Research Reports

Use of Reduced Irrigation Operating Pressure in Irrigation Scheduling. I. Effect of Operating Pressure, Irrigation Rate, and Nitrogen Rate on Drip-irrigated Fresh-market Tomato Nutritional Status and Yields: Implications on Irrigation and Fertilization Management

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SUMMARY. Increasing the length of irrigation time by reducing the operating pressure (OP) of drip irrigation systems may result in decreased deep percolation and may allow for reduced nitrogen (N) fertilizer application rates, thereby minimizing the environmental impact of tomato (*Solanum lycopersicum*) production. The objectives of this study were to determine the effects of irrigation OP (6 and 12 psi), N fertilizer rate (100%, 80%, and 60% of the recommended 200 lb/acre N), and irrigation rates [IRRs (100% and 75% of the target 1000–4000 gal/acre per day)] on fresh-market tomato plant nutritional status and yields. Nitrate (NO_3^-)–N concentration in petiole sap of ‘Florida 47’ tomatoes grown in Spring 2008 and 2009 in a raised-bed plasticulture system was not significantly affected by treatments in both years and were within the sufficiency ranges at first-flower, 2-inch-diameter fruit, and first-harvest growth stages (420–1150, 450–770, and 260–450 $\text{mg}\cdot\text{L}^{-1}$, respectively). In 2008, marketable yields were greater at 6 psi than at 12 psi OP [753 vs. 598 25-lb cartons/acre ($P < 0.01$)] with no significant difference among N rate treatments. But in 2009, marketable yields were greater at 12 psi [1703 vs. 1563 25-lb cartons/acre at 6 psi ($P = 0.05$)] and 100% N rate [1761 vs. 1586 25-lb cartons/acre at 60% N rate ($P = 0.04$)]. Irrigation rate did not have any significant effect ($P = 0.59$) on tomato marketable yields in either year with no interaction between IRR and N rate or OP treatments. Hence, growing tomatoes at 12 psi OP, 100% of recommended N rate, and 75% of recommended IRR provided the highest marketable yields with least inputs in a drip-irrigated plasticulture system. In addition, these results suggest that smaller amounts of irrigation water and fertilizers (75% and 60% of the recommended IRR and N rate, respectively) could be applied when using a reduced irrigation OP of 6 psi for the early part of the tomato crop season. In the later part of the season, as water demand increased, the standard OP of 12 psi could be used. Changing the irrigation OP offers the grower some flexibility to alter the flow rates to suit the water demands of various growth stages of the crop. Furthermore, it allows irrigation to be applied over an extended period of time, which could better meet the crop’s needs for water throughout the day. Such an irrigation strategy could improve water and nutrient use efficiencies and reduce the risks of nutrient leaching. The results also suggest that OP (and flow rate) should be included in production recommendations for drip-irrigated tomato.

Best management practices seek to improve the water use efficiency and water quality in agricultural production systems (Florida Department of Agriculture and Consumer Services, 2005). In Florida, sandy soils with low water-holding capacity (0.03–0.10 inch/inch) and high vertical infiltration rates (6–20 inch/h) (U.S. Department of Agriculture, 2006) are common. For drip-irrigated crops such as cantaloupe (*Cucumis melo*) and watermelon (*Citrullus lanatus*), the soil water front moved at a rate of 0.75–1.5 inch/d under commercial conditions (Simonne et al., 2005). This means that for a shallow-rooted vegetable crop, soluble pre-plant fertilizers would have gone beyond the reach of the roots after the first 15 d of crop growth, resulting in low nutrient use efficiency as well as potential pollution of groundwater sources. Modifying soil water-holding capacity with organic or inorganic soil amendments involves applications of large amounts of soil amendments, which would increase production costs (Banedjschafie et al., 2006; Ouchi et al., 1990; Sainju et al., 2002; Sivapalan, 2006; Zhang et al., 2003). Other efforts to increase fertilizer use efficiency have focused on modifying fertilizer rates (Zotarelli et al., 2008), fertilizer placement (Cook and Sanders, 1990), using slow-release fertilizers (Fan and Li, 2009; Guertal 2009; Koivunen and Horwath, 2005; Morgan et al., 2009), planting cover crops (Wang et al., 2005), and/or reducing, splitting, or adjusting IRRs and/or frequency (Badr and El-Yazied, 2007; Elmaloglou and Diamantopoulos, 2008; Karaman et al., 1999; Levin et al., 1979; Poh et al., 2009).

