Evaluation of Irrigation Threshold and Duration for Tomato Grown in a Silt Loam Soil

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SUMMARY. Soil moisture-based, high-frequency, low-volume (pulsed) irrigation management strategies have saved water while maintaining yields of vegetables grown in coarse textured soils. However, little is known regarding the efficacy of soil moisture-based pulsed irrigation on finer textured soils. Therefore, five tensiometer-based, automated irrigation treatments were tested for tomato (*Solanum lycopersicum*) grown in a Maury silt loam soil in 2009 and 2010 in Lexington, KY. Irrigation treatments consisted of paired-tensiometer systems with on/off setpoints of -30/-10, -30/-25, -45/-10, and -45/40 kPa in both 2009 and 2010 and a single-tensiometer system with setpoints of -35 kPa in 2009 and -40 kPa in 2010. In 2009, the pulsed systems (-30/-25, -45/-40, and -35 kPa) irrigated more frequently but for a shorter duration than non-pulsed systems (-30/-10 and -45/-10 kPa). Soil moisture measurements in 2009 suggested that probes set at a depth of 6 inches were more closely matched to irrigation setpoints than those at 12 inches. In both years, the -45/-40 kPa setpoint treatment used the least amount of water while maintaining total marketable yields that were not significantly different from other treatments. Yields were significantly higher in 2009 than 2010, though atypical air temperatures in 2010 may have been the cause. Leaf water potential and relative water content were measured predawn and midday throughout the growing season in 2009 and 2010. Leaf water potential was not significantly affected by the treatments in either year, though leaf relative water content was affected in 2010. In this trial, an automated, soil moisture-based irrigation system maintained yields and saved water when compared with a non-pulsed irrigation system using similar irrigation setpoints for tomato grown in a silt loam soil.

Introduction

More than 65% of U.S. total vegetable acreage is irrigated (Howell, 2001). Although used on $\approx 7\%$ of the total irrigated acreage in the United States, drip irrigation is widely used on high-value crops (Hutson et al., 2004). Improvements in drip irrigation and increases in plasticulture production have prompted significant increases (>500%) in its use over the previous 20–30 years, (Howell, 2001). Drip irrigation, if properly managed, can achieve up to 95% application efficiencies (Rogers et al., 1997).

Because of increases in yield and quality, growers often over irrigate, viewing it as a cheap insurance policy for growing fruits and vegetables. However, just 5 h after the initiation of drip

irrigation, the wetting front under an emitter may reach 45 cm from the soil surface, effectively below the root zone of many vegetables (Elmaloglou and Diamantopoulos, 2007). Water can migrate upward into the root zone through capillary action on fine textured soils; however, movement decreases as texture becomes coarser. Additionally, small-scale variability in soil textures may affect water movement (Jury and Horton, 2004). If water reaches clay subsoil, upward

movement into a coarser loam topsoil can be limited. Fertilizers and pesticides may also leach below the root zone of plants grown in coarse soils when excessive water is applied (Tindall and Vencill, 1995). Methods for improved scheduling and management of irrigation may increase water use efficiency as well as potentially reduce the leaching of agricultural chemicals.

Irrigation scheduling has traditionally been weather or soil based although several plant-based scheduling methods have been proposed (Ferreles et al., 2003; Jones, 2004). In weather-based scheduling, the decision to irrigate relies on the soil water balance. The water balance technique involves determining changes in soil moisture over time on the basis of estimating evapotranspiration (Et) adjusted with a crop coefficient (Penman, 1948). This method takes environmental variables into account along with crop coefficients that are adjusted for growth stage and canopy coverage (Hartz, 1996). However, irrigating based on crop Et values may be subject to inaccuracies as a result of variations in local conditions and production practices (Amayreh and Al-Abed, 2005; Burman et al., 1980). Furthermore, some growers do not have access to appropriate local weather data and the programs necessary to properly schedule irrigation.

Often soil moisture-based methods are used to schedule irrigation. Perhaps the simplest and most common technique is the “feel method,” where irrigation is initiated when the soil “feels” dry (Maynard and Hochmuth, 2007). More sophisticated methods involve using a tensiometer or granular matrix type sensor (Munoz-Carpena et al., 2005; Richards and Gardner, 1936; Smajstrla and Locascio, 1996; Thompson et al., 2006). These methods require routine monitoring

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.1	bar	MPa	10
1	cbar	kPa	1
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
16.3871	inch ³	cm ³	0.0610
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil	mm	39.3701
28.3495	oz	g	0.0353
1	ppm	mg·L ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

