Field Comparison of Tensiometer and Granular Matrix Sensor Automatic Drip Irrigation on Tomato

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Additional index words. **water conservation, soil moisture sensors, soil tension, high frequency, vegetable crops, *Lycopersicon esculentum***

Summary. **A low-volume/high frequency (LVHF) soil moisture-based drip irrigation system was tested on a shallow sandy soil at a commercial tomato (*Lycopersicon esculentum*) farm in southern Florida. Six LVHF irrigation treatments were compared with the standard commercial practice on the farm (control), where a portable pump was used for manual drip irrigation twice each week. In the six LVHF treatments the system was continuously pressurized by means of an electrical pump and a pressure tank, and controlled by an irrigation timer set to irrigate a maximum of five times per day with the irrigation time (i.e., volume) set according to historical evapotranspiration (ET) demands in the area. Two treatments were based on timer schedules, one to supply 100% of the maximum recommended crop water needs in the area based on historical ET (ET-100%), and the other to supply 150% of those needs (ET-150%). The other four treatments were created by interfacing two types of soil moisture sensors (switching tensiometers and granular matrix sensors with control modules) set at two moisture points (wet = 10 kPa, optimal = 15 kPa) in a closed control loop with the irrigation timer programmed at the ET-100% schedule. Results showed that the six LVHF treatments reduced water use while not significantly affecting tomato yields. Switching tensiometers at the 15 kPa set point performed the best (up to 73% reduction in water use when compared to the control, 50% with respect to ET-100%). The results show that water use below historical ET levels can be obtained without sacrificing yield by keeping the root zone moisture at controlled levels with the soil-moisture based system. Routine maintenance was critical for reliable operation of the switching tensiometers. Granular matrix sensor based irrigation behaved erratically, and did not improve water savings compared to ET-100%, indicating that this system was not effective under the conditions of the area due to the sensor's slow response to frequent wetting-rewetting cycles and characteristics of the interface.**

Tomato growers in the United States are at a competitive disadvantage due to off-shore competition from countries where labor is considerably cheaper than in the U.S. Growers will be at an even greater disadvantage with the imminent phase-out of methyl bromide in the U.S. Through proper irrigation, average tomato yields in southern Florida can be maintained (or increased) while minimizing environmental impacts caused by excess applied water and subsequent nutrient leaching. Thus, improving irrigation efficiency can contribute greatly to reducing production costs of tomatoes making southern Florida's tomato industry more competitive and sustainable. Efficient and modern irrigation systems in Florida and other areas where soils with low water holding capacities and shallow rooted crops predominate should utilize the following irrigation principles: 1) low volume-high frequency, 2) soil moisture sensor based scheduling, and 3) automatic operation (Dukes et al., 2003). Soils with water holding capacities in the 4% to 8% range by volume (e.g., sands, gravels) are common in southern Florida and present special water management challenges (Muñoz-Carpena et al., 2002).

Traditional irrigation based on low frequency (a few times per week) and a large volume usually results in over-irrigation in southern Florida soils. With this type of irrigation a large portion of the applied water percolates quickly to the shallow groundwater, potentially carrying with it nutrients and other agrichemicals applied to the soil. In addition, excess water in the root zone from excess irrigation or a high water table can reduce tomato yields (Wang et al., 2004).

As an alternative to traditional irrigation systems, a low volume of water can be applied frequently (several times per day) to maintain a desired moisture range in the root zone that is optimal for plant growth. LVHF also has the potential to minimize leaching. For LVHF systems, the target soil moisture is usually set in terms of soil tension or matric potential (expressed in kPa or cbar), or volumetric moisture (expressed in percent of water volume in a volume of undisturbed soil). Soil water tension is related to the amount of energy that has to be exerted by a plant to extract water from the soil. One other benefit of automatic irrigation techniques is convenience. In a previous experience working

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre	ha	2.4711
1	cbar	kPa	1
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
3.7854	gal	L	0.2642
2.5400	inch(es)	cm	0.3937
25.400	inch(es)	mm	0.0394
1.1209	lb/acre	$kg\cdot ha^{-1}$	0.8922
0.0254	mil	mm	39.3701
28.3495	oz	g	0.0353
6.8948	psi	kPa	0.1450

