkt. Yield Mg ha^{-1}	IWUE* kg frt m^{-3}
		Tomato 2005		
SDI	229	3.1	30.4 a†	13.3 b
SMS1	125	1.7	33.3 a	26.6 a
FT	248	3.3	18.7 b	7.5 c
C.V.(%)			18.6	18.6
		Tomato 2006		
SDI	309	4.1	52.5 ab	17.0 b
SMS1	264	3.5	63.9 a	24.7 a
FT	441	5.9	41.3 b	9.4 c
C.V.(%)			18.8	18.3
		Pepper 2005		
SMS1	111	1.4	25.4 ns	22.9 a
SMS2	206	2.5	9.6	14.4 b
FT	322	3.9	23.1	7.2 c
C.V.(%)			18.7	12.4
		Pepper 2006 – Spring		
SMS1	368	4.7	15.1 ns§	4.1 ns§
SMS2	393	5.0	13.0	3.3
FT	445	5.7	17.1	3.8
C.V.(%)			23.2	19.0
		Pepper 2006 – Fall		
SMS1	283	3.1	47.2 ns§	16.7 a
SMS2	389	4.2	45.3	11.6 b
FT	369	4.0	48.4	13.1 b
C.V.(%)			8.0	20.2

† Means within columns followed by the same lowercase letters are not significantly different ($p < 0.05$) according to Duncan's multiple range test.

§ ns = not significant. *Irrigation water use efficiency calculated as marketable yield divided by irrigation water applied.

In the fall, the overall yield was 65% higher than marketable yields during the spring seasons. This increase was also attributed to favorable weather conditions including the absence of freezing events, and cooler night temperatures during the reproductive phase. The yield in the fall ranged from 45.3 to 48.4 Mg ha^{-1}, but again, no statistical differences were observed between irrigation treatments (Table 1). The use of SMS resulted in a higher IWUE by pepper. Treatment SMS1 was 15% more efficient in water use than the FT treatment. For all seasons, there were no differences in quality of fruits and the number of fruits per square meter (data not shown) between treatments. An establishment phase where similar irrigation was applied to all treatments lasted 15 days after transplanting (DAT); afterwards the irrigation treatments were initiated (Fig. 2AB, 3ABC).

For the tomato trial, the lowest volume of water applied was in the SMS treatment, which received 1.7 and 3.5 mm day^{-1}, for 2005 and 2006 respectively. The corresponding volumes for the SDI treatment were 3.1 and 4.1 mm day^{-1}.

The implementation of an SDI system resulted in higher water application, even with the same SMC threshold for both treatments. This is likely due to the SDI treatments subsurface irrigation drip tape (15 cm below the soil surface) resulting in a slightly drier top soil where the irrigation control sensor was located. Interestingly, the fertigation events under SDI showed higher spikes of SMC than SMS or FT treatments (Fig. 4ABC).The FT treatment resulted in the highest volume of water percolated below root zone. About 18 and 13% of the total irrigation water applied was collected by the lysimeters, in 2005 and 2006, respectively.

