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# Eggplant (*Solanum melongena* L.) Plant Growth and Fruit Yield as Affected by Drip Irrigation Rate

**Juan Carlos Díaz-Pérez**[1]
*Department of Horticulture, University of Georgia, Tifton, GA 31793*

**Touria E. Eaton**
*Cooperative Extension and Research, Lincoln University of Missouri, Jefferson City, MO 64106*

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***Abstract*. Eggplant (*Solanum melongena* L.) is an increasingly popular crop in the United States. In the southeastern United States, eggplant is often produced with high levels of irrigation water [above the rate of crop evapotranspiration (ETc)], resulting in water waste and nitrogen (N) leaching. The objective of this research was to assess the effects of irrigation rate on plant growth and fruit yield in eggplant. The study was conducted in Tifton, GA, in the fall of 2010 and 2011. Eggplant plants cv. Santana were grown on raised beds (1.8 m centers) covered with white plastic film mulch. There was a single drip tape along the center of the bed. The design was a randomized complete block with five treatments and four replications. Treatments consisted of irrigation rates based on ETc (33%, 67%, 100%, 133%, and 167% ETc). Plant growth, chlorophyll index (CI), and volumetric soil water content (SWC) were monitored over the season. In 2010, SWC (0–30 cm deep) increased and soil nitrate levels decreased with increasing irrigation rates. Foliar N and potassium (K), and CI decreased with increasing irrigation rate, probably due to a dilution effect. Stem diameter, leaf dry weight (DW), and vegetative top DW increased with increasing irrigation rate. Net photosynthesis and stomatal conductance ($g_S$) were lowest at 33% ETc. Fruit number and fruit yields (marketable and total) were also lowest at 33% ETc and there were little yield differences among irrigation rates higher than 33% ETc. In 2011, irrigation rate had minor or no effect on SWC, plant growth of mature plants, leaf gas exchange, and fruit number and yield. The no treatment effect observed for eggplant in 2011 was likely because study was conducted in a low field that remained moist most of the time, nullifying the treatment effects. Results suggested that eggplant may tolerate mild water stress, since plants irrigated at 67% ETc produced fruit yields similar to those of plants irrigated at 100% ETc or higher rates. Thus, there is a potential to save water by reducing current irrigation rates without negatively impacting fruit yields.**

Eggplant, also known as aubergine and brinjal, is widely grown and consumed in southern and southeast Asia and has increased in popularity in the United States as a specialty vegetable. In 2001, U.S. eggplant production was valued at $42.5 million, and Georgia, Florida, California, New Jersey, and New York were the top five producers. The U.S. Department of Agriculture has not collected complete domestic production statistics for eggplants since 2001. In 2012, farm gate value in the state of Georgia was $17 million (CAED, 2013). Average eggplant yield in Florida is ≈30 t·ha$^{-1}$ (Ozores-Hampton, 2014).

Eggplant is in the Solanaceae family, as are tomato (*Solanum lycopersicon*) and pepper (*Capsicum annum*) and shares similar environmental and cultural requirements as those crops. However, in contrast to tomato and pepper, eggplant crop can tolerate greater levels of drought stress (Behboudian, 1977). There are several studies on eggplant irrigation carried out in Asia, Africa, and Europe (Aujla et al., 2007; Behboudian, 1977; Chartzoulakis and Drosos, 1995; Gaveh et al., 2011; Karam et al., 2011) showing that eggplant can be produced at moderate levels of drought stress without major impact on fruit yield.

In southeastern United States, eggplant is often produced with high levels of irrigation water (above the rate of ETc) and N fertilizer, resulting in water waste and N leaching. Excessive irrigation rate not only wastes water, but may also result in reduced yields in bell pepper (Díaz-Pérez et al., 2004; Sezen et al., 2006) and tomato (Locascio et al., 1989; Ngouajio et al., 2007). To our knowledge, there are no published studies in the United States on the effect of irrigation rate on the yield and plant growth of drip-irrigated eggplants. Irrigation studies, intended to optimize use of irrigation water, are necessary to enable the protection of water resources in the United States. Therefore, the objective of this research was to assess the effects of irrigation rate on plant growth and fruit yield in eggplant.

## Materials and Methods

*Study site.* The study was carried out at the Horticulture Farm, University of Georgia, Tifton, GA, during the fall of 2010 and 2011. 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 of the farm is a Tifton sandy loam (a fine loamy-siliceous, thermic Plinthic Kandiudults) with pH 6.5. Available water capacity is 18 to 36 mm in the top 30 cm of soil profile (Calhoun, 1983). In 2010, field had a gentle sloping (slope ≈3%); in 2011, field had a nearly level slope. The distance between the 2010 and 2011 fields was ≈70 m.

*Land preparation and planting.* Eggplant plants were grown on plastic film mulch on raised beds (6 × 0.76 m, formed on 1.8-m centers). Before laying mulch, the soil was fertilized with N, phosphorous (P), and K at 60, 26, and 50 kg·ha$^{-1}$, respectively, using 10–10–10 granular fertilizer. At the same time, plastic film mulch [white on 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 [20.3 cm emitter spacing and a 8.3 mL·min$^{-1}$ emitter flow (Ro-Drip, Roberts Irrigation Products, Inc., San Marcos, CA)] was placed 5 cm deep in the center of the bed.