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The authors wish to dedicate this work to the late Dr. H. Bryan. We thank T.T. Dispenza, C. Kameko, M. Codallo, T. Olczyk, R. Regalado, and Q. Wang for their technical support. Pine Island Farms Inc. contributed with the use of experimental plot and Mr. M. Knight (T-Tape Inc.) donated the drip tape used for the experiment. The use of trademarks does not imply the endorsement by the University of Florida. This research was supported by the Florida Agricultural Experiment Station and a grant(s) from Florida Tomato Committee and the Florida Fruit and Vegetable Association, and approved for publication as Journal Series No. R-10435.

with a soil moisture based automatic irrigation system, Dukes et al. (2003) found that once the system is setup and verified, only weekly observation was required.

Soil moisture can be determined by direct (soil sampling) and indirect (soil moisture sensing) methods. Direct methods of monitoring soil moisture are not used for LVHF irrigation scheduling because they are intrusive and labor intensive and can not provide immediate feedback. Soil moisture probes can be permanently installed at representative points in an agricultural field to provide repeated moisture readings over time that can be used as a guide for irrigation scheduling. They generally can be used for manual readings to guide irrigation scheduling, while some of them can also be interfaced directly with the irrigation controller in a closed loop control system (Zazueta et al., 1994) to automate irrigation. Special care is needed when using soil moisture devices in coarse soils, especially in gravelly loam soils (Krome and Chekika series) present in southern Florida (Muñoz-Carpena et al., 2002). Most devices require close contact with the soil matrix that is sometimes difficult to achieve in these soils.

Tensiometers are among the most widely used tension-based soil moisture monitoring devices in Florida (Muñoz-Carpena et al., 2004; Zazueta and Xin, 1994). The device is based on the principle that when a sealed water-filled tube is placed in contact with the soil through a permeable and saturated porous material (ceramic cup), water inside the tube comes into equilibrium with the soil solution [i.e., it is at the same potential as the water held in the soil matrix (soil matric potential)]. Hence, the soil water matric potential is equivalent to the vacuum or tension created inside the tube. They can be used as stand-alone manual instruments or interfaced with an irrigation controller (switching tensiometers) for automatic watering. Switching tensiometers have been used in various applications such as fresh-market tomatoes (Clark et al., 1994; Smajstrla and Locascio, 1994), citrus (*Citrus* spp.) (Smajstrla and Koo, 1986), and bermudagrass (*Cynodon dactylon*) (Augustin and Snyder, 1984) in Florida to automatically control irrigation events based on preset soil matric potential limits. Smajstrla and Koo (1986) discussed the problems associated with using tensiometers to initiate irrigation events in Florida. Problems included entrapped air in the tensiometers, organic growth on the ceramic cups, and the need for recalibration. Smajstrla and Locascio (1996) reported that using switching tensiometers placed at 6-inch depths and set at 10 and 15 kPa tensions in a fine sandy soil in Florida reduced irrigation requirements of tomatoes by 40% to 50% without reducing yields. Li et al. (1998) showed that tensiometers can also be used successfully for manually scheduling tomato irrigation in calcareous gravelly soils (Krome series). In their study, optimal irrigation at 10 kPa increased yield, improved fruit quality and reduced nutrient leaching. Wang et al. (2004) studied tomato yields in Krome soils with irrigation scheduled by manual readings from tensiometers. When compared to irrigation at 5 kPa (control), they found that all three of the other higher tensions (10, 20, and 30 kPa) used significantly improved yields of marketable, large and extra-large fruit. The highest yield increases were obtained at 30 kPa, and were about 29%, 28%, and 22% greater than those at 5 kPa (control) for yields of marketable, extra-large fruit, and large fruit, respectively.

Although used extensively to automate irrigation systems, tensiometers tend to require more maintenance compared to solid-state sensors such as granular matrix sensors (GMS). GMS are similar to tensiometers in that they are made of a porous material that reaches equilibrium with the soil moisture. The soil moisture tension is obtained using a calibration equation with the electrical resistance between electrodes embedded in the porous material (granular matrix block) inserted in the soil. These sensors have been used to automatically irrigate cotton (*Gossipium* spp.) (Meron et al., 1996), onion (*Allium cepa*), potato (*Solanum tuberosum*) (Shock et al., 2002), containerized plants (Hansen and Pasian, 1999), and urban landscapes (Qualls et al., 2001). Generally, GMS have been found to require less maintenance than traditional tensiometers. Similar to many of the automatic tensiometer controlled irrigation systems, Shock et al. (2002) described a system that used GMS to initiate a timed irrigation event. Although GMS provide a mechanism to control irrigation systems, these sensors with factory calibration equations for generic soil types may not provide adequate control for irrigation in coarse Florida soils (Irmak and Haman, 2001).