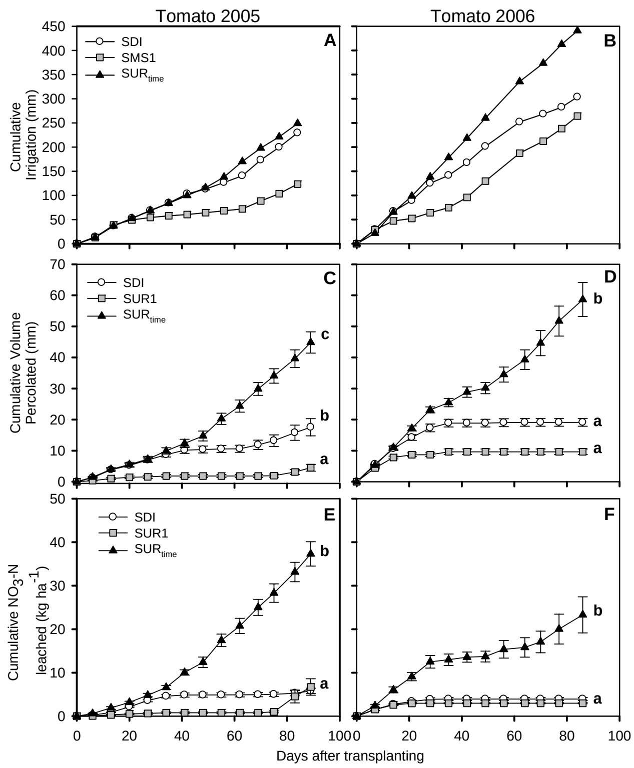

Fig. 2. Cumulative irrigation applied for tomato cultivated in spring 2005 (A) and spring 2006 (B), volume of water percolated in spring 2005 (C) and spring 2006 (B) and cumulative nitrate leaching in spring 2005 (E) and spring 2006. Different letters indicate statistical differences ($P < 0.05$) according to Duncan's test and error bars represent ± half a standard error from the mean, n =4) .

A larger volume of irrigation was applied for FT in 2006 than 2005; however, less percolation occurred, likely due to warm and dry conditions causing higher crop demand. For example, the tomato plants yielded two times more in 2006 which resulted in higher water consumption. The SDI and SMS treatments resulted in a significant reduction of water percolation. The volume percolated under SDI and SMS treatments ranged between 4 to 7% of the total irrigation water applied; however, for these treatments most of the water percolation occurred during the establishment phase, when the irrigation method was similar to FT treatment (Fig. 2CD).

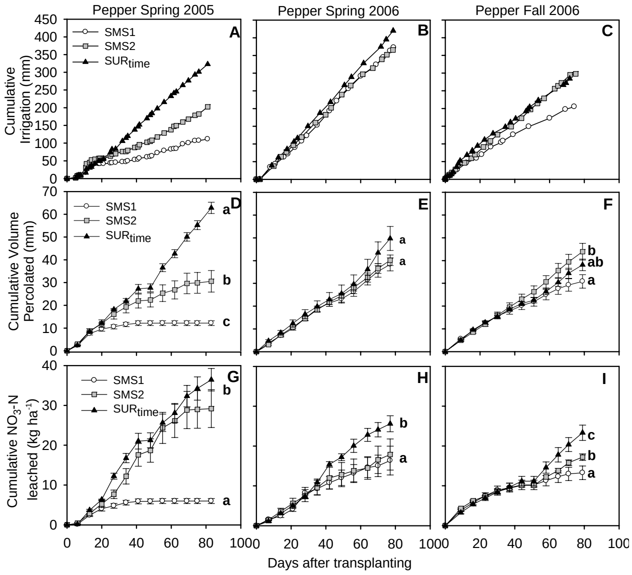

Fig. 3. Cumulative irrigation applied for pepper cultivated in spring 2005 (A), spring 2006 (B) and fall 2006 (C), volume of water percolated in spring 2005 (D), spring 2006 (E) and fall 2006 (F), and cumulative nitrate leaching in spring 2005 (G), spring 2006 (H) and fall 2006 (I). Different letters indicate statistical differences (P < 0.05) according to Duncan test and error bars represent error bars represent ± half a standard error from the mean, n =4)

Cumulative NO_3-N leaching values ranged from 23 to 37 kg ha^{-1} of N for the FT treatment, in 2006 and 2005, respectively. The single high volume nature of the FT treatment is likely the cause of the appreciable drainage below the root zone. Conversely, the SMS and SDI treatments reduced nitrate leaching on the order of 85%, representing a total load of 3 to 6 kg N ha^{-1} (Fig. 2EF). The reduced irrigation rate associated with use of SDI and SMS resulted in higher residual soil N concentrations in the 0-0.3 m soil depth six days after fertigation events, both during initial crop development and towards the end of the growing season.

