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Preplant Sulfur Fertilization Rates and Irrigation Programs on Tomato Growth and Yield

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SUMMARY. A renewed interest in sulfur (S) deficiency has occurred because of reductions in atmospheric depositions of S caused by implementation of clean air regulations around the world. In vegetable production systems, other sources of S exist, such as soil S, fertilizers, and irrigation water. While soil testing and fertilizer labels impart information on quantity of S, it is unknown how much S within the irrigation water contributes to the total crop requirement. Two studies were conducted to determine the influence of elemental S fertilization rates and irrigation programs on tomato (*Solanum lycopersicum*) growth and yield. Irrigation volumes were 3528, 5292, and 7056 gal/acre per day and preplant S rates were 0, 25, 50, 100, 150, and 200 lb/acre. Data showed that neither plant height, leaf greenness, soil pH nor total soil S content was consistently affected by preplant S rates. During both seasons, early marketable fruit weight increased sharply when plots were treated with at least 25 lb/acre of preplant S in comparison with the nontreated control. Early fruit weight of extralarge and all marketable grades increased by 1.5 and 1.7 tons/acre, respectively, with the application of 25 lb/acre of S. There were no early fruit weight differences, regardless of marketable fruit grade, among preplant S rates from 25 to 200 lb/acre. Based upon this result, adding preplant S to the fertilization programs in sandy soils improves tomato yield and fall within the current recommended application range of S (30 lb/acre) for vegetables in Florida. At the same time, irrigation volumes did not consistently influence soil S concentration, soil pH, leaf S concentrations or tomato yield, which suggested that irrigation water with levels of S similar to this location [58 mg·L⁻¹ of sulfate (SO₄) or 19 mg·L⁻¹ of S] may not meet tomato S requirement during a short cropping seasons of 12 weeks, possibly because microbes need longer periods of time to oxidize the current S species in the water to the absorbed SO₄ form.

Crops obtain required S from diverse sources including soil, crop residues, manures, irrigation water, rainfall, atmosphere, and soil amendments and fertilizers (Tabatabai, 1984). In the past, the primary sources of S for crops were from atmospheric deposition, soil, and fertilizers. A reduction of atmospheric

S deposition in conjunction with increased use of high-analysis fertilizer has caused S deficiencies to become more common in crops (Ceccotti et al., 1998; Scherer, 2001). Other than fertilizer sources, soil and water could act as primary S sources for crop production. It is unclear if either one can meet crop requirements for S.

At the plant level, S is indirectly involved in photosynthesis and chlorophyll production (Ahmad and Abdin, 2000), which may be perceived as an increase in greenness in a crop plant. Similarly, improvement in vegetable crop yield and growth occurs when S was included in the fertilizer regime. In potato (*Solanum tuberosum*), Pavlista (2005) found that an application of 28 kg·ha⁻¹ S improved tuber quality and yield compared with no added S. Rhoads and Olson (2000) found highest yields for cabbage (*Brassica oleracea* var. *capitata*) were consistently produced with 22 kg·ha⁻¹ S. Similarly, Susila (2001) found that tomato and cabbage both responded to the addition of S to the fertilizer regime with rates ranging from 0 to 102 kg·ha⁻¹ S. This response occurred regardless of S source and application method (preplant, drip injection, or a combination of both). Both Rhoads and Olson (2000) and Susila (2001) found S sources to be similar and yields were improved across all the studies with S applications within the recommended range for Florida [30 to 40 lb/acre S (Simonne and Hochmuth, 2009)]. None of these studies considered irrigation water SO₄ concentrations as an S source for crop production.

Tomato production in Florida often occurs on deep Spodosols (fine sandy soils) with low organic matter (<2%), which are inherently low in both organic and inorganic S. Previous studies on tomato have found that some S sources such as ammonium sulfate [(NH₄)₂SO₄], ammonium thiosulfate (NH₄S₂O₃), ammonium nitrate [(NH₄NO₃) + (NH₄)₂SO₄], and potassium sulfate (K₂SO₄) affected tomato yields similarly (Santos et al., 2007; Susila, 2001). Elemental S is a less expensive S fertilizer source when compared with other S sources that contain nitrogen (N). Elemental S can be an ideal S source for crop growth and yield because it is high in S analysis, insoluble in water, stable in damp and humid conditions, and has to be oxidized to SO₄-S for plant

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uptake (Solberg et al., 2003). During the process of elemental S fertilizer oxidation by soil microbes, soil pH is lowered. The rate of elemental S oxidation by soil microbes is dependent upon several factors such as carbon substrate, N source, soil temperature, and moisture.

