Yield, Water-, and Nitrogen-use Efficiency in Field-grown, Grafted Tomatoes

Desire Djidonou¹, Xin Zhao^{2,4}, Eric H. Simonne³, and Karen E. Koch³
Horticultural Sciences Department, University of Florida, Gainesville, FL 32611

John E. Erickson²

Agronomy Department, University of Florida, Gainesville, FL 32611

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Abstract. In addition to managing soilborne diseases, grafting with vigorous rootstocks has been shown to improve yield in tomato (*Solanum lycopersicum* L.) production. However, the influence of different levels of nitrogen (N) and irrigation supplies on grafted tomato plants has not been fully examined in comparison with non-grafted plants, especially under field conditions. The objective of this two-year study was to determine the effects of different irrigation regimes and N rates on yield, irrigation water use efficiency (iWUE), and N use efficiency (NUE) of grafted tomato plants grown with drip irrigation in sandy soils of north Florida. The determinate tomato cultivar Florida 47 was grafted onto two interspecific hybrid rootstocks, ‘Beaufort’ and ‘Multifort’ (*S. lycopersicum* × *S. habrochaites* S. Knapp & D.M. Spooner). Non-grafted ‘Florida 47’ was used as a control. Plants were grown in a fumigated field under 12 combinations of two drip irrigation regimes (50% and 100% of commonly used irrigation regime) and six N rates (56, 112, 168, 224, 280, and 336 kg·ha⁻¹). The field experiments were arranged in a split-plot design with four replications. The whole plots consisted of the irrigation regime and N rate combination treatments, whereas the subplots represented the two grafting treatments and the non-grafted plants. Self-grafted ‘Florida 47’ was also included in the 100% irrigation and 224 kg N/ha fertilization treatment as a control. In 2010, the 50% irrigation regime resulted in higher total and marketable yields than the 100% irrigation regime. Tomato yield was significantly influenced by N rates, but similar yields were achieved at 168 kg·ha⁻¹ and above. Plants grafted onto ‘Beaufort’ and ‘Multifort’ showed an average increase of 27% and 30% in total and marketable fruit yields, respectively, relative to non-grafted plants. In 2011, fruit yields were affected by a significant irrigation by N rate interaction. Grafting significantly increased tomato yields, whereas grafted plants showed greater potential for yield improvement with increasing N rates compared with non-grafted plants. Self-grafting did not affect tomato yields. More fruit per plant and higher average fruit weight as a result of grafting were observed in both years. Grafting with the two rootstocks significantly improved the irrigation water and N use efficiency in tomato production. Results from this study suggested the need for developing irrigation and N fertilization recommendations for grafted tomato production in sandy soils.

Grafting is currently practiced worldwide on many high-value cucurbitaceous and solanaceous crops such as watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai], melon

(*Cucumis melo* L.), cucumber (*Cucumis sativus* L.), tomato (*Solanum lycopersicum* L.), eggplant (*S. melongena* L.), and pepper (*Capsicum annuum* L.) for both open-field production and protected culture (Davis et al., 2008; Lee, 1994; Lee and Oda, 2003; Lee et al., 2010). Vegetable grafting has proven to be an innovative and effective technique for controlling soilborne diseases such as fusarium wilt (caused by *Fusarium oxysporum*), verticillium wilt (caused by *Verticillium dahliae*), southern blight (caused by *Sclerotium rolfsii*), and bacterial wilt (caused by *Ralstonia solanacearum*) (McAvoy et al., 2012; Rivard and Louws, 2008; Rivard et al., 2010, 2012) as well as root-knot nematodes (*Meloidogyne* spp.) (Barrett et al., 2012; Bausher, 2009; López-Pérez et al., 2006). Grafting with certain rootstocks has also been shown to improve plant tolerance to abiotic stresses such as high salt and low temperature

(Fernández-García et al., 2004; Schwarz et al., 2010).

Previous studies have demonstrated that in addition to disease management, plant vigor and yield often increase as a result of grafting with vigorous rootstocks. In the case of tomato production, grafted plants can increase marketable yield by ≈20% to 62% over non-grafted plants, depending on scion–rootstock combinations and production conditions (Di Gioia et al., 2010; Lee and Oda, 2003; Leonardi and Giuffrida, 2006; Pogonyi et al., 2005). The improved productivity of grafted plants has been attributed by some studies to the intrinsic vigor of the rootstock and the scion–rootstock interaction, which in turn exerts positive influence on plant nutrient and water absorption, endogenous hormone balance, N assimilation, and photosynthetic processes (Aloni et al., 2010; Kato and Lou, 1989; Lee et al., 2010; Stegemann and Bock, 2009; Yamasaki et al., 1994). Given the physiological and phenotypic modifications caused by grafting with selected, vigorous rootstocks, it is likely that irrigation and fertilization management for maximizing crop yield may differ between grafted vs. non-grafted vegetable production.