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of sensor(s), with irrigation decisions made when soil moisture thresholds have been reached. This requires the development of threshold values for various crops and soil types. Soil water potential (Ψ_s) thresholds for vegetable crops such as tomato and pepper (*Capsicum* spp.) have been developed (Hedge, 1988; Smajstrla and Locascio, 1996; Smittle et al., 1994; Thompson et al., 2007). In threshold studies, Ψ_s levels are maintained at a near constant level using automated systems (Smajstrla and Locascio, 1996), or the soil is wetted for a period of time then allowed to dry out (Thompson et al., 2007). In sandy soils, high-frequency, short-duration (pulsed) irrigation events can reduce water use while maintaining yields of tomato when compared with a traditionally scheduled, high-volume, infrequent irrigation (Munoz-Carpena et al., 2005). Pulsed irrigation results in a shallower wetting front shortly after the irrigation event, increasing application efficiencies (Assouline et al., 2006; Zur, 1976; Zur and Savaldi, 1977). Although data for pulsed irrigation are available for sandy soils, comparisons of the effects of irrigation duration and frequency at different thresholds for vegetables on fine-textured soils are largely unavailable. The purpose of this research was to use a tensiometer-controlled, automated irrigation system to compare pulsed irrigation to longer-duration, high-volume irrigations at different Ψ_s levels for tomato grown using a plasticulture production system in a silt loam soil.

Materials and methods

This study was conducted during 2009 and 2010 at the University of Kentucky Horticulture Research Farm in Lexington, KY (lat. 38°3'N, long. 84°30'W). Seed of 'Mountain Fresh' tomato (Seedway, Elizabethtown, PA) were planted into 72-cell greenhouse trays filled with soilless media (Pro-Mix BX; Premier Tech, Riviere-du-Loup, QC, Canada) on 15 Apr. 2009 and 4 May 2010. Seedlings were greenhouse grown with temperature setpoints of 25/20 °C (day/night). Plants were watered daily as needed and fertilized weekly with a 150 mg·L⁻¹ nitrogen (N) solution (20N-4.4P-16.6K; Scotts, Marysville, OH). Tomato plants were greenhouse grown using recommended practices for transplant production in Kentucky (Coolong et al., 2009a).

Tomato seedlings were transplanted using a waterwheel planter on 29 May 2009 and 14 June 2010. Plants were set into 4 to 5-inch-tall raised beds covered with 1-mil embossed black plastic mulch with a single line of drip irrigation tubing [12-inch emitter spacing, 0.45 gal/min per 100 ft (Aqua-Traxx; Toro, El Cajon, CA)] placed ≈1 inch below the soil surface in the center of each bed. Plants were set ≈4 inches to the side of drip irrigation lines. Beds were ≈30 inches across and spaced on ≈6.5-ft centers. Transplants were placed in single rows on each bed with 18-inch in-row spacing.

The soil was a Maury silt loam series, mesic Typic Paleudalfs. Soil samples were collected after bed formation and transplanting. Five samples were taken from each plot to a depth of 100 cm, in 20-cm segments. The pipette method was used for particle size analysis (Sheldrick and Wang, 1993). Soil texture was found to be either silt loam or silty clay loam. Sand and silt content varied from 6.5% to 11.0% and 49.6% to 73.2%, respectively. Clay content ranged from 19.3% to 39.3%. Bulk densities of soil under natural conditions were determined using a core of known volume (Grossman and Reinsch, 2002). A core sampler was pushed into the soil at depths of 5–15 and 25–35 cm. Soil extracted from the sampler was oven dried and weighed. Bulk density varied from 1.33 to 1.74 g·cm⁻³.

Preplant fertility (19N-8.3P-15.8K; Southern States Cooperative, Richmond, VA) was applied under the plastic mulch at a rate of 75 lb/acre N. Supplemental fertility was initiated 2 weeks after transplanting and was supplied through five fertigation events alternating between calcium nitrate and ammonium nitrate, applied at a rate of 15 lb/acre N per week. Preventative spray schedules for diseases were followed with weekly sprays made according to recommendations for fresh market tomato grown in Kentucky (Coolong et al., 2009a). One application of spiromesifen (Oberon 2SC; Bayer Crop Science, Research Triangle Park, NC) was made in Aug. 2009 to control two-spotted spider mite (*Tetranychus urticae*).

Automated irrigation was managed using paired or single-switching tensiometers (12-inch, model RA; Irrrometer, Riverside, CA). In paired treatments, one tensiometer functioned to turn on irrigation while the other

turned it off. In the single-tensiometer treatment, irrigation solenoids were turned on and off by one switch. A single-tensiometer treatment was chosen to determine if a simpler automated system with one measurement point could be comparable to a two-tensiometer setup. Tensiometers were placed ≈8 inches from the tomato plants and 4 inches from the edge of the raised beds, at a depth of 8 inches from the upper surface of the bed. On/off setpoints for the four two-tensiometer treatments were as follows: on/off -30/-10, -30/-25, -45/-10, and -45/-40 kPa. The single-tensiometer treatment was set at -35 kPa in 2009 and -40 kPa in 2010. These setpoints were based on previously reported thresholds (Coolong et al., 2009b; Wang et al., 2007). Irrigation treatments were implemented on 17 June 2009 and 27 June 2010 after plants were established. The frequency and duration of the automated and manual irrigation events were recorded with data loggers (Hobo U9 State Data Logger; Onset, Cape Cod, MA). Water usage for the season was calculated by multiplying the frequency and duration of irrigation events by the flow rate of drip irrigation tubing at constant pressure (10 psi). There were four replications of irrigation treatments. Treatment plots consisted of 20 plants (measurements were taken on 16 plants in the center of each plot) arranged in a completely randomized design for a total of 20 experimental plots. Previous research indicated that growing conditions in the plots used for this trial were uniform and that a blocking design was not required.