Lower sensor thresholds on pepper generally reduced irrigation application. In the spring of 2005 the drier treatment, SMS1 (8% VWC), received 111 mm of water for the entire season, which was equivalent to an irrigation depth of 1.4 mm d^{-1}. The SMS2 treatment received 206 mm (2.5 mm d^{-1}) and the FT 322 mm (3.9 mm d^{-1}).

In both the spring and fall of 2006, problems related to SMS installation resulted in only a slight variation of irrigation volumes between SMS1 and SMS2 even though the treatments differed in VWC thresholds, 10 and 12% respectively. In fact, the application volumes were similar to the FT treatment (Fig. 3BC). Most the errors that occurred during the two seasons resulted from mistakes in controller programming and sensor wiring. It was discovered that when multiple soil moisture sensors are installed on one timer they tend to cross communicate and allowed excessive irrigation, sometimes in excess of programmed windows. In the fall, the problem was isolated to the beginning of the season.

As expected, the highest volume of water percolated from the FT treatment in spring 2005, with 20% of the total irrigation water applied collected by the lysimeters (Fig. 3D). In that year, the SMS1 and SMS2 treatments resulted in a significant reduction of water percolation. However, due to similar irrigation volume application observed in 2006, there was no differences in volume of water percolated between SMS and FT treatments (Fig. 3 DEF). Cumulative NO_3-N leaching values ranged from 23 to 37 kg ha^{-1} of N for the FT treatment. Nitrate leaching decreased with the use of SMS, as the measured values ranged from 5 to 20 kg ha^{-1} of N (Fig. 3GHI). The only exception was SMS2 in 2005, which leached about 30 kg ha^{-1}of N (Fig. 3G), about 10 kg ha^{-1} of N more than expected. Due to a problem with the irrigation controller at 48 DAT (5/25/2005), right after a fertigation event, about 10 mm of irrigation water was applied in less than 24 hr, which greatly increased nitrate leaching for SMS2 treatment.

3.2. Irrigation management

Fig. 4 illustrates the soil moisture content as measured by TDR probes and the occurrence of scheduled irrigation events during several periods throughout the growing season. As seen in the figures, after each scheduled irrigation event there is a noticeable increase in soil moisture content. The degree to which the soil moisture content increases, however, is dependent upon the irrigation treatment.

For example, all of the soil moisture sensor based treatments irrigate for short periods of time and result in a relatively small increase in soil moisture, consequently decreasing the volume of percolate. On the other hand, the FT treatment irrigates for a longer time period resulting in soil moisture spikes. These spikes in soil moisture appear to only be temporary, as the irrigation water rapidly drains and ultimately the soil moisture content returns to where it was before the event in a relatively short period of time (FT, Fig. 4). 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, explaining the higher percolate values for the FT treatment compared to the other treatments (Fig. 2CD and 3DEF). In fact, similar spikes in soil water content were observed at 25-55 cm showing excessive soil water percolation though the soil profile independent of the plant growth stage (Fig. 4 GHI). In terms of soil water availability to plants, the FT treatment initially seemed to be the most effective; however, excessive water percolation resulted in nutrient leaching (Fig. 2EF and 3GHI) and reduced yield for tomato (Table 1).