In addition to the enhanced fruit yields with grafted plants, plants grafted onto vigorous rootstocks also use irrigation water and fertilizer more effectively for producing marketable fruit yields. Recent research has addressed the growth and yield performance of grafted plants in response to different levels of water or nutrients (Colla et al., 2010, 2011; Rouphael et al., 2008). However, most of these studies focused on cucurbits, especially under greenhouse conditions, with an emphasis on either irrigation or fertilization management rather than a combination of both. In the present study, responses to both nutrients and water are examined together and addressed by comparing grafted vs. non-grafted tomato production under field conditions. This information is important for aiding recommendations to producers who are increasingly adopting grafting for open-field tomato production on a larger scale. Furthermore, conditions in Florida, where the commercial production of fresh market tomato occurs, include sandy soils with low water and nutrient retention capacities (Hartz and Hochmuth, 1996; Hochmuth, 1992; Locascio, 2005). The situation in Florida is compounded by recommendations for N fertilization based primarily on crop type rather than soil tests (Olson et al., 2009). Therefore, the objectives of this study were to 1) determine the influence of irrigation regimes and N fertilizer application rates on yield and yield components of grafted tomato plants grown with drip irrigation in Florida sandy soils; and 2) characterize the influence of grafting with vigorous rootstocks on irrigation water and N use efficiency under these conditions.

Materials and Methods

Grafting and transplant production. The field-grown, determinate tomato cultivar Florida 47 (Seminis Vegetable Seeds, Inc.,

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¹Graduate Research Assistant.

²Assistant Professor.

³Professor.

⁴To whom reprint requests should be addressed; e-mail xzxin@ufl.edu.

St. Louis, MO) was used as the scion and grafted onto two commercially available, interspecific hybrid rootstocks, 'Beaufort' and 'Multifort' (De Ruiter Seeds Inc., Bergschenhoek, The Netherlands). These two rootstocks are currently among the most widely used tomato rootstocks in the United States. Rootstock seeds were sown on 21 Feb. 2010 and 19 Feb. 2011, 2 d before the 'Florida 47' scion, to ensure similar stem diameters at the time of grafting because the rootstock cultivars tend to germinate and emerge more slowly. Plants were splice-grafted (Lee and Oda, 2003) on 16 Mar. 2010 and 20 Mar., 2011, when four to five true leaves were present. Grafted plants were immediately placed in a closed healing chamber equipped with two humidifiers and an auto-control air conditioning system for healing the grafts, where temperature was maintained at 25 ± 3 °C and average relative humidity above 80%. Light and ventilation were introduced gradually after a dark period of 4 d. Twelve days after grafting, grafted plants including 'Florida 47' grafted onto 'Beaufort' (FL/BE) and 'Florida 47' grafted onto 'Multifort' (FL/MU) were completely healed and ready for transplanting to the field. Non-grafted 'Florida 47' (FL) transplants provided the control treatment.

Field production. The field experiments were conducted during the spring seasons of 2010 and 2011 at the Suwannee Valley Agricultural Extension Center in Live Oak, FL (lat. 30.31° N, long. 82.90° W). The soil type was a Blanton-Foxworth-Alpin Complex sandy soil (Natural Resources Conservation Service, 2006). In both years, field plots were disked and plowed, 5 weeks before transplanting, followed by soil fumigation using Telone C-35 (Dow AgroSciences, LLC, Indianapolis, IN) at the rate of 196.4 L·ha⁻¹. The field was fumigated to eliminate interference of soil-borne pest factors. Mehlich-1 soil test results conducted before field preparation showed a high level of soil phosphorus (P) while a low level of soil potassium (K). Three weeks before transplanting, 13N–1.7P–10.8K (Mayo Fertilizer Inc., Mayo, FL) fertilizer was applied at a rate providing 56 kg N/ha, 7.3 kg P/ha, and 46.5 kg K/ha to all plots during bed preparation. Grafted and non-grafted plants were transplanted to raised beds with plastic mulch and drip irrigation on 29 Mar. 2010 and 1 Apr. 2011. Beds were 0.71 m wide and spaced 1.52 m apart (from middle to middle) with 0.46-m in-row spacing for open-field tomato production.

In both years, a split-plot design with four replications was used. The whole-plot treatments, i.e., 12 factorial combinations of two irrigation regimes and six N fertilization rates, were arranged in a randomized complete block design. The subplot treatments included the two grafting treatments FL/BE and FL/MU and the non-grafted 'Florida 47' (FL) as a control, all randomized within each whole plot. There were 12 plants for each treatment combination per replication in both 2010 and 2011. The two irrigation regimes included: 1) 100% irrigation regime based on the commonly used irrigation regime by commercial growers in Florida, i.e., 9354–37,416 L/ha/day