The objective of this work was to evaluate a LVHF automatic irrigation system interfaced with two different soil moisture sensor types in a commercial setting and compare it to the common grower practice in the area and scheduling methods using historical evapotranspiration. Water use, crop yields, advantages and disadvantages of the system and sensors are presented.

Materials and methods

FIELD EXPERIMENT SITE AND CROP MANAGEMENT. A research and demonstration project was conducted on a commercial tomato farm, Pine Island Farms, Miami, Fla. The experiment was conducted in a 1.5-acre experimental plot within a 40-acre commercial tomato field. The soil was Dade fine sand (12 inches overlaying porous limestone bed rock), hyperthermic, uncoated spodic Quartzipsamment (USDA, 1996). Tomatoes were grown on raised beds at 6-ft spacing. Twin rows of drip tape [T-TAPE TSX 508-12-450 (0.6-inch i.d., 12-inch emitter spacing, 0.27-gal/h emitter discharge at 10 psi, 8-mil thick); T-Systems International, San Diego, Calif.] were laid on the beds and covered with plastic mulch according to local production practices (Table 1). During bed formation, fumigant [Dowfume MC-33 (2:1 volumetric mix of methyl-bromide: chloropicrin); Albemarle Corp., Baton Rouge, La.] was injected into the soil at 350 lb/acre during the formation of the raised beds, and immediately thereafter the drip lines and plastic mulch were installed.

After the beds were prepared, planting was postponed 3 months due to a delay in obtaining the electrical power needed to operate the irrigation system. Tomato seedlings ('Florida 47') were transplanted on 4 Feb. 2003 at 24 inches apart along twin staggered rows that resulted in 7255 plants/acre and was identical to the commercial production system. After transplanting, all irrigation treatments and the control were irrigated alike for 10 d (2 h·d^{-1}) to promote seedling establishment. Irrigation treatments were initiated thereafter according to Table 2. Fertilizer injections (fertigation) were in accordance with the farmer schedule

Table 1. Irrigation system specifications and relevant horticultural parameters for the tomato crop.[z]

Hardware	Horticultural parameters
Pump: 745.7 W (1 horsepower)	Maximum crop needs = $3.5\ \text{mm}\cdot\text{d}^{-1}$
Well tank: 750 L, pressure control 244–340 kPa	Surface per sub-plot = $330\ \text{m}^2$ Maximum needs/subplot = $1155\ \text{L}\cdot\text{d}^{-1}$
Controller: Rain-Bird ESP-12LX (Glendora, Calif.)	Maximum time to irrigate each plot ~$60\ \text{min}\cdot\text{d}^{-1}$
Main line: “lay-flat” 50.8 mm	Maximum no. of irrigations per day = 5
Pressure regulators: 136 kPa (end of main line); 68 kPa (after valves)	Time per irrigation event = 12 min/plot
Solenoid valves: 24VAC, 13-mm diameter	
Laterals:	
Drip tape = two lines/bed, T-TAPE TSX 508-12-450 (T-Systems, San Diego, Calif.)	
Internal diameter (i.d.) = 16 mm	
Drip spacing = 0.30 m	
Nominal flow = $5.6\ \text{L}\cdot\text{min}^{-1}$ per 100 m	
Nominal pressure = 52 kPa	
Lateral length: 183 m (two lines)	
Pressure at inlet (*hi*): 68 kPa	
Pressure at end (*ho*): 36 kPa	
Lateral flow: $18.2\ \text{L}\cdot\text{min}^{-1}$ (two lines)	

[z] 1 L = 0.2642 gal; 1 kPa = 0.1450 psi; 1 mm = 0.0394 inch; 1 m = 3.2808 ft; 1 m^2 = 10.7639 ft^2.

by adding extra irrigation events off the preset timer schedule (early morning), to apply equal amounts of water and chemicals for all treatments. Tomatoes were cultured and protected according to local agronomic practices. Pre-plant dry fertilizer (6N–2.6P–10K) at 1431 lb/acre was rototilled into the bed. Dissolved fertilizer (4N–0P–6.7K) was applied weekly at 18 lb/acre during each of the final 5 weeks prior to harvest. There was a 2-week delay of the systemic insecticide injection needed to protect plants from transmission of tomato yellow leaf curl virus (TYLCV) by whiteflies (*Bemisia* spp.), and in initiating fertigation. The delay was caused by equipment difficulties. The first tomato harvest occurred on 21 Apr. 2003 followed by the second and final harvest 2 weeks later, resulting in a 76-d season.

