REDUCING DRIP IRRIGATION OPERATING PRESSURE FOR REDUCING EMITTER FLOW RATE AND IMPROVING IRRIGATION MANAGEMENT

By

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To my family

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LIST OF ABBREVIATIONS

ft	foot
gal	gallon
gph	gallon per hour
gpm	gallon per min
h	hour
lb	pound
psi	pound per square inch
t/acre	ton per acre

Abstract of Thesis Presented to the Graduate School
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The goal of this project is to determine if reducing irrigation system operating pressure (OP) could improve drip irrigation management and be specified as a UF/IFAS recommendation for irrigation scheduling. This was assessed through three objectives to compare a reduced OP of 6 psi to the standard OP of 12 psi. In the first objective to determine the effect on emitter flow rates, water application uniformity and soil water movement, flow rates for three commercial drip tapes were found to decrease to 0.13-0.17 gph at 6 psi compared to 0.19-0.25 gph at 12 psi without affecting uniformity of irrigation at 100 and 300 ft lateral lengths. Using soluble dye as a tracer, depth (D) of the waterfront response to irrigated volume (V) was quadratic $D = 4.42 + 0.21V – 0.001V^2$ ($P < 0.01$, $R^2 = 0.72$) at 6 psi, with a similar response at 12 psi, suggesting that depth of the wetted zone was more affected by water volume applied rather than by OP itself. The depth of wetted zone went below 12 inches when V was about 45 gal/100ft, which represented about 3 hours of irrigation at 6 psi and 1.8 hours of irrigation at 12 psi for a typical drip tape with flow rate of 0.24 gph at 12 psi. This implies that, for the same volume of water applied, reduced OP allowed extended irrigation without increasing the wetted depth. OP also did not affect the width (W) of the wetted front, which was

quadratic $W = 6.97 + 0.25V - 0.002V^2$ ($P < 0.01$, $R^2 = 0.70$) at 6 psi. As the maximum wetted width at reduced OP was 53% of the 28-inch wide bed, reduced OP should be used for two-row planting or drip-injected fumigation only if two drip tapes were used to ensure good coverage and uniform application. Reducing OP therefore offers growers a simple method to reduce flow rate and apply water at rates that match more closely the hourly evapotranspiration to minimize the risk of drainage and leaching losses.

The second objective studied the possibility of growing a tomato crop with reduced water (100% irrigation rate of 1000 gal/acre/day/string vs 75%) and nitrogen (N) fertilizer (100% N rate of 200 lb/acre N vs 80% and 60%) inputs at reduced OP. In one year, marketable yields were greater at 6 psi than at 12 psi (753 vs 598 25-lb cartons/acre, $P < 0.01$) with no significant difference among N rate treatments. But in another year, 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 irrigation rate and N or OP treatments. These results suggest that reduced OP may not be able to provide enough water to meet the needs of a fully growing crop and instead could be more appropriate for use with young plants when water demand is low.

For the third objective to determine soil water movement after a cropping cycle, it was found that response to OP was significant ($P = 0.01$) with maximum average wetted depths of 52 and 63 inches at 6 psi, and 64 and 67 inches at 12 psi, for the respective years of study. In the presence of plants, water moved in the soil at a lower rate of 0.09 inch/10gal/100ft compared to 0.9 inch/10gal/100ft without plants. However, the waterfront had still moved to about 60 inches at the end of the season, indicating that reduced OP alone was not able to keep irrigated water within the crop rootzone of 12 inches. Overall, reducing OP using a commercially available pressure regulator is a simple, practical and inexpensive method to obtain low emitter flow rates that may help to reduce water and fertilizer inputs without compromising uniformity in small fields. Based on these results, we propose that UF/IFAS irrigation recommendation specify reducing OP as a practice in irrigation scheduling to improve on-farm water and nutrient management.

CHAPTER 1
INTRODUCTION

Shrinking world water supplies and increased environmental conservation have put agriculture under intense pressure to reduce water use and minimize risks of pollution by fertilizers and pesticides. Agriculture is the principal user of all water resources, accounting for 70% of water withdrawals worldwide, with industry using nearly 21% and domestic use amounting to 9% (FAO, 2003). Irrigated agriculture produces 40% of the world's food crops on 20% of arable land. To accommodate the food and fiber needs of the increasing world population, agriculture is expected to increasingly improve its water utilization to satisfy a 67% increase in food demand from 2000 to 2030 at a projected water usage increase of only 14% (FAO, 2006).

Common irrigation systems include seepage (or flood), overhead and drip irrigation (Locascio, 2006). Important attributes of irrigation systems are uniformity of water application, water use efficiency (defined as the ratio of water delivered to the crop to water pumped), and cost of installation and maintenance. In seepage irrigation (Figure 1-1), the presence of an impervious soil layer at 20 to 36 inch depth allows the establishment of a perched water table that supplies water to the rootzone by capillarity. Although large amounts of water are required and water use efficiency is only 33%, seepage systems are used on 45% of irrigated crops in the U.S. as they are inexpensive to set up, easy to maintain and continuously supply water to the crop. In overhead irrigation (Figure 1-2), where water is applied to crops by solid set sprinklers, linear moves or center pivots, a much improved water use efficiency of about 75% is achieved. It is used on 50% of irrigated crops in the U.S. despite higher installation and maintenance costs than seepage systems.

Drip irrigation (Figure 1-3) is one of the most promising irrigation technologies of the 21st century that offers high water use efficiency (>85%) and is often specified as a best management irrigation practice for reducing groundwater contamination (Evans et al., 2007; Locascio, 2006). Water is applied directly to plants in small amounts, through water outlets (called emitters) that wet only the soil near the plant, while other parts of the field remain dry. About one-third to one half less amounts of water was used in drip compared to seepage and sprinkler systems (Csizinszky et al., 1987; Locascio and Myers, 1974; Pitts et al., 1988). Furthermore, through the drip line, precise controlled delivery of fertilizers to plant rootzone may lead to higher nutrient use efficiencies and improved yields (Locascio, 2006). Moreover, drip irrigation systems also allow the injection of pesticides for controlling soil-borne pests, nematodes and weeds. However, higher installation and maintenance costs compared to other irrigation methods had limited usage of drip systems to 5% of irrigated crops in the U.S. (Locascio, 2006).

In Florida, drip irrigation is widely used for production of high value vegetables such as tomato (*Solanum lycopersicon*), pepper (*Capsicum annuum*), strawberry (*Fragaria x ananassa*) and cucurbits. Florida is the largest producer of fresh market tomato in the U.S. (Table 1-1). Some 1,000 million lb of tomato was produced by Florida in 2007-2008 on 19% of its total planted vegetable acreage (Figure 1-4). Most tomato production is located in the panhandle near Quincy, FL and Central and South Florida with predominant use of seepage irrigation (Dukes et al., 2010). Approximately 20% of tomato acreage is drip-irrigated (Haman, 2005), but drip irrigated acreage is likely to grow due to tighter regulations on water supplies and quality.

Nitrate pollution is a widespread problem in vegetable producing regions of the U.S. (Hartz, 2006), and regulatory authorities are urging adoption of Best Management Practices (BMPs) to protect water quality. The Federal Clean Water Act (FCWA) of 1977 (U.S. Congress, 1977) required states to monitor the impact of nonpoint sources of pollution on surface and ground waters and to establish Total Maximum Daily Loads (TMDLs) for impaired water bodies (Section 303(d) of FCWA). In 1987, Florida adopted the Surface Water Improvement and Management (SWIM) Act (Section 373.451 F.S.) to protect, restore and maintain Florida's highly threatened surface water bodies (Florida Senate, 2010). The 2001 Florida Legislature authorized Florida Department of Agriculture and Consumer Services (FDACS) to develop BMPs, cost-share incentives and other technical assistance programs to help agriculture to reduce pollutant loads in target watersheds (Section 570.085 F.S.) (Florida Senate, 2010). BMPs are specific, science-based cultural practices, which are determined to be practical and effective in reducing pollutants from agricultural operations. In Florida, statewide agricultural BMPs had been adopted by rule (5M-8 Florida Administrative Code) for vegetables and agronomic crops (FDACS, 2005). By law, growers who voluntarily implement a BMP plan will receive a "presumption of compliance" with state water quality standards. However, recent studies (Farneselli et al., 2008; Simonne et al., 2003; Simonne et al., 2006a) showed that current irrigation BMPs may not be enough to keep irrigated water from going beyond the active vegetable rootzone of 12 inches (Machado et al., 2002) and that nitrate-N (NO_3^--N) concentrations monitored by shallow wells in farms had gone up to 40 mg L^{-1} NO_3^--N even when BMPs are used. Hence, BMPs are a step in the right direction, but they may not be sufficient to fully protect water quality.

Chemicals injected through the drip line are another potential source of groundwater contamination as well. Drip fumigation is an application of drip irrigation that has garnered great attention recently due to the U.S. phase-out on the production and importation of methyl bromide in Jan. 2005 (Section 604 of Clean Air Act) in compliance with the Montreal Protocol on Ozone Depleting Substances (EPA, 2010). Drip fumigation (Chase et al., 2006; Duerksen, 2002; Santos and Gilreath, 2007) was deemed to be an effective method to apply fumigants as it has the advantages of reducing air pollution and minimizing worker exposure to toxic fumigants (Trout and Ajwa, 2003). However, the volume of soil that needs to be wetted for fumigation purposes is quite different from that for water and fertilizer application (Table 1-2). Fumigation requires maximizing the soil wetted area for thorough contact between fumigant and pests or weeds. To achieve uniform whole-bed wetting, drip fumigation may need to be applied for 2 to 10 hours (Chase et al., 2006; Csinos et al., 2001; Trout and Ajwa, 2003). But in these studies, there was no report on the depth of soil water movement and the risk of deep percolation after the long hours of irrigation was not addressed. The risk of groundwater contamination is high for a sandy soil especially with long hours of irrigation. Therefore, when using drip fumigation in a sandy soil, fumigant should be injected in a way that allows for adequate lateral movement without leading to deep drainage.

Drip emitters generally apply small uniform flow of water at rates ranging from 0.16 to 2.0 gal/h (gph) (Clark et al., 1995) at recommended operating pressures of 7 to 35 psi (Thompson, 2003). Crop water requirements depend on crop type, stage of growth, and evaporative demand (evapotranspiration, ET). In Florida and southeast U.S., crop water use or crop evapotranspiration (ETc) of tomato ranges from 0.04 to 0.24 inch per day which approximates to water needs of 12 to 72 gal per 100 ft of bed (Clark et al., 1995). Even when using the lowest available emitter flow rate, a water application rate of 0.16 gph (or 16 gal per 100 ft of bed for 12-inch emitter spacing) provides the plant water needs in a small fraction of the day over which photosynthesis and transpiration occurs, which means that no water is applied during much of the day. Furthermore, ETc varies throughout the day (Zur and Jones, 1981), and the time when irrigation is applied may not correspond to greatest water need. This implies that for every irrigation event, part of the water may not be used by the plant. It is either drained below the crop rootzone or stored in the soil profile. Therefore, lowering the emitter flow rate so that water can be applied at a rate that closely matches evapotranspiration may further improve irrigation efficiency (Assouline, 2002). In the current absence of a commercial drip tape which can do so by design (low flow drip tapes are 16-18 gal/100ft/h), existing flow rates could be reduced by reducing the irrigation operating pressure (OP). However, studies on the use of reduced OP for drip irrigation are limited (Batchelor et al., 1996; Dowgert, 2007; Miller, 1990). Yet, this possibility needs to be tested before it can be recommended. The goal of this project is to determine if reduced OP (thus reduced emitter flow rate) could improve drip irrigation scheduling and be included in University of Florida/Institute of Food and Agricultural Sciences (UF/IFAS) irrigation recommendations and as a BMP.

Table 1-1. Production and value of fresh market tomato in the United States, 2007-2009.

	Production (1000 lb)					Value (1000 $)				
States	2007	2008	2009	Average	Average % of total	2007	2008	2009	Average	Average % of total
FL	333,025	261,450	307,450	300,642	37	424,940	622,251	520,205	522,465	65
CA	277,500	291,375	261,000	276,625	34	374,070	388,112	363,312	375,165	46
VA	38,150	32,900	36,000	35,683	4	55,241	50,929	63,216	56,462	7
GA	45,000	21,000	31,500	32,500	4	52,200	27,048	62,244	47,164	6
TN	28,975	28,000	34,000	30,325	4	39,406	38,080	44,880	40,789	5
Others	118,025	143,700	139,175	133,633	17	222,836	288,877	260,084	257,266	32
US	840,675	778,425	809,125	809,408		1,168,693	1,415,297	1,313,941	1,299,310	

Source: National Agricultural Statistics Service, United States Department of Agriculture, 2010.

Table 1-2. Comparison of drip irrigation characteristics for application of water, nutrients or fumigants.

	Application of:		
	Water	Nutrients	Fumigants
Frequency	Daily, multiple times daily	Daily/weekly	Pre-plant or between crops
Polyethylene mulching	Maybe	Maybe	Required
Target wetted depth	Active rootzone depth of 12 inches	Active rootzone depth of 12 inches	Up to 24 inches depth
Target wetted width	Active rootzone width and emitter-emitter coverage	Active rootzone width and emitter-emitter coverage	Whole bed
Presence of plants	Yes	Yes	No

Figure 1-1. Seepage irrigation used for fall tomato production with plastic mulched raised beds in a commercial farm in central Florida, showing a lateral ditch supplying water to irrigate the beds to the left of the ditch.

Figure 1-2. Overhead sprinkler irrigation mounted on a linear moving system in an experimental field in central Florida. Note the dispersion of the water droplets due to windy conditions.

Figure 1-3. Drip irrigation used for spring tomato production with plastic mulched raised beds in an experimental field in north Florida showing polypipes supplying water to drip tapes below the mulch.

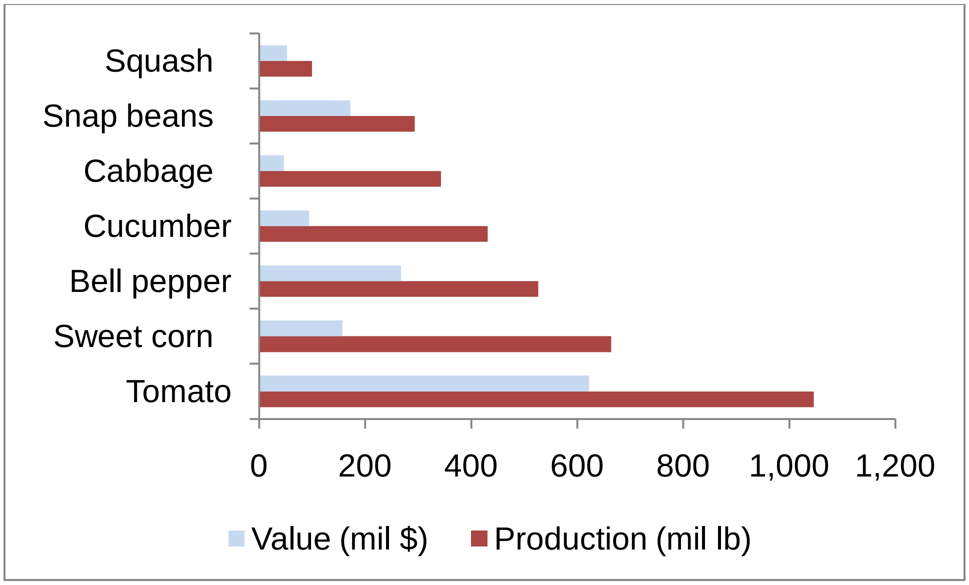

Figure 1-4. Production and value of major vegetables grown in Florida, 2007-2008. Source: National Agricultural Statistics Service, U. S. Department of Agriculture, 2010.

CHAPTER 2
REVIEW OF LITERATURE

Current UF/IFAS recommendations on drip irrigation scheduling include (1) having a target irrigation volume (based on historical weather data or crop evapotranspiration), (2) adjusting the irrigation volume based on soil moisture monitoring, (3) taking into account contribution of rainfall, and (4) having a rule for splitting irrigation events (Simonne et al., 2010a). In addition, (5) irrigation records should be kept. Target irrigation volumes are estimated from daily ETc, which is calculated by multiplying reference evapotranspiration (ETo) by a crop coefficient (Kc). Kc values are available for drip-irrigated plastic-mulched tomatoes (Simonne et al., 2010a).

