Tomato Growth, Yield, and Root Development, Soil Nitrogen and Water Distribution as Affected by Nitrogen and Irrigation Rates on a Florida Sandy Soil

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Abstract. Effective nutrient and irrigation management practices are critical for optimum growth and yield in open-field fresh-market tomato production. Although nutrient and irrigation management practices have been well-studied for tomato production in Florida, more studies of the current highly efficient production systems would be considered essential. Therefore, a two-season (Fall 2016 and Spring 2017) study was conducted in Immokalee, FL, to evaluate the effects of the nitrogen (N) rates under different irrigation regimes and to determine the optimum N requirement for open-field fresh-market tomato production. To evaluate productivity, the study investigated the effects of N rates and irrigation regimes on plant and root growth, yield, and production efficiency of fresh-market tomato. The study demonstrated that deficit irrigation (DI) targeting 66% daily evapotranspiration (ET) replacement significantly increased tomato root growth compared with full irrigation (FI) at 100% ET. Similarly, DI application increased tomato growth early in the season compared with FI. Therefore, irrigation applications may be adjusted downward from FI, especially early during a wet season, thereby potentially improving irrigation water use efficiency (iWUE) and reducing leaching potential of Florida sandy soils. However, total marketable yield significantly increased under FI compared with DI. This suggests that although DI may increase early plant growth, the application of DI throughout the season may result in yield reduction. Although N application rates had no significant effects on biomass production, tomato marketable yield with an application rate of 134 kg·ha⁻¹ N was significantly lower compared with other N application rates (179, 224, and 269 kg·ha⁻¹). It was also observed that there were no significant yield benefits with N application rates higher than 179 kg·ha⁻¹. During the fall, iWUE was higher under DI (33.57 kg·m⁻³) than under FI (25.57 kg·m⁻³); however, iWUE was similar for both irrigation treatments during spring (FI = 14.04 kg·m⁻³; DI = 15.29 kg·m⁻³). The N recovery (REC-N) rate was highest with 134 kg·ha⁻¹ N; however, REC-N was similar with 179, 224, and 269 kg·ha⁻¹ N rates during both fall and spring. Therefore, these study results could suggest that DI could be beneficial to tomato production only when applied during early growth stages, but not throughout the growing season. Both yield and efficiency results indicated that the optimum N requirement for open-field fresh-market tomato production in Florida may not exceed 179 kg·ha⁻¹ N.

Nutrient and irrigation management practices are key aspects of tomato production for optimum yield and fruit quality. Tomato is a vegetable crop with high nutrient demands (Hartz and Hochmuth, 1996). Therefore, effective irrigation and nutrient management practices are essential to maintain N within the crop root extraction zone and mitigate against potential environmental contaminations. The present N recommendation is 224 kg·ha⁻¹ for a tomato growing season in Florida (Hochmuth and Hanlon, 2014; Liu et al., 2016). Vegetable growers in Florida

often apply fertilizer at rates higher than recommended due to the risk of yield reduction in unfavorable weather conditions (Everett, 1976; Hochmuth and Hanlon, 2014; Rhoads et al., 1996). This rate can be an average of 417 kg·ha⁻¹ (Shukla et al., 2014) or higher (up to 470 kg·ha⁻¹) (Cantliffe et al., 2009) for a single production season. Although N is considered to be the most limiting nutrient for most nonleguminous production systems, excessive applications of fertilizer and/or water could lead to nutrient losses from a cropping system (Marchi et al., 2016; Zotarelli et al.,

2007). This is because N in the form of nitrate (NO₃⁻-N) has a high diffusivity rate in soil solution (Sato et al., 2009), resulting in high mobility in the soil, especially under saturated conditions. In sandy soils, NO₃⁻-N moves with the wetting front; therefore, N leaching is a factor of the soil water dynamics (Zotarelli et al., 2007).

Production conditions (warm temperature, good soil aeration, etc.) in the southeastern United States favor rapid conversion of most soil N to NO₃⁻-N (Jansson and Persson, 1982); hence, there are significant contributions of nitrification and denitrification to greenhouse gas emissions from Florida tomato production system (Di Gioia et al., 2017; Jones et al., 2012). In Florida, tomato is predominantly produced in southwest, central, and south regions where Entisols and Spodosols are dominant soil orders. Because of their sandy nature, these soil types have low water-holding capacities, low organic matter contents (within the root depth), and low nutrient retention capacities. Therefore, excessive irrigation and/or N application rates with intense rain events could significantly increase the potential risk of N leaching in these soils (Knox and Moody, 1991; McNeal et al., 1995). Similarly, the N source and rate of application, crop removal capacity, and water displacement below the active root zone could have significant roles in N leaching (Zotarelli et al., 2007).

The leaching loss of NO₃⁻-N from agricultural production systems is a major contributor to both ground and surface water contamination, and this has led to increases in the N load to water bodies, thus increasing water NO₃⁻-N concentrations above the safe limit of 10 mg NO₃⁻-N/L (USGS, 1998). In Florida, irrigation and N fertilizer accounted for the most greenhouse gas (GHG) emissions from open-field tomato production (Jones et al., 2012). Therefore, more studies focused on increasing efficiency and reducing nutrient loss in the environment would be considered critical for the sustainability of Florida tomato production practices (Jones et al., 2012; Sato et al., 2012). As a result, the present study investigated the combination of different N and irrigation application rates under typical Florida tomato growing conditions to determine 1) the optimum N requirement for fresh-market tomato growth and yield using a typical Florida drip irrigation production system, 2) identify the effects of FI and DI application regimes on plant nutrient and water uptake efficiencies, soil moisture conditions and nutrient displacement in sandy soils during tomato production, and 3) determine the effects of both N and irrigation application rates on tomato root growth during the production season.

Materials and Methods

Experimental site and treatment description.

This study was conducted at the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS), Southwest Florida Research and Education Center (SWFREC), in

Immokalee, FL (lat. 26°27'44" N, long. 81°26'36" W; elevation 10.4 m above sea level) during Fall 2016 and Spring 2017 production seasons. The soil at the study location was classified as Spodosol (soil Order) and Immokalee fine sand (soil series) (USDA–NRCS, 2015). The soil slope is nearly flat (0% to 2%) and has a low runoff class with poor natural drainage and relatively high saturated hydraulic conductivity (Ksat) of 15.82 cm·h⁻¹ within the first 15 cm of soil depth (Kadyampakeni et al., 2014). The depth of the seasonal high-water table can be from 46 cm to 91 cm, with low available water storage in the profile (field capacity at 0.09 cm³·cm⁻³ in the upper 15 cm of soil depth) (USDA–NRCS, 2015). In this study, eight treatments consisting of four N rates (134, 179, 224, and 269 kg·ha⁻¹) in two irrigation regimes (daily replacement of 100% and 66% ET) were evaluated in both seasons (Table 1). Except when otherwise mentioned, both irrigation treatments (66% ET and 100% ET) were maintained and applied daily throughout the season. Each treatment consisted of four plot replicates arranged in a split block design with the irrigation regime as the main factor and the N rate as the secondary factor.