Eggplant transplants were produced in a greenhouse using peat-based medium (Pro-Mix, Quakertown, PA) and polystyrene 200-cell (2.5 × 2.5 cm cell) trays. Six-week-old eggplant transplants were planted with a mechanical transplanter on 6 Aug. 2010 and 5 Aug. 2011 in one row per bed, with a 60 cm separation between plants. About 250 mL of starter fertilizer solution (555 mg·L$^{-1}$ N; 821·mg·L$^{-1}$ P; 0 mg·L$^{-1}$ K) was applied directly to the base of each transplant. The length of the experimental plot was 6.1 m. Starting 3 weeks after transplanting, plants were fertilized weekly through the drip system with N and K. Fertilization rates of N and K after transplanting were 0.7, 1.0, 1.5, and 2 kg·ha$^{-1}$·d$^{-1}$ in week 5, week 6; week 7; and weeks 13–15, respectively. Total N–P–K applied in the season was 218 kg·ha$^{-1}$ N, 30 kg·ha$^{-1}$ P, and 181 kg·ha$^{-1}$ K.

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[1] Corresponding author. E-mail: jcdiaz@uga.edu.

*Experimental design and treatments.* The design was a randomized complete block with five treatments and four replications. Treatments consisted of irrigation rates based on ETc (33%, 67%, 100%, 133%, and 167% the rate of ETc). ETc was calculated by multiplying the reference evapotranspiration (ETo) by a crop coefficient (Kc), which is dependent on the crop stage of development. Available Kc values for eggplant were developed for bare soil (unmulched) production. These Kc values, however, are not recommended for crops under plasticulture systems since plastic mulches reduce soil evaporation and ETc (Allen et al., 1998; Pereira et al., 2015; Simonne et al., 2006). The Kc values used in this study were modified relative to those proposed for bell pepper in Florida (Simonne et al., 2006). The Kc values used were 0.25 (week 1 after transplanting), 0.40 (week 2), 0.55 (week 3), 0.70 (week 4), 0.85 (week 5), 1.0 (week 6–11), and 0.8 (week 12–14).

All treatments received equal volumes of irrigation water (88 and 49 mm in 2010 and 2011, respectively) during the crop establishment period (first 4 weeks after transplanting). Irrigation treatments were initiated on week 5. Water was applied when cumulative ETc was $\approx$12 mm, which corresponded to about every 2 to 3 d in mature plants (mean ETo was 5 to 6 mm·d$^{-1}$). Thus, amounts of water per irrigation event were $\approx$4 mm (33% ETc), 8 mm (67% ETc), 12 mm (100% ETc), 16 mm (133% ETc), and 20 mm (167% ETc).

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

*Soil nitrate.* Soil samples were taken from each plot at 0- to 20-cm, 20- to 40-cm, and 40- to 60-cm depths on 8 Nov. 2010. Samples were taken at least 0.5 m away from the borders of the plots and from the previous sampling holes. Samples were air-dried and analyzed for nitrate-nitrogen using standard QuickChem Methods (Lachat Quick-Chem 8000 FIA; Zellweger Analytics, Milwaukee, WI).

*Plant growth.* Eggplant plant height and stem diameter were measured weekly in three mature plants per plot. Plant samples obtained at the end of the season were dried at 70 °C for several days until constant weight was obtained. Leaf, stem, and vegetative top (leaf + stem) DW of individual plants were determined.

*Leaf CI.* Chlorophyll indices were determined twice a week over the season 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 PSII efficiency.* Simultaneous measurements of leaf gas exchange (net photosynthesis, $g_S$, transpiration, and internal $CO_2$ concentration), and fluorescence were determined as PSII efficiency were made with an infrared 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 $\mu$mol·m$^{-2}$·s$^{-1}$ on the reference side. The $CO_2$ concentration was set at 400 $\mu$mol·mol$^{-1}$ with a $CO_2$ mixer and a $CO_2$ tank. Measurements were conducted in developed plants on clear days (photosynthetically active radiation $\approx$2000 $\mu$mol·m$^{-2}$·s$^{-1}$) at 1200–1500 HR Eastern Standard Time in 2010 (6 and 20 Oct. and 9 Nov.) and 2011 (5 Oct.), using two developed and fully exposed leaves per experimental plot.

*Leaf mineral nutrients.* Leaf samples (20 fully developed leaves from new growth) from developed plants were dried at 70 °C for 2 d and analyzed for mineral nutrient concentration at the University of Georgia, Agricultural & Environmental Services Laboratories, Athens, GA.

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

*Harvest.* The harvest lasted from 28 Sept. to 23 Nov. in 2010 and from 23 Sept. to 4 Nov. in 2011. Eggplant fruit were harvested twice per week at commercial stage. Harvested section consisted of 10 plants per plot. Fruit were graded according to U.S. Department of Agriculture standards (USDA, 2013) as marketable or cull and number and weight of marketable and cull fruit were determined. Average fruit weight was derived mathematically from the total weight and the total number of fruits.