depending on the crop stage; and 2) 50% irrigation regime corresponding to 4677–18,708 L/ha/day depending on the crop stage. The six N fertilization rates were 56, 112, 168, 224, 280, and 336 kg·ha⁻¹, which represented 25%, 50%, 75%, 100%, 125%, and 150%, respectively, of the currently recommended total N application rate of 224 kg N/ha (a preplant application at 56 kg N/ha included) for field production of irrigated, round tomatoes in sandy soils in Florida (Olson et al., 2009). Except for the 56-kg N/ha rate, which only included a preplant application of 13N–1.7P–10.8K, ammonium nitrate (34N–0P–0K; Mayo Fertilizer Inc., Mayo, FL) was injected weekly through the drip tape starting 1 week after transplanting (WAT) to provide the remaining amount of N for other fertilization rate treatments. The weekly injected amounts of N for each of these five N fertilization rates during 1 to 2 WAT, 3 to 4 WAT, 5 to 11 WAT, 12 WAT, and 13 WAT, respectively, were as follows: 1) 3.0, 4.0, 5.0, 4.0, and 3.0 kg·ha⁻¹; 2) 6.1, 8.0, 10.0, 8.0, and 6.1 kg·ha⁻¹; 3) 9.1, 12.0, 15.0, 12.0, and 9.1 kg·ha⁻¹; 4) 12.1, 16.0, 19.9, 16.0, and 12.1 kg·ha⁻¹; and 5) 15.1, 20.0, 24.9, 20.0, and 15.1 kg·ha⁻¹. Potassium chloride (Dyna Flo 0N–0P–15K; Chemical Dynamics Inc., Plant City, FL) was also applied through fertigation to provide each treatment with amount of K needed after accounting for the preplant application based on the soil test. The weekly injected amounts of K during the growing season were as follows: 11.8, 9.3, 14.3, 9.3, and 6.7 kg·ha⁻¹ during 1 to 2 WAT, 3 to 4 WAT, 5 to 11 WAT, 12 WAT, and 13 WAT, respectively. The stake-and-weave method was used for trellising the tomato plants. Other cultural practices, including pest control, followed current recommendations for commercial field tomato production in Florida (Olson et al., 2009). Furthermore, daily rainfall data collected by a weather station of the Florida Automated Weather Network (FAWN) located at Live Oak (FAWN, 2011) were used to compare the 2010 and 2011 seasons in terms of rainfall distribution. It should be noted that in addition to the non-grafted 'Florida 47' (FL) controls, self-grafted scion plants (FL/FL) were added as a second set of controls. These were included in the 100% irrigation and N rate (224 kg N/ha) plots to examine the effect of graft injury and initial growth reduction associated with the grafting process.

Yield, irrigation water use efficiency, and nitrogen use efficiency. Mature green tomato fruit and fruit at more advanced ripening stages were harvested from 10 plants in each treatment combination per replication. Fruit were picked 80 and 88 d after transplanting (DAT) in 2010, and 75, 85, and 92 DAT in 2011. They were then graded as extralarge, large, medium, and culls (small fruit and defective fruit). Fruit in each grade were counted and weighed. Total fruit yield, marketable fruit yield, average fruit weight, and average number of fruit per plant were calculated. Irrigation water use efficiency (iWUE) was estimated as the ratio of the marketable fruit yield to the amount of irrigation water

applied during the production season. Nitrogen use efficiency (NUE) was estimated as the ratio of the marketable fruit yield to the amount of N supplied during the production season.

Statistical analyses. Data from the 2010 and 2011 experiments were analyzed separately. Analysis of variance was conducted using the GLIMMIX procedure of SAS Version 9.2 (SAS Institute, Cary, NC). Within each season, yield and yield components, iWUE, and NUE were analyzed with a model including main effects of irrigation regime, N fertilization rate, and grafting treatment. All models also included all possible interaction terms of these factors. An analysis of the conditional studentized residuals indicated no deviations from the normality and homoscedasticity assumptions, and therefore data transformation was not needed. Tukey's test ($\alpha = 0.05$) was used for multiple comparisons.

Results

Seasonal rainfall at the experimental site. Daily rainfall data collected by the weather station located at the research center in Live Oak were used to compare the seasonal rainfall between the 2010 and 2011 trials (FAWN, 2011). The rainfall pattern at the experimental site varied greatly between the 2010 and 2011 growing seasons (Fig. 1). Total rainfall during the growing season was 272 mm in 2010 and 157 mm in 2011. Within the first 4 WAT, there was $\approx 12\%$ higher rainfall in 2011 than in 2010. However, starting from Week 5 through Week 11, an increased amount of rainfall by $\approx 226\%$ occurred in 2010 than in 2011, i.e., 186 mm in 2010 vs. 57 mm in 2011.

Total and marketable fruit yields. Irrigation regime, N fertilization rate, and grafting all showed a significant influence on tomato fruit yields in both 2010 and 2011 experiments (Table 1). In the 2010 trial, the 50% irrigation regime resulted in higher total and marketable fruit yields compared with the 100% irrigation regime. Increases averaged 15% and 19%, respectively (Table 2). Within the six N rates evaluated, total and marketable fruit yields were significantly improved when the N rate increased from 56 to 168 kg·ha⁻¹. However, no significant differences were observed with N rates of 168 kg·ha⁻¹ and above (Table 2). Grafting with the two rootstocks significantly improved the yields of 'Florida 47'. Averaged over the two rootstocks, the increase of total and marketable fruit yields relative to those of non-grafted 'Florida 47' reached 27% and 30%, respectively (Table 2). It was noted that the yield improvement in grafted plants was more pronounced starting in the second harvest, especially with the use of 'Multifort' rootstock (data not shown).

