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Plastic-mulched Bell Pepper (*Capsicum annuum* L.) Plant Growth and Fruit Yield and Quality as Influenced by Irrigation Rate and Calcium Fertilization

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***Abstract*. Bell pepper (*Capsicum annuum* L.) plants have a high demand for water and nutrients. Water stress on bell pepper is associated with reduced yields and incidence of blossom-end rot (BER). High irrigation rates are commonly applied to maximize yields. Excessive irrigation rates, however, may negatively affect bell pepper plants. The objective of this study was to evaluate the effects of irrigation rates and calcium fertilization on plant growth and fruit yield and quality. Trials were conducted in the spring of 2001, 2003, and 2005 at the University of Georgia, Tifton Campus. Drip-irrigated bell pepper (‘Camelot’ or ‘Stiletto’) plants were grown on black plastic mulch. Plants were irrigated with rates that ranged from 33% to 167% of the rate of crop evapotranspiration (ETc). Results showed that irrigation at 70% ETc (2001), 67% ETc (2003), and 50% ETc (2003) were sufficient to maximize vegetative growth and fruit yield and provided yields similar to those at 100% ETc. Leaf net photosynthesis and stomatal conductance (g_S) were reduced, and incidence of BER was increased with reduced irrigation rates (33% and 67% ETc). Incidences of soilborne diseases (*Pythium* spp. and *Phytophtora capsici*) tended to increase in plants receiving excessive irrigation rates (167% ETc). Irrigation rate also affected fruit quality; incidence of BER and fruit soluble solids were both increased at 33% ETc. Calcium fertilization had no effect on soil water content (SWC), plant growth, and incidence of soilborne diseases, and an inconsistent effect on fruit yield and incidence of BER. In conclusion, there is potential for use of irrigation at rates below 100% ETc. Reduced irrigation diminished the volumes of water applied and provided fruit yields similar to those at 100% ETc. Excessive irrigation rates (167% ETc or above) wasted water and resulted in both higher incidences of soilborne diseases and reduced bell pepper yields.**

Use of drip irrigation and plastic film mulch has been associated with increases in yield and quality of bell pepper and other vegetables (Lamont, 1993). Adequate irrigation management is necessary to maximize fruit yield and increase the efficiency in the use of water and nutrients in vegetable crops (Simonne et al., 2010). Bell pepper (*Capsicum annuum* L.) is an important vegetable crop in the state of Georgia, with a farm gate value of $122 million on 2078 ha in 2014 (Wolfe and Stubbs, 2015). Bell pepper plants have a high demand for water and nutrients and are particularly sensitive to water stress during plant establishment and fruit set (Delfine et al., 2001; Wien, 1997). Under high evaporative demand, sprinkler-irrigated bell pepper grown on bare sandy soil in Georgia had higher fruit yields when irrigated at a soil tension of 25 than at 50 or 75 kPa (Batal and Smittle, 1981; Smittle et al., 1994). In Turkey, drip-irrigated bell pepper on bare silty-clay-loam soil had the highest fruit yield and fruit quality when irrigated most frequently [at the lowest value of cumulative pan demand (18–22 mm; every 3–6 d)] and at the highest irrigation rate (pan coefficient = 1.0) (Sezen et al., 2006).

Calcium is transported from the soil to the fruit through the xylem and thus it may be affected by irrigation (Hawkesford et al., 2012; Taylor and Locascio, 2004). High-temperature and high-light conditions and plant drought stress are associated with the occurrence of physiological fruit disorders such as BER (Olle and Bender, 2009). In peppers and tomatoes, BER is caused by a local calcium deficiency during early stages of fruit development (Marcelis and Ho, 1999; Taylor and Locascio, 2004). Under high-temperature conditions, plants may be exposed to periods of drought stress (due to excessive transpiration) that result from insufficient water uptake from the soil, even under high irrigation rates (Agele et al., 2006; Jaimez et al., 1999). The interactions of irrigation rate, calcium fertilization, and the incidence of BER, however, are still not fully understood.

Soils in the Coastal Plain, where most Georgia bell peppers are grown, have low water-holding capacity (Smittle et al., 1994). Excessive irrigation rates (above the rate of ETc) are often applied to maintain high soil moisture to maximize yields. Because of the low cost of water in vegetable crop production in Georgia, there is little incentive for growers to risk fruit yield and quality by withholding water. The effect of excessive irrigation is often assumed to be beneficial or neutral to the crop. Excessive irrigation not only wastes water but may also result in reduced yields in bell pepper (Sezen et al., 2006; Simonne, 2000) and tomato (Locascio et al., 1989; Ngouajio et al., 2007) and enhances nitrate leaching of vegetable crops (Díaz-Pérez and Eaton, 2015; Simonne et al., 2010). The objectives of these studies were to evaluate the effects of drip-irrigation rates (from deficit to excess) and calcium fertilization on plant growth, fruit yield, and fruit quality.

Material and Methods

Study site. Experiments were conducted at the Horticulture Farm, University of Georgia, Tifton, GA. The farm is located at an altitude of 108 m above mean sea level, 31°28′ N latitude and 83°31′ W longitude. The soil is a Tifton sandy loam (a fine loamy, siliceous thermic Plinthic Paleudults) with a pH of 6.0–6.5. Soil analysis by the Soil, Plant, and Water Laboratory (University of Georgia, Athens, GA) showed 112, 132, 739, 114 kg·ha^{-1} for P, K, Ca, and Mg, respectively, and a soil water pH of 6.6. Soil water-holding capacity is 18–36 mm in the top 30 cm of soil profile (Calhoun, 1983).

Land preparation and planting. Before laying plastic mulch, the soil was fertilized with N, P, and K at 60, 26, and 50 kg·ha^{-1}, respectively, using 10–10–10 granular fertilizer. At the same time, plastic film [black, low-density polyethylene, with a slick surface texture, 1.52-m wide, and 25-μm thick (RepelGro; ReflecTek Foils, Inc., Lake Zurich, IL)] was laid with a mulch-laying machine; drip-irrigation tape [20-cm emitter spacing and

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a 0.5 L·h^{-1} emitter flow (Ro-Drip; Roberts Irrigation Products, Inc., San Marcos, CA)] was placed 5-cm deep in the center of the bed.

Bell pepper transplants ['Camelot' (Seminis, Oxnard, CA) in 2001 and 'Stiletto' (Syngenta, Boise, ID) in 2003 and 2005] were produced in a greenhouse using a peat-based medium (Pro-Mix, Quakertown, PA) and polystyrene 200-cell (2.5 × 2.5-cm cell) trays. Six-week-old bell pepper transplants were planted with a mechanical transplanter in the spring (4 Apr. 2001, 7 Apr. 2003, and 18 Apr. 2005) on beds formed on 1.8-m centers, with two rows per bed and 30-cm spacing between plants. Starting 2 weeks after transplanting, plants were fertilized weekly for 11 weeks. Total major nutrients applied were 250 kg·ha^{-1} N, 111 kg·ha^{-1} P, and 243 kg·ha^{-1} K.

