Water Use and Growth of *Hibiscus acetosella* ‘Panama Red’ Grown with a Soil Moisture Sensor-controlled Irrigation System

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Abstract. Efficient water use is becoming increasingly important for horticultural operations to satisfy regulations regarding runoff along with adapting to the decreasing availability of water to agriculture. Generally, best management practices (BMPs) are used to conserve water. However, BMPs do not account for water requirements of plants. Soil moisture sensors can be used along with an automated irrigation system to irrigate when substrate volumetric water content (θ) drops below a set threshold, allowing for precise irrigation control and improved water conservation compared with traditional irrigation practices. The objective of this research was to quantify growth of *Hibiscus acetosella* ‘Panama Red’ (PP#20,121) in response to various θ thresholds. Experiments were performed in a greenhouse in Athens, GA, and on outdoor nursery pads in Watkinsville and Tifton, GA. Soil moisture sensors were used to maintain θ above specific thresholds (0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, and 0.45 $\text{m}^3\cdot\text{m}^{-3}$). Shoot dry weight increased from 7.3 to 58.8 g, 8.0 to 50.6 g, and from 3.9 to 35.9 g with increasing θ thresholds from 0.10 to 0.45 $\text{m}^3\cdot\text{m}^{-3}$ in the greenhouse, Watkinsville, and Tifton studies, respectively. Plant height also increased with increasing θ threshold in all studies. Total irrigation volume increased with increasing θ threshold from 1.9 to 41.6 L/plant, 0.06 to 23.0 L/plant, and 0.24 to 33.6 L/plant for the greenhouse, Watkinsville, and Tifton studies, respectively. Daily light integral (DLI) was found to be the most important factor influencing daily water use (DWU) in the greenhouse study; DWU was also found to be low on days with low DLI in nursery studies. In all studies, increased irrigation volume led to increased growth; however, water use efficiency (grams of shoot dry weight produced per liters of water used) decreased for θ thresholds above 0.35 $\text{m}^3\cdot\text{m}^{-3}$. Results from the greenhouse and nursery studies indicate that sensor-controlled irrigation is feasible and that θ thresholds can be adjusted to control plant growth.

Availability of freshwater worldwide will likely continue to decrease as a result of a growing global population, climate change, and increased agricultural and industrial water demand (Jury and Vaux, 2005). Recent drought in the southeastern United States resulted in more than \$1 billion in crop losses and strained the water supply (Seager et al., 2009). An increasing number of laws and regulations limiting the amount of water available for use in container nurseries has been implemented in states such as California, Florida, North Carolina, Texas, and Oregon (Beeson et al., 2004).

Management of runoff from container nurseries is also facing stricter regulations in areas such as the Chesapeake Bay Watershed and California in efforts to comply with the Clean Water Act (Lea-Cox and Ross, 2001). This has brought attention to the need to understand what impacts water shortages will have on horticultural operations. Adapting to decreasing water supplies will also demand an understanding of the effect of water stress on plant growth and development.

The need to improve irrigation practices and control runoff in container nurseries is well known. Fare et al. (1992) found that irrigation volumes in container nurseries in Alabama varied greatly. Growers surveyed thought they were applying water at a rate of 2.54 $\text{cm}\cdot\text{h}^{-1}$, but actual rates ranged from 0.8 to 3.2 $\text{cm}\cdot\text{h}^{-1}$. Measured irrigation volumes varied as a result of changing container spacing, canopy interference, overwintering structures, and inefficiencies in irrigation systems. Inefficient and excessive irrigation leads to increased runoff of water and nutrients (Million et al., 2007). Best management practices have been adopted by many nurseries to

use water resources more sustainably (Chappell et al., 2012). These methods are beneficial for nursery growers concerned with reducing water use and controlling runoff; however, these irrigation practices are not based on plant water needs. A combination of these methods, along with more sophisticated soil moisture sensor-based irrigation systems that can irrigate based on plant water use, has the potential to reduce the amount of water needed for irrigation and the amount of runoff produced during and immediately after an irrigation event (Wells et al., 2011).

Capacitance soil moisture sensors can accurately measure θ in peat- and bark-based substrates (van Iersel et al., 2009, 2010) indicating potential for use in container nurseries and greenhouses (Majsztrik et al., 2011). The potential of various soil moisture sensors to monitor and/or control substrate/soil water content has been examined in greenhouse and nursery settings with a variety of species, ranging from woody species such as *Acer rubrum* and *Cornus florida* (Lea-Cox et al., 2008a), *Rhododendron* spp. (Lea-Cox et al., 2008b), and *Hydrangea* (van Iersel et al., 2009) to herbaceous species such as *Petunia ×hybrida* (van Iersel et al., 2010) and *Antirrhinum* spp. (Lea-Cox et al., 2009). van Iersel et al. (2009) observed a water savings of 83% using sensor-controlled irrigation compared with the regular nursery irrigation practices in a commercial nursery setting. Through these studies, a better understanding of the potential use of soil moisture sensors as well as a better understanding of plant water requirements is being developed.