In the 2009 growing season, two soil moisture probes (EC-5; Decagon Devices, Pullman, WA) per plot were placed at 6- and 12-inch depths into the raised beds in the same relative location to the tomato plants as tensiometers. Data loggers were unavailable for soil moisture data collection in 2010. On 3 July 2009, an access hole adjacent to the plant bed was dug and probes were inserted into undisturbed soils in the plant bed under the plastic. Probes were inserted in a parallel orientation with the soil surface at depths of 6 and 12 inches. Probes were connected to data loggers (Em 50, Decagon Devices) and soil volumetric water content (VWC) recorded hourly throughout the season.

Tomatoes were harvested five times each year. In 2009, harvests were conducted from 4 Aug. to 8 Sept. In 2010, fruit were harvested from 16 Aug. to 13 Sept. Plants were harvested approximately weekly. Fruit were graded according to U.S. Department of Agriculture (USDA) standards for fresh market tomatoes (USDA, 1991).

Predawn and midday leaf water potential (Ψ_L) and leaf relative water content (RWC) measurements were initiated on 7 July 2009 and 14 July 2010. Measurements of leaf RWC and Ψ_L were conducted during the same time period on the same days throughout the study. Measurements were taken biweekly in 2009 and weekly in 2010. Plant Ψ_L was measured using a pressure chamber (model 615; PMS Instrument Company, Albany, OR) using two recently matured, fully expanded leaves from plants near the center of each plot (Scholander et al., 1965). Leaf RWC, conducted according to the method of Barrs and Weatherley (1962), was determined on samples of five recently matured, fully expanded leaves obtained from plants near the center of each plot. Upon removal from plants, leaves for Ψ_L and RWC were immediately placed in sealed polyethylene bags, packed in a cooler with ice, and measured within 30 min of sampling.

Weather data were obtained from an on-farm weather station (Kentucky Mesonet, Fayette County Station, Lexington, KY) that recorded environmental variables every minute and provided hourly averages (University of Kentucky, 2011). The studies were ended on 8 Sept. 2009 and 13 Sept. 2010.

Statistical analyses were conducted using the GLM, repeated measures, and Fishers least significant difference of SAS statistical software when appropriate

(version 9.1; SAS Institute, Cary, NC).

Results and discussion

The growing season in 2010 was drier and warmer than in 2009. Daily average air temperatures were 71.3 and 72.6 °F in July and August of 2009, respectively, but were 77.5 and 77.4 °F in July and August of 2010, respectively. Rainfall was greater in 2009 than 2010. In 2009, the research site experienced 15.47 inches of rain during the study, while 10.19 inches were received in 2010. Irrigation events and water use are summarized in Table 1. In 2010, less water was applied than in 2009, despite being a hotter and drier growing season. Although it may be expected that greater irrigation would have been required in 2010, the results are supported by field observations. High temperatures observed in 2010 were supraoptimal for tomato plant growth, and plants were smaller in 2010 than in 2009 (Jones, 2008). Typically, soil moisture sensor-based irrigation systems will distribute water in a manner that is reflective of canopy and root growth (Pardossi et al., 2009; Zotarelli et al., 2009). Therefore, it is not unexpected that plants with less leaf area would require less water.

Average water applied ranged from 98,500 to 173,960 gal/acre in 2009 and 85,150 to 130,640 gal/acre in 2010. In 2009, the -30/-10 or -45/-10 kPa treatments irrigated less frequently but for longer periods of time than the -30/-25 and -45/-40 kPa treatments (Table 1). The -45/-10 treatment irrigated the fewest number of times but represented the longest average irrigation duration of the given treatments in 2009. The -45/-40 kPa treatment reflected a pulsed irrigation regime

with 76 irrigation events with an average duration of 40 min in 2009. This treatment also used the least water in the study, with 98,500 and 85,150 gal/acre in 2009 and 2010, respectively (Table 1). The single-tensiometer treatment, which was set at -35 kPa in 2009, irrigated 52 times with an average length of 91 min and was most similar to the -30/-25 kPa treatment. This suggests that a single-tensiometer system can simulate pulsed irrigation, simplifying installation of an automated-irrigation system.