The concentration of S in the irrigation water used throughout North America varies widely. Little research is available about the relationship between S content of irrigation water and S requirement in a fertilization program (Olson and Rehm, 1986). Field sites without mineral-bound S sources may have insufficient S dissolved in soil water to move available S to plant roots (Eriksen et al., 1998). Studies on high SO_4 irrigation water used water with 175, 646, 862, and 1743 $\text{mg}\cdot\text{L}^{-1}$ SO_4 (Drost et al., 1997) and 15.0 and 38.8 $\text{mol}\cdot\text{L}^{-1}$ SO_4 (Papadopoulos, 1986) have found mixed results in improving yield of broccoli (*B. oleracea* var. *italica*) and tomato. In Florida, S concentrations in drinking water wells can range from 0.07 to 460 $\text{mg}\cdot\text{L}^{-1}$ S (in the form of SO_4) with higher concentrations coming from deeper wells (Sacks, 1996). Although these values cover drinking water, the concentration of S within irrigation water drawn from deep wells in Florida is unknown. It has been suggested that water pumped from the Florida aquifer and surface waters may contain appreciable amounts of S for crop production because of the S-like smell commonly associated with hydrogen sulfide volatilization. This often leads to the belief that S in the irrigation water is an S source for crop production (Hochmuth and Hanlon, 2000). Since S concentrations in irrigation water vary widely and current fertilizer practices use high-analysis fertilizer that often lacks S, the objectives of this study were to 1) investigate the effect of S fertilization rates on tomato growth and yield and 2) assess whether irrigation water could provide the necessary S for tomato production.

Materials and methods

Two field studies were conducted at the Gulf Coast Research and Education Center (GCREC) in Wimauma, FL, during Spring (March to July) and Fall (August to December) 2008. The soil at the experiment site was Myakka fine sand (sandy siliceous

hyperthermic Aeric Alaquods) with a pH of 6.6 and 1.3% organic matter. The total S content (both available and unavailable S) of the soil was 23.5 lb/acre S. Irrigation water from deep wells at GCREC had a pH of 7.8 and S concentrations were 19 $\text{mg}\cdot\text{L}^{-1}$. A standard bedder was used to create raised beds that were 5 ft apart at the center, 8 inches high, 28 inches wide across the top, and 32 inches wide at base. Raised beds were fumigated with 50:50 (v/v) methyl bromide and chloropicrin mixture at 170 lb/acre to eliminate weeds, nematodes, and soil pathogens on 14 Feb. and 5 Aug. 2008. Following soil fumigation, two drip tapes (0.45 gal/min per 100 ft of bed; T-Systems International, San Diego, CA) were buried 1 inch deep for irrigation and raised beds were covered with metalized polyethylene mulch (Intergro, Clearwater, FL). 'Tygress' tomato seedlings at the four true-leaf stage were transplanted in a single row with 2-ft spacing between plants on 6 Mar. and 28 Aug. 2008. Tomato plants were staked and tied as described by Csizinszky et al. (2005). All other crop management was conducted according to current recommendations for tomato (Olson et al., 2011).

Treatments were arranged in a split-plot design with six replications, in which the main plots were drip irrigation volumes (3528, 5292, and 7056 gal/acre per day) and the subplots were preplant S rates (0, 25, 50, 100, 150, and 200 lb/acre). Irrigation volumes were based upon the historical Penman method for calculating potential evapotranspiration for west-central Florida (Simonne et al., 2009). Irrigation volumes were adjusted by changing the duration of drip irrigation events: 3528 gal/acre per day was split in three irrigation events of 20 min each, 5292 gal/acre per day

was applied in three irrigation cycles of 30 min each, and 7056 gal/acre per day was applied in three irrigations of 40 min in duration. These irrigation volumes started between 7 and 10 d after transplanting and were maintained until 12 weeks after transplanting (WAT).