Preplanting and planting operations. During bed preparation, a preplant dry fertilizer 16–4–8 (N–P₂O₅–K₂O) was applied for all treatments at a rate of 56 kg·ha⁻¹ N. The same amounts of P and K were applied to all plots. Beds were fumigated using Pic Clor 60 (Agrian, Fresno, CA; active ingredients chloropicrin and 1,3-Dichloropropene at 59.6% and 39.0%, respectively) at a rate of 223 kg·ha⁻¹ and immediately covered with polyethylene mulch. A 1.0-mil white/black (black side up during the cooler spring season and white side up during the warmer fall season) polyethylene mulch (Berry Plastics, Calhoun, GA) was used during each growing season. Each bed had two drip lines (thinwall drip lines, 5-mm streamline Plus 630 series; Netafim, Fresno, CA) running on the soil surface and under the polyethylene mulch for irrigation and fertigation purposes. During each season, drip lines with an application rate of 0.9 L/h/emitter with 60-cm emitter spacing were used. Tomato seedlings (variety Charger; Sakata, Morgan Hill, CA) were transplanted at ≈5 weeks after germination with 60-cm plant spacing in a single row ≈21 d after bed

preparation. Each plot consisted of 90 plants in an area of ≈67 m² (≈268 m² per treatment). During each season, seedlings were planted with a density of 9410 plants/ha.

Irrigation and fertigation practices. Crop water requirements were determined using the SmartIrrigation (SI) vegetable app. SI Vegetable is an ET-based smartphone-enabled application developed for scheduling irrigation of vegetable crops (tomato, watermelon, cabbage, and squash) using real-time and location-specific weather data. SI Vegetable estimated daily reference evapotranspiration (ET_o) using the FAO Penman-Monteith procedure (Allen et al., 1998) and crop coefficient (K_c) to determine crop water requirements (Migliaccio et al., 2016). At the time of scheduling, the SI Vegetable automatically connects to the Florida Automated Weather Network (FAWN), from which meteorological data of the previous 5 d before the scheduling time were extracted for ET_o estimation. The FAWN station used in this study was located within 0.5 km of the study location. K_c values were determined based on the time between the planting and scheduling dates (Migliaccio et al., 2016). More detailed information regarding the SI Vegetable approach for irrigation scheduling was described by Migliaccio et al. (2016). Previous studies have identified that SI Vegetable improved tomato yield and reduced nutrient leaching compared with the historic ET-based irrigation scheduling method (Ayankojo et al., 2018, 2019). Except when otherwise mentioned, both irrigation and fertigation were started after transplanting. The corresponding volume of irrigation (for both irrigation regimes) of every schedule was applied daily (after deducting the volume of water applied during fertigation) to each treatment for 7 consecutive days after scheduling. To prevent excessive water application from a one-time daily irrigation event, daily total irrigation time was applied during two or three daily events (based on the scheduled irrigation volume) controlled by a hose-end irrigation timer

(IZEHTMR; Rainbird, Azusa, CA). Considering the flow rate of the drip line used, the irrigation time was maintained at less than 30 min per event to avoid N leaching in sandy soils (Stanley and Clark, 2004). Except for N, the total nutrient application rate was the same for all treatments and applied according to the current UF/IFAS recommendations for tomato production in Florida (Liu et al., 2016), whereas the total N rate was applied at four different rates (134, 179, 224, and 269 kg·ha⁻¹), with each corresponding to a treatment. Because 56 kg·ha⁻¹ N was applied during the preplant stage, an additional 78 kg·ha⁻¹ N was applied (to reach the lowest N rate treatment at 134 kg·ha⁻¹ N) through fertigation using 18–4–18 (N–P₂O₅–K₂O) ammonium-nitrate fertilizer (Griffin Fertilizer Co., Frostproof, FL). The corresponding amount of fertilizer required to supply the additional N needed for the other N rates (179, 224, and 269 kg·ha⁻¹) was supplied using urea fertilizer (46% N). The corresponding cumulative daily N requirements for each treatment were determined and applied twice per week during each season (Table 2). Total season P₂O₅ (224 kg·ha⁻¹) and K₂O (≈12 kg·ha⁻¹) were applied at the same rate for all treatments during both seasons. During fertigation, the required amount of fertilizer was dissolved in 19 L of water for each treatment and injected in the drip lines using a pressure pump (12 VDC, 1.8 GPM; SHURflo, Cypress, CA). At every fertigation event, fertilizer was injected in the drip lines during the last irrigation cycle of the day to avoid washing of nutrients beyond the root zone.

Tomato biomass estimation and productivity. To determine plant biomass accumulation, both aboveground (leaves, stems, and fruits) and belowground (root) biomass samples were collected at every growth stage (Table 3). One plant representing the plot population was selected per sampling plot (Hartz and Bottoms, 2009) and separated into leaves, stems, roots, and fruits. Root samples were collected by digging the entire root system from the soil

Table 1. Specifications of treatments used during Fall 2016 and Spring 2017.

Treatment	Total N (kg·ha ⁻¹)	Irrigation condition	Detail
T1	135	100% ET	Irrigation 100% App and N 120%
T2	179	100% ET	Irrigation 100% App and N 100%
T3	224	100% ET	Irrigation 100% App and N 80%
T4	269	100% ET	Irrigation 100% App and N 60%
T5	135	66% ET	Irrigation 66% App and N 120%
T6	179	66% ET	Irrigation 66% App and N 100%
T7	224	66% ET	Irrigation 66% App and N 80%
T8	269	66% ET	Irrigation 66% App and N 60%

T = treatment; N = nitrogen; ET = evapotranspiration; App = application.

Table 2. Spread of nitrogen (N) application throughout the season at 100% (224 kg·ha⁻¹ N) of the total N application rate.