Experimental design and treatments. In 2001, the design was a split plot with four replications. Main plots were irrigation rates (70%, 100%, or 130% ETc), and subplots were Ca rates (0 or 200 kg·ha^{-1} Ca). Each plot was a 9.1-m-long bed section. In 2003, the design was a Latin square with five replications and five treatments [irrigation rates (33%, 67%, 100%, 133%, or 167% ETc)]. Each plot was a 7.6-m-long bed section. In 2005, the design was a randomized complete block with four replications and nine treatments [combination of three irrigation rates (50%, 100%, or 150% ETc) and three calcium fertilizer treatments [gypsum (25% Ca and 20% S), Thiocal (calcium thiosulfate, 6% Ca and 19% S; BSP, Fresno, CA), and a nonfertilized control]. Gypsum was applied before planting (7 Mar. 2005) at 2.24 t·ha^{-1} (i.e., 560 kg·ha^{-1} Ca). Thiocal was applied weekly starting 2 weeks after transplanting. At each application, each plant received 120 mL of a Thiocal solution (10.9 mL Thiocal per liter of water), applied at the base of the plant; equivalent to 47 L·ha^{-1} per week, the commercial rate. Plants received a total of 35 kg·ha^{-1} Ca from Thiocal during the entire season. Before the application of Ca treatments into the field, the concentrations of P (mean = 273 kg·ha^{-1}), K (mean = 183 kg·ha^{-1}), Ca (mean = 806 kg·ha^{-1}), Mg (mean = 120 kg·ha^{-1}), Mn (mean = 29 kg·ha^{-1}), and Zn (mean = 9.5 kg·ha^{-1}) were similar among the plots. Each plot was a 7.6-m-long bed section. In all years, there were 1.5-m-long unplanted borders between plots.

Irrigation. The ETc was calculated by multiplying the reference evapotranspiration (ETo) by a crop coefficient (*Kc*), which is dependent on the crop stage of development. The *Kc* values used in this study were 0.25 (week 1), 0.4 (week 2), 0.55 (week 3), 0.70 (week 4), 0.85 (week 5), and 1.0 (week 6 and after). Values of Kc were estimated based on crop canopy cover and were similar to those reported for plastic-mulched bell pepper in Florida (Simonne et al., 2006). All treatments received equal volumes of irrigation water (100% ETc, ≈1–2 times a week, 11 L per meter-bed) during the first 4 weeks after transplanting (crop establishment period).

Irrigation treatments were initiated on week 5. Water was applied when cumulative ETc was ≈13 mm, which corresponded to about every 2 to 3 d (mean ETo was 5 to 6 mm·d^{-1}). Amount of water per irrigation event was 13 mm at 100% ETc. Because bell pepper in this study was grown in light soil on raised beds covered with plastic mulch, with poor lateral water movement, the contribution of rainfall to crop soil moisture was considered to be negligible (Dukes et al., 2010; Simonne et al., 2006).

Soil water content. In 2003, volumetric SWC in the 0–30 cm of soil profile was monitored periodically (every 10 min) with time domain reflectometry (TDR) sensors (two per treatment; CS-610; Campbell Scientific, Logan, UT) connected to a datalogger (CR-10X; Campbell Scientific). The moisture sensors had three metallic 30-cm rods and were inserted vertically within the row between two plants. In 2005, volumetric SWC in the 0–12 cm of soil profile over the season was measured manually every 2–3 d (three readings per experimental plot) with a portable TDR sensor (CS-620; Campbell Scientific). The two metallic 12-cm rods of the TDR sensor were inserted vertically within the row between two plants.

Plant growth. In 2003, plant height and stem diameter were measured on five plants per plot 6 weeks after transplanting. Vegetative top fresh weight (FW) was measured on five plants per plot after the last harvest (10 July). In 2005, two randomly selected plants

