Automated Irrigation Control for Improved Growth and Quality of *Gardenia jasminoides* ‘Radicans’ and ‘August Beauty’

Amanda Bayer, John Ruter, and Marc W. van Iersel¹

Department of Horticulture, University of Georgia, 1111 Miller Plant Sciences Building, The University of Georgia, Athens, GA 30602-7273

Additional index words. volumetric water content, nursery production, woody ornamentals, soil moisture sensor, container plants

Abstract. Sustainable use of water resources is of increasing importance in container plant production as a result of decreasing water availability and an increasing number of laws and regulations regarding nursery runoff. Soil moisture sensor-controlled, automated irrigation can be used to irrigate when substrate volumetric water content (θ) drops below a threshold, improving irrigation efficiency by applying water only as needed. We compared growth of two *Gardenia jasminoides* cultivars, slow-growing and challenging ‘Radicans’ and easier, fast-growing ‘August Beauty’, at various θ thresholds. Our objective was to determine how irrigation can be applied more efficiently without negatively affecting plant quality, allowing for cultivar-specific guidelines. Soil moisture sensor-controlled, automated irrigation was used to maintain θ thresholds of 0.20, 0.30, 0.40, or 0.50 $\text{m}^3\cdot\text{m}^{-3}$. Growth of both cultivars was related to θ threshold, and patterns of growth were similar in both Watkinsville and Tifton, GA. High mortality was observed at the 0.20- $\text{m}^3\cdot\text{m}^{-3}$ threshold with poor root establishment resulting from the low irrigation volume. Height, width, shoot dry weight, root dry weight, and leaf size were greater for the 0.40 and 0.50 $\text{m}^3\cdot\text{m}^{-3}$ than the 0.20 and 0.30- $\text{m}^3\cdot\text{m}^{-3}$ θ thresholds. Irrigation volume increased with increasing θ thresholds for both cultivars. For ‘August Beauty’, cumulative irrigation volume ranged from 0.96 to 63.21 L/plant in Tifton and 1.89 to 87.9 L/plant in Watkinsville. For ‘Radicans’, cumulative irrigation volume ranged from 1.32 to 126 L/plant in Tifton and from 1.38 to 261 L/plant in Watkinsville. There was a large irrigation volume difference between the 0.40 and 0.50- $\text{m}^3\cdot\text{m}^{-3}$ θ thresholds with little additional growth, suggesting that the additional irrigation applied led to over-irrigation and leaching. Bud and flower number of ‘Radicans’ were greatest for the 0.40- $\text{m}^3\cdot\text{m}^{-3}$ θ threshold, indicating that overirrigation can reduce flowering. The results of this study show that growth of the different *G. jasminoides* cultivars responded similarly to θ threshold at both locations. Similarities in growth and differences in irrigation volume at the 0.40 and 0.50- $\text{m}^3\cdot\text{m}^{-3}$ θ thresholds show that more efficient irrigation can be used without negatively impacting growth.

More efficient irrigation management has become a focus in sustainable container plant production (Chappell et al., 2013a) to improve resource use and to mitigate the environmental impact of fertilizers and pesticides found in nursery effluent (Beeson et al., 2004; Bilderback, 2002; Lea-Cox and Ross, 2001). Best management practices such as cyclic irrigation, grouping plants based on water needs, and runoff collection basins are effective methods of improving irrigation (Chappell

et al., 2013a) but do not control irrigation based on actual crop water requirements. Approaches to irrigation control based on substrate volumetric water content and/or daily water use (DWU) apply only the water needed by the crop to replace what is lost resulting from evapotranspiration and can provide greater efficiency (Bayer et al., 2013; van Iersel et al., 2010; Warsaw et al., 2009). Irrigating based on θ and DWU requires knowledge of a diversity of ornamental plant water requirements, which is currently limited (Warsaw et al., 2009). Understanding how plant growth is affected by maintenance of different θ thresholds will allow for species-specific guidelines. Automated irrigation using capacitance sensors to maintain θ thresholds can be used to grow plants at different levels of water availability, allowing for determination of thresholds at which growth is negatively impacted. Irrigation volume can be reduced using θ threshold control while still producing salable plants for a variety of ornamental crops including *Hibiscus acetosella* ‘Panama Red’ (Bayer et al.,

2013), *Gaura lindheimeri* ‘Siskiyou Pink’ (Burnett and van Iersel, 2008), *Hydrangea macrophylla* ‘Mini Penny’ (van Iersel et al., 2009), and *Lantana camara* (Bayer et al., 2014). To date sensor-controlled automated irrigation has largely been used in research; however, wireless sensor networks capable of controlling irrigation are being developed for practical implementation in commercial production (Kohanbash et al., 2013) and have been trialed in nurseries (Belayneh et al., 2013; Chappell et al., 2013b).