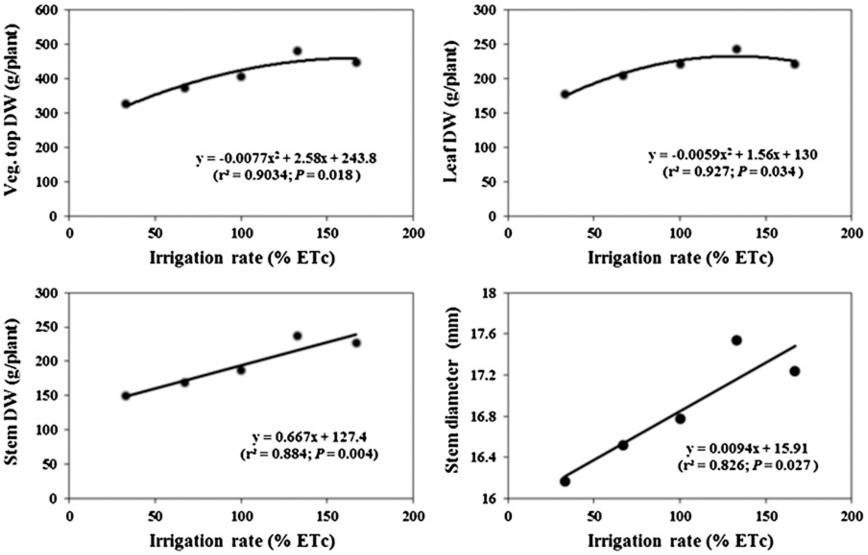

Fig. 1. Vegetative top dry weight (DW), leaf DW, stem DW, and stem diameter of mature eggplant plants as affected by irrigation rate. Irrigation rate was applied as percentage of crop evapotranspiration. Curve was fit by linear regression. Fall of 2010, Tifton, GA.

Table 1. Plant growth, leaf chlorophyll index (CI), and soil water content (SWC) as affected by irrigation rate in eggplant. Fall of 2011, Tifton, GA.

| Rate (%)[z] | Seasonal stem diam (mm) | Mature stem diam (mm) | Seasonal plant ht (cm) | Mature plant ht (cm) | Mature plant DW (kg) | Seasonal CI[y] | Seasonal SWC[x] (%) |
|---|---|---|---|---|---|---|---|
| 33 | 19.6 | 20.6 | 85.9 | 95.2 | 1.59 | 55.8 | 13.6 |
| 67 | 20.4 | 21.4 | 89.6 | 99.8 | 1.73 | 55.2 | 13.7 |
| 100 | 20.5 | 21.7 | 91.2 | 100.1 | 1.74 | 54.9 | 13.4 |
| 133 | 20.2 | 21.1 | 90.6 | 99.2 | 1.73 | 54.0 | 13.2 |
| 167 | 20.1 | 21.1 | 92.6 | 99.4 | 1.69 | 53.7 | 13.1 |
| Significance | | | | | | | |
| L[w] | 0.019 | 0.647 | <0.0001 | 0.490 | 0.743 | 0.0008 | 0.353 |
| Q[w] | 0.032 | 0.298 | 0.043 | 0.287 | 0.314 | 0.967 | 0.728 |

DW = dry weight.

[z] % ETc = percentage of crop evapotranspiration.

[y] Leaf CI measured with chlorophyll meter (SPAD-502; Minolta Co.).

[x] SWC in the 0–12 cm of soil profile measured manually with portable time-domain reflectometry sensor (CS-610; Campbell Sci.)

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

*Irrigation water use efficiency.* Irrigation water use efficiency (IWUE) was calculated by dividing fruit weight ($kg \cdot ha^{-1}$) by irrigation water received by the crop (in mm) for each irrigation treatment.

*Agronomic efficiency of nitrogen.* Agronomic efficiency of nitrogen was calculated by dividing total eggplant fresh fruit weight ($kg \cdot ha^{-1}$) by the amount of N ($kg \cdot ha^{-1}$) applied to the crop.

*Fruit DW content and harvest index (HI).* Five fruit per replicate were dried at 70 °C until constant weight (2–3 d) and weighed to determine their DW. Fruit DW content was calculated as:

$$\text{Fruit dry weight content} = (\text{fruit dry weight}/\text{fruit fresh weight}) \times 100$$

Harvest index (HI) was calculated as:

$$\text{Harvest index} = (\text{total aerial dry weight}/\text{fruit dry weight}) \times 100$$

*Statistical analysis.* Data were analyzed using the General Linear Model and Regression Procedures from SAS (SAS version 9.3, SAS Institute Inc., Cary, NC). Data means were separated by Fisher's protected least significant difference test at 95% confidence and response curves 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. Data from all years were pooled if no year × treatment interactions were found.

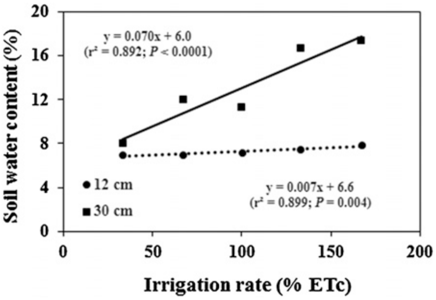

Fig. 2. Seasonal volumetric soil water content (measured at 12- and 30-cm depth) as influenced by irrigation rate. Irrigation rate was applied as percentage of crop evapotranspiration. Line was fit by linear regression. Fall of 2010, Tifton, GA.