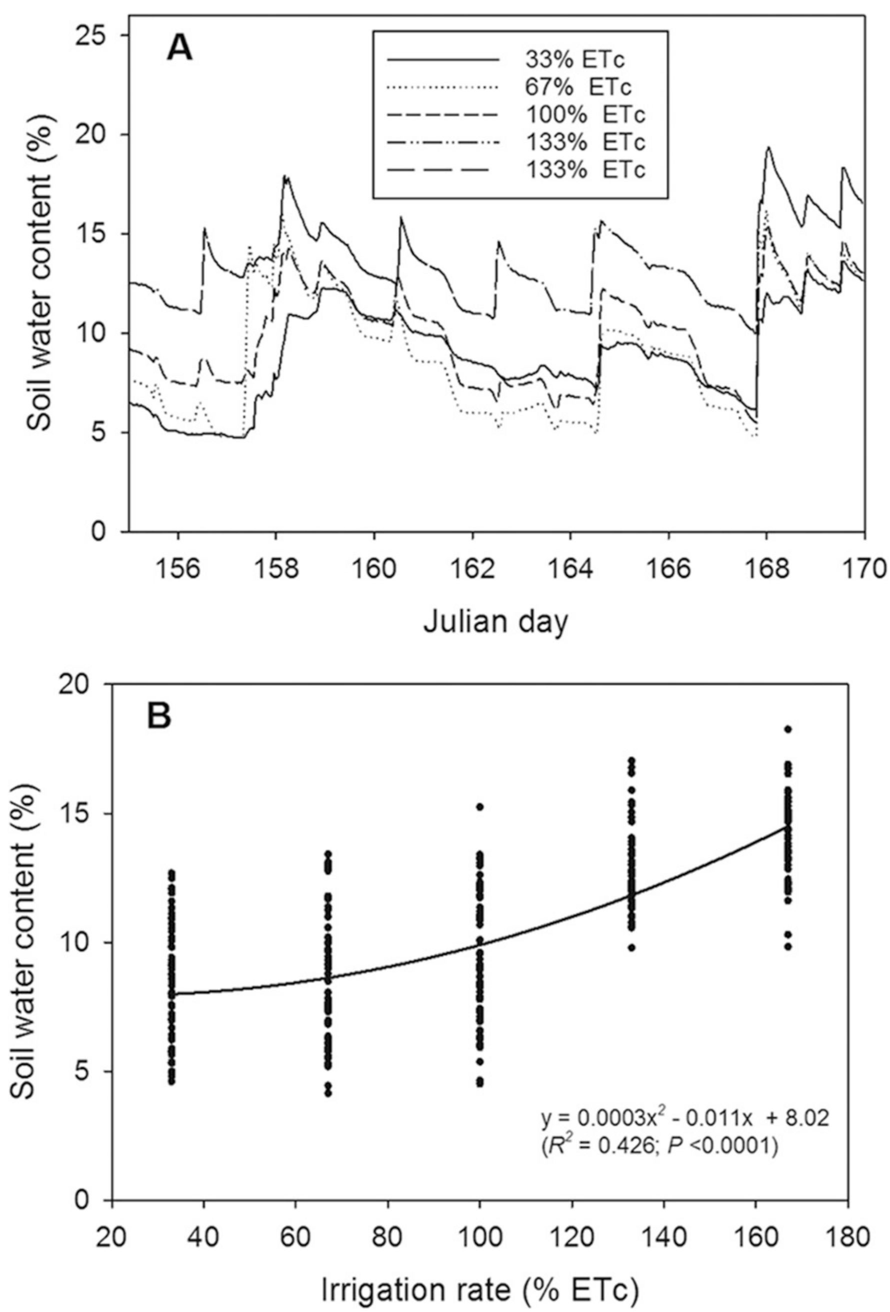

Fig. 1. (**A**) Volumetric soil water content (SWC) during a 15-d period. Each point is the average of two sensors. (**B**) Daily average of SWC as affected by irrigation rate as a percentage of crop evapotranspiration (ETc). Tifton, GA, Spring 2003.

(top and roots) from each replication were removed from the soil (21 July). Plant tops and roots were dried at 70 °C and their dry weights (DWs) were determined.

Plant mineral nutrients. In 2003 and 2005, leaves were sampled three times during the growing season (4, 7, and 10 weeks after transplanting), and fruits were sampled from three different harvests. Leaf and fruit samples were dried at 70 °C for 2 d and analyzed for mineral nutrient concentrations at the University of Georgia Agricultural & Environmental Services Laboratories, Athens, GA.

Leaf chlorophyll index. Chlorophyll indices were determined on 30 June (Spring 2005) on six mature, well-exposed, and healthy leaves per plot using a chlorophyll meter (Chlorophyll Meter SPAD-502; Minolta Co., Ltd., Ramsey, NJ).

Leaf gas exchange and photosystem II (PSII) efficiency. Simultaneous measurements of leaf gas exchange (net photosynthesis, g_S, transpiration, and internal CO_2 concentration) were made with an IR gas analyzer (LI-COR 6400 IRGA with an integrated 6400-40 leaf chamber fluorometer; LI-COR, Inc., Lincoln, NE). PSII efficiency is the fraction of absorbed PSII photons used in photochemistry and is measured with a light-adapted leaf. Water-use efficiency (WUE) was calculated as the ratio between leaf net photosynthesis and leaf transpiration. Air flow rate was set at 300 µmol·m^{-2}·s^{-1} on the reference side. The CO_2 concentration was set at 400 µmol·mol^{-1} with a CO_2 mixer and a CO_2 tank. Measurements were conducted in developed plants on a clear day (*PAR* ≈2000 µmol·m^{-2}·s^{-1}) between 1200 and 1400 HR Eastern Standard Time on 28 May 2003 using two developed and fully exposed leaves per experimental plot.

Plant diseases. Plants were monitored weekly for the presence of tomato spotted wilt (TSW), southern blight (caused by *Sclerotium rolfsii*), and phytophthora blight (caused by *Phytophthora capsici*). Diseased plants were counted and removed from the field. Etiology of disease causal agents was confirmed at the Plant Pathology Clinic, University of Georgia, Tifton, GA.

Harvest. In 2001, mature green bell peppers were harvested on 8, 18, and 29 June. In 2003, harvests were on 10 and 25 June and 9 July. In 2005, harvests were conducted nine times, starting on 13 June and finishing on 3 Aug. Fruit were graded as marketable and unmarketable, according to the U.S. grade standards (USDA, 2005). Among unmarketable fruit, the number of fruit with BER symptoms was also determined. In all years, the harvested section consisted of 10 plants per plot.

Fruit postharvest. In 2001, fruit fluorescence was determined on 15 fruit per treatment; fruit were harvested on 29 June and stored for 11 d at 1 °C. Fluorescence was measured with a Plant Efficiency Analyser (PEA MK2; Hansatech Instruments Ltd., King's Lynn, England).

Fluorescence is an indicator of plant stress and is commonly measured as Fv/Fm, where Fv is variable fluorescence and Fm is maximum fluorescence; low Fv/Fm values indicate plant stress (Maxwell and Johnson, 2000). Fruit water loss rate (WLR), transpiration ratio (TR), firmness, fresh weight, and DW were determined on 20 marketable fruit per treatment. Fruit WLR and TR were measured gravimetrically; fruit placed on a tray, kept at 20 °C (VPD = 1.5 kPa) for 7 d, and weighed daily (Díaz-Pérez et al., 2007).

Fruit initial weights (FW_o, in grams) were used to estimate fruit surface areas (SA, in square centimeters) using a formula ($SA = -0.0026\ FW_o^2 + 1.767\ FW_o + 23.06$) previously determined. Fruit firmness was determined using a hedonic scale (1 = very soft; 5 = very firm) by holding the fruit with the hand and compressing it with the fingers. Soluble solids content (SSC) was measured (5–8 fruit per irrigation treatment) by squeezing a sap aliquot from the fruit and placing the aliquot in a refractometer.

In 2005, five fruit per plot were used to determine thickness of the fruit wall, SSC, and fruit DW. Thickness of the fruit wall (pericarp) was determined by cutting the fruit in two halves at the equatorial region and measuring the thickness of the wall at opposite sides of the fruit with a micrometer. Soluble solids content was measured from the same fruit used to measure pericarp thickness, as described earlier. After SSC measurement, fruit were dried at 70 °C for 2 d to determine DW.

Weather. Weather data (air temperature, ETo, and rainfall) were obtained from a nearby University of Georgia weather station (within 300 m).

Statistical analysis. Data were analyzed using the general linear model and regression procedures from SAS (SAS version 9.3; SAS Inst. Inc., Cary, NC). Data means were separated using Fisher's protected least significant difference test at 95% confidence, and response curves were determined by orthogonal contrasts. Percentages were transformed to arcsin values before analysis. For clarity, nontransformed percentage means were used for presentation in tables and figures.

Table 1. Volumetric soil water content (0–12 cm depth), leaf chlorophyll index, plant biomass, tomato spotted wilt (TSW) incidence, and plant mortality as affected by irrigation rate [percentage of crop evapotranspiration (ETc)] and calcium fertilization in bell pepper (Tifton, GA, Spring 2005).