For the 2011 trial, the effects of N rates on tomato yields were dependent on irrigation regime as reflected by the significant interaction of irrigation regime by N rate (Tables 1 and 3). With the 50% irrigation regime, the total and marketable yields at 56 kg N/ha were significantly lower than those at higher N rates, but yields at 112 kg N/ha and above

Fig. 1. Weekly and cumulative rainfall in Live Oak, FL, during the tomato field trials in 2010 (A) and 2011 (B). Data source: Florida Automated Weather Network (<http://fawn.ifas.ufl.edu/>). Tomato plants were transplanted on 29 Mar. 2010 and 1 Apr. 2011.

Table 1. Analysis of variance of the effects of irrigation regime (I), nitrogen (N) fertilization rate, and grafting (G) on total tomato fruit yield, marketable fruit yield, number of marketable fruit, average weight of marketable fruit, irrigation water use efficiency (iWUE), and nitrogen use efficiency (NUE) in the 2010 and 2011 field trials in Live Oak, FL.

Effect	df	Total fruit yield		Marketable fruit yield		Number of fruit per plant		Avg fruit wt		iWUE		NUE	
		2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
I	1	***	***	***	***	***	NS	***	***	***	***	***	NS
N	5	***	***	***	***	***	***	***	***	***	***	***	***
G	2	***	***	***	***	***	***	***	***	***	***	***	***
I × N	5	NS	***	NS	***	*	**	NS	NS	***	**	NS	*
I × G	2	NS	NS	NS	NS	NS	NS	NS	*	***	***	NS	NS
N × G	10	NS	NS	NS	*	NS	NS	*	*	*	**	*	NS
I × N × G	10	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 2. Main effects of irrigation regime, nitrogen (N) fertilization rate, and grafting on total and marketable yields of 'Florida 47' tomato in the 2010 field trial in Live Oak, FL.

Treatment	Yield (Mg·ha ⁻¹)	
	Total	Marketable
Irrigation (%)		
50	55.5 a ^z	49.8 a
100	48.3 b	41.8 b
N rate (kg·ha ⁻¹)		
56	23.4 c	18.4 c
112	42.8 b	36.3 b
168	57.0 a	49.9 a
224	63.8 a	57.4 a
280	61.9 a	55.4 a
336	62.5 a	57.5 a
Graft		
FL/BE	54.7 a	48.9 a
FL/MU	56.9 a	50.5 a
FL	44.1 b	38.1 b

^zMeans within a column and a treatment category followed by the same letter do not differ significantly at $P \leq 0.05$ according to Tukey's test.

FL/BE = 'Florida 47' grafted onto 'Beaufort'; FL/MU = 'Florida 47' grafted onto 'Multifort'; FL = non-grafted 'Florida 47'.

did not differ significantly. In contrast, under the 100% irrigation regime, significant yield increases were observed as the N rates increased. The total yield at 280 kg N/ha was significantly higher than those at lower N rates but did not differ significantly from that at 336 kg N/ha. A similar trend was found for

the marketable yield, which reached the highest level at 280 kg N/ha, whereas it did not show significant differences from those at 224 and 336 kg N/ha (Table 3). Comparison of the yield response to the two irrigation regimes at each N rate did not show a clear pattern; however, total yields did not differ except at 56 and 280 kg N/ha, whereas marketable yields were similar except at 280 and 336 kg N/ha. Similar to the 2010 experiment, total and marketable fruit yields of the grafted plants (FL/BE and FL/MU) were significantly higher than the non-grafted plants (FL) in the 2011 trial, and a significant grafting × N rate interaction was also observed for marketable fruit yield (Tables 1 and 3). Grafting increased the marketable yield of 'Florida 47' with each N rate at or above 112 kg N/ha, and the yield increase reached 46% at 224 kg N/ha, the currently recommended N rate for non-grafted 'Florida 47'. Grafting also altered the effects of N rates on marketable yield. For example, for non-grafted 'Florida 47', marketable yield at 112 kg N/ha was significantly higher than that at 56 kg N/ha, but it did not show any significant increase at higher N rates. In contrast, the marketable fruit yields of the grafted plants exhibited a significant increase at 280 kg N/ha compared with those at 56 and 112 kg N/ha (Table 3).

Yield components. The marketable yield components, including number of tomato fruit per plant and average fruit weight, were

further examined to identify the contributors to yield responses. In both 2010 and 2011 trials, grafted plants (FL/BE and FL/MU) had significantly more marketable fruit per plant than did non-grafted plants (FL) (Table 1). Grafting increased fruit number by an average of 13% in 2010 and 27% in 2011 (data not shown). The number of marketable fruit per plant was also affected by a significant interaction between irrigation regime and N rate in both years (Table 1). In 2010, under the 100% irrigation regime, the marketable fruit number per plant was significantly lower at 112 kg N/ha, and most reduced at 56 kg N/ha (Table 4). Under the 50% irrigation regime, fruit number was lowest at 56 kg N/ha and was significantly increased at 112 kg N/ha, whereas increasing N rate beyond 112 kg·ha⁻¹ significantly increased the fruit number at 224 and 336 kg N/ha. In the 2011 trial, the marketable fruit number at different N rates under the two irrigation regimes followed the same response of marketable fruit yields (Tables 3 and 4).