These recommendations, however, do not consider water application rate (emitter flow rate), soil hydraulic properties and changes of crop water needs throughout the day. In particular for coarse-textured sandy soils with many macropores and high water conductivities, applying water at a high rate would result in higher risks of water draining downwards and carrying nutrients beyond the crop rootzone. This is further exacerbated when water is applied during periods of the day when there is low evapotranspiration and plant water uptake is limited. In fact, recent studies (Farneselli et al., 2008; Simonne et al., 2003; Simonne et al., 2006a) showed that despite adhering to UF/IFAS recommendations, irrigated water was still moving beyond the active vegetable rootzone of 12 inches (Machado et al., 2002) and that nitrate-N (NO_3^--N) concentrations monitored by shallow wells in farms were found to go up to 40 ppm NO_3^--N.

Units to Express Drip Irrigation Volumes

Clark et al. (1995) discussed comprehensively drip-irrigation design considerations for vegetable production in a sandy soil that takes into account the wetted soil volume, crop water needs and soil hydraulic properties. They suggested that as drip irrigation is applied in linear rows, and the wetted soil volume is a hemispherical cylinder within the row, it is convenient to discuss irrigation requirements and schedules in volumetric units (gal per 100 ft of length) rather than depth units (inches) as is typically used to represent irrigation amounts for overhead or seepage irrigation. For these systems, using vertical amounts of water is appropriate since the entire field is wetted uniformly. Current crop water use estimates are based on daily ET values measured as vertical amounts of water expressed in inches. To convert to volume, it is assumed that each “inch” is equivalent to an acre-inch of water, which is approximated to be 27,150 gal. For drip irrigation this amount of water has to be calculated based on wetted width in each linear row. An acre measures 43,560 square ft. For a wetted width of 1.5 ft, the volume of water for 100 ft of bed is therefore [(ET x 27,150)*1.5/43,560]*100 or more generally (ET x 27,150 x wetted width/435.6). The total amount of water to be applied to an acre of drip irrigated field for different bed spacings and wetted widths is shown in Table 2-1.

Soil Water Flow and Water Holding Capacity

The soil wetted volume from an emitter is affected by the initial soil water content, emitter flow rate, irrigation frequency and duration, capillary movement of water and the water-holding capacity of the soil (Evans et al., 2007). Capillary flow results from the adhesion and cohesion forces of water, and is the dominant form of water movement in small pores when the soil is unsaturated. In contrast, gravitational flow is predominant in large pores when the soil is saturated (when soil pores are filled with water and the soil is at its maximum holding capacity), where water in the large pores will drain downward mainly under the influence of gravitational forces. Once water has moved out of the macropores by gravity and air has moved in, the micropores are still filled with some water and can supply plants with water by capillary flow. The soil is said to be at its field capacity. The volumetric water content at field capacity is typically 12% for a sandy loam and 35% for a clay soil. Most soil leaching occurs due to gravitational flow that drains from the large pores before field capacity is reached, and transports chemicals such as nutrients, pesticides and organic contaminants into deeper soil horizons and possibly into groundwater and rivers (Brady and Weil, 2002).

Rootzone Water Holding Capacity

An irrigation event should be able to provide water to wet the active root zone for uptake of water. Most tomato roots were localized in the top 12-16 inches of the soil (Machado et al., 2002), with about 90% of them found laterally within 8 inch of the stem (Hammami and Daghari, 2007). Assuming a fully expanded active crop root zone of 8 inch radius and 12 inch depth that occupies a cylindrical soil volume ($\pi r^2 h$), in Florida's sandy soils with poor water holding capacity of 0.03-0.10 inch of water per inch of soil (Natural Resources Conservation Service, 2006), the greatest volume of water that could be stored is 0.3-1.0[1] gal in each plant root system. For drip-irrigated tomatoes on 6-ft bed centers grown with plastic mulch on Florida's sandy soils, the estimated daily crop water use (ETc) could be as high as 4,600 gal/acre or 63 gal/100ft (0.95 gal/plant/day for 4,840 plants at 18-inch plant spacing) (Simonne et al., 2010a). Currently, available low to medium drip tape flow rates typically range between 15 to 24

[1] At water holding capacity of 0.03 inch per inch of soil, volume of water that could be stored is (3.14 x 8^2 x 0.03 x 12) = 72.34 cubic inch = 0.3 gal (1 cubic inch is equal to 0.0043 gal).

gal/100ft/h. More commonly, the flow rate of 24 gal/100ft/h is used for tomato production with nearly 2.5 hours of irrigation needed to meet daily plant water demand of 63 gal/100ft (63/24 = 2.5). Irrigating continuously for 2.5 hours in a single irrigation event to supply 0.95 gal of water would exceed a soil water holding capacity of 0.3 gal/plant, thereby increasing the risk of drainage. Hence, UF/IFAS recommends that such irrigation be split into three irrigations of about 1500 gal/acre (0.31 gal/plant) each to replace ETc and not exceed soil water holding capacity. However, ETc varies according to the diurnal flux of solar radiation (Zur and Jones, 1981) within a 24-hour period and each irrigation event maybe applying a water volume that is beyond the crop water needs of that hour (Figure 2-1A), thus leading to increased drainage risks. It may be possible to reduce the drainage potential if reduced amounts of water are applied during each irrigation event within a day (Figure 2-1B), such as using a lower emitter flow rate (for example, using a drip tape with flow rate of 12 gal/100ft/h) so that the same amount of water is applied through having more irrigation events in the day. The ideal irrigation schedule that could eliminate drainage loss is one with variable emitter flow rates that vary according to ETch (Figure 2-1C). However, currently available flow rates are too high to achieve this.

Water Movement in Sandy Soils

Water leaving an emitter is subject to capillarity and gravity. The initial wetting front in dry soil is nearly circular (Figure 2-2) as capillary action dominates and acts equally in all directions from a point source of water for a homogeneous soil. Subsequent wetting fronts tend to be elliptic as gravity influences water to flow downwards in the increasingly saturated zone near the emitter, although capillary action continues at the edge of the wetting front. Such wetted patterns were observed by Simonne et al. (2003)

and Farneselli et al. (2008) where wetted patterns went from round to elongated as irrigated volumes increased for soils where vertical water movement is not impeded. When the waterfront reached an impermeable layer, water spread out laterally followed by upward vertical movement (Simonne et al., 2005).

Soil texture is one of the most important factors affecting water movement and distribution in the soil. Because of the presence of large number of macropores (radius>0.002 inch) in a sandy soil, water is expected to move downwards more rapidly in a sandy compared to a clay soil while horizontal movement (largely by unsaturated flow) is prevalent in the clay (Brady and Weil, 2002). Therefore, for a sandy soil, it is important to prevent the soil from becoming saturated so that there will be reduced downwards gravitational flow. The soil's saturated hydraulic conductivity (K_{sat}) is its ability to transmit water when it is saturated and it is estimated at 7-14 inch/h for sandy soils and 0.07 inch/h for clay soils. Clothier and Heiler (1983) found non-uniform soil water distribution and increased water flow through macropores when the rate of irrigation application was greater than the soil's hydraulic conductivity. Hence Clothier and Green (1994) proposed that the application rate should be matched to the soil's hydraulic conductivity to avoid preferential water movement through macropores and probable losses of irrigation beyond the crop rootzone. As sands have high hydraulic conductivities and are easily saturated, it is necessary to apply water at very low rates to keep the soil from becoming saturated. Levin et al. (1979) reported greatest advance of wetting front laterally and vertically at emitter flow of 2 gph compared to 0.25 gph in a sandy soil, with more water retained in the top 24 inches at 0.25 gph compared to higher flow rates of 0.5, 1 and 2 gph (Table 2-2). Bar-Yosef and Sheikhoslami (1976) also found that in a Nezarim sandy soil, vertical movement was greater at emitter flow rate of 0.66 gph (12 inches depth) compared to 0.066 gph (<8 inches depth), with respective lateral movements of < 6 inches and 7.6 inches.

However, contradicting results were predicted by Schwartzman and Zur (1986), who proposed that wetted depth (D in inches) and width (W in inches) are dependent on hydraulic conductivity of the soil, *Ks*, emitter flow/discharge, *q* (in gph), and the total amount of water in the soil, *V* (in gal), according to:

$$D = 2.54V^{0.63}\left(\frac{Ks}{q}\right)^{0.45} \tag{2-1}$$

$$W = 1.82V^{0.22}\left(\frac{Ks}{q}\right)^{-0.17} \tag{2-2}$$

They noted that doubling *q* tended to increase W by 10% and decrease D by 30% for any given V (Figure 2-3). This effect was especially pronounced in medium and heavy soils (low *Ks*) compared to light soils (high *Ks)*. Ah Koon *et al.* (1990) investigated the effect of emitter flow rate on the water content distribution beneath a crop of sugar cane (*Saccharum officinarum*) in a clay soil and found that increasing the flow rate resulted in an increased lateral movement of water and a decrease in the wetted depth. Conversely, decreasing q at a given V results in increasing the wetted depth and decreasing the wetted width (Figure 2-3).

Badr and Taalab (2007) studied the effect of three emitter flow rates (0.5, 1 and 2 gph) on soil wetting pattern and tomato yield for surface drip irrigation in a sandy soil (Table 2-3). They found that after applying the same volume of water, the wetted front depths had moved to 28, 24 and 20 inches at the respective discharge rates, concluding that increasing the water application rate allowed more water to move laterally, while decreasing the rate causes more water to move downwards. They also reported that a saturated zone formed below the emitter of the 2 gph flow rate but not for the two lower flow rates. This could explain the larger wetted zone for the 0.5 and 1 gph flow rates as water was spread out over a bigger area compared to the 2 gph flow rate. The maximum tomato yield (50,000 lb/acre) was obtained at a flow rate of 0.5 gph while the yield at 2 gph was 16% lower. Bresler et al. (1971) also reported greater downwards water movement (22 inch at 0.01 gal/inch/h compared to 16 inch at 0.13 gal/inch/h) in a Nahal Sinai sandy soil, and suggested that a high flow rate could lead to more rapid water saturation at the water entry point so that there was increased lateral but decreased vertical movement. Similar results were obtained by Brandt et al. (1971) and Csinos et al. (2001). These studies show that reducing emitter flow rate would increase wetted soil depth and decrease wetted width.

Keeping Water and Nutrients in the Crop Rootzone

It will be ideal to irrigate to just meet crop needs, where, moisture content in the soil will not reach saturation and there will be no rapid gravitational flow and drainage of water from the large soil pores. Additionally, water will move mainly by capillary flow which is limited in a sandy soil implying that the wetted volume should be smaller. If this could be achieved, the risks of nutrient leaching would be reduced. The idea of using very low water application rates to match crop ET and keep water within the crop rootzone has been investigated by several researchers. Kenig et al. (1995) and Zur (1976) used pulsating devices to apply water intermittently in pulses that achieved the same soil moisture level as conventional irrigation flow rate but at reduced water volumes and thus increased water savings . Assouline (2002) used very low flow rates of 0.066 gph in corn (*Zea mays*) grown in a sandy soil that tended to improve yields and resulted in a smaller wetted volume compared to higher flow rates of 0.5 and 2 gph. In addition, using low emitter discharges of <0.13 gph reduced water consumption, increased yields and reduced leaching in tomato. Drip tapes of such low discharge rates were available from an Israeli company, Ein Tal Ltd (http://www.ein-tal.com/index.files/Page704.htm), but are not widely marketed in the U.S.

Another approach to achieve extremely low flow rates is to reduce the irrigation system operating pressure (OP), even below the recommended OP. Dowgert et al. (2007) reported higher water use efficiencies with gravity-based systems operating on very low pressures of 2-3 psi, having low flow rates that led to greater lateral water movement and allowed more water to be retained within the crop rootzone. At the low pressure of 3 psi, they obtained measured flow rates that match calculated rates based on *k* and *x* values, and good emission uniformity (> 90%) for lateral lengths of 240 ft. Using 3 psi pressure, they applied 2 inches of water in 36 hours to achieve uniform whole bed soil wetting for onion establishment in Texas whereas the same water amount was applied in 3 hours at standard 10 psi pressure and soil wetting of the bed was not complete. This may allow adequate soil bed wetting for drip fumigation. Furthermore, with the lower rate of water application, they reported water savings of 40% to 60% for potato (*Solanum tuberosum*) and corn, respectively, grown in Chihuahua, Mexico. Such uses of low pressure irrigation systems (3 psi) in smallholder farms had also been reported by Batchelor et al. (1996) and Miller (1990).

The emitter flow rate could be reduced by using a suitable pressure regulator. The pressure regulator is an essential component of a drip irrigation system as it is required to reduce the pressure from a water source which could be pressurized as high as 40-60 psi (Table 2-4) to levels (10-12 psi) at the emitters. Spring-loaded pressure regulators with preset pressure ratings of 10-50 psi and operating between 1.6 to 16 gpm (Keller and Bliesner, 1990) are commonly used to reduce and maintain the pressure downstream. The emitter flow or discharge rate is related to water pressure by

$$q = kp^x \tag{2-3}$$

where q is the discharge rate (gph), *p* is the water pressure (psi), *k* is emitter discharge coefficient and *x* is emitter discharge exponent (Thompson, 2003). The *x* value characterizes the flow type of the emitter and varies from 1 to near zero. When $x = 1$ the emitter is a laminar flow emitter, and flow rate varies directly with pressure, whereas *x* will have a value around 0.65 for long or spiral path emitters, 0.5 for fully turbulent flow emitters, about 0.4 for a vortex emitter, and near zero for a fully pressure-compensating emitter (Evans et al., 2007). For a typical drip tape with $k = 0.081$, the changes in flow rate as pressure increases for various *x* values is shown in Figure 2-4. Current drip tape emitters used for vegetable production in the south-eastern US have *x* values of about 0.5. These emitters are turbulent-flow type and not fully pressure compensating. Their flow rates will vary substantially with pressure.

Uniformity of water application will also vary with pressure (Smajstrla et al., 2008). Safi et al. (2007) suggested that lower pressures of 7 and 13 psi led to less uniform wetting pattern and lower emitter flow rate compared to higher pressures of 20 and 30 psi. Also, they reported that high uniformity of >90% was maintained at drip tape lengths of 300 ft or less and uniformity dropped drastically when length is more than 300 ft.

Visualizing Soil Water Movement

Studies using a blue dye tracer to visualize wetting patterns in the soil (German-Heins and Flury, 2000) had been carried out extensively in Florida to understand water movement for irrigation management and drip fumigation. These studies were focused primarily on varying irrigation times and volumes on the wetted soil depth and width (Table 2-5). Schwartzman and Zur (1986) had predicted that an increase in V in the soil contributed more to an increase in D than to an increase in W so increasing V in order to increase W was a wasteful practice, especially in light soils. Studies carried out for drip fumigation where increasingly long irrigation times and volumes were applied (Eger et al., 2001; Huckaba et al. 2001; Santos et al., 2003) supported this hypothesis and that complete bed wetting could only be achieved with two drip tapes. Even after an excessive irrigation time, one drip tape was unable to achieve complete bed wetting.

Without plants and after a single irrigation event, water moved at a rate of 0.09 inch per gal/100ft of water applied in an Alpin-Blanton-Foxworth sandy soil (Simonne et al., 2006) and the water front reached the 12-inch active root zone depth after an irrigation time of 2-3 hours if a drip tape at 0.24 gph was used (Simonne et al., 2003). This suggested that for irrigation scheduling, irrigation events longer than 2 hours should be split into shorter durations as was proposed by Di Gioia et al. (2009) for pepper irrigation. However, Poh et al. (2010) found no reduction in soil wetted depth when a 4-h irrigation event was applied either as a single event, split into two 2-h events, or four 1-h events. Farneselli et al. (2008) investigated the wetted pattern for long continuous irrigation durations and found a quadratic depth response to irrigated volume ($D = -2 \times 10^{-7} V^2 + 0.008 V + 34$, where D is in cm and V is in L/100m), and maximum depth of about 47 inches at both 38 and 60 h of irrigation, which indicated that water percolation in a sandy soil is high and is very much dependent on the volume of water applied. Eger et al. (2001), however, found that the waterfront had moved to the 12-inch depth in an Eau Gallie fine sand after 10 hours of irrigation at 0.27 gph. This difference could be due to compaction of the soil bed as Eger et al. also observed greater lateral compared to vertical movement as irrigation volumes increased. Bed compaction could be a useful tool to increase the soil wetted width for fumigation and decrease the soil wetted depth for irrigation scheduling. In southern Florida, raised beds for strawberry production are triple-compacted which allowed a single drip tape to be used to supply water for two rows of plants (Figure 2-5).