Preplant S rates were applied as two 2-inch deep bands of elemental S [90% S, prills 2.6 mm diameter (Tiger 90 CR; Tiger-Sul, Calgary, AB, Canada)] located 12 inches apart on top of raised beds before soil fumigation and plastic mulch application. N was applied twice weekly using the recommended rates based upon growth stage as described by Olson et al. (2011). The liquid fertilizer contained no additional S and N. Applied phosphorus (P) and potassium (K) were derived from a mix of calcium nitrate, urea ammonium nitrate, phosphoric acid, and potassium nitrate. An N rate of 200 lb/acre using 6N-0.8P-6.6K liquid fertilizer was delivered using a standard fertilizer injector (Dosatron, Clearwater, FL). All other nutrients were applied based upon tomato production recommendations and interpretation of preseason soil test results (Olson et al., 2011; Simonne and Hochmuth, 2009).

Soil samples were collected for total soil S at 5 WAT in Spring 2008 and at 4 WAT in Fall 2008. Ten soil cores, which constituted a soil sample, were taken from between tomato plants on the center of raised beds to a depth of 6 inches. Soil samples were air dried and then held at 4.4 °C until shipment to the laboratory for analysis. Dried 1-lb soil samples were submitted to a commercial analytical laboratory for soil pH and S concentration (Waters Agricultural Laboratory, Camilla, GA), which was determined by turbidimetry, as described by the American Society for Testing and

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
28.3495	oz	g	0.0353
1	ppm	mg·L ⁻¹	1
2.2417	ton/acre	Mg·ha ⁻¹	0.4461
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

Materials (2006) and the Association of Official Analytical Chemists (2000). Plant tissue samples for S leaf concentrations were collected at 5 WAT in Spring 2008 and at 4 WAT in Fall 2008. Ten most recently matured tomato leaves adjacent to an inflorescence were selected for tissue samples as suggested by Mills and Jones (1996). Dried and ground tissue samples were held at 0 °C until shipment to the laboratory for analysis. A 2-g subsample of each sample was submitted to a commercial laboratory (Waters Agricultural Laboratory) for total S determination by inductively coupled plasma-optical emission spectrophotometry.

Leaf greenness was collected as an indicator of chlorophyll using a colorimeter (SPAD-502; Konica Minolta Sensing, Osaka, Japan) at 6 and 11 WAT in Spring 2008 and at 7 and 11 WAT in Fall 2008. Ten randomly selected recently matured leaves adjacent to an inflorescence were used for leaf greenness assessment. The SPAD-502 colorimeter measures absorption in the red (650 nm) and near-infrared (940 nm) regions of the spectrum (Ling et al., 2011). The meter uses these two values to calculate a numerical SPAD value, which is proportional to the amount of chlorophyll (Blunden et al., 1997). Typical SPAD values are between 0 and 50 with a range of 0 to 80, with 0 = white and 80 = dark green (Ling et al., 2011; Santos, 2010). Plant height was collected at 5 and 13 WAT in Spring 2008, whereas in Fall 2008, plant height was collected at 5 WAT.

Following local practices, tomato fruit were harvested twice during 12 and 13 WAT in Spring 2008 and 11 and 14 WAT in Fall 2008, and they were graded according to the current standards for size categories (Brown, 2011). Sizes were extralarge (2–25/32 inches in diameter), large (2–29/32 to 2–17/32 inches), medium (2–19/32 to 1–9/32 inches), and cull (<2–5/16 inches). Marketable tomato fruit weight was calculated as the sum of medium, large, and extralarge yield for both harvests, while early tomato fruit weight included only the first harvest of each season. All collected measurements were subjected to an analysis of variance to determine single-factor and interactions significance ($P < 0.05$) using a general linear model, as well as the effects of linear contrasts through regression analysis

(SAS version 9.2; SAS Institute, Cary, NC).

Results and discussion

There were significant season by treatment interactions for most of the variables under study with the exception of early and total fruit weight. Therefore, most data were analyzed separately. The irrigation volume by

elemental S rate interaction was not significant for any of the variables during both seasons. Plant height was not influenced by either factor or their interaction (data not presented). Leaf greenness was marginally influenced by either factor, and it changed only late into both seasons (11 WAT) when most fruit are during the fast-filling and maturing stage. During late Spring

Table 1. Effects of irrigation volume and preplant sulfur (S) rates on tomato leaf greenness at Wimauma, FL, in Spring and Fall 2008.