## Results and Discussion

*Weather.* In 2010, average maximal, mean, and average minimum air temperature for the season were 28.8, 22.6, and 16.4 °C, respectively. Cumulative ETo and rainfall for the season were 370 and 184 mm, respectively. In 2011, average maximal, mean, and average minimum air temperature were 28.6, 22.5, and 16.4 °C, respectively. Cumulative ETo and rainfall for the season were 344 and 256 mm, respectively.

*Plant growth.* In 2010, vegetative top DW, leaf DW, stem DW, and stem diameter increased with increasing irrigation rate (Fig. 1). Leaf weight ratio (LWR) [leaf biomass as a fraction of vegetative aboveground biomass (mean = 0.529)] decreased with increasing irrigation rate ($r^2$ = 0.92; $P \leq 0.05$) from LWR of 0.543 at 33% ETc to LWR of 0.493 at 167% ETc, which indicates that plants allocated less biomass to leaves as irrigation rate increased. Bell pepper leaves have reduced leaf thickness at low light and low water stress conditions (Díaz-Pérez, 2013). In 2011, over the season, mean stem diameter was lowest at 33% ETc ($P < 0.05$), although final stem diameter was unaffected by irrigation rate (Table 1). Mean seasonal plant height increased with irrigation rate, ranging from 66 cm (33% ETc) to 93 cm (167% ETc); final plant height (4 Nov.) was unaffected by irrigation rate. Mature plant DW (mean = 1.70 kg) was also unaffected by irrigation rate. Growth differences during midseason but not at the end of the season were probably because of high evaporative demand conditions that impacted plant growth at low irrigation rates during midseason. Late in the season, when evaporative demand was reduced, the effect of irrigation rate on plant growth was less detectable. The no treatment effect observed for eggplant in 2011 was likely because study was conducted in a low field that remained moist most of the time, nullifying the treatment effects.

Reduced eggplant plant growth at irrigation rates below 100% ETo has been previously reported. Eggplant irrigated at 80% pan evaporation, every 8 d, and 70% pan evaporation, every 12 d, had reduction of 18% and 27% in plant height, and 13% and 21% in stem diameter, respectively (Kirnak et al., 2002). In bell pepper exposed to different soil water levels by varying drip emitter spacing, plant height and canopy diameter increased with decreasing emitter

Table 2. Leaf gas exchange and fluorescence as affected by irrigation rate and date in eggplant. Fall of 2010, Tifton, GA.

| Date | Rate (%)$^z$ | Net photosynthesis ($\mu mol \cdot m^{-2} \cdot s^{-1}$)$^y$ | $g_S$ ($mol \cdot m^{-2} \cdot s^{-1}$) | WUE ($\mu mol \cdot mmol^{-1}$) | PS II efficiency ($\mu mol \cdot mmol^{-1}$) |
|---|---|---|---|---|---|
| 6 Oct.$^x$ | 33 | 29.9 | 0.278 | 6.1 | 0.155 |
| | 67 | 28.1 | 0.271 | 5.7 | 0.138 |
| | 100 | 30.8 | 0.301 | 5.8 | 0.158 |
| | 133 | 30.1 | 0.299 | 5.6 | 0.148 |
| | 167 | 24.2 | 0.228 | 5.7 | 0.115 |
| | Mean | 28.6 | 0.275 | 5.8 | 0.143 |
| | L | 0.116 | 0.358 | 0.170 | 0.065 |
| | Q | 0.068 | 0.155 | 0.236 | 0.068 |
| 20 Oct. | 33 | 17.7 | 0.160 | 4.6 | 0.181 |
| | 67 | 34.5 | 0.393 | 4.4 | 0.219 |
| | 100 | 39.1 | 0.445 | 4.4 | 0.238 |
| | 133 | 35.6 | 0.430 | 4.1 | 0.218 |
| | 167 | 35.8 | 0.458 | 3.9 | 0.220 |
| | Mean | 32.5 | 0.377 | 4.3 | 0.215 |
| | L | <0.0001 | <0.0001 | 0.002 | 0.007 |
| | Q | <0.0001 | <0.0001 | 0.010 | <0.0001 |
| 9 Nov. | 33 | 18.6 | 0.172 | 4.02 | 0.176 |
| | 67 | 24.2 | 0.240 | 3.82 | 0.181 |
| | 100 | 25.1 | 0.251 | 4.0 | 0.188 |
| | 133 | 25.2 | 0.251 | 4.0 | 0.180 |
| | 167 | 23.6 | 0.251 | 3.9 | 0.180 |
| | Mean | 23.3 | 0.233 | 3.9 | 0.181 |
| | L$^w$ | 0.065 | 0.012 | 0.858 | 0.713 |
| | Q$^w$ | 0.013 | 0.006 | 0.977 | 0.621 |
| Significance | | | | | |
| Date (D) | | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Rate (R) | | <0.0001 | <0.0001 | 0.025 | 0.005 |
| D × R | | <0.0001 | <0.0001 | 0.540 | 0.002 |

$g_S$ = stomatal conductance; WUE = water use efficiency; PSII = photosystem II.