Treatment	Soil moisture (%)	Chlorophyll (SPAD unit)	Root dry wt (g/plant)	Top dry wt (g/plant)	TSW (%)	Plant mortality (%)
Irrigation rate (% ETc)						
50	10.2 c^z	69 a	48	353	11	7
100	10.5 b	64 b	45	387	10	11
150	11.1 a	60 c	47	381	13	15
Calcium						
None	10.5	63	51	382	8	10
Gypsum	10.8	65	43	373	11	13
Thiocal	10.5	64	47	365	14	10
Significance						
Irrigation (I)	<0.0001	<0.0001	0.251	0.770	0.577	0.261
Calcium (Ca)	0.073	0.260	0.894	0.349	0.125	0.829
I × Ca	<0.0001	0.247	0.358	0.964	0.680	0.857

^{z}Means separated within columns and treatment group using Fisher's protected least significant difference test ($P \leq 0.05$).

Results and Discussion

Weather. Seasonal mean air temperatures were 22.4 °C (2001), 23.5 °C (2003),

Table 2. Effect of irrigation rate [percentage of crop evapotranspiration (ETc)] and calcium rate on plant growth, fruit yield, and incidence of blossom end rot (BER) in bell pepper (Tifton, GA, Spring 2001).

Treatment	Vegetative top fresh wt (g)	Marketable yield (#/plant)	Marketable yield (g/plant)	Total yield (#/plant)	Total yield (g/plant)	Fruit wt (g/fruit)	BER incidence (%)
Irrigation rate (% ETc)							
70	202 a^z	3.3	492 a	6.0	713 a	148 a	3.6
100	166 b	3.4	459 a	5.5	627 ab	136 b	3.2
130	131 c	2.9	348 b	5.3	548 b	119 c	2.7
Calcium rate (kg·ha^{-1})							
0	170	3.2	435	5.7	654	134	2.6
180	163	3.2	430	5.5	605	134	3.7
Irrigation (I)	<0.001	0.423	0.035	0.208	0.028	0.0002	0.864
Calcium (Ca)	0.465	0.930	0.907	0.416	0.285	0.911	0.467
I × Ca	0.963	0.414	0.648	0.728	0.986	0.619	0.258

^{z}Means separated within columns and treatment group using Fisher's protected least significant difference test ($P \leq 0.05$).

and 24.1 °C (2005). Cumulative rainfall was 183 mm (2001), 350 mm (2003), and 432 mm (2005); cumulative ETo was 375 mm (2001), 457 mm (2003), and 510 mm (2005).

Soil water status. In 2003, trends of volumetric water content (0–30 cm deep) for a 15-d period are shown in Fig. 1A. Average SWC for the season increased with increasing rates of irrigation from 8.2% (at 33% ETc) to 14.1% (at 167% ETc) (Fig. 1B). In the soil of this study, field capacity is at ≈16% of SWC. In 2005, SWC also increased with irrigation rate (Table 1). Calcium fertilization had no effect on SWC.

Plant growth. In 2001, vegetative top FW decreased with increasing irrigation rate above 70% ETc and was unaffected by Ca rate (Table 2). In 2003, plant height (mean = 41.1 cm) and stem diameter (mean = 13.2 cm) 6 weeks after planting were unaffected by irrigation rate (data not shown). Vegetative top FW of mature plants was also unaffected by irrigation rate (Fig. 2). Plants supplied with high irrigation rates in 2003 were visually more chlorotic compared with plants irrigated at medium rates (100% ETc), possibly because of increased nutrient leaching at high irrigation rates (Díaz-Pérez and Eaton, 2015; Simonne et al., 2010). In 2005, root and top DW were unaffected by irrigation rate or Ca treatment (Table 1).

Plant growth is a physiological process susceptible to water stress (Hsiao and Xu, 2000). Responses to reduced irrigation may be variable. In a greenhouse study, bell pepper displayed decreased shoot biomass with irrigation rates below 100% ETc (Fernández et al., 2005). Our data showed, however, that bell pepper vegetative top growth was not significantly diminished under mild water stress [70% ETc (2001), 67% ETc (2003), and 50% ETc (2005)]. Similarly, withholding irrigation was found not to impact bell pepper plant height (Ngouajio et al., 2008). In a study on bell pepper under shade, plants under 50% and 75% ETc had increased stem diameter growth rate and increased vegetative top compared with full irrigation (Rodríguez-Padrón et al., 2015a).

Gas exchange. On the day gas exchange was measured, net photosynthesis increased with increased irrigation rate up to 100% ETc and remained about constant with further increases in irrigation rate (Fig. 3A). Stomatal conductance increased with increasing irrigation rate (Fig. 3B). Photosynthetic WUE was highest at the lowest irrigation rate and decreased with increasing irrigation rate up to 100% ETc and remained about constant with further increases in irrigation rate (Fig. 3C).

The reduced gas exchange variables at 67% ETc and below compared with higher irrigation rates in this study suggests that bell pepper plants were affected by water stress. Similarly, midday g_S and leaf water potentials, water uptake rates (sap flow), and hydraulic conductance through the plant to the canopy are reported to be diminished at reduced irrigation regimes in bell pepper (Agele et al., 2006). In another study, gas exchange variables in rainfed bell pepper plants were lower than those in irrigated plants (Delfine et al., 2002). Under rainfed conditions, bell pepper plants have decreased leaf photosynthesis because of reduced leaf g_S compared with plants under well-irrigated conditions (Delfine et al., 2001). In habanero

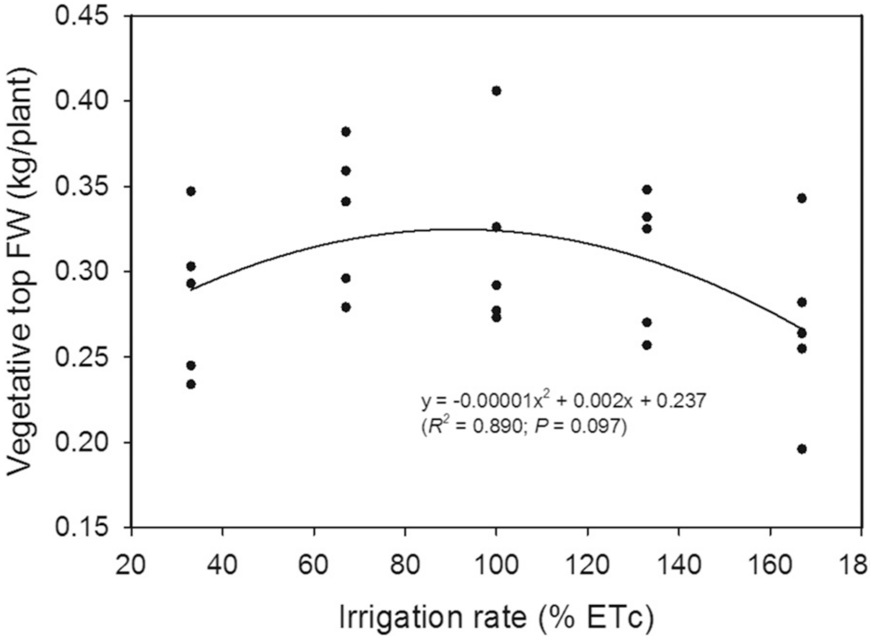

Fig. 2. Vegetative top fresh weight in bell pepper plant growth as affected by irrigation rate as a percentage of crop evapotranspiration (ETc). Each point is the average of five plants. Tifton, GA, Spring 2003.