For the above studies, plants were absent and the impact of plant water uptake was not considered and care should be taken to extrapolate these results for irrigation recommendations in commercial farms. In a study conducted in a commercial farm with drip-irrigated muskmelon (*Cucumis melo*) and watermelon (*Citrullus lanatus*), Simonne et al. (2005) created various irrigation volumes by using different drip tape flow rates and found that water movement was greater early in the season (1-5 weeks after establishment). Furthermore, water was kept within the crop rootzone for major part of the season although some drainage was likely to occur on light-textured soils even when UF/IFAS recommended practices were followed. This suggested that further refinement of irrigation scheduling was needed to prevent water and nutrients from moving beyond the crop rootzone.

Goal and Objectives of Project

Although drip irrigation is included as an irrigation BMP, and many details of drip irrigation for tomato production has been established (Clark et al., 1995, Locascio, 2006), there is still a need to fine-tune the irrigation scheduling to improve water use efficiency and minimize the risks of nutrient leaching and pollution. The use of reduced irrigation OP to reduce emitter flow and water application rate is a relatively unexplored method that could improve water retention in the crop rootzone by reducing soil wetted depth and increasing soil wetted width. This application is also relevant for drip fumigation where extended irrigation durations are necessary to provide adequate soil bed wetting and contact time between the fumigant and target organisms.

However, limited information exists on the use of such low flow rates achieved by manipulating the irrigation OP on tomato production. Furthermore, reports on effect on the wetted depth at decreased emitter flow rates had been contradictory. The goal of these experiments was to determine if a reduced irrigation system OP (through reduced emitter flow rate) could improve drip irrigation management by decreasing the soil wetted depth for irrigation scheduling and increasing the wetted width for drip fumigation. The specific hypotheses and objectives of the project were:

- **Hypothesis 1**: Reduced OP will reduce drip tape emitter flow rates and reduced soil wetted depth and increased wetted width.
- **Objective 1**: Determine the effects of reduced irrigation system OP on the flow rates, uniformity and soil wetted depth and width in three commercially available drip tapes.
- **Hypothesis 2:** At reduced OP and emitter flow rates, reduced amounts of fertilizer and irrigation rates could be used to produce comparable yields to standard fertilizer and irrigation rates.
- **Objective 2:** Determine the effects of reduced irrigation system OP coupled with reduced fertilizer and irrigation rates on fresh market tomato nutritional status and yield.
- **Hypothesis 3:** Wetted soil depth and width is decreased by the presence of plants under standard and reduced OP irrigation.
- **Objective 3:** Determine the wetted depth and width for a tomato crop under reduced OP irrigation and compare responses to previous studies without plants.

To meet the three objectives, experiments were conducted using a reduced OP of 6 psi tested against a standard OP of 12 psi. Chapter 3 describes studies without plants to determine emitter flow rates, water application uniformity and soil water movement (objective 1) using three commercial drip tapes and at two lateral lengths of 100 ft and 300 ft. The possibility of growing a tomato crop with reduced water and fertilizer inputs at reduced OP was investigated in Chapter 4. Chapter 5 documents how deep the soil water has moved (as visualized by blue dye) after a cropping cycle.

Table 2-1. Amount of water (gal) for a drip-irrigated acre at different bed spacings and wetted widths assuming an evapotranspiration (ET) of 0.10 inches per day.

Wetted fraction	Amount per 100ft[z] (gal/100ft)	Amount of irrigated water per acre for: Bed spacing (ft) (No. of linear rows per acre[y])		
		4 (10,890)	6 (7,260)	8 (5,445)
Area under plastic (2.5 ft)	15.6	1,699	1,133	849
Wetted area (1.5 ft)	9.3	1,013	675	506
Seepage (entire acre)[x]			2,715 gal	

[z] Amount of water per 100 ft obtained by [(0.10 inch x 27,150 gal x 2.5 ft (or 1.5 ft)) / 435.6 square ft]

[y] No. of linear rows per acre obtained by (43560 square ft/bed spacing)

[x] Amount of water applied per acre using seepage is included for reference, obtained by (0.10 inch x 27,150 gal)

Table 2-2. Research showing decreased wetted depth (in inches) and increased wetted width (in inches) at low emitter flow rates (in gph unless otherwise stated) (or increased wetted depth and decreased wetted width at high emitter flow rates)

Reference	Soil type	Crop	Location	Flow rate	Wetted depth	Wetted width	Notes
Levin et al., 1979	Sand	None	South Africa	1 4	36 46	24 28	High flow – increased wetted area Low flow – decreased wetted area but average water content increased
Bar-Yosef and Sheikholslami, 1976	Sand	None	Israel	0.066 0.66	8 12	6 6	Higher flow rate led to increased soil wetted depth
Bar-Yosef, 1977	Sand	Tomato	Israel	0.66	18	18	Irrigated volume = 2.5 and 5 gal/day. Higher soil moisture content in wetted zone at 5 gal/day

Table 2-3. Research showing increased wetted depth (in inches) and decreased wetted width (in inches) at low emitter flow rates (in gph unless otherwise stated) (or decreased wetted depth and increased wetted width at high emitter flow rates)

Reference	Soil type	Crop	Location	Flow rate	Wetted depth	Wetted width	Notes
Ah Koon et al., 1990	Clay soil	Sugar cane	Mauritius	0.25, 0.5, and 1			High flow - increased width, decreased depth
Badr and Taalab, 2007	Sand	Tomato	Egypt	0.5	28	30	Zone of saturation beneath emitter at 2 gph but not at 0.5 or 1 gph
				1	24	35	
				2	20	40	
Brandt et al. 1971	Sandy loam	None	Israel	0.02 gal/inch/h	10	9	Irrigated volume (V) = 0.26 gal
					24	18	V = 1.5 gal
				0.04 gal/inch/h	8	10	V = 0.26 gal
					22	19	V = 1.5 gal
Bresler, 1971	Nahal Sinai sand	None	Israel	0.01 gal/inch/h	22	16	Larger water entry saturated zone at high flow rate leading to greater wetted width and decreased depth.
				0.02 gal/inch/h	24	16	
				0.04 gal/inch/h	19	18	
				0.13 gal/inch/h	16	2	
Csinos et al., 2001	Fuquay loamy sand	None	Georgia, U.S.	0.16		21	Wetted depth not reported. Same wetted area at all flow rates.
				0.24		21	
				0.30		18	

Table 2-4. Example of pressure losses due to friction in the components of a drip irrigation system.

Component	Pressure (psi)
Water supply[z]	80
Main lines[y] (500 ft)	-2.0
Screen filter	-5.0 max
Water meter	-15.0
Submains[y] (500 ft)	-2.3
Miscellaneous @ 10%	-2.4
Pressure at 1st lateral[x]	~53 psi

[z] Initial pressure at water supply.
[y] Pressure losses are proportional to pipe lengths, generally 0.39 psi loss per 100 ft pipe length.
[x] This pressure is subsequently reduced by an in-line pressure regulator to recommended drip tape operating pressures of 10-12 psi. Note that pressure regulators have a recommended range of flow.

Table 2-5. Research carried out in Florida on effect of various irrigation volumes (in gal/100ft) and durations on soil wetted depth (in inches) and width (in inches).

Reference	Soil Type	Crop	Volume (irrigation duration)	Depth	Width	Notes
Eger et al., 2001	Eau Gallie fine sand	None	54 (2 h)	8	11	Flow rate of 27 gal/100ft/h. Width and depth increase linearly with irrigated volumes.
			162 (6 h)	11	15	
			324 (12 h)	15	21	
Farneselli et al., 2008	Alpin-Blanton-Foxworth fine sand[z]	None	912 (38 h) or 1440 (60 h)	47		Flow rate of 24 gal/100ft/h. Depth and width increased quadratically with volume
Huckaba et al., 2001	Sandy or sandy loam	None				Flow rate of 27 gal/100ft/h. Increasing percent of bed wetting as irrigation times increased from 2 to 8 h
Santos et al., 2003	Eau Gallie fine sand	None				Flow rate of 27 gal/100ft/h. Quadratic wetted area as irrigation times increased.
Simonne et al., 2003	Alpin-Blanton-Foxworth fine sand	None	24 (1 h)	9”	8”	Flow rate of 24 gal/100ft/h.
			48 (2 h)	11	9	
			96 (4 h)	16	12	
			192 (8 h)	19	15	
Simonne et al., 2005	Fine sand and fine sandy loam	Watermelon Muskmelon				Flow rate of 16-34 gal/100ft/h. Water movement was greater early in the season and water was kept within the crop rootzone for major part of the season
Simonne et al., 2006	Alpin-Blanton-Foxworth fine sand	None	72	12		Flow rate of 16-34 gal/100ft/h Depth and width responses to V were quadratic.

[z] previously classified as Lakeland fine sand

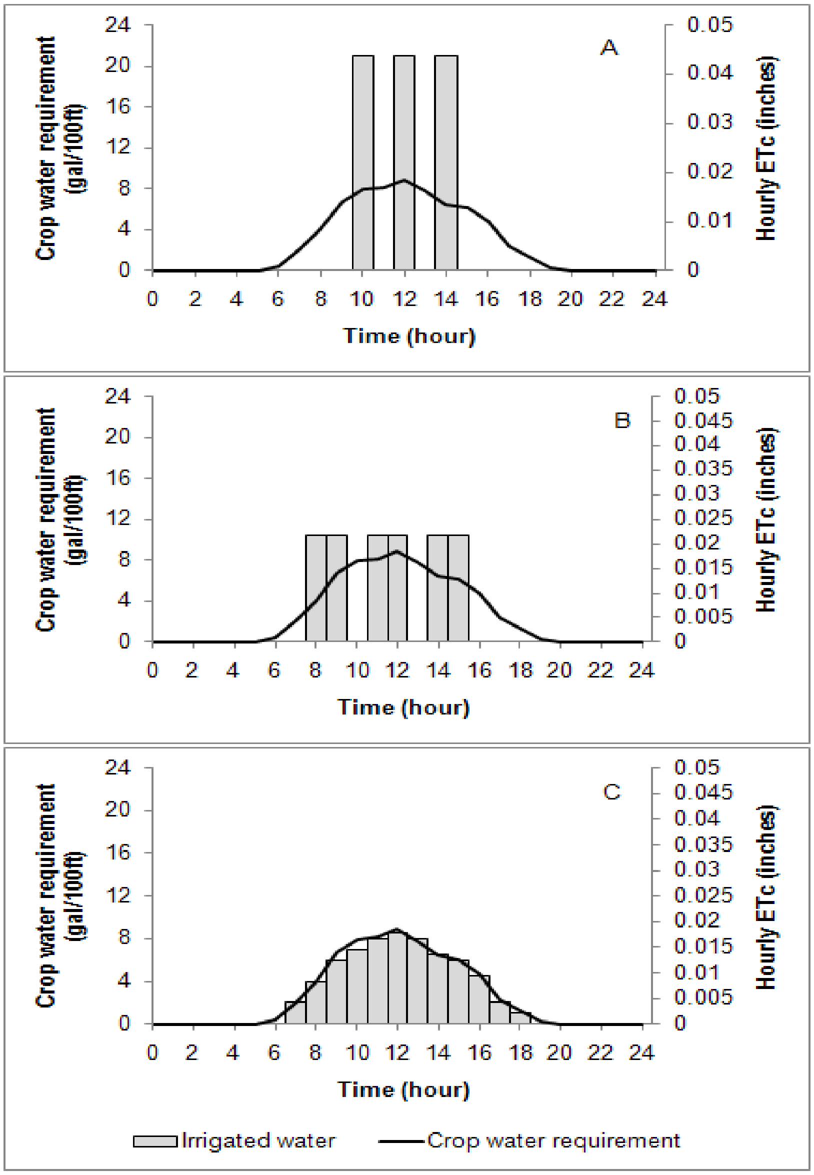

Figure 2-1. Changes in hourly crop water requirement and crop evapotranspiration (ETc) within a 24-h period for open-field production of drip irrigated tomato in central Florida showing (A) current recommended bulk water application through split irrigation scheduling (3 x 1-h grey bars), (B) proposed modified continuous irrigation with reduced operating pressure irrigation system, and (C) ideal continuous irrigation at flow rates that match hourly ETc. Hourly crop water requirement and ETc were estimated based on a reference evapotranspiration of 0.18 inches/acre (or 4,887 gal/acre/d) (Simonne et al., 2010) and diurnal fluctuation in solar radiation in June (FAWN, 2010). Note: for A, B and C, the total daily water application (total grey surface) is constant. Water application rate above ETc (grey bar above the curve) represent the risk of water drainage.

Figure 2-2. Longitudinal section of an Alpin-Blanton-Foxworth sandy soil beneath five emitters showing circular dye pattern after a single irrigation event of 1 hour at 12 psi using drip tape of 16 gal/100ft/h, 12-inch emitter spacing. Note maximum depth of dye was about 8 inches.

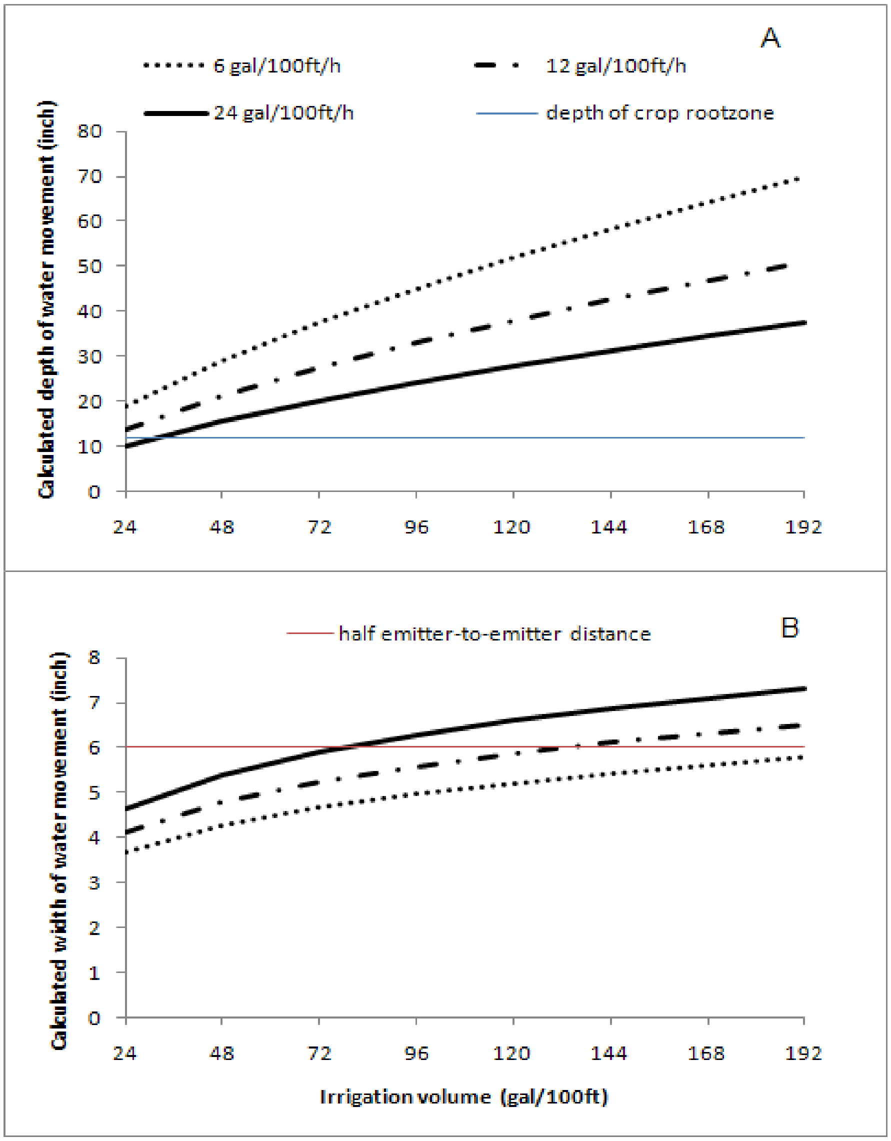

Figure 2-3. Calculated depth (A) and width (B) of water movement for a single emitter in response to increasing irrigation volumes at typical emitter flow rate of 24 gal/100ft/h and increasingly halved flow rates of 12 and 6 gal/100ft/h, based on equations

$$D = 2.54V^{0.63}\left(\frac{Ks}{q}\right)^{0.45} \quad and\ W = 1.82V^{0.22}\left(\frac{Ks}{q}\right)^{-0.17}$$

where D is wetted depth, W is wetted width, *Ks* is the hydraulic conductivity of the soil, *q* is emitter discharge,and *V* the total amount of water in the soil.