$^z$% ETc = percentage of crop evapotranspiration.

$^y$Leaf gas exchange and fluorescence measured with infrared gas analyzer (LI-COR 6400; LI-COR, Inc.).

$^x$Temperature and rainfall on days of measurement: 6 Oct. (maximum temperature = 23.9 °C; minimum temperature = 9 °C; rainfall = 0 mm); 20 Oct. (maximum temperature = 27.1 °C; minimum temperature = 14.6 °C; rainfall = 0 mm); 9 Nov. (maximum temperature = 26.0 °C; minimum temperature = 6.1 °C; rainfall = 0 mm).

$^w$L = linear response; Q = quadratic response.

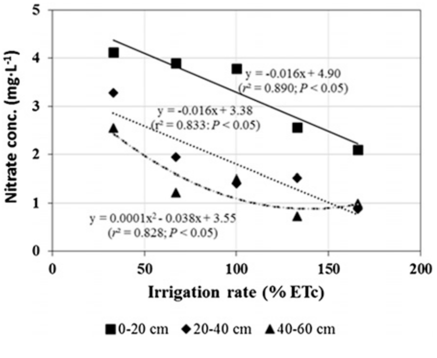

Fig. 3. Effect of irrigation rate and soil depth on the concentration of nitrate-nitrogen in the soil (0 to 60 cm) in drip-irrigated eggplant grown on raised beds and plastic film mulch. Irrigation rate was applied as percentage of crop evapotranspiration. Line was fit by linear regression. Fall of 2010, Tifton, GA.

Table 3. Foliar mineral nutrient concentrations in eggplant as affected by several irrigation rates. Fall of 2010, Tifton, GA.[z]

| | N | P | K | Ca | Mg | S | Al | B | Cu | Fe | Mn | Mo | Na | Ni | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rate (%)[y] | (%) | | | | | | ($\mu g \cdot g^{-1}$) | | | | | | | | |
| 33 | 5.3 | 0.28 | 4.6 | 1.80 | 0.36 | 0.43 | 131 | 37 | 5 | 153 | 546 | 1.6 | 68 | 2.6 | 35 |
| 67 | 5.1 | 0.31 | 4.3 | 1.77 | 0.34 | 0.38 | 108 | 38 | 6 | 137 | 480 | 2.0 | 72 | 2.3 | 33 |
| 100 | 5.1 | 0.33 | 4.7 | 1.71 | 0.35 | 0.40 | 99 | 39 | 6 | 122 | 487 | 1.5 | 80 | 2.2 | 34 |
| 133 | 5.0 | 0.32 | 4.2 | 1.82 | 0.34 | 0.36 | 114 | 42 | 6 | 136 | 478 | 2.7 | 78 | 2.9 | 32 |
| 167 | 4.9 | 0.34 | 4.1 | 1.78 | 0.35 | 0.41 | 107 | 41 | 6 | 127 | 449 | 1.9 | 80 | 2.1 | 31 |
| Significance | | | | | | | | | | | | | | | |
| L[x] | 0.001 | 0.001 | 0.041 | 0.978 | 0.678 | 0.511 | 0.184 | 0.333 | 0.501 | 0.055 | 0.159 | 0.448 | 0.425 | 0.867 | 0.165 |
| Q[x] | 0.007 | 0.005 | 0.079 | 0.958 | 0.865 | 0.406 | 0.139 | 0.634 | 0.722 | 0.067 | 0.359 | 0.685 | 0.704 | 0.956 | 0.384 |

[z] Leaf samples from mature plants (20 Oct. 2010).

[y] % ETc = percentage of crop evapotranspiration.