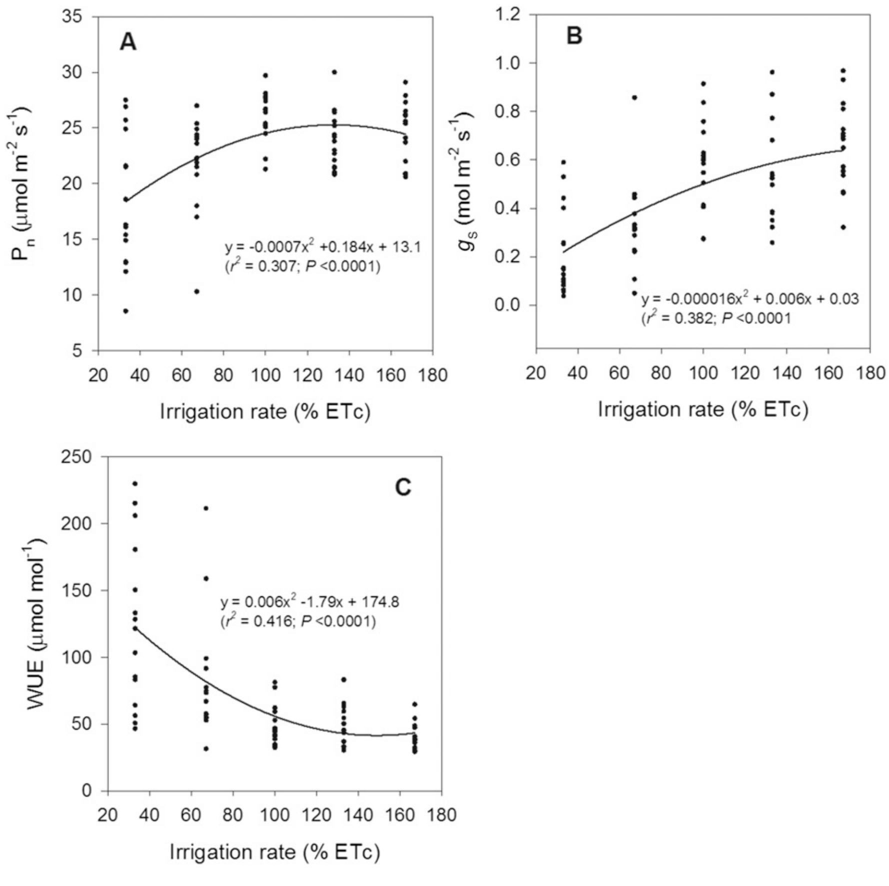

Fig. 3. (**A**) Bell pepper net photosynthesis (P_n), (**B**) stomatal conductance (g_S), and (**C**) photosynthetic water use efficiency (WUE) as affected by irrigation rate as a percentage of crop evapotranspiration (ETc). Each point represents one leaf in an individual plant. Tifton, GA, Spring 2003.

pepper (*Capsicum chinensis* L.), g_S and daily assimilation rate were reduced in plants irrigated every 6 d compared with every 3 d (Jaimez et al., 1999).

Foliar and fruit mineral concentrations. In 2003, foliar N decreased with increasing irrigation rate (Table 3), whereas foliar Fe, Mn, and Zn had an increasing trend with increasing irrigation rate. The rest of foliar mineral nutrients and fruit mineral nutrients were unaffected by irrigation rate. In 2005, foliar N concentration was reduced and Mn concentration was increased with increased irrigation rate, as in 2003 (Table 4). The rest of foliar nutrient concentrations were little affected by irrigation rate. Foliar N concentration was highest in the gypsum treatment, and the rest of the foliar nutrient concentrations were not significantly affected by Ca fertilization.

Fruit concentrations of P, K, Mg, and Mn increased with increasing irrigation rates in 2005 (Table 5). Nitrogen, Ca, and Fe concentrations were not significantly affected by irrigation rate. Fruit nutrients were not significantly affected by Ca fertilization, except for Mg, which was reduced in fruit from plants fertilized with gypsum.

Reduced bell pepper foliar N concentration at high irrigation rates was likely associated with increased nitrate leaching. The dynamics of nutrient movement in the soil is directly affected by irrigation, both rate and frequency. High-frequency irrigation leads to higher Mn concentrations in leaves and fruits and increased concentrations of Cl, N, and P in leaves, compared with once-a-day irrigation (Assouline et al., 2006). Another study showed that leaf concentrations of Ca, Na, P, Fe, Zn, and K were higher in rainfed than those in irrigated plants, whereas nutrient concentrations in fruits were similar in rainfed compared with those in irrigated plants (Delfine et al., 2002).

In our study, the reduced Mg concentration in fruit from plants fertilized with gypsum suggests that Ca had an antagonistic effect on plant Mg uptake or accumulation in the fruit (Hawkesford et al., 2012).

Leaf chlorophyll index decreased with increased irrigation rate (Table 1), which also indicates that high irrigation rates resulted in increased soil N leaching and reduced leaf N concentration. These differences in chlorophyll content were consistent with the presence of more chlorotic leaves at high irrigation rates. Chlorophyll content was unaffected by Ca fertilization. In a study in Michigan, withholding irrigation until fruit set resulted in increased leaf chlorophyll content in bell pepper (Ngouajio et al., 2008).

Plant diseases. In 2001, TSW incidence was low (mean = 3%) and unaffected by irrigation rate and Ca rate. In 2003, incidence of phytophthora blight decreased from 20% (at 33% ETc) with increasing irrigation rate up to 100% ETc and stayed about constant (≈5%) with further increases in irrigation rate. Incidence of southern blight (mean = 18%) was unaffected by irrigation rate. In 2005, TSW incidence and plant mortality were unaffected by either irrigation or calcium fertilization, although plant mortality tended to increase with increasing irrigation rate (P = 0.261) (Table 1). Mortality of bell pepper plants was associated with the incidence of phytophthora root rot and southern blight.

Soilborne diseases such as phytophthora root rot of pepper are often associated with high soil moisture conditions (Cafe-Filho and Duniway, 1995b). Dispersal of *Phytophthora*

Table 3. Effect of irrigation rate [percentage of crop evapotranspiration (ETc)] on mineral nutrients of leaves and fruits of bell pepper (Tifton, GA, Spring 2003).