Total season N rate	Preplant application	N injection rates (weeks after transplanting)				
		1–2	3–4	5–11	12	13–14
----- kg·ha ⁻¹ ·d ⁻¹ -----						
224	50	0.56	1.12	2.80	1.12	0.56

Nutrient application was conducted twice per week using daily application rates. Application rates of potassium are the same for all treatments and similar to the N rate at 100%. All N application rates for other treatments were determined using a corresponding percentage of 224 kg·ha⁻¹ (100% N) for each treatment.

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and washed before oven drying. Dry weights were obtained by placing the sample in a 65 °C oven for 4 d for leaves and for 1 week for stems, fruits, and roots. After drying and weighing, all biomass samples were ground and analyzed for nutrient concentrations in the tissues on a dry weight basis. Total biomass was estimated as the sum of the leaf, stem, fruit, and root dry weights for each treatment during each growing season.

Other root variables such as volume and length were collected using a C1-600 In-Situ Digital Root Imager (CID BioScience, Camas, WA) with a clear acrylic tube that was installed in the soil at 20 cm from the base of the plant at an angle of 55° (to the bed surface) perpendicular to the planting row. The tubes were installed at this angle to capture both lateral and vertical root growth and to reduce the preferential water flow path along the tube. At every growth stage, root images were captured by the root imager and analyzed to determine the total root length and volume for each treatment. Tomato yields for all treatments from each season were evaluated at harvest. Yield sampling was conducted by removing green mature and color break fruit from 10 plants per plot representative of each treatment (from the center beds). Fruit harvest was conducted three times at ≈2-week intervals during each production season. Fresh fruit weight was recorded and estimated as Mg·ha⁻¹, whereas the weight of fruits not of marketable standards was recorded as culls.

Soil NO₃⁻-N, ammonium nitrogen, and moisture distribution. Soil NO₃⁻-N and ammonium nitrogen (NH₄⁺-N) distributions were determined for each treatment at all growth stages. Soil NO₃⁻-N and NH₄⁺-N distributions were evaluated at three different soil depths (0–15, 15–30, and 30–45 cm) with reference to the bed surface. Soil samples were taken from the bed midway between dripline emitter with a soil core sampler (2.8-cm internal diameter). For each soil sample, an analysis for NO₃⁻-N and NH₄⁺-N were conducted. Before analysis, soil samples were maintained at –4 °C until analysis and extracted with 2 M KCl extracting solution. For each sampling depth, a 5-g wet soil sample was weighed and placed in a test tube; then, 40 mL of 2 M KCl solution was added. The mixture was covered and shaken for 30 min. Samples were allowed to rest for 20 to 30 min and then were filtered with Whatman paper number 1 (90 mm). The filtrate was stored in plastic sample bottles and arranged in a well-labeled sample crate. The filtrates were stored at –4 °C until analysis was conducted. Once at room temperature, NO₃⁻-N and NH₄⁺-N analysis was conducted by the spectrophotometric technique using a calibrated Epoch Microplate Reader (BioTek, Winooski, VT) at 660 nm and 540 nm, respectively (Ringue et al., 2011).

Soil moisture sensors (SDI-12 Drill and Drop Probe; Sentek, Stepney, South Australia) were used throughout each season to monitor the soil moisture pattern. The soil moisture sensors use the capacitance method

(Katul et al., 1997; Morgan et al., 1999, 2002) of estimating volumetric water content and were used to determine irrigation effects on the soil moisture status. These sensors consisted of multiple sensing units located at different spots along the length (91 cm) of the probe, allowing for multiple readings across soil depth. Each probe was installed vertically in the soil and connected to a battery-operated data logger and radio unit that powered the probe and stored the data. Two soil moisture sensors were installed per treatment midway between two consecutive plants with moisture readings obtained every 15 min at soil depths of 5, 10, 25, 35, 45, and 55 cm. These soil depths were considered appropriate for this study because ≈85% to 95% of tomato roots are concentrated within the first 30 cm of soil depth (Zotarelli et al., 2009a). The soil moisture sensors were gravimetrically calibrated to the site conditions to avoid error due to site specificity.

Nitrogen recovery and irrigation water use efficiencies. For all treatments during every production season, REC-N and iWUE were calculated as described:

$$REC - N = \frac{NL + NS + NF + NR}{TNA + NI + NM} \quad [1]$$

$$iWUE = \frac{\text{Total marketable yield (kg)}}{\text{Total water applied (m}^3\text{)}} \quad [2]$$

where NL, NS, NF, and NR are the total N uptake partitioned into the leaf, stem, fruit, and root, respectively. NI is the initial soil N content before planting, NM is the amount of inorganic N derived from the mineralization process, and TNA is the total N applied for

each season. The amount of N supply through mineralization was adapted from an average of N mineralization rates estimated as total N using the electro-ultrafiltrations for the Immokalee soil type (Dou et al., 2000).

Statistical analysis. Statistical analysis was conducted during each season using the general linear model (PROC GLM) procedure of SAS version 9.3 (SAS Institute Inc., Cary, NC) to determine treatment effects on yield, iWUE, and REC-N. For repeated measurements such as biomass accumulation, root length and volume, and soil N distributions, the SAS PROC GLIMMIX procedure with the residual maximum likelihood approach was used. Duncan's multiple range test was used ($P = 0.05$) for mean separation when the F-test indicated significant differences among treatments.

Result and Discussion

Weather conditions and irrigation water application. The temperature patterns observed during the two growing seasons were different (Fig. 1A). Average daily air temperatures were lower early during the spring season and increased steadily toward the end of the season, whereas the temperature pattern was higher early during the fall season and decreased as the season progressed. Although temperature patterns were different for both seasons, the average daily air temperatures for the two seasons were similar (12.8 to 28.1 °C during the fall season and 11.9 to 27.5 °C during the spring season). Historically, a large proportion of a typical tomato growing season during spring (planting in early February) in southwest Florida is

Table 3. Description of the tomato developmental stages used as the guide for sampling collection.

Stage	Description
1	From transplant until 9 or more leaves on the main shoot unfolded
2	From first flower open until the eighth inflorescence first flower opened
3	From ninth inflorescence first flower opening until fruits reach typical size but no color changes
4	Fruit maturity until first harvest
5	After first harvest until last harvest

Fig. 1. Daily average temperature (A) and cumulative rainfall (B) during Fall 2016 and Spring 2017 production seasons in Immokalee FL. Data obtained from the Florida Automated Weather Network (FAWN) from 8 Sept. to 20 Dec. during Fall 2016 and from 7 Feb. to 23 May during Spring 2017.

usually cooler than that during fall (planting in early August). Therefore, the length of the tomato growing season during the spring could be 2 weeks or more longer than that during the fall (Ayankoji et al., 2018; Ozores-Hampton et al., 2015). However, in this study, the season lengths were similar (15 weeks after transplanting) during both the fall and spring. Similar season lengths were attributed to not only

similar average daily air temperatures but also the relatively faster warming spring season than those previously reported by Ayankoji et al. (2018) and Ozores-Hampton et al. (2015) in a similar location.