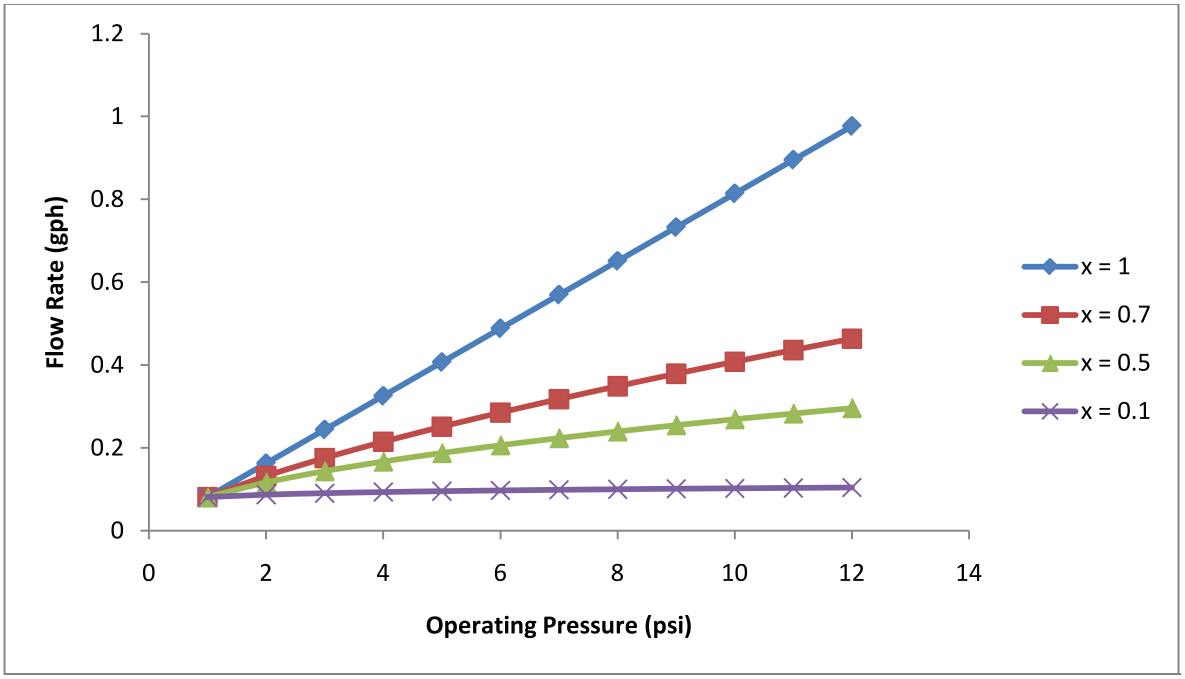

Figure 2-4. Theoretical changes in flow rate as irrigation operating pressure increases for a typical drip emitter with emitter discharge coefficient, k = 0.081 and emitter discharge exponent, x values of 0.1 to 1, calculated from equation, $q = kp^x$ where q is the emitter flow rate (gph), *p* is the water pressure (psi), *k* is emitter discharge coefficient and *x* is emitter discharge exponent.

Figure 2-5. Triple-compacted raised beds for strawberry production using a single drip tape in southern Florida.

CHAPTER 3
EFFECT OF REDUCED IRRIGATION SYSTEM OPERATING PRESSURE ON DRIP-TAPE FLOW RATE, WATER APPLICATION UNIFORMITY AND SOIL WETTING PATTERN ON A SANDY SOIL[2]

Background

In Florida, irrigation scheduling is becoming more important in vegetable production as a result of increasing restriction on use of water resources (Dukes et al., 2010) and the need to improve fertilizer use efficiency (Obreza and Sartain, 2010). Current Best management practices (BMPs) (FDACS, 2005) and University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) recommendations (Simonne et al., 2010a) specify the amount to irrigate, adjusting it based on soil moisture, accounting for rainfall contribution, and splitting irrigation events that are greater than 2 hours.

An irrigation event should be able to provide water to wet the root zone for active uptake of water. Most tomato (*Solanum lycopersicon*) roots were localized in the top 12-16 inches of the soil, with about 90% of them found laterally within 8 inch of the stem (Hammami and Daghari, 2007; Machado et al., 2002). Assuming a fully expanded active crop root zone of 8 inch radius and 12 inch depth that occupies a cylindrical soil volume ($\pi r^2 h$), in Florida's sandy soils with poor water holding capacity of 0.03-0.10 inch of water per inch of soil (NRCS, 2006), the greatest volume of water that could be stored is 0.3-1.0 gal in each plant root system. For drip-irrigated tomatoes on 6-ft bed centers grown with plastic mulch, the estimated daily crop water use (ETc) could be as high as 4,600 gal/acre or 63 gal/100ft (0.95 gal/plant/day for 4840 plants at 18-inch plant spacing) (Simonne et al., 2010a). Currently, available low to medium flow drip

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[2] Submitted to HortTechnology on 30 Sept.2010. Reprinted with permission from Poh, B.L., A. Gazula, E.H. Simonne, R.C. Hochmuth, and M.R. Alligood. (unpublished). Use of reduced irrigation operating pressure in irrigation scheduling. II. Effect of reduced irrigation system operating pressure on drip-tape flow rate, water application uniformity and soil wetting pattern on a sandy soil.

tapes typically range between 15 to 24 gal/100ft/h. More commonly, the flow rate of 24 gal/100ft/h is used for tomato production with nearly 180 min of irrigation needed to meet daily plant water demand of 63 gal/100ft. Irrigating continuously for 180 min to supply 0.95 gal of water exceeds a soil water holding capacity of 0.3 gal/plant, thereby increasing the risk of drainage. Hence, UF/IFAS recommends that such irrigation be split into three irrigations of about 1500 gal/acre (0.31 gal/plant) each to replace ETc and not exceed soil water holding capacity (Figure 2-1A). However, recent research (Farneselli et al., 2008; Simonne et al. 2003; 2006a) has indicated that while UF/IFAS recommendations satisfy plant water needs, they may not be sufficient to keep the wetted front from moving below the typical vegetable active root zone of 12 inches. Shallow (20 ft) water quality monitoring has also found nitrate-N (NO_3^--N) concentrations to spike up to 40 mg L^{-1} NO_3^--N when these recommendations are followed (Simonne et al., 2006b). It may be possible to further reduce the drainage risk if reduced amounts of water are applied during the different irrigation cycles within a day (Figure 2-1B). Current crop water use estimates are based on daily ETc estimates. ETc varies according to the diurnal flux of solar radiation (Zur and Jones, 1981), and 30-40% of daily ET may occur during the 2-hour period between 11 a.m. and 1 p.m. (Clark and Smajstrla, 1996). The crop water need during this period is about 0.4 gal per plant with an hourly requirement of 0.2 gal/plant. Current UF/IFAS recommendations do not take into account the variation in hourly ETc (ETch). Leaching risk could be reduced if drip irrigation provides slow but continuous irrigation that match more closely ETch (Figure 2-1C). This would require a variable flow rate that could be changed by changing operating pressure.

Water can be applied slowly (Figure 2-1 B and C) by using emitter with low flow rates (<15 gal/100ft/h). Studies had found that more water was retained in the upper soil level when a lower emitter flow rate was used. Levin et al. (1979) observed higher soil moisture content and greater water retention in the 0-24 inches depth of a sandy soil at a low flow rate of 0.3 gph compared to higher flow rates of 0.6, 1.2 and 2.4 gph. Bar-Yosef and Sheikhoslami (1976) also found that in a Nezarim sandy soil, vertical movement was greater at higher emitter flow rate of 0.75 gph with the water front moving to more than 12 inches depth and 6 inches sideways compared to the lower flow rate of 0.075 gph where the depth was <8 inches, and width of 7.6 inches. On the other hand, other reports had contradictory findings where greater downwards water movement was observed in a sandy soil at a lower flow rate of 0.6 gph compared to 1.2 and 2.4 gph (Badr and Taalab, 2007). Similarly, Mmolawa and Or (2000) modelled a greater downwards movement of water and solutes in a Nahal Sinai sandy soil when the flow rate was at 1.2 gph compared to 6 gph. Limited information existed about the use of low emitter flow rate on Florida's sandy soils, and it is not clear if lower emitter flow rate would result in decreased or increased downwards movement of water.

Drip tapes with flow rates less than 15 gal/100ft/h are usually not widely available. Lower flow rates could be created by reducing irrigation system operating pressure (OP) since emitter flow rate is empirically related to water pressure by

$$q = kp^x \tag{3-1}$$

where *q* is the emitter flow rate (gph), *p* is the water pressure (psi), *k* is the emitter discharge coefficient and *x* is emitter discharge exponent (Thompson, 2003, Smajstrla et al., 2008). The exponent *x* is unique for each type of drip tape as it varies with the types of emitter and plastic used. For laminar flow type of emitter where flow rate varies directly with pressure, *x* approaches 1. For turbulent orifice flow, *x* is 0.5 while for fully pressure-compensating emitter, *x* is close to 0.1 (Thompson, 2003). Manufacturers typically do not report *k* and *x* values on the drip tape label. Instead, they guaranteed a uniformity at a maximum lateral length, flow rate and OP.

Dowgert et al. (2007) suggested the use of gravity-based systems operating on very low pressures of 2-3 psi, resulting in lower flow rates that allow greater lateral soil water movement in addition to reducing deep percolation, and hence losses of water and crop nutrients. At the low pressure of 3 psi, they obtained measured flow rates that match calculated rates based on *k* and *x* values, and good emission uniformity (> 90%) for lateral lengths of 240 ft. Using 3 psi pressure, they applied 2 inches of water in 36 hours to achieve uniform whole bed soil wetting for onion establishment in Texas whereas the same water amount was applied in 3 hours at standard 10 psi pressure and soil wetting of the bed was not complete. Furthermore, with the lower rate of water application, they reported water savings of 40% to 60% for potato and corn, respectively, grown in Chihuahua, Mexico. We hypothesized that the reduced OP could also be applied in conventional pressurized drip irrigation system to create low flow rates that would apply water slowly and continuously so that plant hourly water needs are met while minimizing losses from deep percolation. However, it is possible that reduced OP may reduce uniformity, which may result in uneven plant growth. The objectives of this study were to determine the effect of using a reduced system OP on the flow rates, uniformity on 100 and 300 ft long laterals and soil wetted depth and width using three commercially available drip tapes.

Materials and Methods

Flow Rates and Uniformity Trials

An experiment was conducted twice at the North Florida Research and Education Center - Suwannee Valley near Live Oak, FL, in the Fall of 2009. The irrigation system consisted of a well, a pump, a back-flow prevention device, a 150-mesh screen filter, in-line pressure regulators of 6 and 12 psi and drip tape. Drip tape was laid flat on top of the ground, without raised bed. Pins were used approximately every 50 ft to keep the drip tapes straight and in place. Operating pressure was regulated by installing in-line pressure regulators (Senninger Irrigation Inc., Orlando, FL.) for the standard OP of 12 psi, 2-20 gpm, and reduced OP of 6 psi, 4-16 gpm. Three drip tapes with 12-inch emitter spacing were tested (Eurodrip, 0.16 gph at 10 psi, Eurodrip U.S.A., Madera, CA; Typhoon, 0.24 gph at 10 psi, Netafim U.S.A., Fresno, CA; and Ro-Drip, 0.24 gph at 8 psi, John Deere Water, San Marcos, CA), and on 100 and 300 ft length laterals. The three drip tapes were designated A, B, and C, respectively. Manufacturers' recommendations for maximum drip tape run lengths range from 300 to 1000 ft long. The low-end 300 ft was chosen as the standard in comparison to a shorter length of 100 ft. After pressurizing the system, water from two consecutive emitters was collected using a catch can for 10 min at every 50 ft interval along each drip tape. There were three (at 0, 50 and 100 ft) and seven (at 0, 50, 100, 150, 200, 250 and 300 ft) sampling points for the 100 and 300 ft lengths, respectively. Flow rate for each drip tape at each length was calculated as the mean emitter discharge of the three to seven sampling points. Uniformity of water application was assessed according to Camp et al. (1997). Briefly, emitter flow variation (q_{var}), coefficient of variation (*CV*), and uniformity coefficient (*UC)* were calculated as:

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \tag{3-2}$$

where q_{max} is the maximum emitter flow rate and q_{min} is the minimum emitter flow rate.

$$CV = \frac{s}{\bar{q}} \tag{3-3}$$

where s represents the standard deviation of emitter flow rates and $\bar{q}$ is the mean emitter flow rate.

$$UC = 100\left[1 - \frac{\frac{1}{n}\sum_{i=1}^{n}|q_i - \bar{q}|}{\bar{q}}\right] \tag{3-4}$$

where n represents the number of emitters evaluated, q_i is the emitter discharge of the ith emitter. The 12 treatments (3 drip tapes x 2 OP x 2 lateral lengths) were replicated four times in a split-split-plot randomized complete block design with OP as main plot factor, drip tape as sub-plot and length as sub-sub-plot. Proc Mixed (SAS version 9.2; SAS Institute, Cary, NC) was used for analysis of variance of the flow rates, q_{var}, CV, and UC in different drip tape type, length and OP treatments.

Dye Tests to Visualize Wetted Zones

Another experiment was repeated at the same location, on an Alpin-Blanton-Foxworth fine sand in Fall 2008 and 2009 using new rolls of tapes each year. Treatments were factorial combinations of OP (12 and 6 psi) and drip tape types (Tape A, B and C) in a split-plot design, with each treatment replicated four times. OP was the main plot factor in randomized complete block design with tape as sub-plot factor. Before the dye test was performed, 28-inch wide raised beds were made, covered with low-density polyethylene mulch and laid with drip tape. Each bed was divided into four plots of 20 ft length for irrigation treatment of 45, 90, 180 or 240 min. Drip tapes between plots were connected by on/off valves. After pressurizing the system, about 1 gal of Brilliant blue CF dye (Terramark SPI High Concentrate, Prosource One, Memphis, TN) was injected at 1:49 (dye:water) dilution rate for about 30 min and plots were subsequently irrigated. The plots with the shortest irrigation times were located farthest away from the water source (Figure 3-1). At the end of each irrigation time, water flow was shut off for that plot. To keep the irrigation system water demand and pressure constant, one additional drip tape of equal length was opened every time when a section of drip tape was turned off. Pressure was monitored at the end of the drip tape using a portable pressure gauge. Transverse sections of the beds on selected emitters were dug by hand after each irrigation time to observe the dye pattern which was indicative of the wetted zone. Measurements of the maximum depth (D, vertical length from the drip tape to the bottom of the blue dye) and width (W, maximum width of the blue dye) of the dye pattern were taken. D and W responses to OP and drip tape type were analyzed using Proc Mixed. As flow rates for each OP and drip tape treatment were different, volumes of water applied would varied depending on the irrigation durations. Irrigated volumes (V) were calculated for each treatment based on flow rates of each drip tape measured at 6 or 12 psi (as described in previous uniformity trials). Regression analysis of D and W responses to irrigated volume was carried out using Proc REG. V was square-root transformed and comparison of intercepts and slopes between 6 and 12 psi treatments was carried out by Proc GLM to determine if the two regression lines were significantly different from one another (Milliken and Johnson, 2001).