Irrigation rate (% ETc)	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	(%)					(ppm)			
Leaves									
33	6.78^z	0.26	5.11	2.78	0.69	15	110	346	290
67	6.55	0.29	5.13	1.52	0.72	13	122	316	274
100	6.43	0.27	5.10	1.78	0.74	13	177	396	275
133	6.19	0.29	5.21	2.53	0.67	17	213	427	290
167	6.02	0.28	5.27	1.65	0.62	15	148	368	278
Significance^y									
L	0.006	0.655	0.947	0.798	0.775	0.883	0.020	0.014	0.002
Q	0.025	0.804	0.988	0.735	0.419	0.663	0.007	0.009	0.005
Fruit									
33	n.d.	0.15	3.50	0.33	0.28	20	118	174	270
67	n.d.	0.15	3.43	0.67	0.34	27	115	166	270
100	n.d.	0.16	3.50	0.28	0.30	20	119	162	253
133	n.d.	0.14	3.55	0.28	0.30	27	113	165	260
167	n.d.	0.17	3.77	0.26	0.31	20	111	167	246
Significance									
L		0.411	0.212	0.371	0.779	0.922	0.670	0.846	0.633
Q		0.587	0.305	0.585	0.813	0.750	0.892	0.936	0.892

[z] Values represent means of samples collected 4, 7, and 10 weeks after transplanting; fruits sampled at three different harvests.

[y] L = linear; Q = quadratic response.

Table 4. Mineral nutrients in bell pepper leaves at the fruiting stage as affected by irrigation rate [percentage of crop evapotranspiration (ETc)] and calcium fertilization. Plants were sampled at the mature stage (Tifton, GA, Spring 2005).

Treatment	N	P	K	Ca	Mg	Mn	Fe
	(%)					(ppm)	
Irrigation rate (% ETc)							
50	4.4 a^z	0.43	3.7	1.0	0.41	46 b	209
100	4.3 a	0.45	3.7	1.0	0.40	45 b	147
150	4.0 b	0.47	3.8	1.0	0.38	55 a	152
Calcium							
None	4.1 b	0.44	3.7	1.0	0.41	47	198
Gypsum	4.4 a	0.44	3.8	1.1	0.38	48	127
Thiocal	4.2 b	0.47	3.7	0.9	0.41	50	183
Significance							
Irrigation (I)	<0.01	0.311	0.821	0.947	0.518	<0.01	0.673
Calcium (Ca)	<0.01	0.125	0.476	0.113	0.427	0.775	0.663
I × Ca	0.663	0.406	0.622	0.186	0.274	0.161	0.364

[z] Means separated within columns and treatment group using Fisher's protected least significant difference test ($P \leq 0.05$).

Table 5. Mineral nutrients in developing bell pepper fruit as affected by irrigation rate [percentage of crop evapotranspiration (ETc)] and calcium fertilization (Tifton, GA, Spring 2005).

Treatment	N	P	K	Ca	Mg	Mn	Fe
	(%)					(ppm)	
Irrigation rate (% ETc)							
50	3.9	0.54 b^z	3.96 b	0.32	0.271 b	20 b	85
100	4.1	0.58 a	4.01 ab	0.32	0.286 ab	20 b	84
150	3.8	0.60 a	4.10 a	0.34	0.293 a	24 a	90
Calcium							
None	3.8	0.57	3.99	0.31	0.292 a	21	91
Gypsum	4.0	0.57	4.06	0.33	0.266 b	21	85
Thiocal	3.9	0.58	4.01	0.33	0.293 a	23	83
Significance							
Irrigation (I)	0.119	<0.01	0.065	0.757	0.045	<0.01	0.541
Calcium (Ca)	0.150	0.311	0.461	0.813	<0.01	0.126	0.327
I × Ca	0.576	0.206	0.065	0.427	0.799	0.592	0.353

[z] Means separated within columns and treatment group using Fisher's protected least significant difference test ($P \leq 0.05$).

capsici and *P. parasitica* occurs by mobilization of their spores in the irrigation water (Cafe-Filho and Duniway, 1995a). In a study evaluating the effects of alternate-row irrigation in chili pepper (*Capsicum annuum*), incidence of phytophthora root rot in plots receiving alternate-row irrigation without fungicides was significantly less than irrigation of every row without fungicides (Biles et al., 1992). In 2001, air temperatures and rainfall were reduced possibly impacting thrips activity and thus explaining the reduced TSW incidence.

Fruit yield and fruit disorders. In 2001, marketable and total fruit weight and individual fruit weight were among the highest at the lowest irrigation rate (70% ETc) and decreased with increasing irrigation rate (Table 2); fruit number (marketable and total) and incidence of BER were unaffected by irrigation rate. Fruit number and yields and incidence of BER were unaffected by Ca application; BER incidence, however, was low (mean = 3.2%). In 2003, irrigation at 67% ETc was among the most productive treatments. Total yield (Fig. 4A) and marketable yield (Fig. 4B) were reduced at both, low (33% ET) and high (167% ET) rates of water application. Incidence of BER declined with increasing irrigation rate (Fig. 4C). Although not significantly, individual fruit size (mean = 145 g) tended to be reduced at low (33% ETc) and high (167% ETc) irrigation rates. In 2005, marketable and total yields and weight of individual fruit at 50% ETc were similar to those at 100% and 150% ETc (Table 6). Fruit weight and marketable and total yields were highest in plants fertilized with gypsum and lowest in plants without Ca. The total number of fruit per plant was unaffected by Ca fertilization. There was no interaction between irrigation rate and Ca fertilization. The incidence of BER was highest at the lowest (50% ET) irrigation rate. The incidence of BER was highest in plants receiving no Ca fertilizer and lowest in plants fertilized with gypsum, although the incidence of BER in plants fertilized with Thiocal was not significantly different compared with that of plants fertilized with gypsum.

Bell pepper has been reported to be susceptible to water stress (Smittle et al., 1994). In the current study, irrigation rates at 70% ETc in 2001 (Table 2), 67% ETc in 2003 (Fig. 4), and 50% ETc in 2005 (Table 6) were sufficient to maximize plant growth and fruit yield and provided yields similar to those at 100% ETc. These results indicate that irrigation rates below 100% ETc may be used without significantly impacting bell pepper fruit yield. Fruit yields at 33% ETc (in 2003), however, were reduced probably because of drought stress, as indicated by the low values of g_S and leaf net photosynthesis.

Fruit yields at 167% (in 2003) were diminished possibly as a response of root hypoxia, N leaching, or both due to excessive irrigation rates. None of our measurements could confirm root hypoxia. Nitrogen leaching at high irrigation rates may occur in light soils such as those of this study, as found for eggplant grown on plastic mulch (Díaz-Pérez and Eaton, 2015). Studies in Florida show that excessive irrigation may cause yield reduction in plastic-mulched bell pepper (Dukes et al., 2010) and tomato (Locascio et al., 1989). Other studies, however, found responses to irrigation to be inconsistent. In bell pepper grown on plastic mulch, fruit yields were found to be highest between 115% and 124% of reference irrigation rate in 2001, whereas yields showed no response to irrigation rate in 2002 (Simonne et al., 2006). In bell pepper grown on bare soil, response to irrigation was found to be affected by the presence of shade net (Rodríguez-Padrón et al., 2015b). Fruit yield in open field was highest with an irrigation rate of 75% ETc, whereas under shaded conditions, yield was highest at 50% ETc.