While these efforts reduced the risk of nutrient leaching, none have been totally successful. Limited attention has been paid to reducing flow rate and increasing the irrigation duration as a means to reduce leaching below the root zone. Currently available drip tape flow rates range between 15 and 24 gal/100 ft per hour for 12-inch emitter spacing at OP of 12 psi. Lower flow rates could be created by reducing OP. Recent work (Dowgert et al., 2007) by the industry suggests higher water use efficiencies with gravity-based drip irrigation systems operating on very low pressures of 4–5 psi. These systems have lower flow rates that allow greater lateral soil water movement in

addition to reducing deep percolation of water and hence reducing losses of water and crop nutrients. However, reducing OP below the manufacturer's recommendation may result in reduced uniformity of the drip irrigation system and greater risk of emitter clogging.

Current University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) irrigation scheduling recommendations include a target water volume adjusted to weather conditions and crop age, a measure of soil moisture, a method to account for soil moisture from rainfall, and a rule for splitting irrigation (Simonne et al., 2010). Splitting irrigation events greater than 2 h would result in bulk application of water several times per day of which the crop receives surplus amounts of water or no water in a 24-h period. The goal of irrigation is to provide water to replace crop water losses through evapotranspiration. Evapotranspiration varies throughout the day, with the highest crop water need during midday (Allen et al., 1998). Frequent applications of smaller amounts of irrigation are known to be more efficient and environmentally sustainable (Clothier and Green, 1994; Zotarelli et al., 2009). A reduced OP and flow rate would extend irrigation duration and provide near-continuous watering of the plants that mimics evapotranspiration losses when water is applied just enough to meet crop needs, thus reducing leaching losses of water and crop nutrients. With the prospect of better water use efficiency, the amounts of fertilizers and water applied could potentially be reduced. Hence, the objectives of this study were to determine the effects of reduced irrigation OP of 6 psi coupled with reduced fertilizer rates (80% and 60% of the recommended 200 lb/acre N) and IRRs (75% of the target 1000–4000 gal/acre per day) on fresh-market tomato nutritional status and yield.

Materials and methods

The experimental field located at the North Florida Research and Education Center—Suwannee Valley near Live Oak, FL, was planted with a rye (*Secale cereale*) cover crop in Fall 2007 and 2008 and disked the following February both years. Fertilization was based on the results of Mehlich-1 soil test and followed current recommendations (Olson et al., 2010). Pre-plant fertilizers [13N–1.7P–10.8K; Mayo Fertilizer, Mayo, FL], at 50 lb/acre of N and potassium oxide, were applied during bed preparation 3 weeks before transplanting. No additional phosphorus (P) fertilizer was applied as soil test results indicated very high soil P. Two drip tapes [24 gal/100 ft per hour at 12 psi, 12-inch emitter spacing (Ro-Drip; John Deere, San Marcos, CA)] were laid together in the middle of each bed for the independent application of irrigation water and fertilizer. Six-week-old 'Florida 47' tomato plants were established on raised beds [Alpin-Foxworth-Blanton sand (U.S. Department of Agriculture, 2006)] with black plastic mulch on 30 Apr. 2008 and 8 Apr. 2009 [days after transplanting (DAT) = 0]. Beds were 28 inches wide and spaced 5 ft apart with 18-inch in-row spacing for open-field tomato production.

Treatments were factorial combinations of N rate (100%, 80%, and 60% of UF-IFAS recommendation), drip irrigation system OP (12 and 6 psi), and IRR (100% and 75% UF-IFAS irrigation recommendation) (Table 1). OP was regulated by installing pressure regulators (Senninger Irrigation, Orlando, FL) for the standard OP of 12 psi and reduced OP of 6 psi. Current UF-IFAS N fertilizer recommendation for tomato (seasonal application 200 lb/acre N) was used as the 100% N rate, which was reduced to 80% (160 lb/acre) and 60% (120 lb/acre) for other N rate