Results and Discussion

Flow Rates and Uniformity

The measured pressure at the end of the drip tape averaged 5.5 (range 5-6) and 10.5 (range 9-12) psi for the respective 6 and 12 psi OP treatments. Data from the two repetitions of the experiment were pooled as repetition x OP was not significant (P = 0.40 for FR, P = 0.99 for q_{var}, P = 0.91 for CV and P = 0.86 for UC). Because tape x length interaction was significant ($P \leq 0.01$), the variables flow rate FR, q_{var}, CV, and UC were analyzed separately by drip tape. Measured FR more closely match theoretical ones for Tape A, while measured flow rates was 10-25% lower for Tape B and C at both 6 and 12 psi OP (Table 3-1) compared to theoretical FR, which could be attributed to different types of plastic materials used to manufacture the drip tapes. At 6 psi OP, FR were reduced to 0.13, 0.17 and 0.16 gph, a decrease of 32%, 23% and 38% compared to FR at 12 psi for Tapes A, B and C ($P \leq 0.01$ for all three tapes), respectively. This shows that FR can be reduced by reducing OP and the flow rates at reduced OP could be approximated from k and x values, which could be obtained from manufacturers. Flow rate was also significantly affected by drip tape length with higher FR of 0.17, 0.20 and 0.23 gph at 100 ft compared to 0.15, 0.18 and 0.18 gph at 300 ft for Tapes A (P < 0.01), B (P = 0.02) and C (P < 0.01), respectively.

Emitter flow variation (q_{var}) of < 0.1 may be regarded as “good” and q_{var} >0.2 as “unacceptable” (Wu and Gitlin, 1979). Coefficient of variation (CV) is classified as “excellent” at < 5% and “unacceptable” at >15% (ASAE, 2010). A uniformity coefficient (UC) of >90% is considered as “excellent” and <50% is “unacceptable” (Smastrjla et al. 2008). The uniformity parameters q_{var}, CV and UC were not significantly affected by OP in all three drip tapes (Table 3-2). However, q_{var} for Tape A was “unacceptable” at 0.23

at 6 psi compared to 0.10 at 12 psi. Tape B had "good" q_{var} of 0.09 at both 6 and 12 psi, while Tape C had moderate q_{var} of 0.16 and 0.14 for 6 and 12 psi, respectively. A similar trend in CV was obtained for each drip tape with Tape B showing "excellent" CV below 5%. However, all three tapes showed "excellent" UC greater than 90%. These results show that reducing the system OP did not practically reduce the uniformity of water application although certain drip tape type may show greater variations in emitter flow.

Tape length had a significant effect on the uniformity of Tape B and C but not on that of Tape A. Longer runs of Tape B and C showed greater q_{var} (0.13 gph and 0.22 gph for Tape B and C, respectively, both $P < 0.01$) and greater CV [5% and 9% for Tape B ($P = 0.03$)and C ($P < 0.01$), respectively] compared to short runs (q_{var} of 0.05 and 0.09 gph for Tape B and C, respectively; CV of 3% and 5% for Tape B and C, respectively). The q_{var} at 300 ft for both tapes were considered as "unacceptable" although CV values were "acceptable". Based on these results, reduced OP seems to be more appropriate for short runs as they allow for greater uniformity. Poor uniformity of water application and unevenly distributed water would create zones of over/under irrigations, reduction in crop growth uniformity, leading to potential yield reductions and excessive nutrient leaching (Dukes et al., 2010). This makes reduced OP a practice better suited for small fields, or for large fields with multiple zones and short rows.

Although reducing OP significantly reduced flow rates (0.13 to 0.17 gph) without affecting uniformity of irrigation, the flow rates obtained were comparable to currently available drip tapes with low flow of 0.15 gph. Therefore, to apply water to more closely match hourly water needs in a sandy soil and reduce drainage risks, currently available low flow drip tape could be used. However, having a drip tape at a higher flow rate of

0.24 gph offers more versatility to the grower. By installing an adjustable in-line pressure regulator, he could reduce the flow rates to match the periods of low ETc and revert to high flow rates during maximum ETc. It is important for the grower to select the right type of drip tape that would have low variation at reduced OP. To do so, it would be helpful if manufacturers could provide expected flow rates, and information on other uniformity parameters such as q_{var} and CV at reduced OP on the drip tape label so that growers could make an informed decision on whether the drip tape is suitable to be used in a system with reduced OP.

Movement of Waterfront

The dye pattern appeared as a round to elliptical blue ring surrounding an uncolored section of soil as clear water was injected after the dye (Figure 3-2). This pattern was similar to those reported in this and other sandy soils of Florida (Faneselli et al., 2008; Simonne et al., 2003; 2005; 2006a; Zotarelli and Dukes, 2010.) Because, year x OP and tape x OP interactions were not significant for D (P = 0.26 and 0.06, respectively) and W (P = 0.05 and 0.36, respectively), responses to irrigated volume were pooled for both years and all drip tapes. Depth response to volume of irrigated water was quadratic and described as $D = 5.34 + 0.16V – 0.0007V^2$ ($P < 0.01$, R^2 = 0.80) at 12 psi and $D = 4.42 + 0.21V – 0.001V^2$ ($P < 0.01$, $R^2 = 0.72$) at 6 psi (Figure3-3A). The intercepts and slopes for the transformed regression lines were not significantly different (P = 0.37 and 0.60, respectively) which indicated that depth response to volume was not affected by OP. The depth of wetted zone was beyond the active crop root zone of 12 inches when V was about 45 gal/100ft, which represented about 3 hours of irrigation at 6 psi and 2 hours of irrigation at 12 psi for a typical drip tape with flow rate of 24 gal/100ft/h (Tape C). These results show that, for the same volume of water applied, reduced OP allowed extended irrigation without increasing the wetted depth.

The width of the wetted front also showed a quadratic response to irrigated volume and could be described as $W = 7.58 + 0.17V – 0.0006V^2$ ($P < 0.01$, $R^2 = 0.77$) at 12 psi and $W = 6.97 + 0.25V – 0.002V^2$ ($P < 0.01$, $R^2 = 0.70$) at 6 psi (Figure 3-3B). The intercepts and slopes of the transformed lines were not significantly different ($P = 0.37$ and 0.94, respectively), which indicates that OP did not affect the width of the wetted zone. For a fixed V within the tested range of 9-108 gal/100ft, the increase in wetted width at 6 psi was numerically greater, although not significant, than at 12 psi. However, maximum W of 14.8 inches was reached at a lower V (V = 62.5 gal/100ft) for the 6 psi treatment, which accounted for 53% of the 28-inch wide bed. At 12 psi, maximum W of 19.6 inches (70% of bed width) was predicted at V = 142 gal/100ft. Previous studies had reported wetted bed width of 57% (Simonne et al. 2006a) to 70% (Santos et al., 2003) when irrigation was applied at 10-12 psi. These results suggest that reduced OP is more suited for crops planted in single-row arrangements if a single drip tape were used because if there were two rows of plants, there may not be sufficient lateral movement of water to irrigate plants at the sides of the bed. Additionally, if reduced OP were used for drip-injected soil fumigant, it would be necessary to use two drip tapes to ensure good coverage and uniform application of the fumigant as was suggested by Csinos et al. (2001) who found maximum wetted bed width of 60% for a 25-inch wide bed. For irrigation scheduling purposes, using a low OP of 6 psi can wet an area of about 7.5 inches on either side of the drip tape, and with complete emitter-to-emitter coverage of 12 inches estimated to be at V = 25 gal/100ft (about 1.5 hour of irrigation). These results showed that for a given irrigated volume, reduced OP did not decrease the depth nor increase the width of the wetted zone. Instead, the actual volume of irrigated water applied is more important in determining movement of the waterfront.

Summary of Findings

With the use of reduced OP (6 psi), flow rate for the three selected drip tapes was significantly reduced by 23%-38% depending on the type of drip tape. Short runs (100 ft) of drip tapes were more uniform than long runs (300 ft) although it also depends on the drip tape type. Reduced OP is more appropriate for short runs as they allow for greater uniformity, making reduced OP more suited for small fields, or for large fields with multiple zones and short rows. It is important to select a suitable drip tape that has low variation and high uniformity in water application. Reduced OP did not decrease the depth of the waterfront in the soil nor affect the wetted width for a given irrigated volume applied. The crop root zone depth of 12 inches was attained after 3 hours of irrigation at 6 psi compared to 2 hours at 12 psi, indicating that reduced OP allows extended irrigation without moving the waterfront downwards. Maximum wetted bed width at reduced OP was about 53% of bed width which makes reduced OP more suited for single-row plant crops if only a single drip tape were used. Reduced OP offers growers a simple method to reduce flow rate so that irrigation water could be applied at rates that match more closely the hourly ET without the risk of leaching losses. Growers could make better choices of drip tape if manufacturers provided information on flow rates, emitter variation and uniformity at different OP on the drip tape labels. Lastly, reduced OP and hence reduced water application rate should be included as a UF/IFAS recommended practice for better irrigation scheduling and management and as a possible BMP.

Table 3-1. Theoretical and measured flow rates (FR) for three drip tapes at 6 and 12 psi operating pressure (OP) and two lengths of 100 and 300 ft.

Treatment	Flow rate (gph)[z]					
	Tape A[y]		Tape B		Tape C	
	Theoretical[x]	Measured	Theoretical	Measured	Theoretical	Measured
OP (psi)						
6	0.13	0.13b[w]	0.19	0.17b	0.21	0.16b
12	0.19	0.19a	0.26	0.22a	0.30	0.25a
P value		0.01		<0.01		<0.01
Length (ft)						
100		0.17a		0.20a		0.23a
300		0.15b		0.18b		0.18b
P value		<0.01		<0.01		<0.01
OP x Length (*P*)		0.45		0.47		0.01

[z]gph = gallon per hour.

[y]Tape A: Eurodrip, 0.16 gph at 10 psi, Eurodrip U.S.A., Madera, CA; Tape B: Typhoon 0.24 gph at 10 psi, Netafim U.S.A., Fresno, CA; and Tape C: Ro-Drip, 0.24 gph at 8 psi, John Deere Water, San Marcos, CA.

[x]Theoretical FR calculated from flow equation $q = kp^x$ where q is the emitter flow rate (gph), p is the operating pressure (psi), k is the emitter discharge coefficient and x is emitter discharge exponent. Tape A: k = 0.055, x = 0.49; Tape B: k = 0.084, x = 0.45; Tape C: k = 0.081, x = 0.52.

[w]Values are pooled data from two experiments conducted in Fall 2009 in Florida (repetition x factor: P = 0.40) and values with different letters within the same column are significantly different at α=0.05 by pairwise comparison with least-squared means.

Table 3-2. Emitter flow variation (q_{var}), coefficient of variation (*CV),* and uniformity coefficient (*UC),* and their ratings (Rt) for three drip tapes at 6 and 12 psi operating pressure (OP) and two lengths of 100 and 300 ft.

Treatment	Uniformity parameters																	
	Tape A[z]						Tape B						Tape C					
	q_{var}		CV		UC		q_{var}		CV		UC		q_{var}		CV		UC	
	(%)	Rt[y]	(%)	Rt	(%)	Rt	(%)	Rt	(%)	Rt	(%)	Rt	(%)	Rt	(%)	Rt	(%)	Rt
OP (psi)																		
6	23	U	12	M	91	E	9	G	4	E	97	E	16	M	8	M	94	E
12	10	M	5	M	97	E	9	G	4	E	97	E	14	M	7	M	95	E
P value	0.09		0.09		0.09		0.99		0.85		0.78		0.50		0.56		0.57	
Length (ft)																		
100	15	M	10	M	93	E	5b[x]	G	3b	E	96b	E	9b	G	5b	M	96b	E
300	18	M	8	M	95	E	13a	M	5a	M	98a	E	22a	U	9a	M	93a	E
P value	0.25		0.30		0.17		<0.01		0.04		0.06		<0.01		<0.01		<0.01	
OP x Length (*P*)	0.59		0.21		0.12		0.11		0.13		0.15		0.77		0.74		0.69	

[z]Tape A: Eurodrip, 0.16 gal/h at 10 psi, Eurodrip U.S.A., Madera, CA; Tape B: Typhoon 0.24 gal/h at 10 psi, Netafim U.S.A., Fresno, CA; and Tape C: Ro-Drip, 0.24 gal/h at 8 psi, John Deere Water, San Marcos, CA.

[y]Ratings q_{var}: "G" = good <10%, "M" = moderate 10%-20%, "U" = unacceptable >20%; CV: "E" = excellent <5%, "M" = moderate 5%-15%, "U" = unacceptable >15%; UC: "E" = excellent >90%, "U" = unacceptable <50%.

[x]Values are obtained from pooled data of two experiments conducted in Fall 2009 in Florida (repetition x factor: *P* = 0.99 for q_{var}, *P* = 0.91 for CV and *P* = 0.86 for UC) and values with different letters within the same column are significantly different at α=0.05 by pairwise comparison with least-squared means.

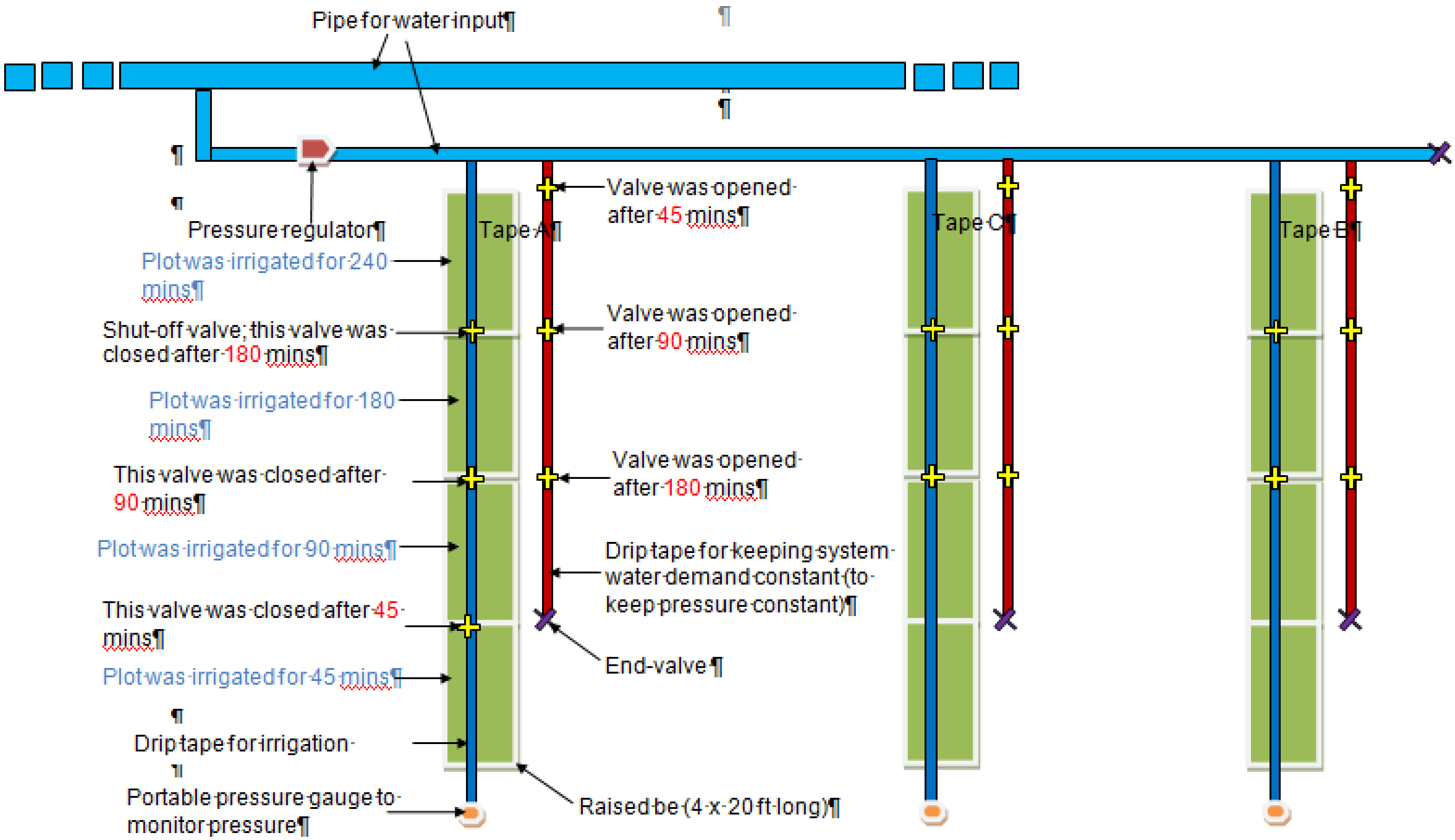

Figure 3-1. Schematic diagram of treatment plots showing drip tape (blue line) with shut-off valves to create irrigation treatment durations of 45, 90, 180 and 240 min. An additional drip tape (red line) with shut-off valves was used to keep the water demand and pressure constant by turning on a section of equal length as each section of the treatment tape was closed.