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

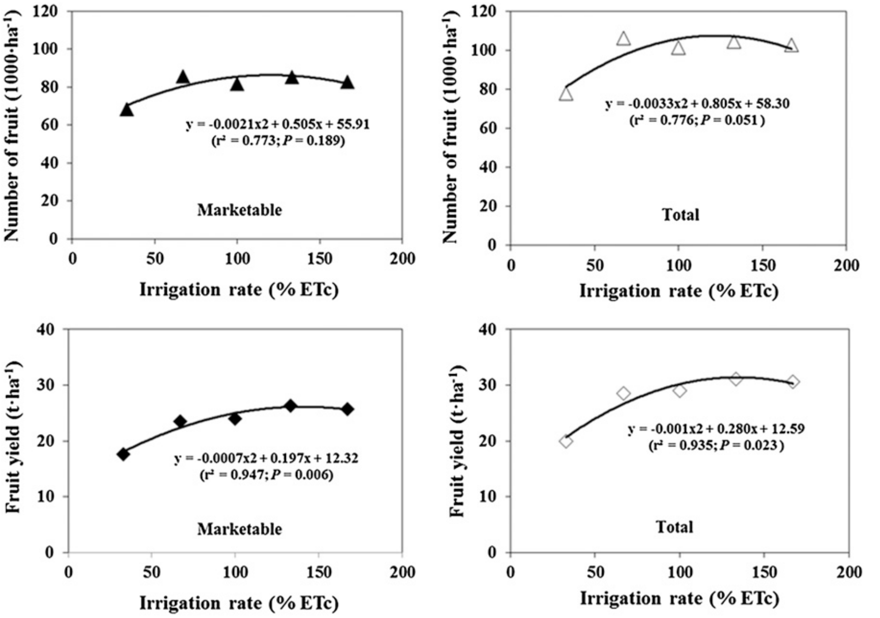

Fig. 4. Cumulative number of fruit and fruit yields as affected by irrigation rate in drip-irrigated eggplant grown on raised beds and plastic film mulch. Irrigation rate was applied as percentage of crop evapotranspiration. Line was fit by linear regression. Fall of 2010, Tifton, GA.

spacing (i.e., with increased soil water levels) (Madramootoo and Rigby, 1991).

*Leaf CI.* In 2010, CIs decreased with increased irrigation rate ($P = 0.006$), from 60.8 at 33% ETc to 59.0 at 167% ETc. In 2011, CI decreased from 55.8 at 33% ETc to 53.7 at 167% ETc (Table 1). Decreased CI values with increased irrigation rates were likely due to dilution effect of nutrients, since plant growth was enhanced with increased irrigation rates. Decreased CI with increased irrigation rates may also be associated with increased nitrate leaching under high irrigation rates.

*Soil water content.* In 2010, the effect of irrigation rate on SWC varied with soil depth. At 0- to 30-cm depth, SWC increased with increasing irrigation rates (Fig. 2), whereas at 0- to 12-cm depth SWC was unaffected by irrigation rate. Differences in soil moisture in the different soil depths indicate a higher soil water uptake by plants, because of greater presence of roots at 0–12 cm than at 0- to 30-cm depth; they also indicate that high rates of irrigation (>100% ETc) result in wasted water because much water at 0- to 30-cm depth was not taken up by the crop; and they suggest that soil moisture measurement at 0- to 30-cm depth was more sensitive to detect changes in soil moisture than measurement at 0- to 12-cm depth.

As in 2010, seasonal SWC at 0- to 12-cm depth was also similar among irrigation rates (mean = 13.4%) in 2011. In addition to the high presence of roots at 0- to 12-cm depth, SWC values were similar among treatments in 2011 probably because the study was conducted in a low field, with a nearly level slope, where soil was commonly moist throughout the season, likely due to lateral water movement from upper sections of the field. There was an impermeable clay layer 30- to 40-cm deep in the soil profile that probably allowed water to flow from upper to lower areas within the farm.

*Leaf gas exchange.* In 2010, the effect of irrigation rate on leaf gas exchange varied by date (Table 2). Net photosynthesis, $g_S$, and photosynthetic WUE were unaffected by irrigation rate on 6 Oct. 2010. Lack of treatment differences on 6 Oct. was probably attributable to relatively low temperatures on day of measurement (mean temperature = 16.4 °C), resulting in low crop evaporative demand and low crop water stress. Net photosynthesis and $g_S$ were lowest at 33% ETc on 20 Oct. and 9 Nov. Water use efficiency was highest and PSII efficiency was lowest at 33% ETc on 20 Oct. The fact that gas exchange variables were not reduced at 67% ETc compared with higher irrigation rates suggests that plants at 67% ETc were likely unaffected by water stress. However, since gas exchange measurements were conducted only in mature plants, late in the season, when evaporative demand was reduced, it is possible that earlier in the season plants may have had experienced increased water stress at reduced irrigation rates, as suggested by the reduced plant growth at reduced irrigation rates. In 2011, leaf net photosynthesis (mean = 28.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$), $g_S$ (mean = 0.248 $mol \cdot m^{-2} \cdot s^{-1}$), WUE (mean = 4.24 $\mu mol \cdot mmol^{-1}$), and PSII (mean = 0.189 $\mu mol \cdot mmol^{-1}$) were unaffected by irrigation rate. Air maximal and minimal temperature on the day of measurement were 27.5 and 11.0 °C, respectively. Lack of differences in gas exchange are consistent with the lack of differences in plant growth among irrigation rates observed in 2011.

Irrigation at 33% ETc was probably insufficient to satisfy eggplant water requirements, as suggested by the reduced leaf gas exchange values (Table 2). Reduced irrigation rates can result in decreased gas exchange in solanaceous crops. Transpiration, leaf $g_S$, and leaf net photosynthesis in eggplant were reduced with water stress and effects varied depending on stress severity and duration (Sarker et al., 2005). In habanero pepper (*Capsicum chinense* Jacq.), there was reduced $g_S$ and net photosynthesis with increased time between irrigations (Jaimez et al., 1999).

*Soil nitrate.* Soil nitrate concentration decreased with increasing irrigation rate ($P = 0.002$) and soil depth ($P = 0.003$), indicating that nitrate leaching to the deepest parts of the soil was enhanced with increased irrigation rates (Fig. 3). Decreased soil nitrate concentration may also be due to high N uptake by the crop, as suggested by augmented vegetative growth with increasing irrigation rate. Nitrate present at 40–60 depth is usually lost as it is not recovered by plants' roots. Decreased nitrate in 40- to 60-cm zone is thus solely due to leaching.