Management of irrigation water can also be beneficial for reducing the spread of soilborne pathogens. Losses resulting from soilborne pathogens can be $\approx 30\%$ for problem crops such as dwarf gardenias (*Gardenia jasminoides* ‘Radicans’ and ‘MADGA 1’), which are high-value yet problematic crops for many growers (Chappell et al., 2013b). *Phytophthora cinnamomi* was among the most prevalent pathogens in *Gardenia jasminoides* production at a commercial nursery in Georgia (Chappell et al., unpublished results). Control of θ has been shown to reduce pathogen pressure and disease incidence not only limiting losses, but also reducing the need for pesticide applications (Chappell et al., 2013b). Economic analysis of wireless sensor network-controlled irrigation and standard nursery irrigation practices in a commercial nursery in Georgia found shortened production time, 50% reduction in loss resulting from disease, and reduced fertilizer and fungicide applications, which resulted in a 20.6% increase in profits (Lichtenberg et al., 2013).

Greater allocation of resources to root development vs. shoot growth in water-limited conditions has been reported as a plant adaptation for survival (Kozłowski and Pallardy, 2002; Silva et al., 2012). Although the impact of soil moisture sensor-controlled irrigation on shoot growth is well known, information is limited on the effects on root growth (Bauerle et al., 2013). Bauerle et al. (2013) found that root distribution affected substrate moisture measurements in container-grown tree species with greater variability with greater biomass and/or coarser roots. An understanding of how root growth is affected by θ is valuable not only for container plant production, but also the establishment of plants in the landscape.

Comparing the growth of *Gardenia jasminoides* ‘August Beauty’ and ‘Radicans’ grown at various θ thresholds will provide further information about how irrigation can be applied more efficiently without negatively impacting plant quality. On-farm trials have shown that sensor-controlled irrigation can prevent root disease problems in *Gardenia jasminoides* and shorten the production cycle (Chappell et al., 2013b). However, there has been no research to determine the optimal θ threshold for *Gardenia jasminoides*. This study compared growth of more challenging *Gardenia jasminoides* ‘Radicans’ and faster-growing, less problematic *Gardenia jasminoides* ‘August Beauty’. The objectives of this study were to see if both cultivars exhibit similar growth responses to

Received for publication 12 Aug. 2014. Accepted for publication 20 Nov. 2014.

The research was funded by USDA-NIFA-SCRI (award no. 2009-51181-05768).

We thank Sue Dove for her assistance with this research and McCorkle Nurseries for supplying plant material and substrate. We thank Bob Teskey, Matthew Chappell, and Sheryl Wells for their suggestions on the manuscript.

¹To whom reprint requests should be addressed; e-mail mvanier@uga.edu.

Fig. 1. Substrate volumetric water content (lines) and rain (bars) over the course of the 191-d Tifton (right graphs) and 190-d Watkinsville (left graphs) experiments. *Gardenia jasminoides* 'August Beauty' (upper graphs) and 'Radicans' (lower graphs) were irrigated when substrate volumetric water content dropped below the irrigation threshold (0.20, 0.30, 0.40, 0.50 $\text{m}^3 \cdot \text{m}^{-3}$). Drying of substrates to θ thresholds after rain events was generally achieved within days for both experiments.

Fig. 2. Cumulative irrigation volume for the production of *Gardenia jasminoides* 'August Beauty' and 'Radicans' as a function of the volumetric water content thresholds at which irrigation occurred over the course of the 191- (Tifton) or 190-d (Watkinsville) period. Cumulative irrigation volume increased with increasing volumetric water content threshold ($P = 0.0001$). Data were log-transformed before analysis to account for differences in variance among treatments. Trendlines represent quadratic regression curves for 'August Beauty' and cubic regression curves for 'Radicans'.

θ levels, to compare shoot vs. root growth, and to determine whether θ affects the susceptibility of plants to *Phytophthora cinnamomi*.

Materials and Methods

Research was conducted at the University of Georgia Horticulture Farm in Watkinsville, GA, from 4 May to 9 Nov. 2011 and at the University of Georgia Tifton Campus from 18 Apr. to 25 Oct. 2011. The studies were conducted at two locations to compare plant responses under different environmental conditions.

Plant material. *Gardenia jasminoides* ‘August Beauty’ and ‘Radicans’ in 3.8-L black plastic containers were obtained from McCorkle Nurseries (Dearing, GA) on 5 Apr. 2011. Plants were grown in a pine bark substrate with 1.97 kg·m⁻³ lime, 0.74 kg·m⁻³ Micromax® (Everris, Dublin, OH), 0.74 kg·m⁻³ gypsum, and 1.98 kg·m⁻³ of controlled-release fertilizer (Osmocote Pro 18-6-12; 18.0N-2.6P-10.0K; Everris, Dublin, OH). Plants were kept well watered for 2 or 4 weeks (Tifton and Watkinsville, respectively) to allow for root establishment of the recently transplanted cuttings.