Consistent with the higher marketable yield under the 50% irrigation regime in 2010, the average fruit weight was also significantly greater. Significant effects of grafting, N rate, and their interaction were also evident in average fruit weight (Table 1). Grafting with the two rootstocks significantly increased the average fruit weight of 'Florida 47' at most N rates tested but not at 112 kg·ha⁻¹ (data for 2010 not shown). In the 2011 experiment, the impact of grafting on average fruit weight also reflected significant interaction effects associated with irrigation regime and N rate (Table 1). Under the 50% irrigation regime, grafted plants (FL/BE and/or FL/MU) showed significantly greater average fruit weight than the non-grafted plants at each of the six N rates applied. In contrast, under the 100% irrigation regime, the average fruit weight did not differ between grafted and non-grafted 'Florida 47' at 56 kg N/ha (Table 5). Under the recommended irrigation regime (100%) and N rate (224 kg·ha⁻¹), the average marketable fruit weight was increased by grafting by approximately 17% in contrast to the non-grafted plants.

Irrigation water use efficiency. The iWUE relative to marketable fruit yields was affected by significant two-way interactions among grafting, irrigation regime, and N rate. Results were similar in the 2010 and 2011 trials (Table 1). In both years, a marked decline of iWUE was observed when the irrigation regime was increased from 50% to 100% irrespective of grafting and N rate treatments (Fig. 2A–D). In 2010, the highest value of iWUE was achieved at 224 and 280 kg N/ha within the 50% and 100% irrigation regimes, respectively, whereas it did not differ significantly between N rates at and above 168 kg·ha⁻¹ within each irrigation regime. The iWUE at 112 kg N/ha was significantly higher than that at 56 kg N/ha under the 50% irrigation regime; however, such a difference was not observed under the 100% irrigation regime (Fig. 2A). In 2011, under the 50% irrigation regime, the iWUE at 112 kg N/ha was significantly higher than that at

Table 3. Total and marketable yields of 'Florida 47' tomato as influenced by interactions between irrigation regime, nitrogen (N) fertilization rate, and grafting in the 2011 field trial in Live Oak, FL.

N rate (kg·ha ⁻¹)	Total fruit yield (Mg·ha ⁻¹)		Marketable fruit yield (Mg·ha ⁻¹)		Marketable fruit yield (Mg·ha ⁻¹)		
	50%	100%	50%	100%	FL/BE	FL/MU	FL
	(irrigation regime)		(irrigation regime)				
56	25.4 Ba ^z	18.6 Db	21.7 Ba	15.8 Da	21.7 Ca	20.2 Cab	14.4 Bb
112	54.4 Aa	51.5 Ca	49.4 Aa	45.9 Ca	51.8 Ba	53.2 Ba	38.0 Ab
168	59.3 Aa	57.3 Ca	53.2 Aa	52.9 BCa	58.3 ABa	57.3 ABa	43.7 Ab
224	55.9 Aa	63.2 Ba	50.8 Aa	58.7 ABa	61.3 ABa	61.0 ABa	42.0 Ab
280	55.3 Ab	72.8 Aa	48.8 Ab	66.8 Aa	65.1 Aa	64.8 Aa	43.3 Ab
336	54.3 Aa	65.1 ABa	47.9 Ab	60.8 ABa	62.6 Aa	60.9 ABa	39.6 Ab

^zMeans followed by the same uppercase letter within a column, and means followed by the same lowercase letter within a row are not significantly different at $P \leq 0.05$ according to Tukey's test.

FL/BE = 'Florida 47' grafted onto 'Beaufort'; FL/MU = 'Florida 47' grafted onto 'Multifort'; FL = non-grafted 'Florida 47'.

Table 4. Number of marketable tomato fruit per plant as influenced by interaction between irrigation regime and nitrogen (N) fertilization rate in the 2010 and 2011 field trials in Live Oak, FL.

N rate (kg·ha ⁻¹)	2010		2011	
	Irrigation regime (%)		Irrigation regime (%)	
	50	100	50	100
56	8 Ca ^z	7 Ba	9 Ba	7 Da
112	16 Ba	12 Bb	19 Aa	17 Ca
168	19 ABa	18 Aa	20 Aa	19 BCa
224	22 Aa	18 Aa	20 Aa	21 ABa
280	19 ABa	20 Aa	19 Ab	23 Aa
336	22 Aa	18 Aa	18 Ab	22 ABa

^zMeans followed by the same uppercase letter within a column, and means followed by the same lowercase letter within a row are not significantly different at $P \leq 0.05$ according to Tukey's test.

Table 5. Average weight of marketable tomato fruit from grafted and non-grafted 'Florida 47' plants as influenced by interaction between irrigation regime and nitrogen (N) fertilization rate in the 2011 field trial in Live Oak, FL.

N rate (kg·ha ⁻¹)	Avg fruit wt (g/fruit)		
	Graft	50% irrigation regime	100% irrigation regime
56	FL/BE	165.2 ab ^z	161.7 a
	FL/MU	177.1 a	159.2 a
	FL	154.0 b	170.9 a
112	FL/BE	182.7 a	190.6 a
	FL/MU	185.6 a	203.1 a
	FL	165.6 b	174.3 b
168	FL/BE	188.7 ab	192.7 ab
	FL/MU	189.6 a	210.6 a
	FL	174.7 b	175.2 b
224	FL/BE	192.8 a	201.2 a
	FL/MU	178.3 ab	200.1 a
	FL	166.6 b	171.5 b
280	FL/BE	193.6 a	190.9 b
	FL/MU	182.0 a	211.5 a
	FL	157.0 b	195.0 b
336	FL/BE	190.1 a	202.5 a
	FL/MU	190.3 a	194.3 ab
	FL	156.9 b	180.2 b

^zMeans followed by the same letter within a column within the same N fertilization rate are not significantly different at $P \leq 0.05$ according to Tukey's test.