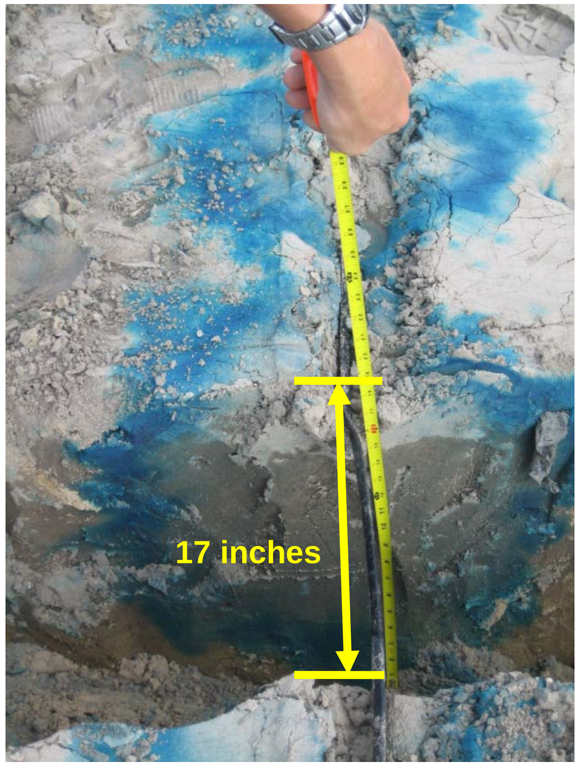

Figure 3-2. Transverse section of an Alpin-Blanton-Foxworth sandy soil beneath one emitter showing elliptical dye pattern after irrigating for 4 hours at 12 psi using drip tape of 24 gal/100ft/h, 12-inch emitter spacing. Note that the water front reached the 17-inch depth.

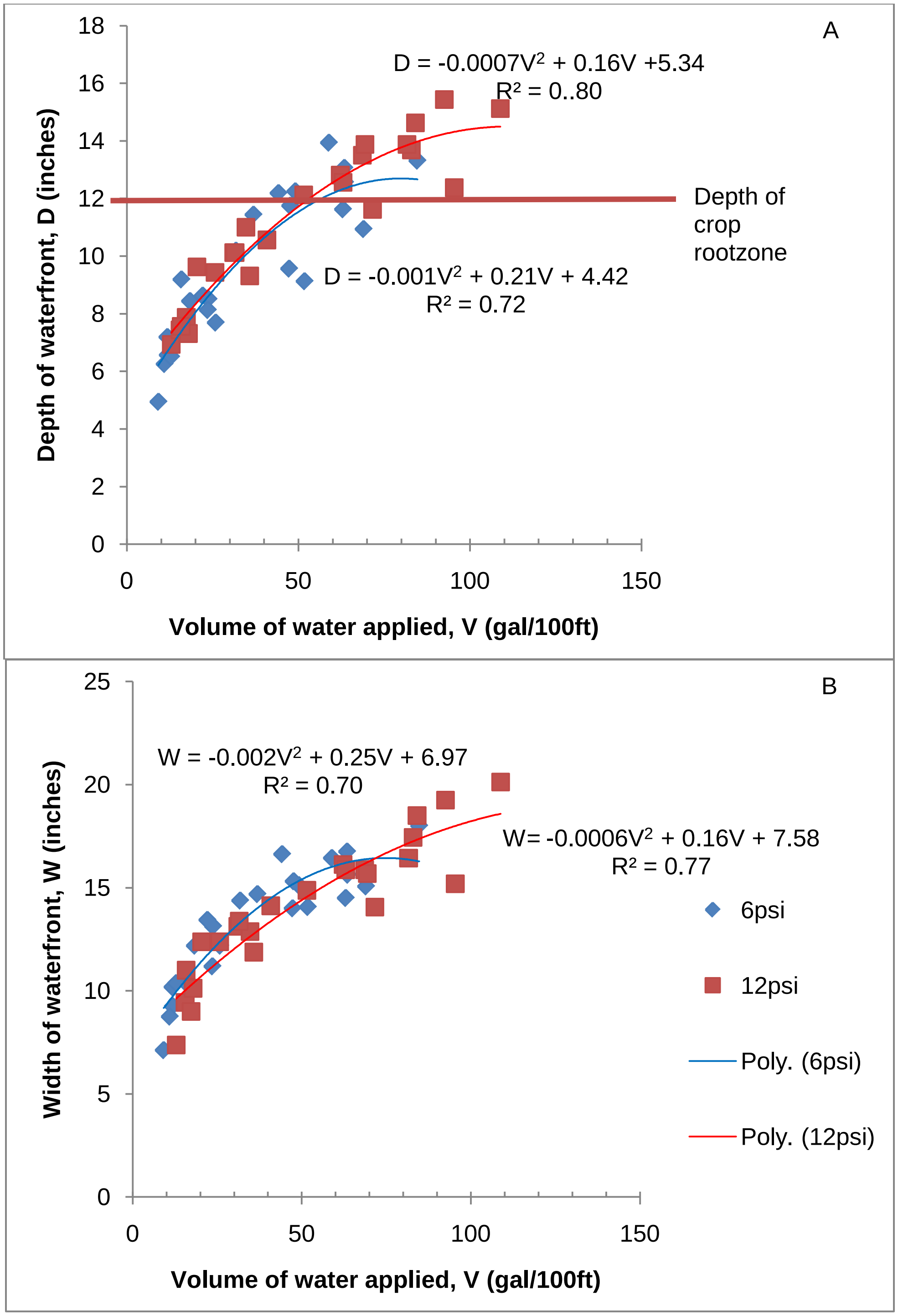

Figure 3-3. Effect of irrigation volume (gal/100ft) on depth (A) and width (B) of wetted zone at operating pressure of 6 and 12 psi on an Alpin-Blanton-Foxworth sandy soil using selected drip tapes (12-inch emitter spacing) differing in flow rates. Data was pooled from two years [year x OP and tape x OP interactions were not significant for D (*P* = 0.26, 0.06, respectively) and W (*P* = 0.05, 0.36, respectively)].

CHAPTER 4
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[3]

Background

Best management practices (BMPs) seek to improve the water use efficiency and water quality in agricultural production systems (FDACS, 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) (NRCS, 2006) are common. For drip irrigated crops such as muskmelon (*Cucumis melo*) and watermelon (*Citrullus lanatus*), the soil water front moved at a rate of 0.75-1.5 inch/day in 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 days of crop growth, resulting in low nutrient use efficiency as well as potential pollution of ground water sources. Modifying soil water holding capacity with organic or inorganic soil amendments (Banedjschafie et al.; 2006, Ouchi et al., 1990; Sainju et al., 2002; Sivapalan, 2006; Zhang et al., 2003) involves applications of large amounts of soil amendments which would increase production costs. 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 irrigation rates and/or frequency (Badr and El-Yazied,

[3] Submitted to HortTechnology on 15 Sept. 2010. Reprinted with permission from Poh, B.L., A. Gazula, E.H. Simonne, F. Di Gioia, R.C. Hochmuth, and M.R. Alligood. (unpublished). 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.

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 15-60 gal/100ft/h for 12-inch emitter spacing at operating pressure (OP) of 10 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., 2010a). Splitting irrigation events greater than two hours would result in bulk application of water several times a day of which the crop receives surplus amounts of water or no water in a 24-hour 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 mid-day (Allen et al., 1998). Frequent applications of smaller amounts of irrigation are known to be more efficient and environmentally sustainable (Zotarelli et al, 2009; Clothier and Green, 1994). A reduced OP and flow rate would extend irrigation duration and provide near-continuous watering of the plants that mimics evapotranspiration losses where 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 irrigation rates (IRR, 75% of the target 1000 to 4000 gal/acre/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 the Fall of 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 Inc, Mayo, FL) at 50 lb/acre of N and K_2O were applied during bed preparation three weeks before transplanting. No additional P fertilizer was applied as soil test results indicated very high soil P. Two drip tapes (John Deere Ro-Drip, San Marcos, CA; 24 gal/100ft/h at 12 psi; 12-inch emitter spacing) were laid together in the middle of each bed for the independent application of irrigation water and fertilizer. Six-week-old ‘Florida 47’ tomato (*Solanum lycopersicum*) plants were established on raised beds (Alpin-Foxworth-Blanton sand, NRCS, 2006) with 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% IFAS irrigation recommendation) (Table 4-1). Operating pressure was regulated by installing pressure regulators (Senninger Irrigation Inc., 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) 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 (34-0-0, Mayo Fertilizer Inc, Mayo, FL) 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 (Dyna Flo 0-0-15, Chemical Dynamics Inc, Plant City, FL) to provide K for each treatment. An irrigation rate of 1000 gal/acre/day/string commonly used in the industry was designated as 100% IRR and was reduced to 750 gal/acre/day/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 (Figure 4-1) to 4,000 gal/acre/day for 100% IRR as the crop season progressed to meet greater crop water requirements. The volume of irrigation water applied was controlled through timers (Orbit Irrigation Products Inc., 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 based on monitoring of soil moisture using a handheld time domain reflectometry meter (HydroSense, Campbell Scientific Inc., Logan, UT). Daily temperature and rainfall data were collected by a weather station of the Florida Automated Weather Network (FAWN) located at Live Oak (FAWN, 2009). Other cultural practices (staking, 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, 8 weeks after transplanting (WAT) in 2008 and 5, 7, 9, 11 WAT in 2009, which corresponded to 1st flower, 1-inch-diameter fruit, 2-inch-diameter fruit and 1st harvest growth stages in 2008 and to 1st flower, 2-inch-diameter fruit, 1st and 2nd 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 nitrate (NO_3^--N) and potassium (K^+) concentrations using ion-specific electrodes (Cardy meter, models C-141 and C-131 for NO_3-N and K, respectively, Horiba Instrument Company, 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 twelve beds approximately 150-ft long each. 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., 2002a). Near the field, the water source was divided into two 2-inch pipes. One line was further split into four for the OP x IRR treatments, the other one was split into three for the N rate treatments. Hence, a total of seven polypipes were used to distribute the water and fertilizer treatments to the plots. Four polypipes supplied the OP x IRR treatments (6 psi, 100% IRR; 6 psi, 75% IRR; 12 psi, 100% IRR; 12 psi, 75% IRR) and three polypipes supply the N rate treatments (60%, 80% and 100%). The polypipes were color coded; drip tapes in each plot were connected to the corresponding polypipe according to treatment. Petiole sap NO_3^--N and K^+ concentrations, and total and marketable yield responses to the treatments were analyzed using Proc GLM 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 (Figure 4-2) and were typical for spring crops in north Florida. In 2008, rainfall events occurred on 16 days (23% of growing season) during 30 Apr. to 8 July resulting in total rainfall of 5.8 inches. In 2009, rainfall events occurred on 26 days (31% of season) during 8 Apr to 1 July resulting in 8.4 inches of rain (FAWN, 2009). Leaching rainfall events (defined as 3 inches in 3 days or 4 inches in 7 days) 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, 101 lbs N/acre in 2008 and 178, 146, 114 lbs N/acre 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/100ft/h and for the 6 psi treatment was less than 12 gal/100ft/h. However, the actual flow rates averaged 24 and 7.2 gal/100ft/h in 2008, and 20 and 6 gal/100ft/h 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 (7.0-7.7acre-inches) and 190,000-240,000 gal/acre (7.0-8.8 acre-inches) in 2008 and 2009, respectively (Figure4- 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 north Florida.

Tomato Plant Petiole Sap NO_3^--N and K^+ Concentration

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 4-2). However, for the IRR, petiole sap NO_3^--N concentration was significantly higher ($P < 0.01$) for 75% IRR compared to 100% IRR only at fruits 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 42 kPa 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 1st flower stage in 2008 and at 1st harvest stage in 2009 (Table 4-2).

In 2008, petiole sap K^+ concentrations at all the growth stages were not significantly different for all the respective treatments (Table 4-3A). In 2009, as N x OP interaction was significant for most growth stages, the effect of OP was analyzed separately by N rate (Table 4-3B). 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 1st harvest ($P < 0.01$) growth stages at 60% N, at 2-inch fruit ($P = 0.01$) and 2nd harvest ($P < 0.01$) at 80% N, and at 1st flower ($P < 0.01$) and 2nd harvest ($P = 0.03$) at 100% N. Sap K^+ concentration was significantly higher for 75% IRR at the first harvest growth stage ($P = 0.04$). 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 fruit stage in 2008 and at 1st flower stage in 2009 (Table 4-3B).

Nitrogen rate did not affect the petiole sap NO_3^--N concentration. Although, in general the concentration was higher with higher nitrogen rate. 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 showed that crop nutritional status could 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 to 12 psi (Table 4-4). 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 about 8% lower yields obtained at 6 psi compared to 12 psi. N rate had a significant effect with greater total ($P = 0.04$) and marketable ($P = 0.04$) yields at 100% N rate. Irrigation rate, however, had no significant effect on the yields.

The yields in 2008 was half that 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. Based on the results in 2009, however, to attain maximum yields, the standard 12 psi OP, 100% recommended N rate and 75% recommended irrigation rate were still required.

Using Low OP for Early Crop Season

In the early part of the season when plants were small, the reduced OP (6 psi) in combination with reduced irrigation (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 0.25 gph resulted in a smaller wetted soil volume compared to higher flow rates of 0.5, 1 and 2 gph for a sandy soil, with more water and nutrients being retained within the crop root zone. Simonne et al. (2005) reported greater downwards water movement during the early part of the muskmelon 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 as water and nutrient uptake capacity was limiting for small plants. 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 downwards movement of water and nutrients into the soil. In this study, by four weeks after transplanting, the tomato plants at the reduced OP treatment were irrigated for four hours daily from 9 to 11 a.m. and 3 to 5 p.m. so that plants were irrigated for a major part of the day. If the reduced OP strategy was adopted for the first four 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. To 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 high when using low irrigation OP, so the water source should be of high quality and well-filtered and weekly chlorination of the drip system should be carried out.

Summary of Findings

In an Alpin-Blanton-Foxworth sand of northern Florida, higher fresh market tomato yields were obtained at a reduced irrigation OP in one year with reduced fertilizer and irrigation rates, and 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 irrigation rate 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 irrigation rate of 75% and fertilizer rate of 60% of recommended levels, respectively, an irrigation strategy using an OP of 6 psi during the first four weeks of a tomato crop season would improve water and nutrient use efficiencies and hence reduce risks of nutrient leaching. However, due to 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.

Table 4-1. 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 system.

Treatment no.	N rate[z] (%)	OP (psi)	IRR[y] (%)	Preplant fertilizer[x] (lb/acre)	Target N rate (lb/acre per day)[w] Time after transplanting (weeks)				
					1-2	3-4	5-11	12	13
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

[z] N rate: 100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre.
[y] IRR: 100% = 1000 to 4000 gal/acre per day, 75% = 750 to 3000 gal/acre per day.
[x] Pre-plant fertilizer used was 13N-1.7P-10.8K.
[w] Ammonium nitrate and potassium chloride were used for weekly fertilizer injection.

Table 4-2. Nitrate-nitrogen concentration (ppm) 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 nitrogen (N) rate, 6 and 12 psi operating pressure (OP) and 75% and 100% irrigation rate (IRR).