*Foliar mineral nutrient concentrations and CI.* In 2010, foliar N and K concentrations decreased and P increased with increasing irrigation rate (Table 3). Other foliar nutrients concentrations were unaffected by irrigation rate. Nitrogen, K, and CI decreased with irrigation rate, possibly as a result of a dilution effect associated with increased aboveground plant growth. In addition, at high irrigation rates plants likely had reduced access to soil N due to increased nitrate leaching. Plant water stress in eggplant can reduce foliar N, P, and K concentrations compared with well-irrigated plants (Kirnak et al., 2002). In the present study, however, only foliar P was reduced at low irrigation rate.

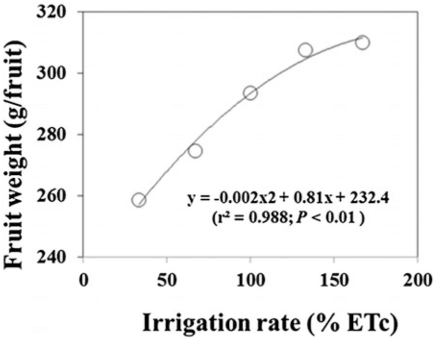

Fig. 5. Individual fruit weight as influenced by irrigation rate in drip-irrigated eggplant grown on raised beds and plastic film mulch. Irrigation rate was applied as percentage of crop evapotranspiration. Line was fit by linear regression. Fall of 2010, Tifton, GA.

Chlorophyll indices have been used as indirect estimators of chlorophyll and leaf N concentrations (Liu et al., 2006). Crop drought stress may influence leaf morphology (e.g., increased specific leaf weight) in plants (Larcher, 1995); these variations in leaf morphology may also influence CI, making difficult to use CI to estimate leaf N (Díaz-Pérez, 2013). In our study, CI values increased with increasing leaf N ($R^2 = 0.921$; $P = 0.001$), supporting the use of chlorophyll meter to estimate leaf N.

*Yield.* In 2010, fruit number and fruit yields (marketable and total) were lowest at 33% ETc and there were little yield differences among irrigation rates higher than 33% ETc (Fig. 4). Individual fruit weight was also reduced at 33% ETc (Fig. 5). There was a higher correlation between fruit number and fruit yield ($R^2 = 0.94$; $P < 0.0001$) than between individual fruit weight and fruit yield ($R^2 = 0.15$; $P = 0.027$), suggesting that marketable yield was determined more by fruit number than individual fruit weight. In greenhouse-grown eggplant, soil water deficit decreased fruit number but not fruit size (Chartzoulakis and Drosos, 1995). In a study with different levels of irrigation and N fertilizer, eggplant fruit yield was more related with fruit number than with fruit size (Aujla et al., 2007). In another study, soil water deficits also reduced eggplant fruit size, but the effect of drought stress on fruit number was not evaluated (Kirnak et al., 2002). In 2011, irrigation rate had no effect on the number or yields of marketable, cull, and total fruit, or on individual fruit weight (Table 4). There were no significant interactions between harvest dates and irrigation rates. There was also a higher correlation between fruit number and fruit yield ($R^2 = 0.92$; $P < 0.0001$) than between individual fruit weight and fruit yield ($R^2 = 0.185$; $P = 0.001$). Results suggest that eggplant may tolerate moderate water stress, since plants irrigated at 67% ETc produced fruit yields similar to those of plants irrigated at 100% ETc or higher rates. Thus, there is a potential to reduce irrigation rates below 100% ETc without negatively impacting fruit yields.

Table 4. Fruit yield of eggplant as affected by irrigation rate. Fall of 2011, Tifton, GA.

| | Marketable | | Cull | | Total | | Fruit wt |
|---|---|---|---|---|---|---|---|
| Rate (%)$^z$ | (1000/ha) | (t·ha$^{-1}$) | (1000/ha) | (t·ha$^{-1}$) | (1000/ha) | (t·ha$^{-1}$) | (g/fruit) |
| 33 | 164 | 36 | 8.4 | 1.6 | 191 | 37 | 197 |
| 67 | 169 | 37 | 4.2 | 0.8 | 191 | 38 | 198 |
| 100 | 154 | 35 | 7.9 | 1.6 | 178 | 36 | 203 |
| 133 | 180 | 41 | 5.5 | 1.2 | 205 | 42 | 206 |
| 167 | 179 | 40 | 8.4 | 1.3 | 207 | 41 | 199 |
| Significance | | | | | | | |
| L$^y$ | 0.206 | 0.140 | 0.778 | 0.918 | 0.208 | 0.145 | 0.502 |
| Q$^y$ | 0.341 | 0.324 | 0.247 | 0.747 | 0.297 | 0.322 | 0.503 |

$^z$% ETc = percentage of crop evapotranspiration.

$^y$L = linear; Q = quadratic response.