FL/BE = 'Florida 47' grafted onto 'Beaufort'; FL/MU = 'Florida 47' grafted onto 'Multifort'; FL = non-grafted 'Florida 47'.

56 kg N/ha, but the N rates above 112 kg·ha⁻¹ did not lead to any significant increase of iWUE. Within the 100% irrigation regime, the iWUE reached the highest value at 280 kg N/ha, but it did not differ significantly from values at 224 and 336 kg N/ha (Fig. 2B). Furthermore, iWUE of the grafted plants was significantly higher relative to that of non-grafted plants at both irrigation regimes in both years, although the difference tended to vary with the irrigation regime (Fig. 2C–D). In 2010, the averaged iWUE values of the

grafted plants were greater than that of the non-grafted plants by 29% under the 50% irrigation regime and by 32% under the 100% irrigation regime. In 2011, the average increase in iWUE as a result of grafting was 54% and 36% under 50% and 100% irrigation regimes, respectively. In general, both grafted and non-grafted plants in each season exhibited a consistent increase of iWUE with the increasing N rate from 56 to 168 kg·ha⁻¹ (Fig. 2E–F). A further improvement of iWUE at 224 kg N/ha was observed

in grafted plants but not in non-grafted 'Florida 47', especially in 2010. Increasing the N rate from 224 to 336 kg·ha⁻¹ did not result in any pronounced change of iWUE. Furthermore, the performance of the two rootstocks used also seemed to differ at certain N rates. In both years, grafting significantly enhanced the iWUE at different N rates except that there was no significant difference between the iWUE of FL/MU and FL at 56 kg N/ha, whereas FL/BE and FL showed similar levels of iWUE at 168 kg N/ha in 2010.

Nitrogen use efficiency. In the 2010 trial, the main effect of irrigation regime was significant, whereas the significant effect of N rate on NUE was dependent on grafting (Table 1). NUE was 20% higher in the 50% irrigation regime compared with the 100% irrigation regime (data not shown). Moreover, compared with the non-grafted 'Florida 47', grafted plants with the two rootstocks enhanced NUE significantly at each N rate except the 168 kg N/ha treatment (Table 6). On average, the increase in NUE resulting from grafting with the vigorous rootstocks were 81% and 23% with the 56 and 112 kg N/ha, respectively, while ranging from 26% to 38% when increasing the N rate from 224 to 336 kg·ha⁻¹. In addition, for both FL/BE and FL/MU, increasing the N rate from 56 to 336 kg·ha⁻¹ consistently decreased the NUE. However, the decrease was mainly significant between the two lower N rates (56 and 112 kg·ha⁻¹) and the two higher N rates (280 and 336 kg·ha⁻¹). With the non-grafted plants, NUE was significantly reduced at 280 and 336 kg N/ha compared with those at 112 to 168 kg·ha⁻¹. Furthermore, in 2011, the main effect of grafting was significant, whereas the significant effect of N rate on NUE was related to the irrigation regime (Table 1). In 2011, grafted plants with the two rootstocks increased NUE by 42% relative to that of non-grafted plants (data not shown). Under both irrigation regimes regardless of the grafting treatment, the rate of 112 kg N/ha resulted in the highest NUE, whereas the lowest NUE was observed at 336 kg N/ha (Table 6). NUE values at certain N rates were also influenced by the irrigation regimes. At 56 kg N/ha, the NUE was significantly higher under the 50% irrigation regime, whereas the opposite was observed at each of the higher N rates 224 kg·ha⁻¹ or greater.

Fig. 2. Irrigation water use efficiency (iWUE) as influenced by interaction between irrigation regime and nitrogen (N) fertilization rate (A–B), by interaction between irrigation regime and grafting (C–D), and by interaction between N fertilization rate and grafting (E–F) in 2010 and 2011, respectively. Irrigation water use efficiency was estimated as the ratio of the marketable fruit yield to the amount of irrigation water applied during the production season. Treatment values at each irrigation regime or each N fertilization rate followed by the same letter are not significantly different at $P \leq 0.05$ according to Tukey's test. FL/BE = 'Florida 47' grafted onto 'Beaufort'; FL/MU = 'Florida 47' grafted onto 'Multifort'; FL = non-grafted 'Florida 47'.