As with temperatures, the rainfall patterns also differed during both seasons (Fig. 1B). Cumulative rainfall totals were 195 mm and 175 mm during the fall and spring seasons,

respectively. Although the season rainfall totals tended to be similar in both seasons, most rain occurred early during fall and later during spring (Fig. 1B). Approximately 187 mm (96% of the total rainfall recorded for the fall season) occurred within the first 40 d after transplanting (DAT), whereas the amount of rainfall recorded for the same period (40 DAT) during the spring season was 39 mm (22% of the total season observed). According to Liu et al. (2018), leaching rain occurs when 76 mm to 102 mm of rain is received within 3 to 7 consecutive days for vegetable crops grown on bare ground. Therefore, leaching events due to rainfall were considered negligible during both seasons, not only because no leaching rainfall events were observed during either of the seasons but also because of the presence of plastic mulch.

The ETo and crop water requirement through evapotranspiration (ETc) followed similar patterns as previously described for temperature during each season (Fig. 2A and B). Due to the decreasing temperature in the fall, ETo decreased steadily during the production season, resulting in lower ETc compared with that in the spring. For the 100% ETc (FI) treatment, the irrigation water application was much lower than the ETo early

Fig. 2. Weekly irrigation water applied and reference evapotranspiration during Fall 2016 (A) and Spring 2017 (B) production seasons in Immokalee, FL.

Fig. 3. Average daily soil moisture content at full irrigation (A, B) and deficit irrigation (C, D), and daily precipitation events during Fall 2016 and Spring 2017 production seasons in Immokalee, FL.

during the fall season due to the lower Kc. However, crop water requirements increased during the season as the crop developed. Historically, in southwest Florida, the spring

is a relatively drier season compared with the fall. Therefore, irrigation was applied at the FI rate during the first 2 weeks after transplanting (WAT) for both DI and FI

treatments to ensure optimum moisture conditions for plant establishment. Compared with the fall season, ETo during the spring season was lower early in the season and

Fig. 4. Effects of irrigation and N application rates on soil $\text{NH}_4^+\text{-N}$ (A) and $\text{NO}_3^-\text{-N}$ (B) distribution across tomato growth stages during Fall 2016 in Immokalee, FL (FI and DI = irrigation at 100% and 66% ETo, respectively).

Fig. 5. Effects of irrigation and N application rates on soil $\text{NH}_4^+\text{-N}$ (A) and $\text{NO}_3^-\text{-N}$ (B) distribution across tomato growth stages during Spring 2017 in Immokalee, FL (FI and DI = irrigation at 100% and 66% ETo, respectively).

steadily increased during the season, thereby increasing the crop water requirement (Fig. 2B).

The total irrigation water values applied during the fall season were ≈ 275 mm and 182 mm for FI and DI, respectively (Fig. 2A); however, these values were 428 mm and 293 mm for the same irrigation treatments during the spring season (Fig. 2B). Despite a similar range of daily average temperatures observed during both growing seasons, the total irrigation water application was $\approx 55\%$ higher for each irrigation treatment during spring than during fall. Higher irrigation water values applied during the spring were attributed to the differences in the temperature patterns during both seasons. Because temperatures increased during the spring, the crop water requirement (ETc) increased. Also, the periods of higher temperatures during the spring season coincided with the period of active growth and fruit development with the maximum Kc value, thus resulting in higher irrigation water applications contrary to the pattern observed during fall season.

Sensor-based soil moisture distribution. Average daily soil moisture contents (ASMC) during the fall season were $0.12 \text{ cm}^3 \cdot \text{cm}^{-3}$ and $0.14 \text{ cm}^3 \cdot \text{cm}^{-3}$ for DI and FI, respectively (Fig. 3A and C), whereas the ASMC were $0.10 \text{ cm}^3 \cdot \text{cm}^{-3}$ and $0.11 \text{ cm}^3 \cdot \text{cm}^{-3}$ for DI and FI, respectively, during spring season (Fig. 3B and D). The variation in the soil moisture content (SMC) between the two seasons was due to the differences in rainfall events before planting and early after planting during each season. The fall season (planting date 9 Sept.) was preceded by periods of high and frequent rainfall events (from June to August) compared with a drier period (November to January) that preceded the spring planting date (2 Feb.). Similarly, the higher rainfall events (≈ 187 mm) observed early (within 40 DAT) during fall also contributed to the higher SMC compared with 29 mm observed during spring for the same period after transplanting.

Based on the previously described moisture characteristics of the soil at the study location with a field capacity of $\approx 0.10 \text{ cm}^3 \cdot \text{cm}^{-3}$ of SMC (Kadyampakeni et al., 2014), the observed soil moisture levels in both seasons indicated ample moisture conditions for plant uptake, especially for the FI irrigation schedule (Fig. 3A and B). Although ASMC was higher early in the fall season, moisture levels declined steadily (due to the low water-holding capacity of the soil at the study site) during the season. In the fall season, SMC declined faster for DI (Fig. 3C) early during the growing season compared with the FI treatment (Fig. 3A). At soil depths of 25, 35, 45, and 55 cm, ASMC started to steadily decline at ≈ 35 DAT for treatments with DI; however, the moisture contents at soil depths of 45 and 55 cm were steady until ≈ 55 DAT under FI. Despite the effects of rainfall on SMC early during the fall season, SMC within the top 15 cm of the soil depth was lower for DI compared with FI. The faster decline in SMC and lower moisture content under DI during the fall season was attributed to lower irrigation applications;

hence, this could reduce the leaching potential compared with FI. This suggests that early in the season (from growth stages 1 to 2), lower irrigation applications (DI) could fulfill the tomato water requirement, especially during the wet growing season in Florida sandy soils. This practice may enhance water conservation and may contribute to mitigating nutrient leaching early in the season. This practice could have important economic and ecological benefits in Florida because it is a common practice for most vegetable growers to apply 100% of the total season fertilizer before planting (Ozores-Hampton et al., 2015).