There were smaller differences among the pulsed and non-pulsed irrigation treatments in 2010 compared with 2009. In 2010, the number of irrigations ranged from 18 in the -45/-40 kPa treatment to 28 in the -30/-25 kPa treatment, and 44 in the -40 kPa treatment. In 2010, smaller plants demanding less water may have allowed sufficient time for greater movement of water in the plant bed through capillary action during the day (Jury and Horton, 2004), resulting in less frequent irrigations. In 2010, the pattern of irrigation duration and frequency for the single-tensiometer treatment was similar to 2009, but the other treatments were less reflective of the 2009 treatments. Although the frequency of irrigation in 2010 did not reflect the pulsed treatment settings as closely as in 2009, the amount of water applied was more representative of what would be expected in a pulsed system (Zotarelli et al., 2009).

Soil VWC data were recorded hourly at depths of 6 and 12 inches in 2009 and generally were representative of the irrigation treatments (Fig. 1A–E). There were significant differences in soil VWC between the different treatments at the depths measured (Table 2). In addition, there was a significant depth by treatment interaction

Table 1. Mean number of irrigation events, irrigation time per event, and irrigation volume for the season 'Mountain Fresh' tomato grown under five automated irrigation regimes in 2009 and 2010 in Lexington, KY.

Irrigation treatment on/off (kPa) ^z	2009			2010		
	Irrigations (no.)	Mean irrigation time (min/event)	Mean irrigation vol (gal/acre) ^y	Irrigations (no.)	Mean irrigation time (min/event)	Mean irrigation vol (gal/acre)
-30/-10	39	110	138,996	28	144	130,637
-30/-25	59	91	173,956	22	140	99,792
-45/-10	21	221	150,368	22	167	119,037
-45/-40	76	40	98,496	18	146	85,147
-35 or -40 ^x	52	93	156,686	44	84	119,750

^z1 kPa = 1.0 cbar.

^yAssuming 7200 row ft (2194.6 m) per acre with drip irrigation emitter rate of 0.45 gal/min per 100 ft (0.0559 L·min⁻¹·m⁻¹); 1 gal/acre = 9.3540 L·ha⁻¹.

^xSingle tensiometer treatment set at -35 kPa in 2009 and -40 kPa in 2010.

Fig. 1. Average daily soil volumetric water content measured at depths of 6 inches [● (15.24 cm)] and 12 inches [○ (30.48 cm)] as well as daily rainfall (▼) during the 2009 growing season for five automated, tensiometer-controlled irrigation regimes: on/off –30/–10 kPa (A), –30/–25 kPa (B), –45/–10 kPa (C), –45/–40 kPa (D), and –35 kPa (E) for ‘Mountain Fresh’ tomato grown in Lexington, KY; 1 kPa = 1.0 cbar, 1 cm³ = 0.0610 inch³, 1 cm = 0.3937 inch.

Table 2. Mean volumetric water content (VWC) and differences between VWC measured at depths of 6 and 12 inches (15.2 and 30.5 cm) for ‘Mountain Fresh’ tomato grown in under five automated irrigation regimes in 2009 in Lexington, KY.

Irrigation treatment on/off (kPa) ^z	VWC at 6 inches (VWC6) (%)	VWC at 12 inches (VWC12) (%)	Difference (VWC12 – VWC6) (%)
–30/–10	22.5 a ^y	31.8 b	9.3 b
–30/–25	21.7 b	33.4 a	11.7 a
–45/–10	20.3 c	24.5 e	4.2 d
–45/–40	19.6 d	26.4 d	6.8 c
–35	20.3 c	27.6 c	7.3 c

^z1 kPa = 1.0 cbar.

^yValues in the same column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher’s least significant difference test.

for soil VWC (Fig. 1A–E). With the exception of a period of high rainfall in late July and early August, treatments

had a consistent level of soil VWC in 2009 (Fig. 1A–E). In all treatments, soil VWC was greatest at a depth of 12

inches. Excavation of a representative sample of tomato plants and intact roots after harvest indicated that maximum rooting depth of plants ranged from 12 to 15 inches, with 80% of roots residing in the top 6 inches of soil (data not shown). Average soil VWC at 6 inches ranged from 19.6% to 22.5% (Table 2). At a depth of 12 inches, soil VWC was significantly different in all treatments, ranging from 24.5% to 33.4%. The soil VWC measured at a depth of 6 inches more closely represented the applied irrigation treatments and water applied than when measured at 12 inches. Rooting depth and soil VWC results suggest that 6 inches may be an appropriate depth to monitor soil moisture in plasticulture-grown tomato.

The difference between soil VWC at 6 and 12 inches was greatest in the –30/–25 kPa and smallest in the –45/–10 kPa treatment (Table 2). Much of this difference was due to an increase in the soil VWC at the 12-inch depth. Interestingly, for a given threshold (–30 or –45 kPa) in the paired tensiometer treatments, the pulsed treatments had a larger difference in soil VWC between the 6- and 12-inch depths.