Discussion

Grafting influence on fruit yields of tomato under field conditions. Grafting the determinate 'Florida 47' tomato plants with vigorous rootstocks 'Beaufort' and 'Multifort' significantly improved total and marketable fruit yields at almost all N rates applied in this study. Moreover, grafted plants tended

to show greater potential for yield improvement with the increase of N than non-grafted plants, particularly in the 2011 trial. Compared with non-grafted tomato plants, it is likely that grafted plants may require a higher level of N for maximizing yield performance. Fruit is an important sink for carbohydrates and amino acids in tomato plants (Valle et al., 1998). Given the greater number of fruit per

plant and higher average fruit weight of grafted plants, the sink strength of the grafted plants would have been at a higher level relative to that of the non-grafted plants. This stronger fruit sink of grafted tomato may partly reflect a greater demand for nutrients, especially N. Future work is warranted to elucidate the nutrient requirement for field production of grafted tomatoes with different

Table 6. Nitrogen (N) use efficiency^a of 'Florida 47' tomato plants as influenced by interaction between N fertilization rate and grafting in the 2010 field trial and interaction between irrigation regime and N fertilization rate in the 2011 field trial in Live Oak, FL.

N rate (kg·ha ⁻¹)	Nitrogen use efficiency (kg·kg ⁻¹)				
	2010			2011	
	Graft			Irrigation regime (%)	
	FL/BE	FL/MU	FL	50	100
56	382.88 Aa ^b	388.06 Aa	212.89 ABb	388.54 ABa	282.33 Bb
112	348.83 Aa	341.74 ABa	281.67 Ab	441.20 Aa	409.96 Aa
168	299.92 ABa	320.90 ABa	270.53 Aa	317.04 BCa	315.47 Ba
224	282.14 ABa	278.94 BCa	207.57 ABb	226.96 CDb	262.32 BCa
280	215.60 BCa	220.36 Ca	157.41 Bb	174.24 Db	238.71 BCa
336	175.11 Ca	192.88 Ca	145.66 Bb	142.85 Db	181.02 Ca

^aNitrogen use efficiency (NUE) was estimated as the ratio of the marketable fruit yield to the amount of N supplied during the production season.

^bMeans followed by the same uppercase letter within a column, and means followed by the same lowercase letter within a row are not significantly different at $P \leq 0.05$ according to Tukey's test.

FL/BE = 'Florida 47' grafted onto 'Beaufort'; FL/MU = 'Florida 47' grafted onto 'Multifort'; FL = non-grafted 'Florida 47'.

combinations of scions and rootstocks. In the present study, the two interspecific tomato hybrid rootstocks demonstrated an overall similar yield improvement. Although the rootstocks used are well known for their high resistance to several soilborne diseases, the increased yields observed here with fumigated soils could be attributed primarily to the vigorous characteristics of the rootstocks. The positive scion–rootstock interactions would have improved plant growth and development. Yield enhancement from grafting, even in a low disease pressure, has been reported previously with solanaceous and cucurbitaceous vegetables (Leonardi and Giuffrida, 2006; Proietti et al., 2008; Ruiz et al., 1997). In this study, fruit yields were similar for self-grafted (FL/FL) and non-grafted (FL) plants under the recommended irrigation regime and N rate (data not shown), thus reinforcing the suggestion that yield increase could be attributed mainly to the specific rootstocks used rather than the grafting process per se. Lykas et al. (2008) reported an increase of tomato yield resulting from self-grafting in a greenhouse hydroponic study. However, it was unclear how consistent the self-grafting effect was because their study was not repeated in a second season. Nevertheless, it has been suggested that the growth and yield enhancement in grafted vegetable plants are largely contributed by the use of selected rootstocks rather than the grafting process per se (Davis et al., 2008; Lee and Oda, 2003; Lee et al., 2010).

In general, data here showed that increases in both fruit number per plant and average fruit weight contributed to the overall improvement of marketable fruit yield from grafted plants. These results concur with some previous reports (Lee and Oda, 2003; Passam et al., 2005), but Di Gioia et al. (2010) did not observe a significant change in yield components as a result of grafting. In our study, the cull fruit yield (small, immature, and/or damaged fruit) did not differ significantly between grafted and non-grafted tomato plants (data not shown). However, the percentage of cull fruit out of the total harvest was reduced in grafting treatments by 28% on average relative

to the non-grafted plants. Underlying mechanisms inherent to growth vigor and yield enhancement by grafted plants are often attributed to enhanced nutrient and water uptake (Rouphael et al., 2008; Ruiz et al., 1997) and improved endogenous hormone status (Aloni et al., 2010; Lee et al., 2010).

Seasonal variation of the irrigation and N rate effects. Under the two irrigation regimes tested in this study, increasing N rate significantly increased fruit yields of both grafted and non-grafted tomato plants to a maximum amount, which then did not show any significant increase with higher levels of N application. These results were consistent with previous studies by Hebbar et al. (2004), Scholberg et al. (2000), and Topcu et al. (2007) using tomatoes grown under diverse environmental conditions. The influence of irrigation regime and N rate on total and marketable yields varied between 2010 and 2011 seasons. In 2010, the 50% irrigation regime led to significantly higher fruit yields as compared with the 100% irrigation regime. In contrast, in 2011, yields under the 100% irrigation tended to be higher than those with the 50% irrigation at N rates above 224 kg·ha⁻¹. The inconsistent results over these two seasons could be largely related to the variation of environmental conditions, especially the rainfall. The 2010 growing season had a higher level of rainfall than 2011, particularly during the plant reproductive stage. This period corresponded to the prime period of fruit development during which the nutrients applied through fertigation accounted for ≈60% of the total nutrient supply after transplanting. Florida's sandy soils are characterized by poor water holding capacity and are more prone to nitrate (NO₃⁻) leaching (Simonne et al., 2004, 2006). With the heavier rainfall in 2010, NO₃⁻ leaching problem in sandy soils at the experimental site could have been worse and therefore reduced N uptake by plants. A study by Zotarelli et al. (2009a) in Citra, FL, reported similar interannual differences in tomato yields when rainfall was greater along with higher temperatures in the middle of the growing season. Improving irrigation scheduling based on soil moisture