	2008 [z,y]				2009 [z,y]			
Treatment	1st flower	1-inch fruit	2-inch fruit	1st harvest	1st flower	2-inch fruit	1st harvest	2nd harvest
N rate (%)[x]								
60	393	556	415	411	1135	730	226b	215
80	431	867	420	459	1213	794	245b	209
100	440	789	513	484	1109	781	312a	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	1252a	783	261	231
12	401	721	439	442	1053b	754	260	204
P value	0.17	0.81	0.38	0.60	<0.01	0.52	0.97	0.08
IRR (%)[w]								
75	436	741	512a	453	1133	737	268	220
100	406	733	384b	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 (ppm)[v]	600-800	400-600	400-600	300-400	600-800	400-600	300-400	200-400
N x OP (*P*)	0.75	0.14	0.11	0.76	0.53	0.61	0.64	0.30
N x IRR (*P*)	0.81	0.49	0.27	0.16	0.78	0.37	0.49	0.36
OP x IRR (*P*)	0.10	0.25	0.28	0.98	0.73	<0.01	0.14	0.87

[z] Values with different letters within the same column and under a specific treatment effect are significantly different at α=0.05 according to Duncan's multiple range test .
[y] Growth stages – 1st flower: 1st open flowers; 1-inch fruit: fruit at 1–inch diameter; 2-inch fruit: fruit at 2-inch diameter
[x] N rate: 100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre.
[w] IRR: 100% = 1000 to 4000 gal/acre per day, 75% = 750 to 3000 gal/acre per day
[v] Sufficiency range from Olson et al. 2010.

Table 4-3. Potassium (K^+) concentration (ppm) 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 operating pressure (OP) and 75% and 100% irrigation rate (IRR).

A. 2008 [z,y]

Treatment	1st flower	1-inch fruit	2-inch fruit	1st harvest
N rate (%)[x]				
60	4669	2186	4893	3963
80	4631	2263	5087	4150
100	4744	2081	5133	3719
P value	0.80	0.72	0.61	0.11
OP (psi)				
6	4721	2104	4991	4033
12	4642	2249	5091	3854
P value	0.58	0.43	0.83	0.28
IRR (%)[w]				
75	4783	2249	5182	4100
100	4579	2104	4900	3788
P value	0.15	0.43	0.06	0.06
N x OP (*P*)	0.88	0.83	0.22	0.28
N x IRR (*P*)	0.44	0.05	0.03	0.92
OP x IRR (*P*)	0.36	0.11	0.92	0.38

B. 2009 [z,y]

Treatment		1st flower	2-inch fruit	1st harvest	2nd harvest
N rate (%)[x]	OP (psi)				
60	6	2750a	3450	4588a	3538
	12	2463b	3350	3913	3075
	P value	<0.01	0.25	<0.01	0.20
80	6	2500	3413a	3950	3413a
	12	2588	3200b	3863	2725b
	P value	0.31	0.01	0.59	<0.01
100	6	2713a	3213	3825	3250a
	12	2388b	3338	3888	2813b
	P value	<0.01	0.08	0.72	0.03
IRR (%)[w]					
75		2579	3338	4104a	3200
100		2554	3317	3904b	3071
P value		0.60	0.61	0.04	0.35
Sufficiency range (ppm)[v]		3500-4000	3000-3500	2500-3000	2000-2500
N x OP (*P*)		<0.01	<0.01	<0.01	0.71
N x IRR (*P*)		0.09	0.43	0.14	0.62
OP x IRR (*P*)		0.09	0.76	0.14	0.93

[z] Values with different letters within the same column and under a specific treatment effect are significantly different at α=0.05 using Duncan's multiple range test .
[y] Growth stages – 1st flower: 1st open flowers; 1-inch fruit: fruit at 1–inch diameter; 2-inch fruit: fruit at 2-inch diameter
[x] N rate: 100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre.
[w] IRR: 100% = 1000 to 4000 gal/acre per day, 75% = 750 to 3000 gal/acre per day
[v] Sufficiency range from Olson et al. 2010.

Table 4-4. Seasonal fresh market tomato yields in number of 25-lbs cartons per acre for 2008 and 2009 at 60%, 80% and 100% of nitrogen (N) rate, 6 and 12 psi operating pressure (OP) and 75% and 100% irrigation rate (IRR).

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

[z] Values with different letters within the same column and under a specific treatment effect are significantly different at α=0.05 using Duncan's multiple range test .

[y] Tomato 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.

[x] N rate: 100% = 200 lb/acre, 80% = 160 lb/acre, 60% = 120 lb/acre.

[w] IRR: 100% = 1000 to 4000 gal/acre per day, 75% = 750 to 3000 gal/acre per day

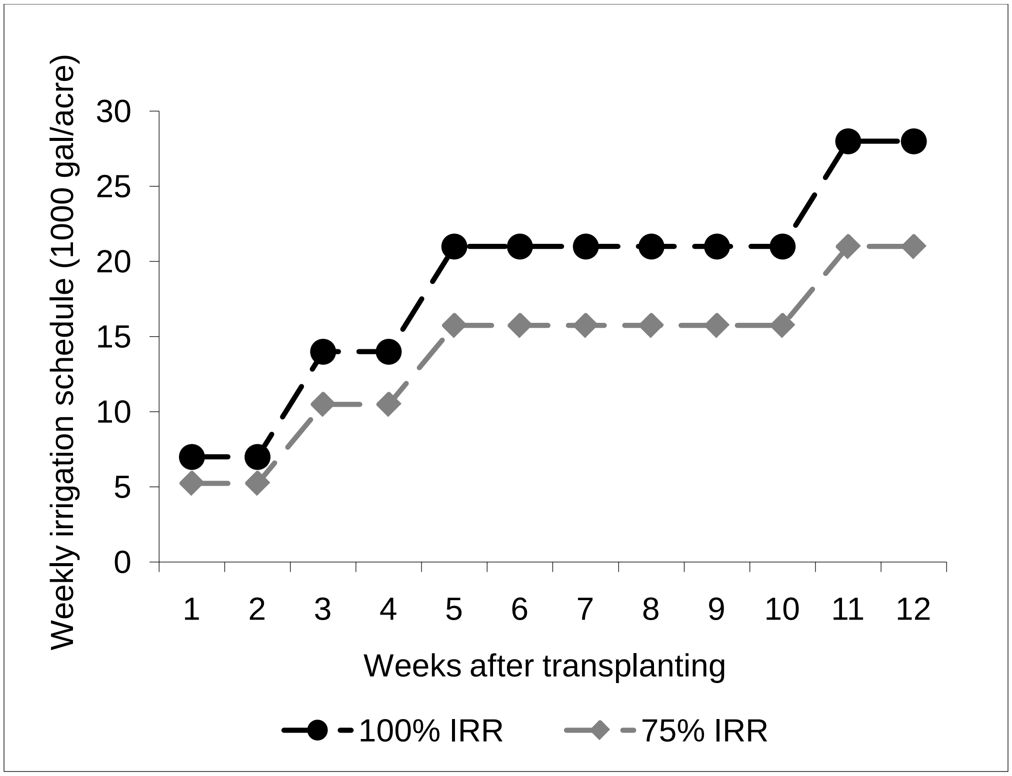

Figure 4-1.Target weekly irrigation (1000 gal/acre) schedule for Spring 2008 and 2009 ‘Florida 47’ fresh market tomato production with raised bed plasticulture system.

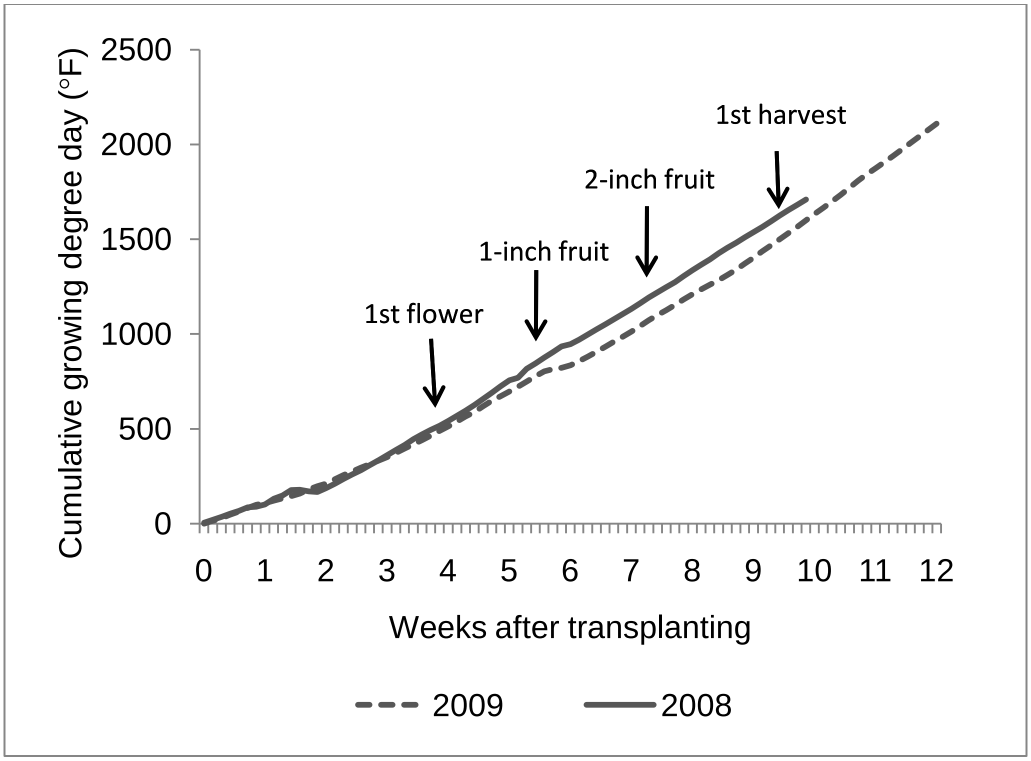

Figure 4-2. Cumulative growing degree day during the growing seasons for Spring 2008 (30 Apr. to 8 July) and 2009 (8 Apr. to 1 July) in Live Oak, FL, indicating time of various crop growth stages for open field ‘Florida 47’ fresh market tomato production. Base temperature used to calculate growing degree day was taken to be 50°F.

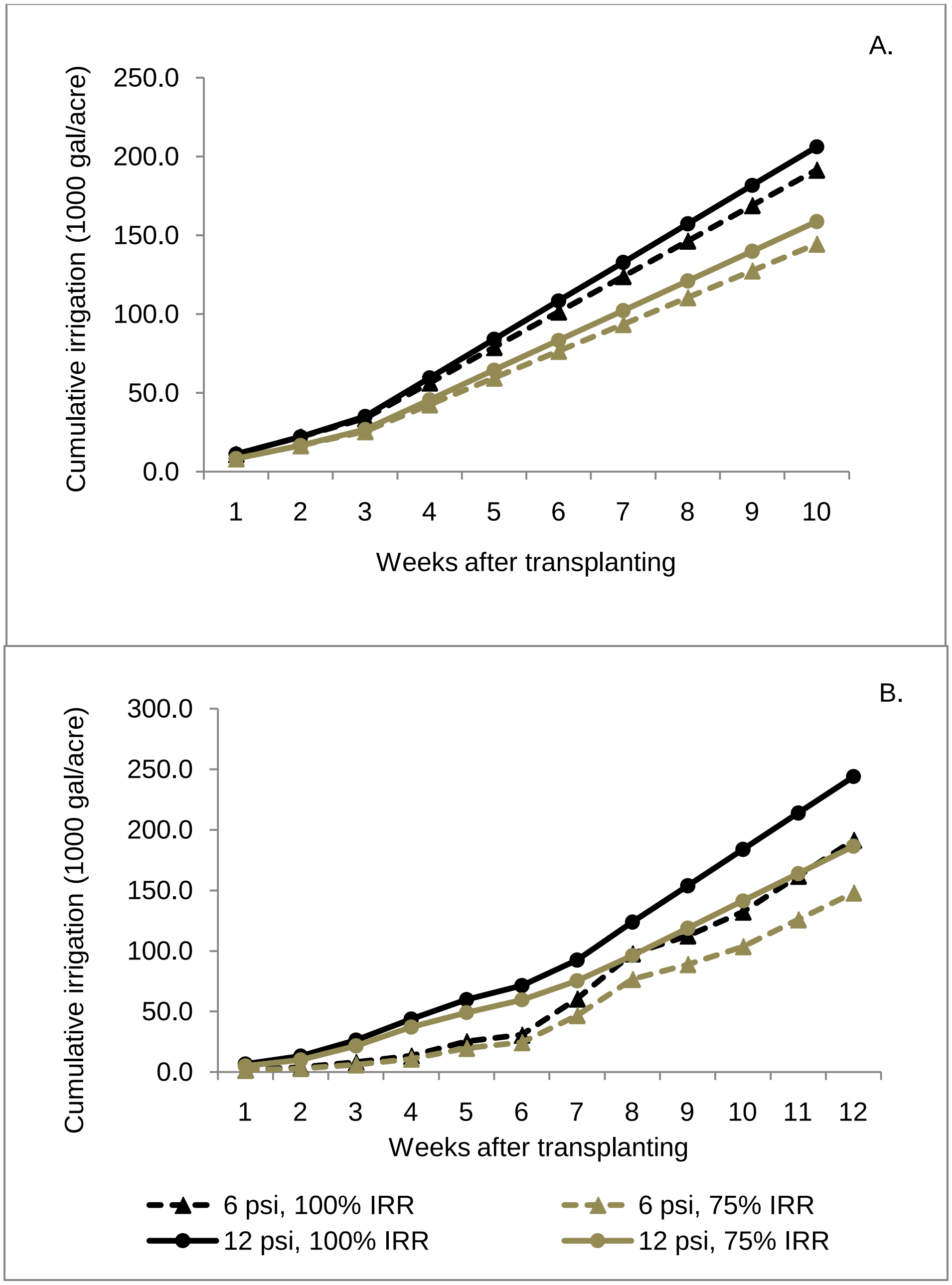

Figure 4-3. Actual cumulative irrigation* applied (1000 gal/acre) for Spring 2008 (A) and 2009 (B) 'Florida 47' fresh market tomato production with raised bed plasticulture system on an Alpin-Blanton-Foxworth fine sand using a medium-flow drip tape (24 gal/100ft per hour) flow rate; 12-inch -emitter spacing, mulched beds were 28 inches wide at two OP (6 and 12 psi) and two irrigation rates (100% and 75% of 1000 to 4000 gal/acre per day). (*In 2008, amount of weekly irrigation was estimated based on flow rates measured for three weeks and extrapolated to subsequent weeks. In 2009, amount of weekly irrigation was estimated based on weekly flow rates.)

CHAPTER 5
MOVEMENT OF THE WETTED FRONT UNDER DRIP-IRRIGATED TOMATOES GROWN ON A SANDY SOIL[4]

Background

Keeping water and nutrients within the crop rootzone is a main goal of nutrient Best Management Practices (FDACS, 2005). The ideal irrigation schedule should keep irrigation water in the rootzone and provide adequate soil moisture to meet plant needs (Simonne et al., 2010b). Current recommendations to keep irrigation water in the root zone are to (1) have a target irrigation amount based on weather demand and stage of plant growth, (2) fine-tune this volume based on soil moisture (volumetric water content or soil water potential), (3) split irrigation into small events, (4) account for rainfall contribution to crop water needs, and (5) keep irrigation records (Simonne et al., 2010a).

Studies involving the use of a blue soluble dye as a tracer to visualize depth and width of the wetted zone showed that irrigation water may move below the rootzone even when irrigation recommendations were followed. Studies that used single, short (1-8 hours) irrigation durations indicated that the rate of vertical water movement in North Florida soils ranged between 0.6 to 0.9 inch/10 gal/100ft (Simonne et al. 2002b, 2003, 2006a). Surprisingly, no reduction in vertical water movement rate was found when a 4-hours irrigation event was applied either as a single event, split into two 2-hours events, or 4 1-hour events (Poh et al., 2009). Using single, but long (38 and 60 hours) irrigation duration, Farneselli et al. (2008) reported a quadratic depth response to

[4]Submitted to Florida State Horticultural Society Proceedings on 10 June 2010. Reprinted with permission from Poh, B.L., A. Gazula, E.H. Simonne, R.C. Hochmuth, and M.R. Alligood. (unpublished). Movement of the wetted front under drip-irrigated tomatoes grown on a sandy soil.

irrigation volume ($D = -2 \times 10^{-7} V^2 + 0.008 V + 34$, where V is in L/100m) with a minimum depth increase of 0.3 inch/10 gal/100ft at a maximum V of 1610 gal/100ft. These results demonstrated that the water infiltration rate in sandy soils was high (6-20 inch/h) for an Alpin-Blanton-Foxworth sandy soil (NRCS, 2006), and that current irrigation recommendations and strategies were unable to keep water in the 0-12 inch rootzone.