Similar to the fall season, the soil moisture distribution during the spring season was different for both irrigation treatments (Fig. 3B and D). The average daily SMC was higher within the top 15 cm of soil depth for DI (Fig. 3D) compared with FI (Fig. 3B), with the highest moisture content at a soil depth of 35 cm. The SMC was lower and below field capacity throughout the season at deeper soil layers (45–55 cm) for DI compared with FI. This result suggests that the

vertical movement or distribution of soil moisture using the DI treatment (66% ETc of the current SI Vegetable app) may not go beyond the first 25 cm of the soil depth. Although restraining soil moisture within this depth under tomato production may be critical for mitigating nutrient leaching (especially on sandy soil), the lower moisture content at the lower depth may reduce plant growth and yield. This is because tomato roots have been reported to grow 40 cm deep or more under drip irrigation (Machado et al., 2003; Oliveira et al., 1996; Zotarelli et al., 2009a).

Soil $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ distributions.

There were observable treatment (N and irrigation application rates) effects on soil $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ distributions across the crop growth stages (CGS) in both growing seasons. Soil $\text{NH}_4^+\text{-N}$ concentrations at CGS 1 and 2 (Fig. 4A) during the fall season and CGS 1 during spring (Fig. 5A) were generally higher within the 0- to 15-cm soil depth compared with the lower depths. This suggests that irrigation management as applied during these seasons maintained inorganic N

Fig. 6. Effects of irrigation and N application rates on tomato root length during Fall 2016 (A) and Spring 2017 (B) production seasons in Immokalee, FL.

within the upper soil depths and prevented potential leaching events. In both seasons, the soil $\text{NH}_4^+\text{-N}$ concentration was similar for all N application rates early in the season (CGS 1). Similar soil $\text{NH}_4^+\text{-N}$ concentrations among all treatments at this stage occurred because the same amount of N ($56 \text{ kg}\cdot\text{ha}^{-1}$ N) was applied during the preplant stage for each treatment. However, later during the fall season, at CGS 2 and CGS 4, the soil $\text{NH}_4^+\text{-N}$ concentration was highest at $269 \text{ kg}\cdot\text{ha}^{-1}$ N and lowest at $135 \text{ kg}\cdot\text{ha}^{-1}$ N, regardless of the irrigation regime. A similar trend was observed at CGS 3 when the soil $\text{NH}_4^+\text{-N}$ concentration was lowest with $135 \text{ kg}\cdot\text{ha}^{-1}$ N compared with the other N rates.

The observed result for the soil $\text{NO}_3^+\text{-N}$ concentration during each season followed a pattern similar to those observed for $\text{NH}_4^+\text{-N}$. The general pattern of soil $\text{NO}_3^+\text{-N}$ during each season indicated that the $\text{NO}_3^+\text{-N}$ concentration was lowest with the $135 \text{ kg}\cdot\text{ha}^{-1}$ N application rate across all CGS compared with the higher application rates, regardless of the irrigation regime (Figs. 4B and 5B). It could be observed that $\text{NO}_3^+\text{-N}$ at CGS 2 and 3 during fall and $\text{NH}_4^+\text{-N}$ at CGS 3 during the spring season were lower under the FI irrigation treatments compared with the DI treatments. Lower soil $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^+\text{-N}$ contents for the FI irrigation treatment suggest possible leaching events, especially during the fall season. Similarly, soil $\text{NO}_3^+\text{-N}$ and $\text{NH}_4^+\text{-N}$ concentrations were lowest (generally between 0.1 and $4 \text{ mg}\cdot\text{kg}^{-1}$) at the end of each growing season (CGS 5), with no observable differences among treatments. Low nutrient concentrations at this

stage indicated that little or no nutrients were left in the soil after harvesting, thus reducing postharvest soil nutrient residue and its potential environmental impacts. The soil $\text{NO}_3^+\text{-N}$ and $\text{NH}_4^+\text{-N}$ concentrations presented in this study were higher (especially early in the season) than those presented by Brewer et al. (2018) using similar N application rates during the 2013 and 2014 growing seasons with drip irrigation. However, these values were lower than those presented by Sato et al. (2009) using similar N application rates during the Spring and Winter seasons of 2006 in Immokalee, FL, with seepage irrigation. Higher soil $\text{NO}_3^+\text{-N}$ and $\text{NH}_4^+\text{-N}$ concentrations (especially early in the season) as presented in their report occurred because 100% of the total season N ($224 \text{ kg}\cdot\text{ha}^{-1}$ N) was applied once during the preplant stage compared with $56 \text{ kg}\cdot\text{ha}^{-1}$ N applied during the preplant stage in the present study.

Tomato root growth and development as affected by irrigation and N application rates. Irrigation and N application rates had significant effects on tomato root growth and development in both seasons. The effects of irrigation and N application rates on tomato root growth and development in both seasons are presented in Fig. 6. During the spring season, root growth was significantly enhanced under DI compared with FI, irrespective of N application rates (Fig. 6B and D).

Generally, the effects of each irrigation regimes on tomato root growth were similar for both seasons. Total root length and volume were higher for DI compared with FI across all CGS except for root volume early

in the season (CGS 2). At CGS 2 during the fall season, the total root length was higher for DI compared with FI (Fig. 6A). However, irrigation had no effects on root volume (Fig. 6C) at this CGS. The observed differences in root length early in the fall season may not have been directly related to the availability of soil moisture for plant uptake. This is because the SMC (regardless of irrigation regime) early in the season was above the field capacity up to a soil depth of 55 cm. Therefore, less root growth (root length) early in the season for FI could possibly be a result of the high SMC compared with the DI regime. As previously discussed, the average SMC within the first 15 cm early in the season occurred with FI compared with DI.

Interestingly, root length and volume with a lower irrigation regime (DI) tended to decline generally at GCS 4 compared with other stages during both growing seasons. Between CGS 3 and 4 is the period of active reproductive growth (from flowering to fruit maturity); therefore, lower root growth between these stages could be a result of the diversion of resources (photosynthates and nutrients) from vegetative growth (including root) to reproductive growth. The N application rate had a significant impact on tomato root growth and development during both seasons. However, unlike the irrigation treatments, these differences were isolated (especially during the fall season) among treatments with no specific or consistent pattern across the CGS. Therefore, based on the present results of this study, no clear effects of the N application rate on tomato root growth could be inferred.

Table 4. Analysis of variance results for tomato biomass (TB) production during Fall 2016 and Spring 2017 growing seasons in Immokalee, FL.