Treatments and data collection. Identical soil moisture sensor-controlled irrigation systems, based on that described by Nemali and van Iersel (2006), were used in both locations. Both locations had 16 plots with plots being experimental units consisting of 18 to 20 plants. Soil moisture sensors (10HS; Decagon Devices, Pullman, WA) were inserted into two pots in each of the 16 plots at an $\approx 45^\circ$ angle. Sensors were inserted with the prongs extending into the center of the substrate to a depth at which the entire sensor was in the substrate. The 32 sensors were connected to a multiplexer (AM416; Campbell Scientific, Logan, UT), which was connected to a data logger (CR10; Campbell Scientific). The data logger excited the sensors with 2.5 VDC and measured the resulting voltage output from the sensors every 20 min.

The voltage readings from the sensors were converted to θ using our own calibration [$\theta = -0.401 + 1.0124 \times \text{output (V)}$] developed using the method described by Nemali et al. (2007). When both sensor measurements were less than the θ threshold for that plot (0.20, 0.30, 0.40, or 0.50 m³·m⁻³), the data logger signaled the relay driver (SDM16AC/DC controller; Campbell Scientific) to open the appropriate solenoid valve (sprinkler valve; Orbit, Bountiful, UT). Plants were irrigated with 60 mL of water over a period of 2 min using dribble rings (Dramm, Manitowoc, WI) connected to pressure-compensated drip emitters (Netafim USA, Fresno, CA). The small amount of water applied at each irrigation event was chosen to maintain θ at a stable level in the absence of rain. If a plant with a sensor died during the course of the experiment, the sensor was moved to another pot.

Soil moisture readings from each sensor were averaged and stored every 2 h and the number of irrigation events per plot was

Table 1. Average temperature, relative humidity, vapor pressure deficit, and rainfall over the course of the 191- and 190-d experiments in Tifton and Watkinsville, GA.

	Avg temp (°C)	Relative humidity	Vapor pressure deficit (kPa)	Rainfall (mm)
Tifton	25.2	63.5%	1.38	599
Watkinsville	23.1	66.5%	1.20	387

Fig. 3. Shoot dry weight (top) and root dry weight (bottom) of *Gardenia jasminoides* ‘August Beauty’ and ‘Radicans’ as affected by irrigation thresholds (θ) (0.20, 0.30, 0.40, and 0.50 m³·m⁻³) for irrigation. Data were normalized before analysis by dividing all data by cultivar averages to account for natural differences in growth habit among cultivars. Means with the same letter indicate that the main effect of θ thresholds is nonsignificant ($P \leq 0.05$). There were no location effects or cultivar by θ interaction effects.

recorded daily. The total irrigation volume for a plot was calculated from the number of irrigation events and the volume of water applied per irrigation event. Environmental conditions were measured using a temperature and relative humidity sensor (HMP50; Vaisala, Woburn, MA), a quantum sensor (SQ-110; Apogee Instruments, Logan, UT), and a rain gauge (ECRN-50; Decagon Devices) connected to the data logger. On 11 Aug. 2011 two to three plants from each plot at the Watkinsville location were inoculated with 5 g of *Phytophthora cinnamomi* colonized rice grains produced through the method for inoculum production described by Holmes and Benson (1994). Inoculated plants were kept on the same irrigation line but were physically separated from other plants to avoid pathogen spread through leached water. Plants were monitored for signs of disease for the remainder of the experiment.

Bud and bloom count was performed biweekly from August through October at

the Watkinsville location. At the conclusion of the 191- and 190-d experiments (Tifton and Watkinsville, respectively), plant height and width were recorded. Ten of the uppermost fully expanded leaves were collected and leaf size was measured using a leaf area meter (LI-3100; LI-COR, Lincoln, NE). Shoots were cut off at the substrate surface and were dried at 80 °C after which dry weight was determined. Substrate was washed from the roots, which were then dried at 80 °C and dry weight was determined. Compactness was calculated as shoot dry weight/plant height.