Irrigation treatments. Seven irrigation treatments, each with three replicates, were established on beds 600 ft long (Fig. 1 and Table 2). Treatments t1–t6 were LVHF. All replications, except those for time-based treatments (t5 and t6), were controlled independently by a commercially available time based irrigation controller (ESP Series; Rain Bird, Inc., Glendora, Calif.) by means of a solenoid valve (Table 1). A water meter and pressure regulator were installed at the entrance of the drip lines. An electrical pump in line with a pressurized tank maintained pressure in the system. Table 1 provides details of the design of the irrigation system installed in the plot. The soil moisture sensors were installed 100 ft from the solenoid valve, between plants, in the center of the bed and wired in closed loop control with the irrigation timer (Zazueta et al., 1994) according to the manufacturers’ specifications. The low-tension switching tensiometers used (model TGA-LT; Irrometer Co., Riverside, Calif.) contain an adjustable tension level selector mounted on top of the tensiometer gauge that was set to the desired tension (read directly on the gauge, 10 and 15 kPa for t1 and t2, respectively). When the gauge needle falls below the set point (wetter soil) the magnetic relay in the selector opens (irrigation override). The GMS were

Table 2. Description of the irrigation treatments, soil moisture based sensor control, and soil moisture thresholds used in this research.

Treatment no.	Treatment	Description	Sensor	Set point threshold [kPa (cbar)][y]
t1	T-10	Soil tension based, max. of five events/day (12 min each)	Switching low-tension tensiometer (model TGA-LT; Irrometer, Inc., Riverside, Calif.)	10
t2	T-15	Soil tension based, max. of five events/day (12 min each)	Switching low-tension tensiometer (model TGA-LT)	15
t3	WM-10	Soil tension based, max. of five events/day (12 min each)	Granular matrix sensor (Watermark WEM-II; Irrometer, Inc.)	10
t4	WM-15	Soil tension based, max. of five events/day (12 min each)	Granular matrix sensor (Watermark WEM-II)	15
t5	ET-100%	Five events/day (12 min each) to apply 100% of maximum crop needs[z]	---	---
t6	ET-150%	Five events/day (18 min each) to apply 150% of maximum crop needs[z]	---	---
t7	Control (farmer)	Standard grower’s schedule (2–3 times/week, 2–3 h/irrigation) typical in the area (high volume–low frequency)	---	---

[z] Based on maximum tomato water needs for Miami (Simonne et al., 2001).

interfaced with proprietary electronic modules (WEM II; Irrometer Co.) that contained an adjustment dial to set differing soil moisture levels [i.e., wet = positions 1 to 4 (10 to 25 kPa); intermediate = positions 5 to 8 (35 to 70 kPa); dry = positions 9 to 11 (85 to 120 kPa)]. Positions 1 and 3 (10 and 15 kPa) were selected for treatments t3 and t4, respectively, based on initial testing in the laboratory with the field soil. With both systems the timer is overridden (i.e., current is not sent to the valve and the solenoid valve remains closed) if sufficient soil water is available (matric potential less than 10 or 15 kPa). Irrigation windows were established based on treatment t5 [ET-100% (i.e., five events/day for each sensor based replication)] corresponding to the crop maximum water requirement (ET) for tomatoes recommended in the Miami area based on historical ET estimates (Simmone et al., 2001). A significant volume of water can potentially be saved with this system during periods of reduced plant-water needs, and the moisture kept at optimal levels in the root zone.

Water use and yield analysis. Water use in each treatment was continuously recorded by a positive displacement water meter equipped with a magnetically actuated reed switch [PSM-T (5/8 × 1/2 inch); ABB Water Meters, Ocala, Fla.] connected to an event data logger (H7-002-04; Onset Computer Corp., Bourne, Mass.). Weekly readings were also manually taken from the counters in each water meter. Values obtained from replications in each treatment were averaged.