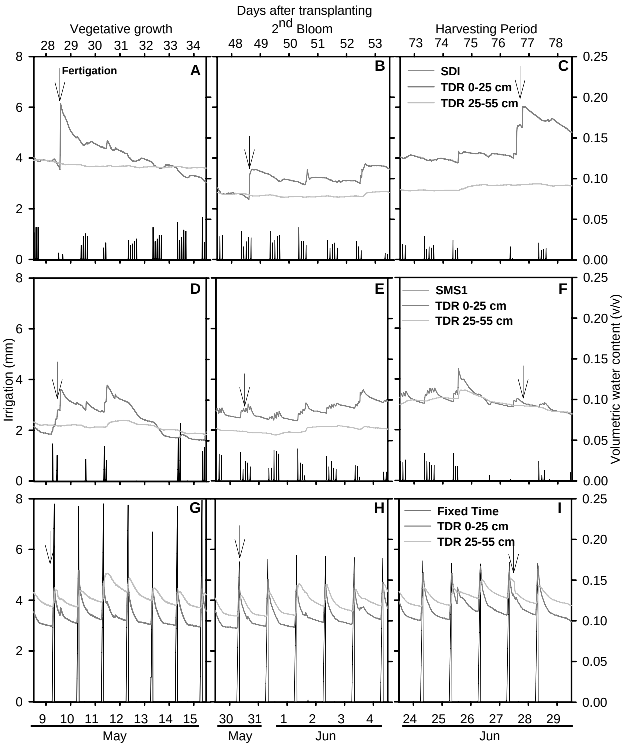

Fig. 4. Daily irrigation events and soil moisture content (0-25 and 25-55 cm depth) for tomato in three plant developtment stages (vegetative growth, 2nd bloom and harvesting period) in spring 2006. The arrows indicate fertigation events.

On the other hand, irrigation water from the SMS treatments produced a relatively steady soil moisture content over time, as irrigation water was distributed across multiple irrigation events according to the soil moisture threshold. In addition, almost no variation in soil moisture was registered by TDR probes at 25-55 cm soil depth layer, indicating that volume of water applied at soil surface did not exceed root water extraction.

3.3. Two Dimensional Measurements

The results of the matrix measurements are seen in Figs. 5 and 6. Figs. 5 displays soil moisture measurements from the entire season. A comparison of the soil moisture distributions seen in the two figures confirms the SMS treatments are held at a lower soil moisture throughout the season, especially evident in the bed edge. The bed edge (represented by the W and E probe locations) for the FT treatment is kept between 8.0% to 10.0%, while the SMS treatment bed edge dropped below 5.0% during the peak of the growing season. The low bed edge soil moisture content implies an accurate allocation of water as none of the applied water reaches the bed edge (outside the main root concentration).

3.4. Modeling

The optimization process yielded a set of hydraulic parameters that calibrated the model to measured field data with a 0.86 R^2 value. The coupled relationship between the water and nutrient dynamics is revealed in Fig. 6. Salinity can be considered a good indicator of nitrate movement and the figures confirm more salts are moved through the soil profile. Also, more salt retention is seen in the SMS1 treatment in the bed edge. The resulting set of hydraulic parameters is listed here: θ_r = 3.0 m^3m^{-3}; θ_s = 35.5 m^3m^{-3}; α = 0.071; n = 1.59; and K_s = 7.44 cm min^{-1}. The averaged shallow edge probe location was excluded from the optimization process as data collected from this location was observed to be unreliable. The single event simulation was irrigated for two hours daily from 0600 to 0800 hrs. The high frequency simulation was irrigated for 24 min windows five times daily starting at 0800, 1000, 1200, 1400, and 1600 hrs. Flow data collected from a treatment similar to SMS1 (same 10% threshold and irrigation windows) revealed 52% of events were bypassed throughout the season, with a standard deviation of 24%.

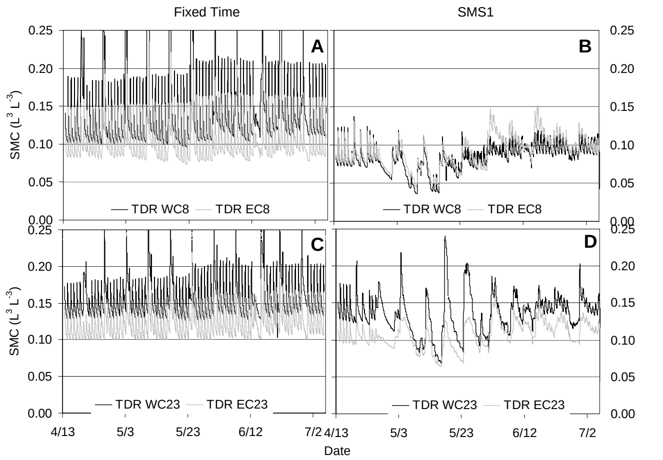

Fig. 5. TDR soil moisture readings for the FT and SMS1 treatment from both the TDR. Probes in the center locations of the matrix are labeled EC and WC. Probes in the edge locations of the matrix are labeled E and W. Depths are denoted by the 8 and 23 labels, representing 8 cm and 23 cm below the surface respectively. (A) displays the center probes at 8 cm for FT; (B) displays the center probes at 8 cm for SMS1; (C) displays the center probes at 23 cm for FT and (D) displays the center probes at 23 cm for SMS1.