Crop growth stage	Season	Source	df	Leaf	Stem	Root	Fruit	TB
Stage 1	Fall 2016	Irrigation (I)	1	*	*	—	—	*
		Nitrogen (N)	3	NS	NS	—	—	NS
		I $\times$ N	3	NS	NS	—	—	NS
	Spring 2017	I	1	NS	NS	—	—	NS
		N	3	NS	NS	—	—	NS
Stage 2	Fall 2016	I $\times$ N	3	NS	NS	—	—	NS
		I	1	NS	**	NS	—	*
		N	3	NS	NS	NS	—	NS
	Spring 2017	I $\times$ N	3	NS	NS	NS	—	NS
		I	1	NS	NS	NS	—	NS
Stage 3	Fall 2016	N	3	NS	NS	NS	—	NS
		I $\times$ N	3	NS	NS	NS	—	NS
		I	1	NS	NS	NS	NS	NS
	Spring 2017	N	3	NS	NS	NS	NS	NS
		I	1	NS	NS	NS	NS	NS
Stage 4	Fall 2016	N	3	*	*	NS	*	**
		I $\times$ N	3	NS	NS	NS	**	NS
		I	1	**	NS	NS	NS	NS
	Spring 2017	N	3	NS	NS	NS	NS	NS
		I $\times$ N	3	NS	NS	NS	NS	NS
Stage 5	Fall 2016	I	1	NS	NS	NS	NS	NS
		N	3	NS	NS	NS	NS	NS
		I $\times$ N	3	NS	NS	NS	NS	NS
	Spring 2017	I	1	NS	NS	NS	NS	NS
		N	3	NS	NS	NS	NS	NS
		I $\times$ N	3	NS	NS	NS	NS	NS

*, **Statistically significant difference among treatment at α values between 0.01 and 0.05 and between 0.005 and 0.009, respectively. NS = no significant difference at $\alpha \leq 0.05$.

An increase in root growth under the DI irrigation condition is an indication of tomato genetic plasticity to changes in the environment known as primed acclimation (Rowland et al., 2012; Vincent et al., 2019). This term is often used when a crop is subjected to a mild water deficit condition during the vegetative growth stages, and it has been applied as an important water conservation strategy for reducing irrigation application and increasing iWUE in crop production (Vincent et al., 2019). In an agroecosystem, primed acclimation (PA) is a physiological response of the crop (often through modifications of the aboveground and belowground biomass partitioning ratio) to adjust to or recover from the abiotic stress conditions (Rowland et al., 2012). Examples of the applications of PA in crop production include increased root:shoot ratios and increased rooting depths compared with nonprimed crops (Byrd et al., 2014; Rowland et al., 2012). As observed in this study, the increase in root growth through deficit irrigation could suggest an important opportunity for a potential water conservation strategy to enhance iWUE in tomato production. Therefore, because water conservation practices are becoming more relevant in agricultural production, research focused on the application of PA in tomato production in future studies could be considered essential.

Effects of irrigation management and N application rates on tomato growth and biomass accumulation. Table 4 shows the analysis of variance (ANOVA) for biomass production (for all categories of plant parts) as affected by N rates and irrigation management at each CGS and season. The ANOVA within each growing season indicated that there were no significant interactions between irrigation management and N application rates among all biomass categories (fruit, stem, leaf, root, and total biomass) except for fruit during CGS 4 in the fall season. The lack of significant interaction with total biomass accumulation suggests that the effects of irrigation and N rates on tomato growth were independent. Therefore, irrigation and N rates were analyzed separately in each season.

Although tomato biomass samplings were conducted for all plant parts (leaf, stem, fruit, and root), the results are presented for total biomass production (sum of leaf, stem, fruit, and root) for each CGS in each season. The effects of irrigation management on tomato biomass production differed in both seasons. Early during the fall season (CGS 1 and 2), the lower irrigation regime (DI) increased biomass production compared with FI (Fig. 7). However, there were no significant differences between irrigation treatments regarding total biomass production across all CGS during the spring season. The lower tomato biomass production with the FI treatment early during the fall season was attributed to the lower soil $\text{NH}_4^+\text{-N}$ concentration observed with FI, especially at CGS 2. These results suggest that irrigation applications may be adjusted downward from FI, especially early during a wet season, thereby

potentially improving iWUE and reducing the leaching potential of Florida sandy soils.

Similar to the effects of irrigation application on tomato biomass production, the effects of N application rates on tomato growth and biomass production were minimal and not consistent during both seasons (Fig. 8). Treatment effects were only observed at CGS 1 and 3 during the fall and spring seasons, respectively. At CGS 1 during the fall season, plant growth was reduced at the lowest N rate ($135 \text{ kg}\cdot\text{ha}^{-1} \text{ N}$), whereas at CGS 3, tomato growth was significantly higher at the highest N rate ($269 \text{ kg}\cdot\text{ha}^{-1} \text{ N}$) during the spring season. Because a similar amount of N ($56 \text{ kg}\cdot\text{ha}^{-1}$, 25% of total N requirement) was applied during the preplant stage for all treatments, the increase in plant growth with the N rate early during the fall season could not have resulted from treatment (N rates) effects. The lower biomass production for the low N rates could be due to

a sampling error or random variability within the field condition.

Effects of irrigation practices and N rates on tomato yield. The ANOVA performed within each growing season (Tables 5 and 6) indicated that there were no significant interactions between irrigation practices and N application rates across all yield categories (medium, large, extra-large, cull, and marketable yield (TMY) during the spring season. Therefore, irrigation and N rates were analyzed separately in each season across all yield categories except for marketable yield during the spring season when the effects of irrigation and N rates were analyzed together.

During the fall season, irrigation had no effects on tomato yield for medium, large, and cull (fruit of unmarketable quality); however, the FI treatment increased tomato yield for extra-large and TMY categories compared with the DI treatment (Table 5). Similar to

Fig. 7. Effects of irrigation practice on tomato biomass production during Fall 2016 and Spring 2017 seasons in Immokalee, FL. *Statistically significant difference among treatment at $\alpha = 0.05\text{--}0.01$.

Fig. 8. Effects of nitrogen application rates on tomato biomass production during Fall 2016 and Spring 2017 seasons in Immokalee, FL. **Statistically significant difference among treatment at $\alpha = 0.009-0.005$.