Harvest was carried out in 183-ft^2 subplots of 15 plants each distributed along the center row of each treatment. Eight subplots were harvested for treatments t1–t4, and three subplots for t5–t7. Fruit were graded following Florida Tomato Committee Standards (Brown, 2000) and were segregated into extra-large, large, medium and culls after each harvest, to calculate the marketable and total fruit yields. Data were analyzed by analysis of variance and means were compared using Duncan's multiple range test at the 5% level of significance (SAS Institute, Cary, N.C.).

Results and discussion

Water use. Irrigation water use results are summarized in Table 3.

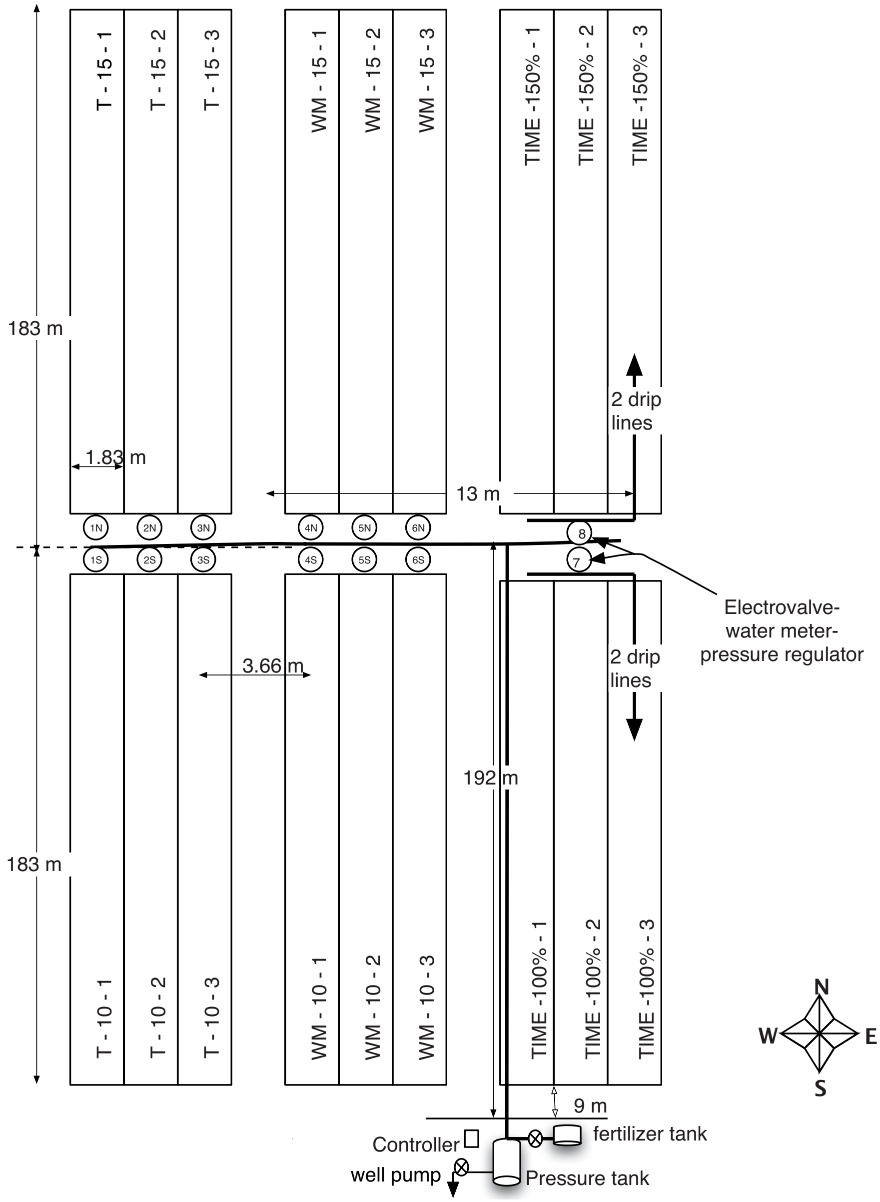

Fig. 1. Tomato plot layout showing irrigation experimental treatments with three replications, where the control (farmer's tomato field) continues on both sides of the plot (1 m = 3.2808 ft).