treatments. Ammonium nitrate (34N–0P–0K; Mayo Fertilizer) was used to provide the required N. After pre-plant fertilization, the remaining N fertilizers were injected weekly through the dripline (Olson et al., 2010) together with potassium chloride [0N–0P–12.5K (Dyna Flo 0–0–15; Chemical Dynamics, Plant City, FL) to provide potassium (K) for each treatment. An IRR of 1000 gal/acre daily per string commonly used in the industry was designated as 100% IRR and was reduced to 750 gal/acre daily per string for the 75% IRR treatment. The "string" refers to the use of string to support plants during staking and denotes the growth stage of the crop with typically four strings used during the season. Irrigation volume was gradually increased (Fig. 1) to 4000 gal/acre per day for 100% IRR as the crop season progressed to meet greater crop water requirements. The volume of irrigation water applied was controlled with timers (Orbit Irrigation Products, Bountiful, UT). Water meters installed at the sub-mains of each OP treatment were read weekly and were used to monitor actual amounts of water applied. The duration of irrigation was progressively increased as greater irrigation volumes were needed during later growth stages and were based on monitoring of soil moisture using a handheld time domain reflectometry meter (HydroSense; Campbell Scientific, Logan, UT). Daily temperature and rainfall data were collected by a weather station of the Florida Automated Weather Network located at Live Oak, FL (University of Florida, 2009). Other cultural practices (staking and pest control) followed current UF-IFAS recommendations for tomato production (Olson et al., 2010).

Plant nutritional status was monitored using petiole sap testing at 5, 6, 7, and 8 weeks after transplanting

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
102.7902	acre-inch(es)	m ³	0.0097
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
0.1242	gal/100 ft	L·m ⁻¹	8.0520
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

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Table 1. Treatment combinations of nitrogen (N) rate, operating pressure (OP), and irrigation rate (IRR) for Spring 2008 and 2009 'Florida 47' fresh-market tomato production in plasticulture systems.

Treatment no.	N rate (%) ^z	OP (psi) ^y	IRR (%) ^x	Pre-plant fertilizer (lb/acre) ^w	Time after transplanting (weeks)				
					1–2	3–4	5–11	12	13
					Target N rate (lb/acre per day) ^v				
1	100	12	100	50	1.13	1.50	1.88	1.50	1.13
2	100	12	75	50	1.13	1.50	1.88	1.50	1.13
3	100	6	100	50	1.13	1.50	1.88	1.50	1.13
4	100	6	75	50	1.13	1.50	1.88	1.50	1.13
5	80	12	100	50	0.8	1.1	1.4	1.1	0.8
6	80	12	75	50	0.8	1.1	1.4	1.1	0.8
7	80	6	100	50	0.8	1.1	1.4	1.1	0.8
8	80	6	75	50	0.8	1.1	1.4	1.1	0.8
9	60	12	100	50	0.6	0.8	0.9	0.8	0.6
10	60	12	75	50	0.6	0.8	0.9	0.8	0.6
11	60	6	100	50	0.6	0.8	0.9	0.8	0.6
12	60	6	75	50	0.6	0.8	0.9	0.8	0.6

^z100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre; 1 lb/acre = 1.1209 kg·ha⁻¹.

^y1 psi = 6.8948 kPa.

^x100% = 1000–4000 gal/acre per day, 75% = 750–3000 gal/acre per day; 1 gal/acre = 9.3540 L·ha⁻¹.

^wPre-plant fertilizer used was 13N-1.7P-10.8K.

^vAmmonium nitrate and potassium chloride were used for weekly fertilizer injection.

Fig. 1. Target weekly irrigation schedule for Spring 2008 and 2009 'Florida 47' fresh-market tomato production using raised-bed plasticulture systems at two irrigation rates: 100% (1000–4000 gal/acre per day) and 75% (750–3000 gal/acre per day); 1 gal/acre = 9.3540 L·ha⁻¹.

(WAT) in 2008 and 5, 7, 9, and 11 WAT in 2009, which corresponded to first-flower, 1-inch-diameter fruit, 2-inch-diameter fruit, and first-harvest growth stages in 2008 and to first-flower, 2-inch-diameter fruit, first-harvest, and second-harvest growth stages in 2009, respectively. Ten petioles from most recent fully expanded leaves were sampled per plot, cut into half-inch-long pieces, and placed into a garlic press to extrude sap to determine NO₃⁻-N and K⁺ concentrations using ion-specific electrodes (Cardy meter, models C-141 and C-131 for NO₃⁻-N and K, respectively; Horiba Instrument, Kyoto, Japan).