Blossom-end rot is related to numerous factors including low plant water status, high temperature, ABA, and nutrient imbalances, but the underlying cause of BER is inadequate amount of Ca in the blossom-end of the fruit (de Freitas et al., 2011; Taylor and Locascio, 2004). Calcium contents between

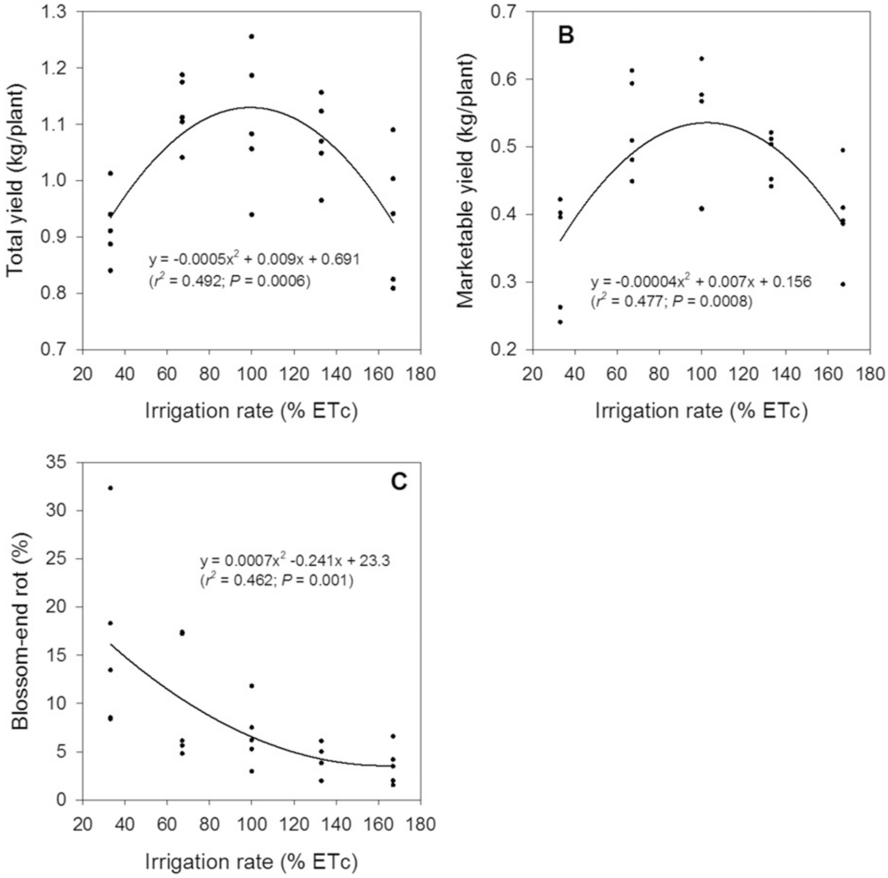

Fig. 4. (**A**) Bell pepper total fruit yield, (**B**) marketable yield, and (**C**) incidence of blossom end rot as affected by irrigation rate as a percentage of crop evapotranspiration (ETc). Each point is the average of 25 plants. Tifton, GA, Spring 2003.

Table 6. Bell pepper fruit yields and incidence of blossom-end rot (BER) as affected by irrigation rate [percentage of crop evapotranspiration (ETc)] and calcium fertilization (Tifton, GA, Spring 2005).

	Marketable		Total		Fruit wt[z]	BER
Treatment	(# fruit/plant)	(kg/plant)	(# fruit/plant)	(kg/plant)	(g)	(%)
Irrigation rate (% ETc)						
50	5.2	0.75	10.47	1.16	145	10 a
100	5.6	0.83	10.74	1.21	147	5 b
150	5.1	0.75	10.40	1.17	147	5 b
Calcium						
None	5.0 b[z]	0.69 b	10.26	1.09 b	141 b	9 a
Gypsum	5.8 a	0.88 a	10.88	1.29 a	151 a	5 b
Thiocal	5.2 ab	0.76 ab	10.40	1.16 ab	146 ab	7 ab
Significance						
Irrigation (I)	0.332	0.339	0.851	0.750	0.893	<0.0001
Calcium (Ca)	0.108	0.016	0.632	0.023	0.036	<0.0001
I × Ca	0.403	0.524	0.776	0.373	0.959	0.778

[z] Means separated within columns and treatment group using Fisher's protected least significant difference test ($P \leq 0.05$).

pepper fruit with and without BER are known to be different (Lee et al., 2012b). Calcium is transported by mass flow through the xylem (Hawkesford et al., 2012). Fruit yield and BER responses to Ca fertilization in this study were inconsistent. Incidence of BER was increased at reduced irrigation rate probably because of reduced Ca transport to the fruit. Low Ca concentrations in the fruit are considered one of the main causes of BER (Taylor and Locascio, 2004). Bell pepper plants benefited (increased fruit yields and reduced BER incidences) from Ca applications in 2005 (Table 6) but not in 2001 (Table 2). In drip-irrigated pepper grown in black plastic mulch, total yield of total marketable increased and yield of scalded fruit decreased with increasing Ca rate (Alexander and Clough, 1998). In a greenhouse study in Israel, the lowest BER incidence in bell pepper occurred with the most frequent irrigation and the highest Ca concentration in the nutrient solution (Bar-Tal et al., 2001). Incidence of BER was found to be affected by Ca and the ratios of Ca with its antagonistic cations K, Mg, and NH4-N (Lee et al., 2012a).

Postharvest fruit quality. In 2001, fruit DW content decreased with increasing irrigation rate (Table 7). Fruit WLR, TR, and Fv/Fm were lowest at the lowest irrigation rate (70% ETc). Fruit firmness was unaffected by irrigation rate. Fruit TR was lowest and Fv/Fm was highest with Ca fertilization. Fruit DW, WLR, and firmness were unaffected by Ca fertilization. In 2003, SSC decreased with increasing irrigation (Fig. 5). Fruit WLR (mean = 0.574%·d^{-1}·kPa^{-1}) and TR (mean = 23.75 μmol·m^{-2}·s^{-1}·kPa^{-1}) were unaffected by irrigation rate. In 2005, fruit biomass and fruit DW percentage decreased with increasing irrigation rate and were unaffected by Ca fertilization (Table 8). Fruit pericarp thickness was unaffected by either irrigation rate or Ca fertilization. Soluble solids content decreased with increasing irrigation rate but was uninfluenced by Ca fertilization.