These results indicate that the automated irrigation management system used in this trial provided the desired soil moisture regimes, similar to previously suggested thresholds (Munoz-Carpena et al., 2005; Wang et al., 2007). In addition, the utility of using an automated system for conducting irrigation research in a field setting has been demonstrated.

Total marketable yields were unaffected by irrigation treatment in 2009 but were significantly affected in 2010 (Table 3). However, there was not significant year by treatment interactions for yield parameters measured. In 2009, total marketable fruit yields averaged 44,780 kg·ha^{–1}. Yields of medium fruit averaged 16,750 kg·ha^{–1}, with large and extra large fruit contributing 12,970 and 15,050 kg·ha^{–1}, respectively. In 2009, the –35 kPa treatment had significantly less large fruit than the other treatments. However, this did not result in different total marketable yields. Average fruit weight was 287 g/fruit in 2009 and was unaffected by irrigation treatment. Cull fruit averaged 27.6% in 2009 and were not significantly different among treatments.

Table 3. Mean yields of medium, large, extra large, and total marketable fruit; average fruit weight; and percentage of cull fruit for tomato 'Mountain Fresh' grown with five automated irrigation regimes in 2009 and 2010 in Lexington, KY. Fruit were graded according to U.S. Department of Agriculture standards for fresh market tomatoes.

Irrigation treatment on/off (kPa) ^z	Total marketable yield (kg·ha ⁻¹) ^z	Medium fruit (kg·ha ⁻¹)	Large fruit (kg·ha ⁻¹)	Extra large fruit (kg·ha ⁻¹)	Avg fruit wt (g/fruit) ^y	Cull fruit (%)
2009						
-30/-10	46,250	15,410	13,610 ^x a	17,230	296	25.8
-30/-25	46,050	16,100	13,980 a	15,960	287	27.8
-45/-10	44,880	15,040	14,510 a	15,330	297	26.5
-45/-40	48,210	21,060	13,230 a	13,920	278	25.3
-35	38,500	16,150	9,530 b	12,820	278	32.8
Treatment ^w	NS	NS	*	NS	NS	NS
2010						
-30/-10	19,730 a	10,510	5,240	3,980 ab	104	50.2
-30/-25	15,460 b	9,860	3,700	1,900 c	103	55.8
-45/-10	18,300 ab	9,130	4,260	4,910 a	108	50.3
-45/-40	16,590 ab	9,230	3,890	3,480 b	106	57.8
-40	17,460 ab	10,130	4,330	3,000 bc	106	53.3
Treatment	*	NS	NS	*	NS	NS
Year × treatment	NS	NS	NS	NS	NS	NS

^z1 kPa = 1.0 cbar; 1 kg·ha⁻¹ = 0.8922 lb/acre.

^yAverage weight of marketable fruit; 1 g = 0.0353 oz.

^xValues in the same column and year followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

^wNS, * = not significant and significant at $P \leq 0.05$, respectively.

In 2010, total marketable fruit yields were significantly affected by irrigation treatment. Yields of medium and large fruit were unaffected, averaging 9750 and 4280 kg·ha⁻¹, respectively. However, yields of extra large fruit were affected by irrigation regime (Table 3). Yields of extra large fruit were lowest in the -30/-25 kPa treatment and highest in the -45/-10 and -30/-10 kPa treatments. When comparing the longer-duration irrigation regimes (-30/-10 and -45/-10 kPa) to the pulsed (-30/-25 and -45/-40 kPa) programs, the extended-duration regimes had higher yields of extra large fruit at a given setpoint. The -30/-10 kPa program yielded significantly more extra large fruit than the -30/-25 kPa regime. Similarly, the -45/-10 kPa treatment yielded significantly more extra large fruit than the -45/-40 kPa treatment. The pulsed, -40-kPa treatment had yields of extra large fruit that were significantly different from the -45/-10 kPa treatment, but no others. The -45/-40 kPa treatment used the least amount of water while producing yields that were no different from the highest yielding treatments in both years of the trial. Average fruit weight was 105 g/fruit and was unaffected by irrigation regime in 2010. The

average percentage of cull fruit was unaffected by treatment in 2010 and was 53.5%. In 2010, the cull rate was significantly greater than in 2009. The high percentage of cull fruit was the result of large numbers of small fruit in 2010.