Experimental design and data analysis. The experiment was designed as a split-split plot design with two replications with the main plot being location and the splits being θ and cultivar. Data were analyzed using the PROC MIXED procedure of SAS (SAS Version 9.2; SAS Institute, Cary, NC) with $P = 0.05$ considered statistically significant. Treatment means were separated using either

Fig. 4. Total dry weight as a function of the total volume of irrigation water applied. Dry weight increased linearly with increasing irrigation volume (indicated by solid lines) for the 0.20- to 0.40- $\text{m}^3\cdot\text{m}^{-3}$ thresholds (Tifton, 'August Beauty': $y = 8.188 + 1.6533x$, $R = 0.94$; Watkinsville, 'August Beauty': $y = 8.1315 + 1.1508x$, $R = 0.95$; Tifton, 'Radicans': $y = 0.6594 + 1.7552x$, $R = 0.99$; Watkinsville, 'Radicans': $y = 0.6245 + 0.9760x$, $R = 0.91$). Extrapolation of these linear relationships to the dry weight observed at the 0.50- $\text{m}^3\cdot\text{m}^{-3}$ threshold (dashed lines) estimates the irrigation volume expected at the 0.50- $\text{m}^3\cdot\text{m}^{-3}$ threshold if these linear relationships continued. Horizontal arrows show the deviation from these relationships and are estimates of the leachate volume with the 0.50- $\text{m}^3\cdot\text{m}^{-3}$ thresholds.

the SLICE or PDIFF option of PROC MIXED. Curve fitting was done using SigmaPlot (Systat, San Jose, CA). Log transforms were performed when necessary to account for unequal variance among treatments. Plant growth measurements were normalized by dividing each data point by the average of all data for that growth parameter for that particular cultivar. After normalization the average across all treatments for a cultivar was one. Without normalization there was a large cultivar effect on plant growth, because 'August Beauty' is a much larger, faster-growing cultivar than 'Radicans'. This large difference in growth between the two cultivars masked any cultivar-by- θ interactions when non-normalized data were used for analysis. Normalization of the data allowed us to test for interactive effects cultivar by θ on growth but not for the main cultivar effect.

Results and Discussion

Substrate water content. At the onset of the θ treatments, drying of substrates to the higher θ thresholds was achieved quickly, whereas drying to lower θ thresholds, specifically 0.20 $\text{m}^3\cdot\text{m}^{-3}$, required more time (30 to 34 d in Tifton and 23 d in Watkinsville) as a result of low water use of the plants and rainfall. After the θ thresholds were reached, θ was effectively maintained above the θ thresholds throughout the experiment (Fig. 1) with irrigation frequency adjusting to increasing plant size and changing environmental conditions. Average θ s for Tifton were 0.32 ± 0.06 , 0.35 ± 0.05 , 0.43 ± 0.03 , and $0.52 \pm 0.02 \text{ m}^3\cdot\text{m}^{-3}$ for the 0.2, 0.3, 0.4, and 0.5- $\text{m}^3\cdot\text{m}^{-3}$ thresholds, respectively. Average θ s for Watkinsville were 0.29 ± 0.06 ,

Fig. 5. Area of the uppermost fully expanded leaf of *Gardenia jasminoides* 'August Beauty' and 'Radicans' as affected by irrigation threshold. Data were normalized before analysis by cultivar averages to account for natural differences in growth habit among cultivars. Leaf size was lower with the 0.20- and 0.30- $\text{m}^3\cdot\text{m}^{-3}$ thresholds than with the 0.40- and 0.50- $\text{m}^3\cdot\text{m}^{-3}$ thresholds ($P = 0.002$). Leaves in Tifton were larger than those in Watkinsville ($P = 0.01$), which may be the result of differences in environmental conditions among the two locations.

0.39 ± 0.06 , 0.42 ± 0.02 , and $0.52 \pm 0.02 \text{ m}^3\cdot\text{m}^{-3}$ for Watkinsville. Fluctuations in θ occurred with larger variations, the result of rain events, which occurred frequently in both locations. Rainfall events caused larger increases in θ for the lower θ thresholds, likely because of higher θ thresholds being close to container capacity. Rain resulted in a larger increase in θ when the θ was low, because at high θ , rain is more likely to result in leaching. Therefore, the average θ was closer to the θ threshold at higher thresholds. Plant water use and evapotranspiration resulted in the substrate water contents decreasing to θ thresholds after rain events.

Maintenance of the 0.50- $\text{m}^3\cdot\text{m}^{-3}$ threshold required frequent irrigation with 10 to 504 irrigation events per week depending on rainfall and plant water use. This demonstrates the inefficiency of maintaining high θ thresholds and the greater likelihood of over-irrigation. Leaching was not measured but was observed frequently at the 0.50- $\text{m}^3\cdot\text{m}^{-3}$ threshold.

Irrigation volume. Cumulative irrigation volume increased with increasing θ thresholds ($P = 0.0001$) for both cultivars and at both locations (Fig. 2), as previously described for other species (Bayer et al., 2013; Burnett and van Iersel 2008; van Iersel et al.,

Fig. 6. Height (top) and width (middle) and compactness (bottom) of *Gardenia jasminoides* 'August Beauty' and 'Radicans' as affected by irrigation threshold. Data were normalized by cultivar averages before analysis to account for differences in growth habit between cultivars. Irrigation thresholds with the same letter indicate that the main effect of irrigation, averaged over both cultivars, is nonsignificant ($P \leq 0.05$).