Irrigation volume (gal/acre per day) ^z	Leaf greenness			
	Spring 2008		Fall 2008	
	6 WAT ^y	11 WAT	7 WAT	11 WAT
	[SPAD value (0–80 scale)] ^x			
3528	48	48	45	48
5292	47	44	44	43
7056	46	43	44	44
$P < 0.05$	NS	*	NS	NS
Linear contrasts (irrigation volume)	NS	*	NS	NS
Preplant S rates (lb/acre)^z				
0	48	45	46	45
25	48	46	45	48
50	46	44	44	45
100	48	45	42	46
150	47	47	44	44
200	47	46	46	42
$P < 0.05$	NS	NS	NS	*
Linear contrasts (preplant S rates)	NS	NS	NS	*

^z1 gal/acre = 9.3540 L·ha⁻¹, 1 lb/acre = 1.1209 kg·ha⁻¹.

^yWAT = weeks after transplanting.

^x0 = white, 80 = dark green.

NS, *Nonsignificant and significant at $P < 0.05$, respectively, according to linear regression contrasts.

Table 2. Effects of irrigation volume and preplant sulfur (S) rates on soil pH and total S content at Wimauma, FL, in Spring and Fall 2008.

Irrigation volume (gal/acre per day) ^z	Soil pH				Total soil S (lb/acre) ^z	
	Spring 2008		Fall 2008		Spring 2008	Fall 2008
	5 WAT ^y	13 WAT	4 WAT	15 WAT	5 WAT	4 WAT
3528	6.7	6.3	6.8	6.7	22.4	31.9
5292	6.6	6.3	6.7	6.7	22.8	33.1
7056	6.6	6.1	6.7	6.8	21.9	30.0
$P < 0.05$	NS	NS	NS	NS	NS	NS
Linear contrasts (irrigation)	NS	NS	NS	NS	NS	NS
Preplant S rates (lb/acre)^z						
0	6.7	6.8	6.7	6.7	20.1	29.6
25	6.6	6.6	6.7	6.8	23.0	32.1
50	6.6	6.2	6.7	6.7	20.4	29.9
100	6.6	6.2	6.7	6.8	20.3	31.0
150	6.6	6.0	6.8	6.8	24.3	31.4
200	6.6	5.8	6.8	6.8	26.3	34.8
$P < 0.05$	NS	*	NS	NS	NS	NS
Linear contrasts (preplant S rates)	NS	*	NS	NS	NS	NS

^z1 gal/acre = 9.3540 L·ha⁻¹, 1 lb/acre = 1.1209 kg·ha⁻¹.

^yWAT = weeks after transplanting.

NS, *Nonsignificant and significant at $P < 0.05$, respectively, according to linear regression contrasts.

2008, leaf greenness declined with increased irrigation volumes, while in Fall 2008, the same occurred only when preplant S rates incremented (Table 1). These results are somewhat similar to those shown by Barbieri et al. (2009) in which S nutrition did not have an effect on leaf greenness of turnip (*Brassica rapa*).

The vast majority of total soil S measurements and soil pH were not influenced by either irrigation volumes or applied preplant S rates during both seasons (Table 2). However, preplant S rates affected the end-of-season pH values in Spring 2008, decreasing linearly as preplant S rates increased, which is expected from the application of elemental S in the soil. The fact that the nontreated control plots (0 lb/acre of S) had the same total soil S than the other S-treated plots at 4 or 5 WAT confirmed that this measurement is not an appropriate indicator of available S in the soil. Seasonal temperature differences between cropping seasons may have played a significant role in soil pH differences. For instance, spring tomato production season in Florida tends to start cool in late February and early March (minimum 38 °F, maximum 86 °F) and end hot in June (minimum 66 °F, maximum 97 °F), whereas fall tomato production season between August and December is the reverse. Solberg et al. (2003) suggested that elemental S fertilizers require oxidation time to become plant-available $\text{SO}_4\text{-S}$, which may help explain the lack of differences in applied elemental S. The oxidation of the applied preplant S rates might need longer than 12 weeks, which is the average tomato production season in Florida, to become fully oxidized by soil microbes in Florida sandy soils.