Yields for all grades of fruit and total marketable fruit were significantly greater in 2009 than in 2010. Total marketable fruit yields ranged from 38,500 to 48,210 kg·ha⁻¹ in 2009 and 15,460 to 19,730 kg·ha⁻¹ in 2010. Yields were appropriate for fresh market tomato grown in Kentucky in 2009, which typically average 45,500 kg·ha⁻¹, but were considered low in 2010 (Woods, 2008). The growing season in 2010 was warmer than 2009, resulting in smaller plants with significantly lower yields. Yields of medium fruit, which were not significantly affected by irrigation treatment in either year, were lower in 2010 than 2009 (Table 3). Medium fruit yield averaged 16,750 kg·ha⁻¹ in 2009 and 9750 kg·ha⁻¹ in 2010, a reduction of ≈41%. However, yields of large and extra large fruit were reduced by 67% and 77%, respectively, in 2010. This reduction in yield of large and extra large fruit was reflected in average fruit weight, which was reduced from an

average of 287 g/fruit in 2009 to 105 g/fruit in 2010. Air temperatures during the summer of 2010 were supra-optimal for field tomato production in Kentucky (Jones, 2004). The higher than normal temperatures in July and Aug. 2010 resulted in yield losses for many fruiting vegetables in Kentucky (Seebold and Coolong, 2010; Spalding and Coolong, 2010).

In both years of this trial, the -45/-40 kPa treatment used the least water. The most typical irrigation practice for fresh market tomato growers in Kentucky would be reflected in the -30/-10 and -40/-10 kPa treatments where plants may be watered for 3 or 4 h, once or twice per week. Trials conducted with sandy soils reported similar water savings through pulsed irrigations, without significant differences in yield compared with typical grower practices (Munoz-Carpena et al., 2005; Zotarelli et al., 2009). This suggests that irrigation practices may be altered in Kentucky to achieve additional water savings.

Predawn and midday plant Ψ_L and leaf RWC were analyzed to determine if physiologic stresses were imposed. Predawn and midday Ψ_L were unaffected by irrigation in 2009 and 2010 (Fig. 2A–E). In both years,

Fig. 2. Leaf water potential for five automated, tensiometer-controlled irrigation regimes: on/off $-30/-10$, $-30/-25$, $-45/-10$, and $-45/-40$ kPa; and -35 or -40 kPa for 'Mt. Fresh' tomato grown in Lexington, KY, in 2009 and 2010. Midday water potential in 2009 (A) and 2010 (B), and predawn leaf water potential in 2009 (C) and 2010 (D); 1 MPa = 10.0 bar, 1 kPa = 1.0 cbar.

midday Ψ_L was significantly greater than predawn Ψ_L . The increase in Ψ_L from predawn to midday varied according to sampling date. On 6 Aug. 2009, Ψ_L increased from 0.6 MPa at predawn to 7.7 MPa at midday, but on 1 Sept. 2009, Ψ_L increased from 4.2 at predawn to 7.6 MPa at midday. In 2009, a decrease in predawn Ψ_L was observed on 6 and 18 Aug. (Fig. 2C), which occurred after a rain event (Fig. 1A–E). In 2010, predawn Ψ_L increased significantly on 28 July and 11 Aug. (Fig. 2D), which did not correspond with a particular rain event but did correspond with a period of daily high air temperatures greater than 90 °F. Ngouajio et al. (2008) reported similar fluctuations throughout the growing season when measuring Ψ_L bell pepper.

Predawn water potential was significantly greater in 2010 than in 2009. Average predawn Ψ_L for the 2010 season was 4.2 MPa compared with 2.2 MPa in 2009 (Fig. 2C and D). This may be due to the higher temperatures observed in the 2010 growing season. Saranga et al. (1991) reported positive correlations between Ψ_L and air temperature. Although environment

affected Ψ_L in 2009 and 2010, irrigation regime was not shown to significantly affect Ψ_L .

Predawn and midday leaf RWCs were measured. Generally, leaf RWC remains stable during initial increases in Ψ_L and then decreases with further increases in Ψ_L (Barrs and Weatherley, 1962; Smart and Bingham, 1974). Predawn leaf RWC was significantly higher than midday leaf RWC in 2009 and 2010 (Fig. 3A–D). Predawn and midday leaf RWCs were significantly affected by sampling date in both years, fluctuating in response to the environment. Typically on those dates when Ψ_L increased, leaf RWC decreased. This was particularly evident on 28 July and 11 Aug. 2010. In 2010 midday leaf RWC was significantly affected by treatment (Fig. 3B). In 2010, midday leaf RWC was significantly greater in the -40 kPa treatment than the other treatments. The season average midday leaf RWC of the -40 kPa treatment was 89.5%, while the other treatments averaged 87.2% (Fig. 3B). This indicates that the -40 kPa treatment experienced slightly less water stress during midday sampling in 2010. The -40 kPa

treatment irrigated at a much greater frequency (44 events) than all others in 2010 (Table 1). Leaf RWC, which measures water in leaves relative to a state of full turgor, may remain stable despite changes in Ψ_L as plants compensate for changes in soil moisture or the environment (Barrs and Weatherley, 1962; Bennett, 1990; Smart and Bingham, 1974). Frequent irrigation events could have allowed for water to be readily available to the plant during midday stress.