Table 3. Total water use over the tomato season and comparison to the commercial field irrigation and evapotranspiration based treatments.

No.	Treatment[y]	Water applied (mm)[x]	Percent change[z] from control (t7)	Percent change from ET based (t5)
t1	Tensiometer at 10 kPa (T-10)	112	–67	–39
t2	Tensiometer at 15 kPa (T-15)	91	–73	–51
t3	GMS at 10 kPa (WM-10)	182	–46	–2
t4	GMS at 15 kPa (WM-15)	172	–49	–7
t5	100% of maximum crop needs (ET-100%)	185	–45	---
t6	150% of maximum crop needs (ET-150%)	262	–22	+42
t7	Control (farmer)	335	---	+81

[z] $Change = 100 \times \frac{Treatment - Control}{Control}$

[y] 1 kPa = 1 cbar.

[x] 1 mm = 0.0394 inch.

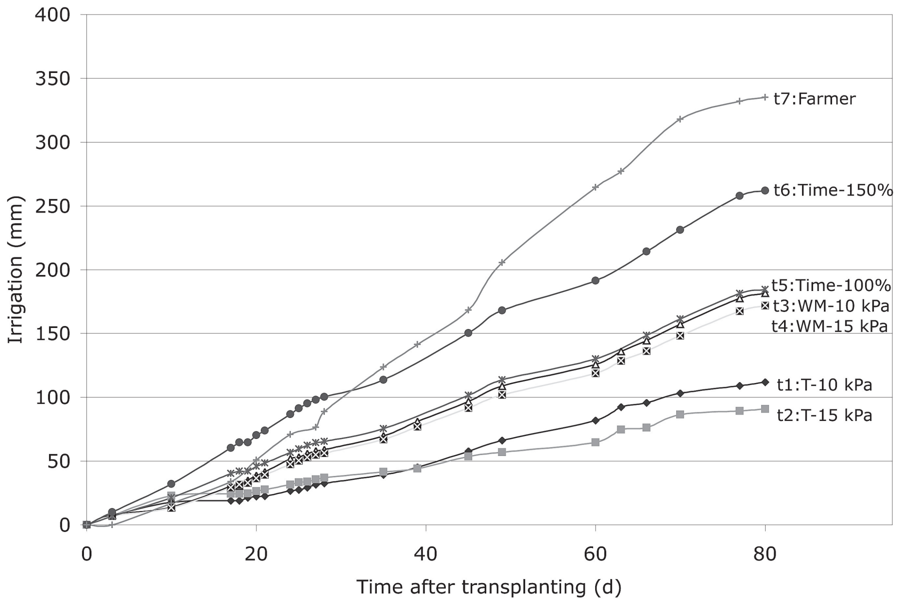

Fig. 2. Average cumulative water applied in each automatic irrigation treatment and control during the tomato season (1 mm = 0.0394 inch; 1 kPa = 1 cbar).

Treatments t1–t6 used substantially less water than traditional irrigation in the commercial field control (t7). The automated system with switching tensiometers (t1–t2) reduced water use the most (67% to 73%). A change in the moisture set point (soil tension above which the irrigation is allowed to start) for this sandy soil, from 10 to 15 kPa, reduced irrigation 19% (112 to 91 mm) with tensiometers but only 5% (183 to 173 mm) with GMS based irrigation (Table 3). Timer-based LVHF with no sensors (t5–t6) also conserved water by limiting over-irrigation that was evident on the producer treatment. The standard commercial schedule (t7) used about 81% more water than the maximum crop water needs for the area (ET-100%, treatment 5). Compared to irrigation based on maximum crop water needs (t5), as shown in the last column of Table 3, the tensiometer-based treatments (t1–t2) resulted in a substantial decrease in water use (39% to 51%) while use of the GMS based system (t3–t4) did so only marginally (2% to 7%). The maximum recommended crop water requirement (Simmone et al., 2001) was calculated based on the measured long-term reference evapotranspiration (ETo) and crop coefficients (Kc) for tomatoes in the area. However the recommendations do not consider soil moisture storage, and in these shallow soils relatively high volume irrigation events every few days will exceed the soil water storage capacity. The water savings obtained with the tensiometer soil moisture based irrigation strategy are due to application of water in small amounts to match the soil water holding capacity depending on how much is withdrawn by the plants. The results show that drip irrigation based on soil water tension can result in irrigation volume less than maximum crop water requirements calculated by historical ET.