Tomatoes were harvested when at least 50% of fruit in all trusses were

at breaker stage at 69 DAT in 2008 and at 75 and 84 DAT in 2009. Fruit were graded as extra large, large, medium, and culls (U.S. Department of Agriculture, 1991), weighed, and counted. Marketable fruit yields were calculated by adding the extra large, large, and medium grades.

The experimental design was a randomized complete block design with four replications that used eight beds, each ≈150 ft long. The four replications were established in 25-ft sections of each bed (20-ft-long plots; 5-ft planted buffers). Two drip tapes were placed at the center of the bed when the beds were formed, which allowed the independent application of water and fertilizer treatment to

each plot (Simonne et al., 2002). Near the field, the water source was divided into two 2-inch-diameter pipes. One line was further split into four for the OP × IRR treatments, and the other one was split into three for the N rate treatments. Hence, a total of seven polyethylene (PE) pipes were used to distribute the water and fertilizer treatments to the plots. Four pipes supplied the OP × IRR treatments (6 psi, 100% IRR; 6 psi, 75% IRR; 12 psi, 100% IRR; and 12 psi, 75% IRR), and three pipes supplied the N rate treatments (60%, 80%, and 100%). The PE pipes were color coded; drip tapes in each plot were connected to the corresponding PE pipe according to treatment. Petiole sap NO₃⁻-N and K⁺ concentrations and total and marketable yield responses to the treatments were analyzed using analysis of variance, and treatment means were compared using Duncan's multiple range test (SAS version 9.2; SAS Institute, Cary, NC).

Results and discussion

CROP CYCLE AND WEATHER CONDITIONS. In 2008, tomato field production began 30 Apr. and ended 8 July for a cropping season of 10 weeks. High June temperatures inhibited flower development; therefore, only one harvest was taken at 69 DAT. The 2009 growing season was 12 weeks long, from 8 Apr. to 1 July, with two harvests at 75 and 84 DAT. Cumulative growing degree day experienced by the

crops in both years were similar (Fig. 2) and were typical for spring crops in northern Florida. In 2008, rainfall events occurred for 16 d (23% of growing season) during 30 Apr. to 8 July, resulting in a total rainfall of 5.8 inches. In 2009, rainfall events occurred for 26 d (31% of season) during 8 Apr. to 1 July, resulting in 8.4 inches of rain (University of Florida, 2009). Leaching rainfall events (defined as 3 inches in 3 d or 4 inches in 7 d) did not occur in either year, and therefore no supplemental fertilizer was provided. Because the length of growing seasons was different, actual seasonal N rates applied were 152, 127, and 101 lb/acre N in 2008 and 178, 146, and 114 lb/acre N in 2009 for 100%, 80%, and 60% N treatments, respectively.

FLOW RATES AND IRRIGATION VOLUMES. The expected flow rate for the 12-psi treatment was 24 gal/100 ft per hour and for the 6-psi treatment was less than 12 gal/100 ft per hour. However, the actual flow rates averaged 24 and 7.2 gal/100 ft per hour in 2008 and 20 and 6 gal/100 ft per hour in 2009, for the 12- and 6-psi OP treatments, respectively. The objective of this work was to apply the same volume of irrigation water, but over a longer period of time. Hence, to supply equivalent volumes of water for both OP treatments, the duration of irrigation was extended for the reduced OP treatments. During peak irrigation periods, the reduced OP treatments were provided with 10–12 h of irrigation while the standard OP treatments had 4 h.

The target irrigation volumes were 220,000 and 170,000 gal/acre (8.1 and 6.3 acre-inches) for the 100% and 75% IRR treatments, respectively. At 100% IRR, plants received cumulative irrigation volumes of 190,000–210,000 gal/acre (7.0–7.7 acre-inches) and 190,000–240,000 gal/acre (7.0–8.8 acre-inches) in 2008 and 2009, respectively (Fig. 3). At 75% IRR, cumulative irrigation volumes were 140,000–160,000 gal/acre (5.2–5.9 acre-inches) and 150,000–190,000 gal/acre (5.5–7.0 acre-inches) in 2008 and 2009, respectively. In both years, the lower irrigation amounts were for the 6-psi treatments. The volumes applied were close to the water permitting allocation for tomato irrigation, typically 6–8 acre-inches for a spring crop in northern Florida.

TOMATO PLANT PETIOLE SAP NO_3^- -N AND K^+ CONCENTRATION.