With the exception of midday leaf RWC in the -40 kPa treatment in 2010, no other irrigation treatment exhibited significant differences in Ψ_L or leaf RWC. This suggests that although there were differences in frequency, duration, and amount of irrigation applied, no particular treatment resulted in documented plant stress.

Conclusions

Pulsed irrigation regimes have been developed through the use of soil moisture sensors and irrigation controllers. The utility of these systems has been demonstrated on sandy soils, where water use is reduced without sacrificing yields (Munoz-Carpena

Fig. 3. Leaf relative water content for five automated, tensiometer-controlled irrigation regimes: on/off -30/-10, -30/-25, -45/-10, and -45/-40 kPa; and -35 or -40 kPa for 'Mountain Fresh' tomato grown in Lexington, KY, in 2009 and 2010. Midday leaf relative water content in 2009 (A) and 2010 (B), and predawn leaf relative water content in 2009 (C) and 2010 (D); 1 kPa = 1.0 cbar.

et al., 2005). The results of this 2-year trial suggest that pulsed irrigation, when controlled by soil moisture sensors, can reduce water use if maintained at an appropriate threshold. The single tensiometer and -30/-25 irrigation systems were effective at applying water in pulses. However, the -45/-40 kPa irrigation regime used the least amount of water in both years while maintaining yields. This suggests that a pulsed irrigation system may be appropriate for plasticulture tomato production on a silt loam soil when thresholds are determined. Our data as well as others (Wang et al., 2007) suggest that using a paired tensiometer system with setpoints of -45/-40 kPa can be effective, though additional research should be conducted at lower soil moisture tensions to determine the limit for setpoints for tomato grown in a plasticulture system on a silt loam soil.

Literature cited

- Amayreh, J. and N. Al-Abed. 2005. Developing crop coefficients for field-grown tomato (*Lycopersicon esculentum* Mill.) under drip irrigation with black plastic mulch. *Agr. Water Mgt.* 73:247-254.
- Assouline, S., M. Moller, S. Cohen, M. Ben-Hur, A. Grava, K. Narkis, and A. Silber. 2006. Soil-plant system response to pulsed drip irrigation and salinity: Bell pepper case study. *J. Soil Sci. Soc. Amer.* 70:1556-1568.
- Barrs, H.D. and P.E. Weatherley. 1962. A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Aust. J. Biol. Sci.* 15:413-428.
- Bennett, J.M. 1990. Problems associated with measuring plant water status. *HortScience* 25:1551-1554.
- Burman, R.D., P. Nixon, J. Wright, and W. Pruitt. 1980. Water requirements, p. 189-234. In: M. Jensen (ed.). *Design and operation of farm irrigation systems*. Amer. Soc. Agr. Eng., St. Joseph, MI.
- Coolong, T.C., R. Bessin, K. Seebold, J. Strang, and R.T. Jones. 2009a. Vegetable production guide for commercial growers 2010-11. Univ. of Kentucky Coop Ext. Serv. Bul. ID-36.
- Coolong, T.C., J. Strang, and A. Lentz. 2009b. The effects of pulsing drip irrigation on tomato yield and quality in Kentucky, p. 39-40. In: 2009 Fruit and vegetable research report. Univ. of Kentucky Coop Ext. Serv. Bul. PR-603.
- Elmaloglou, S. and E. Diamantopoulos. 2007. Wetting front advance patterns and water losses by deep percolation under the root zone as influenced by pulsed drip irrigation. *Agr. Water Mgt.* 90:160-163.
- Fereres, E., D.A. Goldhammer, and L.A. Parsons. 2003. Irrigation water management of horticultural crops. *HortScience* 38:1036-1042.
- Grossman, R.B. and T.G. Reinsch. 2002. The solid phase, p. 201-228. In: J.H. Dane and G.C. Topp (eds.). *Methods of soil analysis, part 4, physical methods*. Soil Sci. Soc. Amer., Madison, WI.
- Hartz, T.K. 1996. Water management in drip-irrigated vegetable production. *HortTechnology* 6:165-167.
- Hedge, D.M. 1988. Irrigation and nitrogen requirements of bell pepper (*Capsicum annuum* L.). *Indian J. Agr. Sci.* 58: 668-672.
- Howell, T.A. 2001. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* 44:281-289.