The main water savings obtained with the tensiometers occurred from 10 to 40 d after transplanting (DAT; Fig. 2). This time period corresponds to the time when the plants are small and water demands are low. During this time, the soil remained wet (above 10 and 15 kPa for t1 and t2, respectively) between irrigation events and the sensors blocked most of the scheduled events in t1 and t2 (potential of up to five events/day) compared to time based treatments and control (t5–t7). This is shown in Fig. 2 by diverging lines during that period. In addition, t1–t2 have flatter water use slopes after 60 DAT which indicates that plant water needs stabilized at the end of the season.

CROP YIELDS. Tomato yields at the experimental plots (t1–t6) were not significantly different to those of the control (t7), except for the wettest time-based treatment, ET-150% (t6; Table 4; $\alpha = 0.05$). In t1 and t3–t7, yields were similar to the Florida average of 34,300 lb/acre (Maynard, 2001) and similar to average yields in Miami–Dade County of 35,100 lb/acre (Li et al., 2002). The farmer field (t7) had more extra-large fruit than t1–t3 and t6. Although not sta-

Table 4. Tomato yield and grades obtained for the total harvest from each experimental treatment.

	Total marketable fruit			Total extra-large fruit			Total large fruit		
Treatment[z]	Yield (kg·ha^{-1})[y]	No. (no./ha)[x]	Size (g)[w]	Yield (kg·ha^{-1})	No. (no./ha)	Size (g)	Yield (kg·ha^{-1})	No. (no./ha)	Size (g)
Tensiometer at 10 kPa (T-10)	36602 ab	241581 a	151 b	11385 b	50828 bc	221 a	17467 a	113017 a	155 bc
Tensiometer at 15 kPa (T-15)	39096 a	242179 a	161 ab	14734 ab	66375 bc	222 a	17933 a	117801 a	153 bc
GMS at 10 kPa (WM-10)	40584 a	248757 a	164 ab	15254 ab	65179 bc	233 a	18178 a	116605 a	156 abc
GMS at 15 kPa (WM-15)	40889 a	254139 a	160 ab	16038 ab	77737 ab	207 a	17365 a	107635 a	162 ab
100% of maximum crop needs (ET-100%)	40638 a	242179 a	168 a	16689 ab	68767 abc	242 a	16797 a	105243 a	160 ab
150% of maximum crop needs (ET-150%)	28153 b	166237 b	170 a	10650 b	46642 c	231 a	12169 b	72355 b	169 a
Control (farmer)	45243 a	287625 a	156 ab	20493 a	96872 a	211 a	17299 a	120193 a	144 c

[z] 1 kPa = 1 cbar; GMS = granular matrix sensors.
[y] 1 kg·ha–1 = 0.8922 lb/acre.
[x] 1 ha = 2.4711 acres.
[w] 1 g = 0.0353 oz.
[v] Different letters depict statistically different means at $P \leq 0.05$ (Duncan's multiple range test).

tistically significant, the experimental plot yields were numerically lower than that of the control grower's surrounding farm. This could be explained by the following: 1) the lower rate of dry fertilizer incorporated into the experimental beds (1430 lb/acre) than in the commercial beds (1590 lb/acre) following recommendations for the area (Li et al., 2002); 2) a greater TYLCV incidence observed in the experimental plots than in the farmer field; and 3) the delay in initiation of fertigation with respect to the control. The greater TYLCV incidence was caused by the 2-week delay in injecting the systemic insecticide needed to protect the plants from infection by whiteflies.