Increased monitoring of irrigation applications is necessary to compensate for changing conditions in nurseries and to ensure irrigation is being applied uniformly and efficiently (Fare et al., 1992). Plant size has been found to be a determining factor in plant water use (Knox, 1989) and water use generally increases with plant age (Million et al., 2007). Research has related plant water use to plant growth index and pan evaporation (Knox, 1989) or growth index and leaf area (Nui et al., 2006), which were shown to be good descriptors of water use for multiple species. Maintenance of specific leaching fractions has also been used to adjust irrigation in response to increasing plant size (Owen et al., 2008). However, these methods do not adjust to day-to-day changes in weather. To more effectively reduce water use without reducing plant quality, the relationship between plant growth and substrate θ needs to be quantified. Substrate θ can be monitored by growers, allowing them to adjust irrigation in real time to adapt to current plant water needs.

Our research compared growth and water use of *Hibiscus acetosella* ‘Panama Red’ maintained at various substrate θ levels using soil moisture sensor-controlled, automated irrigation. The objectives of this project were 1) to quantify the water use of *Hibiscus acetosella* ‘Panama Red’ in both a controlled greenhouse setting and outdoor nursery settings; 2) to determine which environmental conditions most strongly affect day-to-day changes in water use;

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and 3) to describe how growth of *Hibiscus acetosella* 'Panama Red' is affected by θ .

Materials and Methods

Greenhouse study

Plant material and growing conditions. Research was conducted at University of Georgia in Athens, GA. Rooted cuttings of *Hibiscus acetosella* 'Panama Red' (PP#20121) were transplanted into 3.8-L containers containing a peat (25% by volume) and pine bark (75% by volume) mix with starter nutrients, wetting agent, and Dolomitic limestone (Fafard nursery mix; Sungro, Agawam, MA) on 17 June 2010. One cutting was planted per pot and cuttings were pruned to three nodes to assure uniform starting material (64 pots total, arranged in 32 groups of two plants each). Pots were top-dressed with 24 g controlled-release fertilizer (Graco 16 month, 14N–3.4P–11.6K with minors; Graco Fertilizer Co., Cairo, GA) immediately after transplanting, after which the cuttings were watered in. Plants were hand-watered during the first week, after which the irrigation treatments were started.

Treatments and data collection. Plants were watered using a soil moisture sensor-controlled, automated irrigation system similar to that described by Nemali and van Iersel (2006). One capacitance sensor (EC-5; Decagon Devices, Pullman, WA) was inserted into each pot. The 64 capacitance sensors were connected to a data logger (CR10; Campbell Scientific, Logan, UT) using two multiplexers (AM16/32; Campbell Scientific). The data logger excited the sensors with 2.5 VDC and measured the resulting voltage output from the sensors every 10 min. The voltage output (V) was then converted to θ ($\text{m}^3 \cdot \text{m}^{-3}$) using our own substrate-specific calibration ($\theta = -0.4745 + 1.7647 \times V$) using the method described by Nemali et al. (2007). The θ data from the two pots in each plot were averaged and when the average θ was below the threshold for a particular plot (0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, or $0.45 \text{ m}^3 \cdot \text{m}^{-3}$), the data logger opened an irrigation valve for 20 s using a relay driver (SDM-CD16AC; Campbell Scientific). Plants were irrigated using pressure-compensated drip emitters ($8 \text{ L} \cdot \text{h}^{-1}$; Netafim, Fresno, CA), which applied 45 mL per plant per irrigation. If this was not enough water to raise θ above the thresholds, plants were watered again 10 min later. The data logger monitored the number of irrigations, allowing us to calculate the daily and total water use per plant.

Environmental conditions in the greenhouse were monitored using a quantum sensor (SQ110; Apogee Instruments, Logan, UT) and a temperature and relative humidity sensor (HMP50; Vaisala, Woburn, MA) connected to the data logger. These sensors were measured every 20 s and the data logger recorded the daily minimum, maximum, and average. In addition, the data logger calculated the vapor pressure deficit (VPD) from the air temperature and relative humidity and the DLI from the quantum sensor data.