Fig. 2. Cumulative growing degree day during the growing seasons in Spring 2008 (from 30 Apr. to 8 July) and Spring 2009 (from 8 Apr. to 1 July) in Live Oak, FL, indicating time of various crop growth stages for open-field 'Florida 47' fresh-market tomato production. Base temperature used to calculate growing degree days was 50 °F; first flower = first open flowers, 1-inch fruit = fruit at 1-inch diameter, 2-inch fruit = fruit at 2-inch diameter; 1 inch = 2.54 cm, $(^{\circ}\text{F} - 32)/1.8 = ^{\circ}\text{C}$.

Fig. 3. Actual cumulative irrigation applied in Spring 2008 (A) and Spring 2009 (B) for 'Florida 47' fresh-market tomato production with raised-bed plasticulture system using medium-flow drip tape [24 gal/100 ft (3.0 L·m⁻¹) per hour], 12-inch (30.5-cm) emitter spacing, 28-inch-wide (71.1-cm-wide) mulched beds at two operating pressures [6 and 12 psi (41.4 and 82.7 kPa, respectively)] and two irrigation rates (100% and 75% of 1000–4000 gal/acre per day). In 2008, amount of weekly irrigation was estimated based on flow rates measured for 3 weeks and extrapolated to subsequent weeks. In 2009, amount of weekly irrigation was estimated based on weekly flow rates; 1 gal/acre = 9.3540 L·ha⁻¹.

Because different amounts of N and IRR were applied in 2008 and 2009, the responses of tomato petiole sap

nutrient concentrations and yields were analyzed separately by years. No significant interactions occurred between

N rates, OP, or IRR at most of the growth stages for petiole sap NO_3^- -N concentrations. In 2008, plant petiole sap NO_3^- -N concentrations at all the growth stages were not significantly different for N rate and OP treatments (Table 2). However, for IRR, petiole sap NO_3^- -N concentration was significantly higher ($P < 0.01$) for 75% IRR compared with 100% IRR only at fruit 2-inch-diameter stage. In 2009, NO_3^- -N concentrations at all the crop growth stages were again not significantly different for all the treatments except for higher 100% N rate at first-harvest growth stage ($P = 0.03$) and higher 6-psi OP treatment at first open flowers ($P < 0.01$). All treatments had sufficient or exceeding NO_3^- -N concentration in most of the growth stages except at first-flower stage in 2008 and at first-harvest stage in 2009 (Table 2).

In 2008, petiole sap K^+ concentrations at all the growth stages were not significantly different for all the respective treatments (Table 3A). In 2009, as $\text{N} \times \text{OP}$ interaction was significant for most growth stages, the effect of OP was analyzed separately by N rate (Table 3B). Operating pressure had a significant effect, with the 6-psi OP treatment

having higher sap K^+ concentration at first open flowers ($P < 0.01$) and first-harvest ($P < 0.01$) growth stages at 60% N, at 2-inch-diameter fruit ($P = 0.01$) and second-harvest ($P < 0.01$) growth stages at 80% N, and at first flower ($P < 0.01$) and second-harvest ($P = 0.03$) growth stages at 100% N. Sap K^+ concentration was significantly higher for 75% IRR at the first-harvest growth stage ($P = 0.04$). All treatments had sufficient or exceeding K^+ concentration at most of the growth stages except at 1-inch-diameter fruit stage in 2008 and at first flower stage in 2009 (Table 3).

Nitrogen rate did not affect the petiole sap NO_3^- -N concentration. Similarly, OP and IRR treatments had no significant effect on sap NO_3^- -N concentrations, although in general higher NO_3^- -N concentrations were obtained at the 6-psi or 75% IRR treatments. This could be due to a solute concentrating effect as less irrigation water was available with these treatments. These results show that crop nutritional status can be maintained at sufficiency levels with reduced OP and reduced fertilizer and irrigation inputs.

FRESH-MARKET TOMATO YIELDS. In 2008, OP had a significant effect on the total ($P < 0.01$) and marketable ($P < 0.01$) yields as well as on the extra large and medium tomato grades, with total yield increase of 21% at 6 psi OP compared with 12 psi OP (Table 4). N rate and IRR had no significant effect on both total and marketable yields. In 2009, OP had a significant effect on the marketable yields ($P = 0.05$), with $\approx 8\%$ lower yields obtained at 6 psi compared with 12 psi. N rate had a significant effect with greater total ($P = 0.04$) and marketable ($P = 0.04$) yields at 100% N rate. IRR, however, had no significant effect on the yields.