Despite the large reduction in water use in t1–t6 with respect to the control, there was not a large impact on fruit quality (Brown, 2000). Although the wettest treatments (Time-150% and T-10 kPa; t6 and t1, respectively) also yielded the fewest large and extra-large fruit, the automatic irrigation system controlled by the switching tensiometer at 15 kPa yielded the highest large and extra-large yield as well as overall yield while conserving 73% of the water compared to the standard commercial irrigation practice (t7). This same treatment reduced water use approximately 50% compared to irrigation based on the area's maximum recommended crop water needs (t5). Although t1–t4 resulted in less irrigation applied compared to the maximum crop requirement based on historical ET data (t5), crop yields were not negatively impacted. The high water use efficiency obtained by high frequency low volume soil moisture (tensiometer) based drip irrigation (t1–t2) for this crop can be explained in terms of: 1) monitoring moisture and applying water in just the small volume of soil where the crop roots are contained in our conditions (bed width and shallow depth to rock layer); and 2) supplying the crop water needs in limited (but physiologically sufficient at 15 kPa, Wang et al., 2004) quantities on a close to real-time mode. This rapid response of the system to plant water needs, as dictated by radiation, temperature, relative air humidity, wind, plant phenology, etc., is a powerful water-saving feature of the method.

ASSESSMENT OF WATER SENSORS AND TREATMENTS. Tensiometers, when subject to weekly maintenance, performed well and consistently for each treatment (<7.5% water use differences across replicates). However, if left unattended for more than 1 week, air entered the tensiometers, breaking the water column. This was more frequent in the driest treatment (15 kPa) after which twice weekly maintenance (Monday and Friday) was adopted. From a practical point of view it is essential in southern Florida field conditions to include routine maintenance of tensiometers. This routine consists of opening the tensiometer, refilling the column, pumping to purge air bubbles and recapping. Preferably this should be done at least one hour before the first daily irrigation set-time or after the last one to give sufficient time for the soil and the tensiometer to equilibrate before the next irrigation. Care should be taken not to break the tensiometer contact with the surrounding soil by twisting when uncapping for refilling. A de-aerated solution of water boiled for 20 min with a few drops of algaecide (unscented household bleach) gives the best results. Two of the tensiometers had to be replaced during the season. One was accidentally punctured when staking the tomatoes and the other one had a faulty seal that made it discharge frequently.

The granular matrix sensor based irrigation system performed erratically across repetitions and treatments. Two characteristics of GMS-based irrigation system contribute to these results. First, the low set points needed for this coarse soil (15–25 kPa) are close to the lower limit of usability for these sensors (7 kPa). Second, the sensors exhibit a marked delay in responding to quick soil moisture changes typical of high frequency irrigation, especially during re-wetting phases. In addition, the commercial system used here includes an interface box with a dial on a scale from 1–11 (and an OFF position to by-pass the sensor). The same dial setting in the three replications of each treatment gave very different soil moisture readings from tensiometers installed just 10.2 cm (4 inches) from the GMS. Also, consecutive steps in the dial scale (from 1 up) did not correspond to the increases in field soil tension given by the manufacturer. As a result, although about 50% water savings were observed with respect to the control (commercial farm, t7), no appreciable difference in water savings was found between the 10 and 15 kPa treatments (settings 1 and 3 in the dial scale). Furthermore, compared to the ET-100% treatment only 2% to 7% water savings were observed. In fact, since the granular matrix sensors were interfaced with the timer pre-set with the same schedule as that for t5, i.e., five irrigation events per day of 12 min each, these results indicate that the system failed to override irrigation events (Fig. 2). In addition, two interface boxes had to be replaced during the season after they stopped working spontaneously. The LVHF time-based treatments (t5 and t6) performed well, without requiring any maintenance.

Conclusions

One year of yields for tomatoes irrigated with an automated irrigation system based on feedback from tensiometers and GMS were not different than those achieved with standard commercial irrigation scheduling practices and reduced total applied water by up to 73%. Switching tensiometers at 15 kPa performed the best. The high efficiency in water use obtained is explained in terms of the rapid response of the irrigation system to plant needs, as well as the limited soil volume targeted by the method. A substantial reduction in deep percolation and in ensuing chemical transport is expected. Although water savings were obtained with the application of the low volume-high frequency concept (applying water to meet 100% of the maximum crop water needs in small quantities several times per day), these savings were increased when irrigation was automatically controlled with soil moisture sensors. However, not all sensors tested performed the same. Routine maintenance (refilling and pumping) was critical for reliable operation of the switching tensiometers, especially on the driest treatment of 15 kPa (twice per week in our conditions). The granular matrix sensor based irrigation system behaved somewhat erratically and did not improve water savings compared to the case where 100% of the maximum plant water needs were applied with a LVHF system set for five daily irrigation events (12 min each) with no sensors.

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