2010). For 'August Beauty', average cumulative irrigation volume ranged from 0.96 to 63.21 L/plant in Tifton and 1.89 to 87.87 L/plant in Watkinsville. For 'Radicans', cumulative irrigation volume ranged from 1.32 to 125.58 L/plant in Tifton and from 1.38 to 261.21 L/plant in Watkinsville. Differences in irrigation volumes between locations were likely the result of differences in environmental conditions, specifically rainfall (Tifton: 599 mm, Watkinsville: 387 mm), but also temperature and vapor pressure deficit (Table 1). Cumulative irrigation totals do not include any water plants received from rainfall. It is not clear why there was a large difference in irrigation volumes between cultivars; however, differences in leaf area

and growth habit may have contributed to the differences in water use.

The large variation in irrigation volume between the replications of the 0.50-m³·m⁻³ threshold is likely the result of the difficulty in maintaining the 0.50-m³·m⁻³ threshold, which is near container capacity, and the likelihood of excessive irrigation and leaching. This may have also been influenced by sensor-to-substrate contact with the possibility that large bark pieces in the substrate created air pockets that interfered with uniform substrate contact. Air pockets near the sensor lower the dielectric measurement and could result in a sensor underestimating θ (Decagon Devices, 2014), which could result in irrigation. Burnett and van Iersel (2008) also

reported greater between-replication variation in water use at high thresholds with leaching observed. Container capacity was not quantified; however, leaching frequently occurred with the 0.50-m³·m⁻³ threshold even in the absence of rain.

Plant growth. Shoot and root dry weights of 'August Beauty' were generally higher than those of 'Radicans' so data were normalized by cultivar to allow for comparisons of θ thresholds on growth patterns between cultivars. Shoot dry weight of 'August Beauty' increased from 3.5 to 59 g and that of 'Radicans' from 2.7 to 33 g for increasing θ threshold. Shoot dry weight was lower with 0.20 and 0.30-m³·m⁻³ thresholds than with 0.40 and 0.50-m³·m⁻³ thresholds (Fig. 3), but unaffected by the location or the cultivar-by-threshold interaction.

Increasing shoot dry weight with increasing θ thresholds has been reported for *Gaura lindheimeri* 'Siskiyou Pink' (Burnett and van Iersel, 2008) and *Hibiscus acetosella* 'Panama Red' (Bayer et al., 2013) with salable plants produced at moderate thresholds (0.25 to 0.35 m³·m⁻³ and 0.35 to 0.40 m³·m⁻³, respectively). Reduced irrigation volumes have been used to produce plants with minimal reductions in plant growth. Groves et al. (1998) found that irrigation volume of *Cotoneaster dammeri* 'Skogholm' could be reduced by 40% from the volume needed to produce the maximum dry weight while still producing plants with 90% of the maximum shoot dry weight. Tyler et al. (1996) found a reduction of only 8% of maximum shoot dry weight for *Cotoneaster dammeri* 'Skogholm' with a leaching fraction of 0.0 to 0.2 instead of 0.4 to 0.6. Applying 6% to 75% less water than the control treatment of 19 mm·d⁻¹ increased shoot dry weight or had no effect on 23 different woody ornamental species (Warsaw et al., 2009). Our results support these findings with shoot dry weight of plants produced at the 0.40-m³·m⁻³ threshold similar to those grown at the 0.50-m³·m⁻³ threshold while receiving 49% and 87% less water for 'August Beauty' and 'Radicans', respectively.

Root dry weight increased with increasing θ threshold from 1.51 to 37.3 g/plant for 'August Beauty' and from 1.11 to 15.69 g/plant for 'Radicans' (Fig. 3). The small root systems of plants grown at the 0.20 and 0.30-m³·m⁻³ θ thresholds demonstrate that these thresholds were insufficient for good root establishment. This resulted in high mortality rates for both cultivars at both locations at the 0.20-m³·m⁻³ threshold (72% in Tifton and 79% in Watkinsville). The 0.30-m³·m⁻³ threshold also resulted in high mortality (49% in Tifton, 13% in Watkinsville) and growth was less than for higher θ thresholds.

Similar to this study, Álvarez and Sánchez-Blanco (2013) found that root dry weight of *Callistemon citrinus* 'Firebrand' was reduced with increasing drought stress, although moderate drought stress resulted in similar root dry weight as the control treatment. Fulcher et al. (2012) reported less root growth of *Hibiscus rosa-sinensis* 'Cashmere

Wind' with the lowest θ setpoint ($0.22 \text{ m}^3 \cdot \text{m}^{-3}$) but similar root dry weight among plants with the higher θ setpoints ($0.30, 0.41, 0.49 \text{ m}^3 \cdot \text{m}^{-3}$). Tyler et al. (1996) found that root dry weight of *Cotoneaster dammeri* 'Skogholm' was unaffected by irrigation volume. The variability in root dry weight with irrigation volume may be the result of natural variability in root growth responses to θ among species or as a result of substrate physical properties.