The yields in 2008 were half those in 2009, implying that the reduced OP treatment response was positive in 2008 possibly because of low crop growth and demand for water and fertilizer inputs. However, based on the results in 2009, to attain maximum yields, the standard 12 psi OP, 100% recommended N rate, and 75% recommended IRR were still required.

USING REDUCED OP FOR EARLY CROP SEASON. In the early part of the season when plants were small, the reduced OP (6 psi) in combination

Table 2. Nitrate–nitrogen (NO_3^- -N) concentration in tomato petiole sap at selected growth stages in 2008 and 2009 for ‘Florida 47’ fresh-market tomato production in plasticulture system at 60%, 80%, and 100% of N rate, 6 and 12 psi (41.4 and 82.7 kPa) operating pressure (OP), and 75% and 100% irrigation rate (IRR).

Treatment	NO_3^- -N concn ($\text{mg}\cdot\text{L}^{-1}$) ^z							
	Growth stage ^y (2008)				Growth stage (2009)			
	First flower	1-inch Fruit	2-inch Fruit	First harvest	First flower	2-inch Fruit	First harvest	Second harvest
N rate (%) ^x								
60	393	556	415	411	1135	730	226 b ^w	215
80	431	867	420	459	1213	794	245 b	209
100	440	789	513	484	1109	781	312 a	228
P value	0.36	0.15	0.07	0.26	0.38	0.46	0.03	0.57
OP (psi)								
6	441	753	459	461	1252 a	783	261	231
12	401	721	439	442	1053 b	754	260	204
P value	0.17	0.81	0.38	0.60	<0.01	0.52	0.97	0.08
IRR (%) ^v								
75	436	741	512 a	453	1133	737	268	220
100	406	733	384 b	450	1172	800	254	215
P value	0.29	0.96	<0.01	0.95	0.54	0.16	0.59	0.69
Sufficiency range ($\text{mg}\cdot\text{L}^{-1}$) ^u	600–800	400–600	400–600	300–400	600–800	400–600	300–400	200–400
$\text{N} \times \text{OP}$ (P)	0.75	0.14	0.11	0.76	0.53	0.61	0.64	0.30
$\text{N} \times \text{IRR}$ (P)	0.81	0.49	0.27	0.16	0.78	0.37	0.49	0.36
$\text{OP} \times \text{IRR}$ (P)	0.10	0.25	0.28	0.98	0.73	<0.01	0.14	0.87

^z1 $\text{mg}\cdot\text{L}^{-1}$ = 1 ppm.

^yFirst flower = first open flowers, 1-inch fruit = fruit at 1 inch diameter, 2-inch fruit = fruit at 2 inch diameter; 1 inch = 2.54 cm.

^x100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre; 1 lb/acre = 1.1209 $\text{kg}\cdot\text{ha}^{-1}$.

^wValues with different letters within the same column and under a specific treatment effect are significantly different at $\alpha = 0.05$ via Duncan's multiple range test.

^v100% = 1000–4000 gal/acre per day, 75% = 750–3000 gal/acre per day; 1 gal/acre = 9.3540 $\text{L}\cdot\text{ha}^{-1}$.

^uSufficiency range from Olson et al. (2010).

Table 3. Potassium (K⁺) concentration in tomato petiole sap at selected growth stages in 2008 (A) and 2009 (B) for ‘Florida 47’ fresh-market tomato production in plasticulture system at 60%, 80%, and 100% of nitrogen (N) rate, 6 and 12 psi (41.4 and 82.7 kPa) operating pressure (OP), and 75% and 100% irrigation rate (IRR).