sensors and crop needs will help reduce nitrate leaching in field tomato production in sandy soils (Simonne et al., 2010; Zotarelli et al., 2009b). In this study, significant yield improvement was generally not observed with N rates above 168 kg·ha⁻¹. This is in line with results reported by Zotarelli et al. (2009a) who in a three-year study did not find any significant difference in fruit yields of the same tomato cultivar Florida 47 in north Florida in response to three N rates (176, 220, and 330 kg·ha⁻¹). With the same tomato cultivar (non-grafted) and experimental site as our study, Poh et al. (2011) observed a difference in yields as a result of interannual environmental disparities. In one season, these authors obtained fruit yields of 44, 43, and 49 Mg·ha⁻¹ at 134, 179, and 224 kg N/ha, respectively, with a significant difference between the highest N rate and the other two lower N rates, whereas such a trend was not found in the other season. In another field study in central Florida on the specialty tomato cultivar Tasti-Lee, a significantly higher total marketable yield was found at 307 kg N/ha as compared with those at 229 and 268 kg N/ha over two seasons (Santos et al., 2010).

Grafting influence on irrigation water and nitrogen use efficiency. Regardless of the irrigation levels, 'Florida 47' grafted onto the two rootstocks was more efficient in water use for fruit production compared with the non-grafted plants. These results concur with previous reports on rootstock effects on the iWUE relative to marketable fruit yield. According to Lykas et al. (2008), grafting with 'He-mans' rootstock improved WUE (measured as amount of harvested fruit per volume of transpired water) of greenhouse-grown 'Big Red' tomato by ≈112%, although self-grafted 'Big Red' also exhibited a similar increase. Improvement of WUE was also observed by Rouphael et al. (2008) on mini-watermelon under field conditions. The enhanced WUE found in grafted plants in these studies was mainly the result of the improvement of fruit yields rather than reduced water use. In both 2010 and 2011 trials, the 100% irrigation regime resulted in a decrease in iWUE as opposed to the 50% irrigation regime despite the use of grafting with rootstocks. This indicates that the full irrigation regime probably caused an excess in water supply, which did not favor fruit yield development. Similar findings were reported previously by Rouphael et al. (2008) on mini-watermelon, Cabello et al. (2009) on melon, and Kirnak et al. (2002) on eggplant. The enhancement in WUE in reduced irrigation regimes is often attributed to various adaptive physiological mechanisms, which involve changes in water relations and gas exchange (Bloch et al., 2006; Rajabi et al., 2009). It is suggested that under drought stress, water loss associated with plant carbon fixation can be reduced (Bloch et al., 2006). Increase in WUE of plants under reduced water supply may also be related to certain morphological changes in plants such as deeper root systems and canopy modification (Zhang et al., 1998).

In addition to improved iWUE, grafting with appropriate rootstocks may also induce greater diversity in terms of NUE as compared with non-grafted plants. Our data showed that when averaged over irrigation regimes and N rates, grafted plants were more N use efficient in marketable fruit production by $\approx 35\%$ and 42% compared with non-grafted plants in 2010 and 2011, respectively. An increase of NUE relative to yield by 12% in grafted melon was reported by Colla et al. (2010) in comparison with non-grafted plants. In another study on mini-watermelon, Colla et al. (2011) observed a 38% increase in NUE of grafted plants in contrast to non-grafted plants. Similar to the improvement of iWUE, higher NUE observed with grafted plants in this study was associated with greater yields in grafted plants than non-grafted plants. Although grafting, irrigation regime, and N rate showed relatively consistent effects on iWUE between 2010 and 2011, their influence on NUE varied with the production season. The significant interaction effect of irrigation regime and N application on NUE in 2011 suggested differential effects of N rates under different irrigation regimes. Except for the lowest N rate, increasing N rates under both irrigation regimes resulted in reduced efficiency of N use for yield production. Only one tomato scion cultivar was used in this study. Future research will need to involve more scions and rootstocks to identify the scion-rootstock interactions and specific traits of rootstocks in relation to the improvement of iWUE and NUE in grafted tomato plants.

Conclusions

This study demonstrated that use of grafted plants could significantly improve fruit yields in field production of drip-irrigated tomato in sandy soils in Florida. The increase of marketable yields resulted from both more fruit per plant and higher average fruit weight. Grafting with the two interspecific tomato hybrid rootstocks used here also led to significant enhancement in efficiency of water and N use. Overall, the two rootstocks performed similarly. Moreover, variation in environmental conditions, particularly rainfall, contributed greatly to the influence of irrigation and N application on fruit yields. Future studies are warranted to explore the N requirement for grafted tomato production under field conditions, because data here indicate that these needs are likely to differ from those of non-grafted tomatoes.

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