The relationship between total dry weight and irrigation volume demonstrates that irrigating to maintain θ above the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold applied excessive water with little additional plant growth compared with the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold (Fig. 4). Dry weight increased linearly with increasing irrigation volume for the 0.20 - to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds with average cumulative irrigation volumes $1.44, 10.54$, and 31.49 L/plant , respectively (Tifton, 'August Beauty': $y = 8.188 + 1.6533x, R = 0.94$; Watkinsville, 'August Beauty': $y = 8.1315 + 1.1508x, R = 0.95$; Tifton, 'Radicans': $y = 0.6594 + 1.7552x, R = 0.99$; Watkinsville, 'Radicans': $y = 0.6245 + 0.9760x, R = 0.91$) (solid lines, Fig. 4). Extrapolating the linear relationship for the 0.20 - to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds (dashed lines, Fig. 4) demonstrates the proportional increase in total dry weight and irrigation that would be expected at the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold if a linear response continued. The difference between the actual irrigation volume (134.47 L/plant average) and the extrapolated line of estimated irrigation volume with the linear relationship of the 0.20 - to $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds is an estimation of leaching, which was 19 to 335 L (horizontal arrows, Fig. 4). The $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold produced additional dry weight but not in proportion to the additional irrigation water applied, suggesting that the additional irrigation water leached from the container. Irrigation volume was 49% and 87% less

with the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold than with the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold for 'August Beauty' and 'Radicans', respectively.

Similar to other growth parameters, leaf size was lower with the 0.20 - and $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds than with the 0.40 - and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds ($P = 0.0026$, Fig. 5). Different environmental conditions could explain the significant location effect on leaf size ($P = 0.0137$) with Tifton plants having larger leaves. Leaf size of *Hibiscus acetosella* 'Panama Red' also increased with increasing θ threshold (Bayer et al., 2013). Leaf elongation is sensitive to drought stress (Lambers et al., 2008). Reduced leaf size contributes to decreased plant growth under drought because of reduced canopy light interception and photosynthesis (Burnett and van Iersel, 2008).

Plants grown at the 0.40 - and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds were taller than those grown at the 0.20 - and $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds for both cultivars ($P = 0.0001$). Height of 'August Beauty' ranged 12.6 to 47.0 cm in Tifton and from 14.0 to 41.7 cm in Watkinsville. For 'Radicans' average height increased from 12.2 to 26.0 cm in Tifton and from 10.5 to 21.5 cm in Watkinsville. Average height of the two cultivars responded differently to θ thresholds ($P = 0.0115$; Fig. 6) with θ having a greater effect on 'August Beauty' than 'Radicans'. The height of 'August Beauty' grown at the $0.20 \text{ m}^3 \cdot \text{m}^{-3}$ threshold was 67% less than at the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold, whereas for 'Radicans' this difference was 44% . Plant width was lower with the 0.20 - and $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds than with the 0.40 - and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds ($P = 0.0001$; Fig. 6). Width for 'August Beauty' ranged from 8.5 to 32.2 cm and from 8.7 to 39.0 cm for 'Radicans'. Compactness, shoot dry mass per unit plant height, is a measure of plant density (van Iersel and Nemali, 2004). Compactness increased with θ thresholds to the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold ($P = 0.0001$;

Fig. 6) with compactness not different for the 0.40 - and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds.

Increasing height with increasing θ threshold was also reported for *Hibiscus acetosella* 'Panama Red' (Bayer et al., 2013), *Gaura lindheimeri* 'Siskiyou Pink' (Burnett and van Iersel, 2008), and *Callistemon citrinus* 'Firebrand' (Alvarez and Sánchez-Blanco, 2013). In contrast, Fulcher et al. (2012) found that shoot length of *Hibiscus rosa-sinensis* 'Cashmere Wind' was greatest for intermediate treatments rather than high or low θ treatments. Increasing compactness with increasing θ threshold was reported for *Hibiscus acetosella* 'Panama Red' (Bayer et al., 2013).

No visible signs of *Phytophthora cinnamoni* infection were observed at any θ threshold with no death of inoculated plants. Possible reasons include poor survival of inoculum or not enough time for symptoms to appear. It is also possible that pathogen infections occur when substrates go through cycles of excessive wetting and drying, which can cause root stress or damage (Graham and Menge, 1999), which did not frequently occur in this study because of the maintenance of θ thresholds and extreme wetting to drying only occurring for the lowest thresholds after rain events.