Treatment	(A) K ⁺ concn (mg L ⁻¹) in 2008 ^z			
	Growth stage ^y			
	First flower ^y	1-inch Fruit ^y	2-inch Fruit ^y	First harvest ^y
N rate (%) ^x				
60	4669	2186	4893	3963
80	4631	2263	5087	4150
100	4744	2081	5133	3719
<i>P</i> value	0.80	0.72	0.61	0.11
OP (psi)				
6	4721	2104	4991	4033
12	4642	2249	5091	3854
<i>P</i> value	0.58	0.43	0.83	0.28
IRR (%) ^w				
75	4783	2249	5182	4100
100	4579	2104	4900	3788
<i>P</i> value	0.15	0.43	0.06	0.06
Sufficiency range (mg·L ⁻¹) ^v	3500–4000	3000–3500	3000–3500	2500–3000
N × OP (<i>P</i>)	0.88	0.83	0.22	0.28
N × IRR (<i>P</i>)	0.44	0.05	0.03	0.92
OP × IRR (<i>P</i>)	0.36	0.11	0.92	0.38
Treatment	(B) K ⁺ concn (mg L ⁻¹) in 2009			
	Growth stage			
	First flower ^y	2-inch Fruit ^y	First harvest ^y	Second harvest ^y
N rate (%)				
60				
6 psi (OP)	2750 a ^u	3450	4588 a	3538
12 psi (OP)	2463 b	3350	3913 b	3075
<i>P</i> value	<0.01	0.25	<0.01	0.20
80				
6 psi (OP)	2500	3413 a	3950	3413 a
12 psi (OP)	2588	3200 b	3863	2725 b
<i>P</i> value	0.31	0.01	0.59	<0.01
100				
6 psi (OP)	2713 a	3213	3825	3250 a
12 psi (OP)	2388 b	3338	3888	2813 b
<i>P</i> value	<0.01	0.08	0.72	0.03
IRR (%)				
75	2579	3338	4104 a	3200
100	2554	3317	3904 b	3071
<i>P</i> value	0.60	0.61	0.04	0.35
Sufficiency range (mg·L ⁻¹)	3500–4000	3000–3500	2500–3000	2000–2500
N × OP (<i>P</i>)	<0.01	<0.01	<0.01	0.71
N × IRR (<i>P</i>)	0.09	0.43	0.14	0.62
OP × IRR (<i>P</i>)	0.09	0.76	0.14	0.93

^z1 mg·L⁻¹ = 1 ppm.

^yFirst flower = first open flowers, 1-inch fruit = fruit at 1 inch diameter, 2-inch fruit = fruit at 2 inch diameter; 1 inch = 2.54 cm.

^x100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre; 1 lb/acre = 1.1209 kg·ha⁻¹.

^w100% = 1000–4000 gal/acre per day, 75% = 750–3000 gal/acre per day; 1 gal/acre = 9.3540 L·ha⁻¹.

^vSufficiency range from Olson et al. (2010).

^uValues with different letters within the same column and under a specific treatment effect are significantly different at $\alpha = 0.05$ via Duncan's multiple range test.

with reduced IRR (75% recommended irrigation) and N fertilizer rate (60% N recommended rate) would be a good strategy to increase irrigation and nutrient use efficiency. According to Levin et al. (1979), a lower water flow rate of 1 L·h⁻¹ resulted in a smaller wetted soil volume compared with higher flow

rates of 2, 4, and 8 L·h⁻¹ for a sandy soil, with more water and nutrients being retained within the crop root zone. Simonne et al. (2005) reported greater downward water movement during the early part of the cantaloupe growing season (1–5 weeks after crop establishment) when plants were small and

suggested that a lower flow rate may help to keep the wetted zone within the root zone. Scholberg et al. (2009) reported a need for more frequent (daily) fertigation during initial crop growth in pepper (*Capsicum annuum*) as water and nutrient uptake capacity was limiting for small plants.

Table 4. Seasonal fresh-market tomato yields for 2008 and 2009 at 60%, 80%, and 100% of nitrogen (N) rate, 6 and 12 psi (41.4 and 82.7 kPa) operating pressure (OP), and 75% and 100% irrigation rate (IRR).