Table 5. Effects of irrigation practice and nitrogen (N) rates on tomato yield during the Fall 2016 growing season in Immokalee Florida.²

Season	Main effect	Medium ^y	Large	Extra-large	Cull	TMY
Fall 2016	Irrigation (I)					
	FI	2.41	19.60	48.37	6.31	70.38
	DI	2.78	17.09	41.11	5.52	60.99
	N rate (kg-ha ⁻¹)					
	134	2.65	15.45	32.45 b	6.54	50.56 b
	179	2.77	19.98	52.51 a	6.40	75.26 a
	224	2.43	20.09	45.89 a	6.26	68.41 a
Significant level	269	2.43	18.59	50.18 a	4.68	71.20 a
	Irrigation	NS	NS	*	NS	*
	N rate	NS	NS	***	NS	***
	I × N	NS	NS	NS	NS	NS

²Reported values are averages of four replications.

^yMedium = medium fruit size diameter [(d) 5.72 < d < 6.43 cm]; large = large fruit size (6.34 < d < 7.00 cm); extra-large = extra-large fruit size (d > 7.00 cm); culls = fruit of unmarketable quality.

FI = full irrigation at 100% evapotranspiration; DI = deficit irrigation at 66% evapotranspiration; TMY = total marketable yield.

*, ***Statistically significant difference among treatments at α values between 0.01 and 0.05 and at <0.005, respectively. NS = no significant difference at $\alpha \leq 0.05$.

irrigation treatments, the effects of N rates were only significant for extra-large and TMY. Yield (both extra-large and TMY) with the 134 kg-ha⁻¹ N application rate was significantly lower compared with that with other N application rates (179, 224, and 269 kg-ha⁻¹). It was also observed that there were no significant differences in tomato TMY at N application rates higher than 179 kg-ha⁻¹ (Table 5). During the spring season (Table 6), tomato yields were 30%, 19%, 25%, and 17% higher for medium, large, extra-large, and cull (unmarketable yield) categories, respectively, with the FI treatment compared with the DI treatment. Similar to the fall season, the yield (for large and culls) was lower at the lowest N rate (134 kg-ha⁻¹ N) compared with that at the N application rate of 269 kg-ha⁻¹ N. However, no significant differences were observed across all N rates for medium and extra-large fruit categories. The TMY was similar for 179, 224, and 269 kg-ha⁻¹ N at FI, and it was significantly higher than any other combination of irrigation practice and N application rates during the spring season. The TMY were $\approx 13\%$ and 33% lower for the DI irrigation treatment compared with the FI during fall and spring seasons, respectively. A higher yield gap (between FI and DI) during the spring season suggested a higher magnitude of drought stress (for DI) during the drier spring compared with the fall.

These results suggest that under appropriate irrigation and N management practices for tomato production in Florida, N application rates higher than 179 kg-ha⁻¹ may not improve tomato yield; hence, there are potential economic and environmental benefits associated with reduced N rates compared with the present N recommendation in Florida. These results agreed with those of previous studies conducted to evaluate tomato production with similar N rates. According to Djidonou et al. (2013), there was no yield benefit at N rates higher than 168 kg-ha⁻¹ (N rates ranged from 56 to 336 kg-ha⁻¹) under drip irrigation in Live Oak, FL. A similar result had been previously reported by Hochmuth and Maynard (1996) based on an N rate trial performed in Miami-Dade County, where there was no significant difference in tomato yield with 168 to 252 kg-ha⁻¹ total season N application rates. Similarly, in a more recent study by Ozores-Hampton et al. (2012), the maximum tomato yield was reported with the 172 kg-ha⁻¹ N application rate during Spring 2007 under seepage irrigation.

Although the DI rate (as applied in this study) has no detrimental effects on tomato growth, the results of both seasons indicated that tomato yield was significantly reduced under DI treatment compared with FI treatment. Despite an increase in water savings and potential mitigation of nutrient leaching for DI, our results clearly demonstrated that DI applications throughout the growing season may be insufficient to meet tomato water demands, resulting in the reported yield loss. These results were similar to those reported by Ayankoko et al. (2018) for tomato under a similar growing condition in Florida. Similar

Table 6. Effects of irrigation practice and nitrogen (N) rates on tomato yield during the Spring 2017 growing season in Immokalee, FL.^z

Season	Main effect	Medium ^y	Large	Extra large	Cull	Irrigation	N rate (kg·ha ⁻¹)	TMY
Spring 2017	Irrigation (I)	Mg·ha ⁻¹				Mg·ha ⁻¹		
	FI	8.09	14.34	36.47	11.09	FI	134	43.77 b
	DI	5.70	11.89	27.29	9.23	FI	169	64.51 a
	N rate (kg·ha ⁻¹)					FI	224	64.07 a
	134	6.35	10.04	28.57	12.28	FI	269	63.52 a
	179	6.68	13.89	33.65	9.32	DI	134	46.15 b
	224	7.39	13.54	34.37	10.94	DI	169	43.95 b
	269	7.16	14.98	30.93	8.11	DI	224	46.51 b
Significant level	Irrigation	***	**	***	*	—	—	—
	N rate	NS	**	NS	*	—	—	—
	I × N	NS	NS	NS	NS	—	—	**

^zReported values are averages of four replications.^yMedium = medium fruit size diameter [(d) 5.72 < d < 6.43 cm]; large = large fruit size (6.34 < d < 7.00 cm); extra-large = extra-large fruit size (d > 7.00 cm); culls = fruit of unmarketable quality.

FI = full irrigation at 100% evapotranspiration; DI = deficit irrigation at 66% evapotranspiration; TMY = total marketable yield.

*, **, ***Statistically significant difference among treatments at α values between 0.01 and 0.05, between 0.005 and 0.009, and at <0.005, respectively. NS = no significant difference at $\alpha \leq 0.05$.

results were also reported by Rowland et al. (2012) regarding a row crop (peanut) in which DI (applied at 50% ETc throughout the season) reduced yield compared with that resulting from FI. Although DI has been documented to increase soluble solids in tomato fruits, this relative advantage of DI for tomato fruit quality usually comes with overall yield reductions (Mitchell et al., 1991).

With the influence of rainfall during the fall season, a lower yield at the lower irrigation regime (DI) may not have been anticipated. As previously described, early in the fall season, the SMC was similar (especially at the lower soil depths) regardless of irrigation conditions; however, SMC did not remain similar with the FI and DI treatments throughout the season. Starting at ≈ 55 DAT during the fall season, soil moisture at 5, 15, and 35 cm decreased (up to 20%) below field capacity with DI, thereby reducing the total amount of available soil water for plant uptake compared with FI that constantly maintained SMC at or above field capacity throughout the season. Based on the field observations during the growing seasons, anthesis (initiation of flowering) began at ≈ 24 DAT, whereas fruit setting peaked between 50 and 60 DAT (data not included). Therefore, reducing plant available water at this stage (as observed in this study under DI conditions) could significantly reduce fruit formation and enlargement, thereby reducing yield. Similar results were observed during the spring season for DI, with SMC at soil depths of 35 and 45 cm found to be lower than the field capacity throughout the season.