'Radicans' flowered more than 'August Beauty' over the observation period ($P < 0.0001$; Fig. 7). There was no effect of θ threshold on flowering of 'August Beauty'. For 'Radicans' the volumetric water content effect on bud and bloom varied with observation date with the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold consistently having the most buds and blooms. There was poor bud development at the 0.20 - and $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds for both cultivars, similar to other growth parameters. For 'Radicans', fewer buds at the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold than the $0.4 \text{ m}^3 \cdot \text{m}^{-3}$ threshold could possibly be the result of the excessive irrigation applied and potential

Fig. 7. Average number of buds plus blooms per plant from Aug. to Nov. 2011 for the Watkinsville, GA, location. Irrigation threshold did not significantly affect the number of buds and blooms of 'August Beauty' at any time. For 'Radicans', there was a significant interactive effect of date and θ threshold on the number of buds and blooms. Means with the same letter within a specific date are nonsignificantly different from each other ($P < 0.05$). Bars that are not shown indicate that the plants had no flowers or buds. 'Radicans' plants grown at the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ θ threshold had the most buds and blooms on all observation dates.

loss of nutrients at the $0.50\text{-m}^3\text{-m}^{-3}$ threshold. A flush of growth was observed for the $0.30\text{-m}^3\text{-m}^{-3}$ plants after more frequent rains in October. Flowering of those plants occurred at that time (delayed compared the 0.40- and $0.50\text{-m}^3\text{-m}^{-3}$ plants), suggesting that if deficit irrigation is being used to slow growth, flowering can be delayed. Álvarez and Sánchez-Blanco (2013) found that flowering of *Callistemon citrinus* was not reduced from the control with moderate deficit irrigation ($\theta \approx 40\%$) but was reduced for the severe deficit treatment ($\theta \approx 20\%$). Our results suggest that flowering also may be negatively impacted by overirrigation.

Conclusions

Gardenia jasminoides ‘August Beauty’ and ‘Radicans’ had similar growth responses to θ thresholds indicating that the challenges in ‘Radicans’ production are not solely related to irrigation management. However, θ thresholds reduced height, width, shoot dry weight, root dry weight, and leaf size at the 0.20- and $0.30\text{-m}^3\text{-m}^{-3}$ θ thresholds compared with the 0.40- and $0.50\text{-m}^3\text{-m}^{-3}$ θ thresholds.

The $0.20\text{-m}^3\text{-m}^{-3}$ θ threshold was insufficient for root establishment leading to high mortality rates for both species and at both locations (72% in Tifton and 79% in Watkinsville). Root establishment may have also impacted the growth at the $0.30\text{-m}^3\text{-m}^{-3}$ threshold; the threshold was enough to maintain plants (low mortality) but growth was less than for higher θ thresholds. Poor growth at the lower θ thresholds shows the importance of root establishment using higher θ thresholds when using deficit irrigation. The large difference in irrigation volume between the 0.40- and $0.50\text{-m}^3\text{-m}^{-3}$ θ thresholds suggests that the additional irrigation applied by maintaining a high θ threshold leads to overirrigation and leaching with little additional growth. Bud and flower numbers of ‘Radicans’ with the 0.40- and $0.50\text{-m}^3\text{-m}^{-3}$ θ thresholds show that overirrigation can reduce flowering.

There was little or no difference in growth between the 0.40- and $0.50\text{-m}^3\text{-m}^{-3}$ θ thresholds for either cultivar. Irrigation was more efficient at the $0.40\text{-m}^3\text{-m}^{-3}$ θ thresholds with little leaching observed. These results show that cultivars with different growth habits respond similar to θ thresholds and that alteration of volumetric water content can be used for growth control. Further research examining the effect of water deficit on elongation will allow for manipulation of irrigation for growth control.