Table 5. Irrigation, cumulative rainfall, IWUE, and AEN of eggplant crop grown on plastic film mulch. Fall of 2010 and 2011, Tifton, GA.

| | Irrigation (mm) | | Rainfall (mm) | | Total water (mm) | | IWUE$^y$ (kg·ha$^{-1}$·mm$^{-1}$) | | AEN$^x$ (kg·kg$^{-1}$ N) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Rate (%)$^z$ | 2010 | 2011 | 2010 | 2011 | 2010 | 2011 | 2010 | 2011 | 2010 | 2011 |
| 33 | 149 | 83 | 217 | 318 | 366 | 401 | 134 | 449 | 92 | 172 |
| 67 | 211 | 118 | 217 | 318 | 428 | 436 | 135 | 321 | 131 | 178 |
| 100 | 272 | 152 | 217 | 318 | 489 | 470 | 107 | 238 | 133 | 166 |
| 133 | 333 | 187 | 217 | 318 | 550 | 505 | 93 | 225 | 143 | 193 |
| 167 | 394 | 221 | 217 | 318 | 611 | 539 | 78 | 184 | 141 | 187 |
| Significance | | | | | | | | | | |
| L$^w$ | | | | | | | <0.0001 | <0.0001 | 0.006 | 0.146 |
| Q$^w$ | | | | | | | 0.0002 | <0.0001 | 0.006 | 0.324 |

$^z$% ETc = percentage of crop evapotranspiration.

$^y$IWUE = irrigation water use efficiency (IWUE = fruit wt/irrigation water); fruit wt = total fruit fresh weight (kg·ha$^{-1}$); irrigation water (mm).

$^x$AEN = agronomic efficiency of nitrogen (AEN = fruit wt/total N); total fruit fresh weight (kg·ha$^{-1}$); total N applied (kg·ha$^{-1}$).

$^w$L = linear; Q = quadratic response.

*Irrigation water use efficiency and agronomic efficiency of nitrogen.* Plants received more irrigation water in 2010 than in 2011 as a result of reduced rainfall in 2010 (Table 5). In both years, IWUE decreased with increasing irrigation rate. IWUE was greatly reduced and there were significant effects of irrigation rates on several variables in 2010, but not in 2011. Increased IWUE and increased SWC in 2011 (mean = 13.4% at 0- to 12-cm depth) relative to SWC in 2010 (mean = 7.5% at 0- to 12-cm depth) are probably associated with increased contribution of soil water from rainfall and drainage water from upper areas of the field; in 2011, field used was low and nearly flat.

Although there were differences in leaf N among irrigation treatments, fruit yield was likely more related to irrigation rate than to leaf N. Total yield showed a quadratic relationship with leaf N ($R^2 = 0.185$; $P = 0.013$); total yield was unaffected by leaf N below 5.1% and was lowest at the highest leaf N (5.3%) occurred at the lowest irrigation rate (33% ETc).

Agronomic efficiency of N increased with irrigation rate in 2010 likely as a result of increased fruit yield associated with improved plant water status; AEN was unaffected by irrigation rate in 2011. AEN values in this study (range 92 to 187 kg·kg$^{-1}$ N) were lower compared with values of other studies on eggplant (range = 324 to 859 kg·kg$^{-1}$ N) (Aujla et al., 2007), probably because the harvest period in this study was reduced. Low AEN values may also mean that eggplant crop in this study made inefficient use of N fertilizer, probably in part due to overfertilization. Aujla et al. (2007) reported that irrigation rate and N fertilization rate interacted in drip-irrigated eggplants; they also found that irrigation at 75% pan evaporation and 120 kg·ha$^{-1}$ N produced the greatest yields, and that AEN increased with increased N fertilization rate.

*Fruit DW content and HI.* In year 2010, fruit DW content (mean = 6.2%) was unaffected by irrigation rate. In a study under semiarid conditions, soluble DW or soluble solids in eggplant decreased with increased irrigation rates (Kirnak et al., 2002). In greenhouse-grown eggplant, increased irrigation rates also decreased fruit DW content (Chartzoulakis and Drosos, 1995).

Harvest index was unaffected by irrigation rate (mean HI = 0.32). These data suggest that eggplant is more tolerant to drought than other solanaceous crops (Behboudian, 1977). Our measurements of HI did not include root biomass. However, under water stress, eggplants possibly allocated increased amounts of assimilates for root growth as occurs in other plants (Larcher, 1995). In habanero pepper, an irrigation rate of 20% of available water produced reduced values of HI (Quintal Ortiz et al., 2012). In tomato, there was no difference in total dry biomass and HI between the control and a partial irrigation treatment, but total dry biomass and HI significantly decreased under regulated deficit irrigation (Lei et al., 2009); moderate water stress–induced osmotic regulation under partial root drying conditions, leading to normal water status and the same level of biomass. Eggplant in our study was also able to maintain high fruit yields at moderate levels of water stress, suggesting that, as tomato, eggplant is also able to develop mechanisms to deal with water stress such as osmoregulation.

In conclusion, the results from this research indicate that eggplant may tolerate moderate water stress, since plants irrigated at 67% ETc had no detrimental effects on plant growth and leaf gas exchange and produced fruit yields similar to those of plants irrigated at 100% ETc. Thus, there is a potential to reduce current irrigation rates without negatively impacting fruit yields or quality.

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