Irrigation water-use efficiency and nitrogen recovery. The iWUE was significantly different between irrigation regimes and N application rates during the fall season, but no differences were observed during the spring season (Table 7). Although TMY was significantly higher with FI compared with that with DI during the fall season, the iWUE was higher for DI (33 kg·m⁻³) than for FI (26 kg·m⁻³). Higher iWUE with DI was attributed to the yield gap between DI and FI treatments and lower total season crop water demands compared with the spring season. Although the

Table 7. Effects of irrigation regime and nitrogen (N) application rates on tomato irrigation water-use efficiency (iWUE) during Fall 2016 and Spring 2017 growing seasons in Immokalee Florida.

Treatment	Total irrigation water applied (m ³ ·ha ⁻¹)	iWUE (kg·m ⁻³)	Total irrigation water applied (m ³ ·ha ⁻¹)	iWUE (kg·m ⁻³)
Water		Fall 2016		
FI	2752	25.57	4278	14.04
DI	1816	33.58	2933	15.29
N (kg·ha ⁻¹)		Spring 2017		
134	2284	21.88 a	3606	13.45
179		32.85 b		15.03
224		29.83 b		15.42
269		31.45 b		14.70
Water	—	***	—	NS
N	—	***	—	NS
Water × N	—	NS	—	NS

FI = full irrigation; DI = deficit irrigation.

***Statistically significant difference among treatments at $\alpha < 0.005$. NS = no significant difference at $\alpha \leq 0.05$.

Table 8. Effects of irrigation regime and nitrogen (N) practices on tomato nitrogen recovery (REC-N) during Fall 2016 and Spring 2017 growing seasons in Immokalee, FL.

Treatments	Total N accumulation (kg·ha ⁻¹)	REC-N (%)	Total N accumulation (kg·ha ⁻¹)	REC-N (%)
Water		Fall 2016		
FI	160.65	64.65	144.42	67.70
DI	258.61	64.78	143.13	67.49
N (kg·ha ⁻¹)		Spring 2017		
134	130 b	86.07 a	123.23 b	85.65 a
179	146 ab	62.66 b	143.82 ab	70.24 b
224	154 ab	55.63 c	150.14 a	60.49 bc
269	176 a	54.50 c	158.43 a	53.98 c
Water	NS	NS	NS	NS
N	§	***	*	***
Water × N	NS	NS	NS	NS

FI = full irrigation; DI = deficit irrigation.

*, ***Statistically significant difference among treatment at α values between 0.01 and 0.05, and <0.005, respectively. §Significant difference at $\alpha = 0.08$. NS = no significant difference at $\alpha \leq 0.05$.

total water applied was $\approx 34\%$ lower for DI than for FI during the fall season, the TMY was just 13% lower for the former, resulting in higher fruit production per unit volume of irrigation water applied. Contrary to irrigation regimes, iWUE was lower with 134 kg·ha⁻¹ N (due to lower yield) compared with that occurring with other application rates. During the spring season, however, iWUE (14 and 15 kg·m⁻³ for FI and DI respectively) was not different between the two irrigation regimes. Tomato yield and total irrigation water applied

during the spring season were $\approx 33\%$ and 34% lower, respectively, for DI and FI, resulting in similar fruit production per unit volume of irrigation water applied. The iWUE observed during this season was similar to that reported by Zotarelli et al. (2009a) under similar N and irrigation conditions.

The REC-N was similar during both seasons and ranged from 54% to 86% (Table 8). The irrigation regime had no effects on REC-N in both seasons; however, the REC-N with the 134 kg·ha⁻¹ N application rate was significantly

higher (86%) than that with higher N rates. The REC-N was 64% with an N application rate of 179 kg·ha⁻¹ N, which was higher than that occurring with the 224 kg·ha⁻¹ N (at 56%) and 269 kg·ha⁻¹ N (at 55%) rates during the fall season. During the spring season, the REC-N was higher with 179 kg·ha⁻¹ N (70%) than with 269 kg·ha⁻¹ N (54%), but it was not different than that occurring with an N rate of 224 kg·ha⁻¹ N (60%). Similar trends in reduced REC-N with an increase in N application were found in the literature (Djidonou et al., 2013; Zhang et al., 2011). However, marketable yield (as previously described) and total N uptake (Table 8) were significantly lower compared with those occurring with other N application rates (N uptake was significant at $\alpha = 0.08$). Therefore, considering the results from this study and potential economic and environmental impacts, an N application rate of 179 kg·ha⁻¹ N could be considered the optimum N rate for open-field fresh-market tomato production in Florida. This is because N uptake and fruit yield benefits for tomato production may be insignificant at higher application rates. REC-N values observed in this study were generally higher than those reported by Zotarelli et al. (2009b) for similar N application for fresh-market tomato grown with drip irrigation in Citra, FL, but similar to those reported by Zhang et al. (2011) for similar N rates for processing tomato.

Conclusions

This study evaluated the effects of N rates under different irrigation regimes to determine the optimum N requirement for open-field fresh-market tomato production. The study also aimed to evaluate the effects of N rates and irrigation regimes on tomato biomass accumulation, root growth, yield, and system efficiencies. The results clearly demonstrated that DI applied to target 66% ET replacement significantly increased tomato root growth compared with FI requirements for open-field fresh market tomato. Also, DI increased growth early in the season compared with FI. Therefore, irrigation applications may be adjusted downward during early crop development from FI, especially early during a wet season, thus potentially improving iWUE and reducing the leaching potential of Florida sandy soils.

The TMY increased under FI conditions compared with DI conditions. This suggests that although DI may increase early plant growth, the application of DI throughout the season may result in yield reduction. These results indicate that 66% ET should be the target irrigation rate at CGS 1 and CGS 2, but that 100% ET should be used from CGS 3 to CGS 5. The iWUE was higher with DI compared with FI during the fall season; however, efficiency was similar for both irrigation regimes during the spring season. It was also observed that there were no yield benefits with N application rates higher than 179 kg·ha⁻¹. Generally, the N recovery rate with the 179 kg·ha⁻¹ N application rate was higher compared with those with 224 and

269 kg·ha⁻¹ N application rates. Therefore, the optimum N requirement during the tomato growing season in Florida may not exceed 179 kg·ha⁻¹.

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