Treatment	Yield (25-lb cartons per acre) ^z									
	Grades ^y (2008)					Grades (2009)				
	Total	Mkt	XL	L	M	Total	Mkt	XL	L	M
N rate (%) ^x										
60	936	704	240	208	256	1841 b ^w	1586 b	683	493 b	410
80	862	629	203	186	239	1816 b	1553 b	664	459 b	430
100	896	693	203	221	269	2027 a	1761 a	716	566 a	479
<i>P</i> value	0.56	0.41	0.39	0.39	0.61	0.04	0.04	0.61	<0.01	0.12
OP (psi)										
6	985 a	753 a	243 a	225	284 a	1824	1563 b	641 b	472 b	450
12	811 b	598 b	188 b	185	225 b	1966	1703 a	735 a	540 a	429
<i>P</i> value	<0.01	<0.01	0.04	0.06	0.02	0.06	0.05	0.04	<0.01	0.44
IRR (%) ^v										
75	916	689	222	205	261	1896	1647	705	516	453
100	880	662	209	205	248	1894	1620	670	496	426
<i>P</i> value	0.52	0.60	0.61	0.10	0.60	0.97	0.70	0.43	0.39	0.31
N × OP (<i>P</i>)	0.11	0.15	0.05	0.08	0.88	0.60	0.49	0.07	0.64	0.09
N × IRR (<i>P</i>)	0.17	0.31	0.93	0.13	0.34	0.14	0.09	0.42	<0.01	0.60
OP × IRR (<i>P</i>)	0.62	0.65	0.85	0.41	0.16	0.31	0.36	0.98	0.02	0.68
CV (%) ^u	21	25	40	34	34	13	15	22	17	21

^z1 25-lb (11.3-kg) carton per acre = 28.0213 kg·ha⁻¹.

^yTomato yields were separated into various grades based on U.S. Department of Agriculture grading standards: Total = marketable grades plus culls, Mkt = marketable grades, XL = extra large grade, L = large grade, M = medium grade.

^xN rate: 100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre; 1 lb/acre = 1.1209 kg·ha⁻¹.

^vValues with different letters within the same column and under a specific treatment effect are significantly different at $\alpha = 0.05$ via Duncan's multiple range test.

^v100% = 1000–4000 gal/acre per day, 75% = 750–3000 gal/acre per day; 1 gal/acre = 9.3540 L·ha⁻¹.

^uCoefficient of variation.

Using a reduced OP in such a case would extend the irrigation duration to better meet the uptake capacity of the small plants and at the same time minimize the downward movement of water and nutrients into the soil. In this study, by 4 WAT, the tomato plants at the reduced OP treatment were irrigated for 4 h daily from 9:00 to 11:00 AM and from 3:00 to 5:00 PM so that plants were irrigated for a major part of the day. If the reduced OP strategy was adopted for the first 4 weeks of the season, a total reduction in irrigation volume of 7% and in N fertilizer usage of 15% could be achieved. As the season progressed, the reduced OP would not work as well possibly because the water output per unit of time was not sufficient to meet the higher crop water demand; it would be necessary to revert to the standard OP. For this purpose, an adjustable in-line pressure regulator could be installed in the drip system for the grower to easily change the irrigation OP to adjust the flow rates at various growth stages.

Using reduced OP, however, requires careful management of the irrigation system. Uniformity of water application could be adversely affected when using an OP below the manufacturer's recommendation. Preferably

short lateral runs of the drip tapes should be used with small irrigation zones controlled by each pressure regulator, which should be installed as close to the drip tapes as possible. Furthermore, the width of the wetted zone could be too small for effective emitter-to-emitter coverage and it may be necessary to use drip tapes with smaller emitter spacing such as 4 or 8 inches to make sure that plants between emitters would be watered. Finally, the risk of emitter clogging would be higher when using low irrigation OP, and so the water source should be of high quality and well-filtered and weekly chlorination of the drip system should be carried out.

Conclusion

In an Alpin–Blanton–Foxworth sand of northern Florida, higher fresh-market tomato yields were obtained at a reduced irrigation OP in 1 year with reduced fertilizer rate and IRR, without affecting the N and K nutritional quality of the plants. In the second year, where the crop cycle was longer, the higher OP and N rate produced greater yields and the IRR could be reduced. These results suggest that the reduced OP of 6 psi could not replace the

standard OP for the whole crop season. Instead, reduced OP could be used for the early part of the season when the plants were small and the OP could be increased as the season progressed. Using reduced OP allowed near-continuous irrigation of plants at a very low flow rate, which better caters to plants' need for water throughout the day, especially for small plants. Combining with a reduced IRR of 75% and fertilizer rate of 60% of recommended levels, an irrigation strategy using an OP of 6 psi during the first 4 weeks of a tomato crop season would improve water and nutrient use efficiencies and hence reduce risks of nutrient leaching. However, because of the risks of poor uniformity, low emitter-to-emitter coverage, and emitter clogging, such a drip system should be tested in commercial fields to determine the applicability of using reduced OP in drip irrigation for tomato production.

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