During the peak growth period, 40% of events were bypassed with a standard deviation of 17%. Most of the bypassed events occurred at the end of the day, during the 1600 hr irrigation window. To mimic what was observed in the field, a third simulation was added that irrigated 80% of the high frequency simulation window and is subsequently labeled 80% high frequency simulation. In other words, for the 80% high frequency simulation 20% of the events were bypassed. To simulate this reduction the irrigation windows were reduced from 24 min to 19 min for the third simulation. Model results indicate that water percolates below the bed area at the hour mark for the single event simulation where as it takes several redistribution periods (majority of the day) for water to reach the same depth for the high frequency simulations. As expected, the reduced water application of the 80% high frequency simulation creates a overall drier bed throughout the simulation period. As observed in the field, the single event simulation reveals a soil moisture regime conducive to leaching. The lower VWC displayed near the root zone for the high frequency simulation are better for root water uptake compared to the high VWC that occurs within a two hour period for the single event simulation. Overall, the simulation results match the VWCs observed in the field for different irrigation treatments.

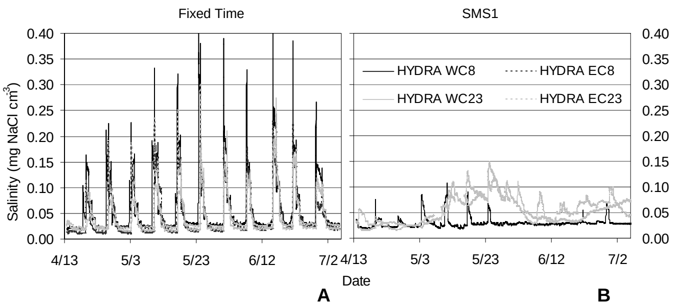

Fig. 6. Salinity readings for the representative FT and SMS treatment from the Hydra Probe matrix. (A) displays probes in the center locations of the matrix labeled EC and WC for FT and (B) displays probes in the center locations of the matrix labeled EC and WC for SMS1. Depths are denoted by the 8 and 23 labels, representing 8 cm and 23 cm below the surface respectively in both graphs.

4.- Conclusions

Soil water controlled irrigation on tomato and pepper resulted in a reduction about 34-60% of irrigation water applied compared to a fixed time based treatment similar to typical grower scheduled irrigation. In addition, yields on tomato were 78% and 54% higher on the two SMS treatments compared to the fixed time treatment, in 2005 and 2006, respectively. Pepper yields on soil moisture sensor controlled treatments were similar to the fixed time treatment. Accordingly, when the amount of irrigation water applied was reduced both percolation of water and NO_3-N leaching decreased significantly. These results show that soil water based irrigation can be used as a water conservation tool and as a means to reduce NO_3-N leaching below the root zone of commercial vegetable cropping systems. Observations from the two dimensional probe setup, again comparing soil moisture sensor and fixed time irrigation treatments, indicate that over irrigation is the main reason for nutrient leaching.

The results of the HYDRUS-2D simulations confirm trends observed in the field. The ability to accurately simulate the different irrigation treatments proves HYDRUS-2D to be a powerful tool for forecasting drip irrigation management changes. The results also suggest simply spreading application times over the entire day as compared to a lumped approach may prove to be a superior management practice allowing for application reductions and possibly improving root water uptake. Of course, the approach would be enhanced by the introduction of a soil moisture sensor for irrigation control.

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