- Hutson, S., N. Barber, J. Kenny, K. Linsey, D. Lumia, and M. Maupin. 2004. Estimated use of water in the United States in 2000. U.S. Geol. Surv. Circ. 1268.
- Jones, H.G. 2004. Irrigation scheduling: Advantages and pitfalls of plant-based methods. *J. Expt. Bot.* 55:2427–2436.
- Jones, J.B. 2008. Tomato plant culture in the field, greenhouse, and home garden. 2nd ed. CRC Press, New York.
- Jury, W.A. and R. Horton. 2004. Soil physics. 6th ed. Wiley, Hoboken, NJ.
- Maynard, D.N. and G.J. Hochmuth. 2007. Knott's handbook for vegetable growers. 5th ed. Wiley, Hoboken, NJ.
- Munoz-Carpena, R., M.D. Dukes, Y.C. Li, and W. Klassen. 2005. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. *HortTechnology* 15:584–590.
- Ngouajio, M., G. Wang, and R.G. Goldy. 2008. Timing of drip irrigation initiation affects irrigation water use efficiency and yield of bell pepper under plastic mulch. *HortTechnology* 18:397–402.
- Pardossi, A., L. Incrocci, G. Incrocci, F. Malorgio, P. Battista, L. Bacci, B. Rapi, P. Marzialesi, J. Hemming, and J. Balendonck. 2009. Root zone sensors for irrigation management in intensive agriculture. *Sensors (Basel Switzerland)* 9:2809–2835.
- Penman, H.L. 1948. Natural evaporation from open water, bare soil, and grass. *Proc. Roy. Soc. Lond. A.* 193:120–145.
- Richards, L.A. and W. Gardner. 1936. Tensiometers for measuring the capillary tension of soil water. *J. Amer. Soc. Agron.* 28:352–358.
- Rogers, D.H., F.R. Lamm, A. Mahbub, T.P. Trooien, G.A. Clark, P.L. Barnes, and K. Mankin. 1997. Efficiencies and water losses of irrigation systems. Kansas State Univ. Coop. Ext. Bul. MF-2243.
- Saranga, Y., J. Rudich, and A. Marani. 1991. The relations between leaf water potential of cotton plants and environmental and plant factors. *Field Crop Res.* 28:39–46.
- Scholander, P.F., H.T. Hammel, E.D. Bradstreet, and E.A. Hemmingsen. 1965. Sap pressure in vascular plants. *Science* 148:339–346.
- Seebold, K. and T. Coolong. 2010. Cultivar evaluations and fungicide programs for managing powdery mildew on pumpkin, p. 40–42. In: 2010 Fruit and vegetable research report. Univ. of Kentucky Coop Ext. Serv. Bul. PR-608.
- Sheldrick, B.H. and C. Wang. 1993. Particle size distribution, p. 499–511. In: M.R. Carter (ed.). *Soil sampling and methods of analysis*. Lewis Publishers, Ann Arbor, MI.
- Smajstrla, A.G. and S.J. Locascio. 1996. Tensiometer-controlled, drip-irrigation scheduling of tomato. *Appl. Eng. Agr.* 12:315–319.
- Smart, R.E. and G.E. Bingham. 1974. Rapid estimates of relative water content. *Plant Physiol.* 53:258–260.
- Smittle, D.A., W.L. Dickens, and J.R. Stansell. 1994. Irrigation affects yield and water use by bell pepper. *J. Amer. Soc. Hort. Sci.* 119:936–939.
- Spalding, D. and T. Coolong. 2010. On-farm commercial vegetable demonstration, p. 8–9. In: 2010 Fruit and vegetable research report. Univ. of Kentucky Coop Ext. Serv. Bul. PR-608.
- Thompson, R.B., M. Gallardo, T. Agüera, L.C. Valdez, and M.D. Fernandez. 2006. Evaluation of the Watermark sensor for use with drip irrigated vegetable crops. *Irrig. Sci.* 24:185–202.
- Thompson, R.B., M. Gallardo, L.C. Valdez, and M.D. Fernandez. 2007. Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors. *Agr. Water Mgt.* 88:147–158.
- Tindall, J.A. and W.K. Vencill. 1995. Transport of atrazine, 2-4 D and dicamba through preferential flowpaths in an unsaturated claypan soil near Centralia, Missouri. *J. Hydrol. (Amst.)* 166:37–59.
- U.S. Department of Agriculture. 1991. United States standards for grades of fresh tomatoes. U.S. Dept. Agr., Washington, DC.
- University of Kentucky. 2011. Lexington, Kentucky climate data. 3 Mar. 2011. <http://www.wagwx.ca.uky.edu/cgi-bin/ky_clim_data_www.pl>.
- Wang, D., Y. Kang, and S. Wan. 2007. Effect of soil matric potential on tomato yield and water use under drip irrigation condition. *Agr. Water Mgt.* 87:180–186.
- Woods, T. 2008. 2008 Vegetable and melon budgets. 4 Apr. 2011. <<http://www.uky.edu/Ag/NewCrops/vegbudgets08.html>>.
- Zotarelli, L., J.M. Scholberg, M.D. Dukes, R. Munoz-Carpena, and J. Icerman. 2009. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. *Agr. Water Mgt.* 96:23–34.
- Zur, B. 1976. The pulsed irrigation principle for controlling soil wetting. *Soil Sci.* 122:282–291.
- Zur, B. and D. Savaldi. 1977. Infiltration under a pulsed water application: 1. The nature of the flow system. *Soil Sci.* 124:127–134.