Literature Cited

- Álvarez, S. and M.J. Sánchez-Blanco. 2013. Changes in growth rate, root morphology and water use efficiency of potted *Callistemon citrinus* plants in response to different levels of water deficit. *Sci. Hort.* 156:54–62.
- Bauerle, T.L., W.L. Bauerle, M. Goebel, and D.M. Barnard. 2013. Root system distribution influences substrate moisture measurements in containerized ornamental tree species. *HortTechnology* 23:754–759.
- Bayer, A., I. Mahbub, M. Chappell, J. Ruter, and M.W. van Iersel. 2013. Water use and growth of *Hibiscus acetosella* ‘Panama Red’ grown with a soil moisture sensor-controlled irrigation system. *HortScience* 48:980–987.
- Bayer, A., K. Whitaker, M. Chappell, J. Ruter, and M. van Iersel. 2014. Effect of irrigation duration and fertilizer rate on plant growth, substrate EC, and leaching volume. *Acta Hort.* 1034:477–484.
- Beeson, R.C., Jr., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in the next ten years. *J. Environ. Hort.* 22:113–115.
- Belayneh, B.E., J.D. Lea-Cox, and E. Lichtenberg. 2013. Costs and benefits of implementing sensor-controlled irrigation in a commercial pot-in-pot container nursery. *HortTechnology* 23:760–769.
- Bilderback, T.E. 2002. Water management is key in reducing nutrient runoff from container nurseries. *HortTechnology* 12:541–544.
- Burnett, S.E. and M.W. van Iersel. 2008. Morphology and irrigation efficiency of *Gaura lindheimeri* grown with capacitance-sensor controlled irrigation. *HortScience* 43:1555–1560.
- Chappell, M., J. Owen, S. White, and J. Lea-Cox. 2013a. Irrigation management practices. In: Yeager, T., T. Bilderback, D. Fare, C. Gilliam, J. Lea-Cox, A. Niemiera, J. Ruter, K. Tilt, S. Warren, T. Whitwell, and R. Write (eds.). *Best management practices: Guide for producing nursery crops*. 3rd Ed. 11 Apr. 2013. <<http://contents.sna.org/bmpirrigation.html>>.
- Chappell, M., S.K. Dove, M.W. van Iersel, P.A. Thomas, and J. Ruter. 2013b. Implementation of wireless sensor networks for irrigation control in three container nurseries. *HortTechnology* 23:747–753.
- Decagon Devices. 2014. How can my soil moisture sensor read a negative number? Decagon Devices, Pullman, WA. 1 May 2014. <<http://www.decagon.com/education/how-can-my-soil-moisture-sensor-read-a-negative-number/>>.
- Fulcher, A., J. Buxton, and R. Geneve. 2012. Developing a physiological-based, on-demand irrigation system for container production. *Sci. Hort.* 138:221–226.
- Graham, J.H. and J.A. Menge. 1999. Root health: Fungal diseases, p. 126–135. In: Timmer, L.W. and L.W. Duncan (eds.). *Citrus health management*. American Phytopathological Society Press, St. Paul, MN.
- Groves, K., S. Warren, and T. Bilderback. 1998. Irrigation volume, application, and controlled-release fertilizers: I. Effect on plant growth and mineral nutrient content in containerized plant production. *J. Environ. Hort.* 16:176–181.
- Holmes, K.A. and D.M. Benson. 1994. Evaluation of *Phytophthora parasitica* var. *nicotianae* as a biocontrol for *Phytophthora parasitica* on *Catharanthus roseus*. *Plant Dis.* 78:193–199.
- Kohanbash, D., G. Kantor, T. Martin, and L. Crawford. 2013. Wireless sensor network design for monitoring and irrigation control: User-centric hardware and software development. *HortTechnology* 23:725–734.
- Kozłowski, T.T. and S.G. Pallardy. 2002. Acclimation and adaptive responses of woody plants to environmental stresses. *Bot. Rev.* 68:270–334.
- Labbers, H., T.L. Pons, and S. Chapin. 2008. *Plant physiological ecology*. 2nd Ed. Springer Verlag, New York, NY.
- Lea-Cox, J.D. and D.S. Ross. 2001. A review of the federal clean water act and the Maryland water quality improvement act: The rationale for developing a water and nutrient management planning process for container nursery and greenhouse operations. *J. Environ. Hort.* 19:226–229.
- Lichtenberg, E., J. Majsztrik, and M. Saavoss. 2013. Profitability of sensor-based irrigation in greenhouse and nursery crops. *HortTechnology* 23:770–774.
- Nemali, K.S., F. Montesano, S.K. Dove, and M.W. van Iersel. 2007. Calibration and performance of moisture sensors in soilless substrates: ECH₂O and Theta probes. *Sci. Hort.* 112:227–234.
- Nemali, K.S. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. *Sci. Hort.* 110:292–297.
- Silva, D.D., M.E. Kane, and R.C. Beeson. 2012. Changes in root and shoot growth and biomass partition resulting from different irrigation intervals for *Ligustrum japonicum* Thunb. *HortScience* 47:1634–1640.
- Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Reduced leaching fractions improve irrigation use efficiency and nutrient efficacy. *J. Environ. Hort.* 14:199–204.
- van Iersel, M.W., S. Dove, J.G. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. *HortScience* 45:277–282.
- van Iersel, M.W. and K.S. Nemali. 2004. Drought stress can produce small, but not compact marigolds. *HortScience* 39:1298–1301.
- van Iersel, M.W., R.M. Seymour, M. Chappell, F. Watson, and S. Dove. 2009. Soil moisture sensor-based irrigation reduces water use and nutrient leaching in a commercial nursery. *Proc. Southern Nursery Assn.* 54:17–21.
- Warsaw, A.L., R.T. Fernandez, and B.M. Cregg. 2009. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. *HortScience* 44:1308–1318.