Recently, the hypothesis that the vertical rate of water movement could be reduced if water were slowly applied had been formulated (Assouline, 2002, Dowgert et al., 2007). This strategy assumed that the slow application of water favored lateral movement by capillarity thereby increasing the width of the wetted zone, and reducing its depth. Using drip tapes with extremely low flow rates 5 gal/100ft/h would allow testing this hypothesis. However, currently commercial available low flow rates are near 15 gal/100ft/h at 12 psi. One approach to achieve extremely low flow rates was to reduce the irrigation system operating pressure, even below the recommended operating pressure. Dowgert et al. (2007) reported higher water use efficiencies with gravity-based systems operating on very low pressures of 4-5 psi, having low flow rates that allow more water to be retained within the crop rootzone in Chihuahua, Mexico. A low flow rate of 0.25 gph allowed greater water retention in the 0-24 inch soil depth compared to higher flow rates of 0.5, 1.1 and 2.1 gph for a sandy soil (Levin et al., 1979). If more water could be held within the crop rootzone, it would mean that less volume of irrigation water needs to be applied. The objective of this study was to determine the potential reduction in downwards water movement under drip-irrigated vegetables at low irrigation operating pressures and irrigation rates.

Materials and Methods

Two tests were conducted where a blue dye was used to visualize soil water movement at the North Florida Research and Education Center - Suwannee Valley near Live Oak, FL in the Springs of 2008 and 2009 on an Alpin-Blanton-Foxworth series sandy soil. Six week old 'Florida 47' tomato transplants were established on plastic-mulched raised beds spaced 5-ft apart and 18-inch within row spacing on 30 Apr. 2008 and 8 Apr. 2009 (Days after Transplanting, DAT = 0). Two drip tapes (John Deere Ro-Drip, San Marcos, CA; 24 gal/100ft/h at 12 psi; 12-inch emitter spacing) were laid together in the middle of each bed to allow independent irrigation and fertilization management. Treatments were factorial combinations of operating pressure (OP; 12 and 6 psi) and irrigation rate (IRR; 100% and 75% IFAS irrigation recommendation) with four replicates. OP was regulated by installing pressure regulators (Senninger Irrigation Inc., Orlando, FL) for the standard OP of 12 psi, 2-20 gpm and reduced OP of 6 psi, 4-16 gpm. The recommended target irrigation volume of 1000 gal/acre/day/string[5] and commonly used in the tomato industry was designated as 100% irrigation rate (IRR) and was reduced to 750 gal/acre/day/string for the 75% IRR treatment. Irrigation volume was increased as the crop season progressed to meet greater crop water requirements (Figure 4-3). The volume of irrigation water applied was controlled by timers (Orbit Irrigation Products Inc., Bountiful, UT) and water meters installed at the sub-mains of each OP treatment were read weekly to determine actual flow rates. As the flow rate of the drip tapes receiving the reduced OP could be as low as 5 gal/100ft/h, the duration of irrigation was increased to maintain the same volume of water applied as the

[5] String is used to denote the stage of plant growth, typically a tomato crop has four strings per season.

recommended OP. At later growth stages, the low operating pressure treatments were provided with 10-12 hours of irrigation while the standard operating pressure treatments were provided with 4 hours of irrigation.

On 14 DAT in 2008 and 21 DAT in 2009, a blue dye (Brilliant Blue CF, Terramark SPI High Concentrate, ProSource One, Memphis, TN) was injected into the drip tapes of all treatments at a rate of 0.7 gal/100ft. This volume of dye was much greater than those used in short duration dye tests (Simonne et al., 2002b; 2003; 2006a), but was used to allow the visualization of the water front at potentially large depths. Tomato plants were grown following current recommendations (Olson et al., 2010) and irrigated according to treatments. The soil was dug transversely below selected emitters to visualize the dye patterns in the soil on 70 and 84 DAT in 2008 and 2009, respectively, using a back hoe. The distance between the position of the drip tape and the dye pattern in the soil was carefully measured in each plot. The response of depth of the wetted zone to operating pressure and irrigation rate was determined using Proc GLM and means separation was by Duncan's multiple range test (SAS version 9.2; SAS Institute, Cary, NC).

Results and Discussion

The period between dye injection and dye visualization corresponded to the time when plants were well-established (and after the first string) to the end of harvest, respectively and included 56 and 63 days of production in 2008 and 2009, respectively. Typical dye patterns previously reported for short irrigation times in sandy soils were elongated and a continuous ring of approximately 1-inch width bordering a colorless area (Simonne et al., 2006a). In this trial, the dye patterns observed were quasi-horizontal blue bands (Figure 5-1) approximately 10 to 15 inches long, not showing a continuous ovoid pattern, that corresponded to the bottom of the dye pattern. Hence, by measuring the depth of the dye, it was possible to measure the depth of the wetted zone, but not its width.

Because the operating pressure x year interaction was significant ($P = 0.04$) and because the days between dye injection and digging were different each year, data were analyzed separately by year. The interaction operating pressure x IRR was not significant for both years ($P = 0.36$ and $P = 0.40$ in 2008 and 2009, respectively). Depth response to irrigation rate was not significant in both years (57-58 inches, $P = 0.73$, and (65-66 inches, $P = 0.60$, in 2008 and 2009, respectively), which indicated that reducing the volume of water applied by 25% did not affect the depth as much as other soil properties. Response to operating pressure was significant in both years ($P = 0.01$) with maximum average wetted depths of 52 and 63 inches at 6 psi, and 64 and 67 inches at 12 psi, respectively for 2008 and 2009 (Figure 5-2). At the low operating pressure, the downwards movement of the waterfront was significantly reduced presumably because more water was retained within the upper surface at the lower flow rate (Levin et al., 1979). However, the waterfront had still moved beyond the 0-12 inch crop rootzone.

Rather than due to reduced downwards movement and increased lateral movement, the effect of the low operating pressure could be due to less volume of water being applied. The total volumes of water applied during the 56-day dye test period in 2008 were 2,300 and 2,500 gal/100ft at 100% IRR and 1,800 and 2,000 gal/100ft at 75% IRR while for the 63-day period in 2009, the volumes were 2,400 and 3,100 gal/100ft at 100% IRR and 1,900 and 2,500 gal/100ft at 75% IRR for the respective 6 and 12 psi treatments. Combining the depth responses to volume of all the treatments (Figure 5-3), a linear relation ($P < 0.01$) was obtained with D = 0.0086V + 41.3 (where D is in inches and V is in gal/100ft), which showed that as the volume of water increased, the depth would increase. However, the low R-square value indicated that other factors, possibly the effect of low operating pressure could be affecting the depth response besides the total volume of water applied.

The rate of downwards movement of water at 0.09 inch/10gal/100ft was much lower than expected based on previous single irrigation studies at rates of 0.9 inch/10gal/100ft (Simonne et al., 2005) and 0.3 inch/10gal/100ft (Farneselli et al., 2008). In the presence of plants, the downwards movement of water in the soil was slowed down possibly due to plant uptake and removal. It is therefore important to keep the crop healthy and actively growing to minimize deep percolation into the soil. Another point to note is that dye test data conducted on single irrigation events without plants should be used with caution when extrapolated to commercial field production with multiple irrigations.

Reducing operating pressure as a means of reducing the depth of the water front is a simple and inexpensive method that growers could implement as an additional BMP. However, this method alone is insufficient to keep water in the rootzone. Also, growers should be aware of the risk the reduced operating pressure represents for uniformity when drip tapes are operated at a lower-than-recommended operating pressure.

Figure 5-1. Transverse section of an Alpin-Blanton-Foxworth fine sand showing a quasi-horizontal blue dye pattern obtained from injecting dye at 21 DAT, growing a crop and irrigating to 84 DAT. Bottom of the band corresponded to the movement of the waterfront.

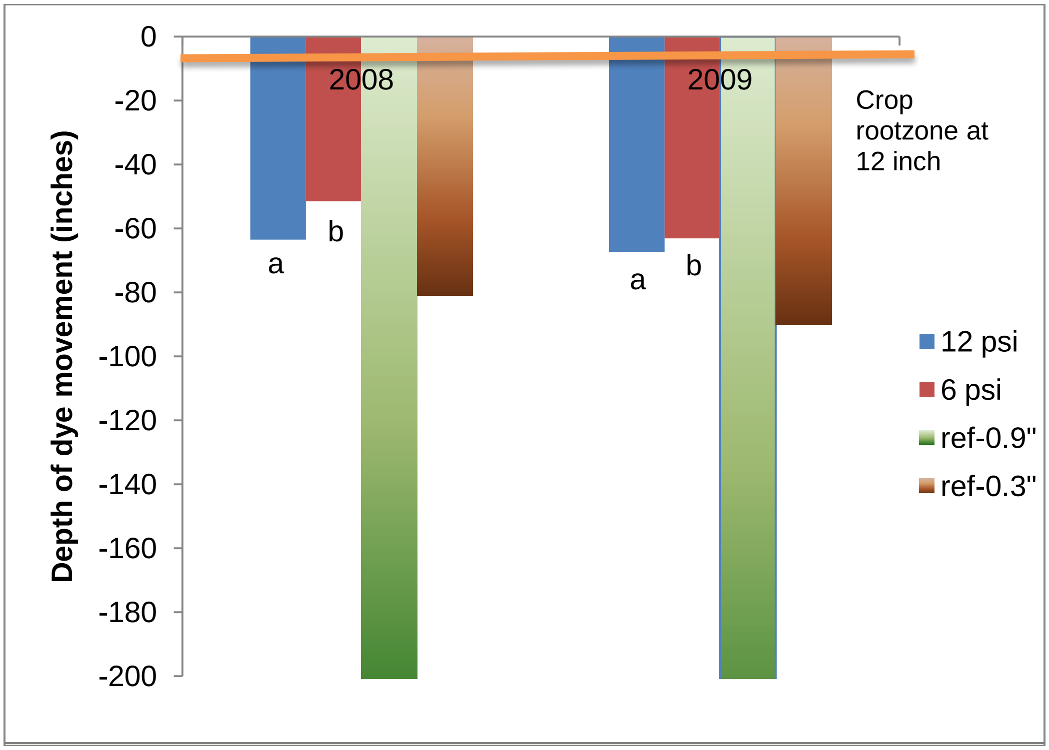

Figure 5-2. Depth (inches) of the waterfront response to irrigation operating pressure of 6 and 12 psi on an Alpin-Blanton-Foxworth fine sand using a medium-flow drip tape (24 gal/100ft/h flow rate; 12-inch emitter spacing, mulched beds were 28 inch wide). Each bar represents the average of 8 measurements. Bars with different letters are significantly different at α=0.05 using Duncan's multiple range test. Expected waterfront depths calculated from rates of 0.3 and 0.9 inch/10gal/100ft were included for reference. The typical depth of crop rootzone at 12 inches was indicated by the horizontal line.

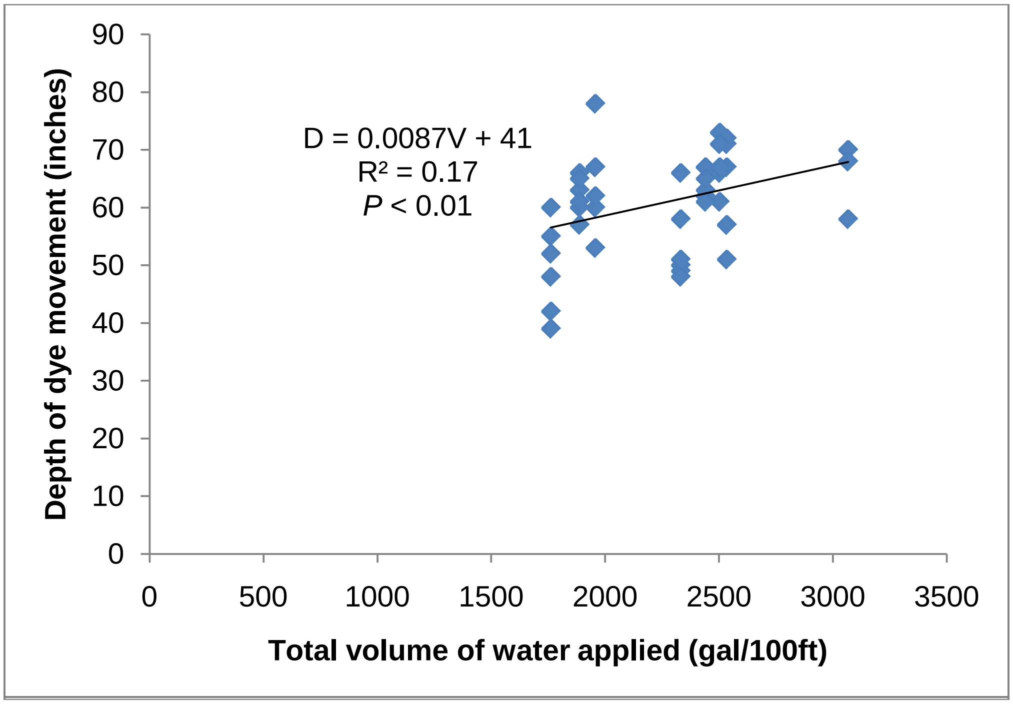

Figure 5-3. Depth response (inches) of the waterfront to total volume of water applied on an Alpin-Blanton-Foxworth fine sand using a medium-flow drip tape (24 gal/100ft/h flow rate; 12-inch emitter spacing, mulched beds were 28 inch wide).

CHAPTER 6
CONCLUSION

The assessment of using reduced OP in this project consisted of a uniformity study, a soil wetted pattern study, the possibility of reducing water and fertilizer inputs and a visualization of how deep a dye moved during a cropping cycle. This project showed that reducing the irrigation system operating pressure (OP) to 6 psi can create lower emitter flow rates of 0.13 to 0.19 gph at 100 and 300 ft lateral runs without affecting the uniformity of water application, although the shorter lateral run tends to give higher uniformity. For the same volume of irrigated water, flow rate did not affect the depth or width of the wetted zone, which increased mainly as a function of irrigated volume. However, due to the reduced flow rates, it will take longer to apply the same volume of water and attain the same depth and width of wetted zone, allowing extended irrigation without moving the waterfront downwards. In this way, a smaller amount of water is applied in each irrigation event and since this more closely matches hourly evapotranspiration, less water will be drained away (as proposed in Figure 2-1B). This is also relevant for drip fumigation as the fumigant could be applied for extended periods without the risk of it being carried deeper into the soil profile and causing groundwater contamination.

In the presence of a tomato crop, it was found that the flow rate was reduced to 0.06 gph, which was too low to meet crop water demands at maximum growth stages and peak crop ET (0.09 to 0.12 gph), resulting in 8% lower marketable yields in one year of study although the plant nutritional status was not affected. It was proposed that reduced OP should be used when the plants are young (for first four weeks after transplanting) and have limited water uptake capacity. As the OP is easily manipulated through installation of an in-line pressure regulator, growers could switch to higher flow rates when plant water demand increases without changing drip tapes.

In the presence of an actively growing crop of tomato, water moved downwards at a lower rate (0.09 inch/10gal/100ft) than when there were no plants (0.9 inch/10 gal/100ft). However, even at reduced OP, the water had still moved to about 60 inches, which was 48 inches below the crop rootzone by the end of the season, which indicated that using a reduced OP and low flow rate alone is not enough to keep the water within the active crop rootzone. This also suggested that part of the water applied from every irrigation cycle was not used up by the crop and was drained downwards, and that therefore, further reductions in water application may be possible. It would probably require a flow rate that varies with hourly crop ET (as suggested in Figure 2-1C) to keep irrigated water from moving beyond the crop rootzone. Applying water when plants most need it during the day, for example, at peak evapotranspiration is also an important consideration.

Overall, reducing OP using a commercially available pressure regulator is a simple, practical and inexpensive method to obtain low emitter flow rates that can help reduce water and fertilizer inputs without compromising uniformity in small fields. Based on these results, we propose that UF/IFAS should specify reducing OP as an irrigation practice to improve irrigation manage and reduce the risks of water and nutrient losses. Reduced OP could also be considered a possible BMP, although we have not assessed the impact of its use on water quality.

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BIOGRAPHICAL SKETCH

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