The increased fruit DW content and SSC associated with reduced irrigation rates are probably due either to a concentration effect or occurrence of osmotic adjustment in fruit cells (Ben-Yehoshua and Weichmann, 1987). As other plant cells, fruit cell expansion is a function of cell turgor (Frensch and Hsiao, 1994). Under water-limiting conditions, bell pepper fruit cells may accumulate solutes to maintain fruit turgor and thus allow for fruit growth. In a greenhouse bell pepper study, fruit SSC was higher at 40% ETc than at 120% ETc (Aladenola and Madramootoo, 2014).

Bell pepper fruit quality and postharvest life are affected by fruit transpiration (Ben-Yehoshua and Weichmann, 1987; Díaz-Pérez et al., 2007). Fruit transpiration or water loss is determined by the vapor pressure difference between the fruit and the surrounding air and by the resistance to water evaporation through the fruit epidermis. High values of WLR and TR at high irrigation rates (Table 7) may result in shortened shelf life of bell pepper (Ben-Yehoshua and Weichmann, 1987; Díaz-Pérez et al., 2007). Increased fruit WLR and TR values with increasing irrigation rates suggest the presence of augmented epidermal resistance to fruit transpiration at low irrigation rates. Apparently, dehydration of fruit epidermal cells in bell pepper has increased resistance to water vapor diffusion

Table 7. Effect of irrigation rate [percentage of crop evapotranspiration (ETc)] and calcium fertilization on dry weight (DW) content, water loss rate (WLR), transpiration ratio (TR), firmness, and fluorescence (Fv/Fm) of bell pepper fruit (Tifton, GA, Spring 2001).

Treatment	Fruit DW (%)	WLR (%·d^{-1}·kPa^{-1})	TR (μmol·m^{-2}·s^{-1}·kPa^{-1})	Firmness	Fv/Fm
Irrigation rate (% ETc)					
70	5.40 a^{z}	0.522 b	21.5 b	3.1	0.592 b
100	5.32 ab	0.542 a	22.2 a	3.2	0.616 a
130	5.26 b	0.548 a	22.2 a	3.1	0.620 a
Calcium rate (kg·ha^{-1})					
0	5.3	0.540	22.1 a	3.1	0.596 b
180	5.3	0.535	21.8 b	3.1	0.622 a
Significance					
Irrigation (I)	0.030	<0.0001	<0.0001	0.148	0.004
Calcium (Ca)	0.311	0.060	0.014	0.490	0.0005
I × Ca	<0.0001	<0.0001	<0.0001	<0.0001	0.665

^{z}Means separated within columns and treatment group using Fisher's protected least significant difference test ($P \leq 0.05$).

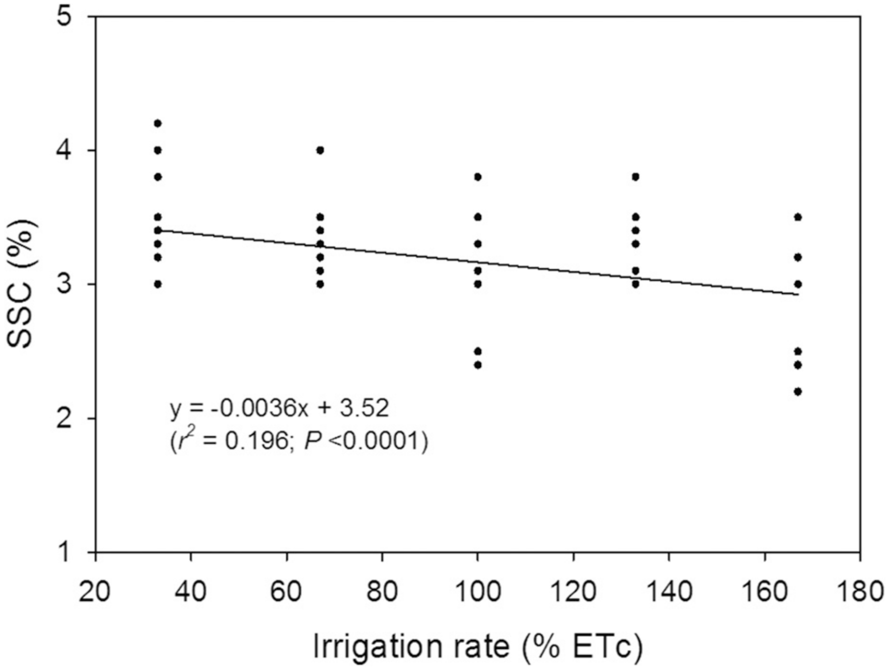

Fig. 5. Soluble solids content (SSC) of bell pepper fruit as influenced by irrigation rate as a percentage of crop evapotranspiration (ETc). Each point represents one fruit. Tifton, GA, Spring 2003.

Table 8. Bell pepper fruit biomass, dry weight (DW), pericarp thickness, and soluble solids content as affected by irrigation rate [percentage of crop evapotranspiration (ETc)] and calcium fertilization (Tifton, GA, Spring 2005).

Treatment	Fruit biomass (g/fruit)	Fruit DW (%)	Pericarp thickness (mm)	Soluble solids (%)
Irrigation rate (% ETc)				
50	11.3 a^{z}	6.3 a	5.8	3.7 a
100	10.6 ab	5.5 b	5.8	3.5 b
150	10.4 b	5.5 b	5.8	3.4 b
Calcium				
None	10.5	5.8	5.7	3.6
Gypsum	10.7	5.7	5.8	3.5
Thiocal	11.0	5.5	5.8	3.5
Significance				
Irrigation (I)	0.082	0.082	0.651	<0.01
Calcium (Ca)	0.410	0.410	0.158	0.849
I × Ca	0.708	0.708	0.619	0.800

^{z}Means separated within columns and treatment group using Fisher's protected least significant difference test ($P \leq 0.05$).

through the cuticle (Díaz-Pérez et al., 2007). Fluorescence is an indicator of plant stress (Maxwell and Johnson, 2000). Decreased bell pepper fruit fluorescence (Fv/Fm) values at reduced irrigation rates indicate that fruit cells were under water stress.

In conclusion, for soils used in this study, bell pepper plant growth and fruit yield and quality were relatively unaffected with 70% ETc (2001), 67% ETc, (2003) and 50% ETc (2005) irrigation rates. Thus, irrigation below 100% ETc may be used without significantly impacting bell pepper yield and quality. Utilization of irrigation below 100% ETc would reduce the volumes of irrigation water applied to the crop and provide fruit yields similar to those at 100% ETc or higher rates. Fruit yield and quality were reduced and incidence of BER was increased at low irrigation rate of 33% ETc. Irrigation rates of 167% ETc resulted in water waste, diminished bell pepper yields, and increased incidences of soilborne diseases. Calcium fertilization had no effect on SWC, plant growth, and incidence of soilborne diseases, and inconsistent effects on fruit yield and the incidence of BER.

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