Irrigation volumes influenced S leaf concentrations in Fall 2008, but not in the previous season (Table 3). Foliar S values ranged between 0.55% and 0.66% S, which are within the sufficiency levels for tomato (Olson et al., 2011; Susila, 2001). One possible explanation for the lack of significance of S rates at 4 and 5 WAT on leaf S concentration could be that the measurements were taken too early into the seasons and the beneficial effect of the nutrient is slowly accumulated over time in the plant. Early yield of extralarge and marketable

fruit were influenced by preplant S rates each season in the combined analysis of both seasons (Fig. 1). However, there was no significant effect of the factor and their interactions on the total fruit weight (extralarge and all marketable categories) during both combined seasons (Table 3),

averaging between 13.6 and 15.2 tons/acre across preplant S rates, which is within the range of yield produced by Florida growers. During both seasons, early marketable fruit weight increased sharply when plots were treated with at least 25 lb/acre of preplant S in comparison with the

Table 3. Effects of irrigation volume and preplant sulfur (S) rates on S concentration in tomato leaves and total fruit weight at Wimauma, FL, in Spring and Fall 2008.

Irrigation volume (gal/acre per day) ^z	S leaf concn (%)		Total fruit wt (tons/acre) ^z	
	Spring 2008	Fall 2008	Spring and Fall 2008	
	5 WAT ^y	4 WAT	Extralarge	Marketable
3528	0.55	0.61	9.9	15.5
5292	0.57	0.66	9.1	14.5
7056	0.57	0.59	8.7	14.0
$P < 0.05$	NS	*	NS	NS
Linear contrast (irrigation)	NS	*	NS	NS
Preplant S rates (lb/acre)^z				
0	0.55	0.64	8.3	13.6
25	0.56	0.60	9.2	14.4
50	0.56	0.61	9.6	14.9
100	0.57	0.63	9.6	15.2
150	0.56	0.63	9.7	15.0
200	0.57	0.62	9.2	15.0
$P < 0.05$	NS	NS	NS	NS
Linear contrasts (preplant S rates)	NS	NS	NS	NS

^z1 gal/acre = 9.3540 L·ha⁻¹, 1 lb/acre = 1.1209 kg·ha⁻¹, 1 ton/acre = 0.4461 Mg·ha⁻¹.

^yWAT = weeks after transplanting.

NS, *Nonsignificant and significant at $P < 0.05$, respectively, according to linear regression contrasts.

Fig. 1. Effects of preplant sulfur (S) rates on early tomato marketable fruit weight of extralarge and all marketable grades. Treatment mean values separated with SE bars; 1 lb/acre = 1.1209 kg·ha⁻¹, 1 ton/acre = 2.2417 Mg·ha⁻¹.

nontreated control. Early fruit weight of extralarge and all marketable grades increased by 1.5 and 1.7 tons/acre, respectively, with the application of 25 lb/acre of S (Fig. 1). There were no early fruit weight differences, regardless of marketable fruit grade, among preplant S rates from 25 to 200 lb/acre. Based upon this result, adding preplant S to the fertilization programs in sandy soils improves tomato yield and fall within the current recommended application range of S (30 lb/acre) for vegetables in Florida (Simonne et al., 2009). These results agree with those presented by Susila (2001), who showed that S fertilization could increase tomato yields. At the same time, irrigation volumes did not consistently influence soil S concentration, soil pH, leaf S concentrations, or tomato yield, which suggested that irrigation water with concentrations of S similar to this location (58 mg·L⁻¹ of SO₄ or 19 mg·L⁻¹ of S) may not meet tomato S requirement during a short cropping seasons of 12 weeks, especially after soil fumigation that might have reduced the microbial conversion rate. It is possible that the form of S present within the irrigation water in Florida needs to be oxidized by microbes to form SO₄, which is the S form absorbed by most crops. While tomato leaf S concentrations stayed within the recommended ranges for S, early yield was increased with the addition of elemental S to the fertilizer regime. Based upon these results, the current recommended rate of 30 lb/acre of S should be incorporated into the fertilizer regime to maximize early yield of fresh market tomato.

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