To verify that the irrigation system accurately maintained different θ s, θ of all pots

was measured at the end of the study using a handheld soil moisture sensor (Theta Probe; Delta T Devices, Cambridge, U.K.) using the factory calibration for soilless substrates. Plant height and the length of five internodes in each plot were measured at harvest, and the area of four fully expanded leaves from the top of the canopy was determined using a leaf area meter (LI-3100; Li-Cor, Lincoln, NE). The shoots were cut off at the substrate surface, dried at 80°C , and weighed. Compactness was calculated as shoot dry weight/shoot length.

Experimental design and data analysis. The experimental design was a randomized complete block with eight θ threshold treatments and four replications. The two plants in a plot were an experimental unit. Data were analyzed using linear and non-linear regression with $P = 0.05$ considered to be statistically significant. Curve fitting was done using SigmaPlot (Systat, San Jose, CA). The effect of plant age and environmental conditions on DWU was modeled using stepwise regression analysis ($P < 0.05$) in SAS (SAS Institute, Cary, NC), using the variables day (days after start of treatments), DLI, average temperature, VPD, and the interactions between day and DLI, temperature, and VPD. Data from the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ threshold was used because it had the highest water availability and most growth, representing water use not limited by water availability.

Nursery studies

Research was conducted at the University of Georgia Horticulture Farm in Watkinsville, GA, from 19 Aug. to 26 Oct. 2010 and at the University of Georgia Tifton Campus in Tifton, GA, from 10 Aug. to 5 Oct. 2010. The studies were conducted at two locations in different U.S. Department of Agriculture hardiness zones (Tifton 8b, Watkinsville 8a) to compare plant responses under different environmental conditions.

Plant material. Rooted *Hibiscus acetosella* 'Panama Red' cuttings were planted in 3.8-L black plastic containers (400 plants at each location). Plants in Tifton were planted in an 8:1 pine bark:sand substrate with 593 g Micromax micronutrient mix (Scotts, Marysville, OH) and 1187 g dolomitic limestone per m^3 . Plants in Watkinsville were planted in a peat (25% by volume) and pine bark (75% by volume) mix with starter nutrients, wetting agent, and Dolomitic limestone (Fafard nursery mix). At the onset of the experiment, all plants were trimmed to a height of 13 cm. Plants at both locations were top-dressed with 18 g of controlled-release fertilizer (Harrell's 5–6 month release; 16N–2.6P–9.1K Professional Fertilizer; Harrell's, Lakeland, FL) and were kept well watered until plants were established and treatments were initiated.

Treatments and data collection. Irrigation was applied using a soil moisture sensor-controlled irrigation system based on that described by Nemali and van Iersel (2006). Soil moisture sensors (10HS; Decagon Devices) were inserted into two pots in each of the 16 plots at approximately a 45° angle directly below the original liner root ball. Sensors were

inserted with the prongs extending into the center of the medium to a depth at which the entire sensor was in the substrate. The 32 sensors were connected to a multiplexer (AM416; Campbell Scientific), which was connected to a data logger (CR10; Campbell Scientific).

The data logger excited the sensors and recorded the voltage readings every 20 min as described for the greenhouse study. The voltage readings from the sensors were converted to substrate water contents using our own calibration [$\theta = -0.401 + 1.0124 \times V$] using the method described by Nemali et al. (2007). When both sensor measurements were less than the θ threshold for that plot (0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, or $0.45 \text{ m}^3 \cdot \text{m}^{-3}$), the data logger signaled the relay driver (SDM16AC/DC controller; Campbell Scientific) to open the appropriate solenoid 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 ($2 \text{ L} \cdot \text{h}^{-1}$; Netafim USA).

Soil moisture readings from each sensor were averaged and stored every 2 h and the number of irrigation events per plot was recorded daily. The daily water use was calculated from the number of irrigation events and the volume of water applied per irrigation event. Note that this daily water use only represents actual plant water use on days without rain and when the θ was at the θ threshold at the start of the day. Leaching was observed at the highest thresholds for the outdoor studies but was not quantified. Environmental conditions were measured using a temperature and relative humidity sensor (HMP50; Vaisala), a quantum sensor (SQ-110; Apogee Instruments), and a rain gauge (ECRN-50; Decagon Devices) connected to the data logger. Vapor pressure deficit was calculated by the data logger using temperature and relative humidity data.

At the conclusion of the experiment, a representative group of 10 plants from each plot was selected for data collection. Plant heights were recorded. Substrate water content was measured using a soil moisture sensor (ThetaProbe; Delta T Devices). The uppermost fully expanded leaves were collected and leaf area was measured using a leaf area meter (LI-3100; Li-Cor). Shoots were cut off at the substrate surface and were dried at 80°C after which dry weight was determined and compactness was calculated as shoot dry weight/shoot length.

Experimental design and data analysis. The experiment was designed as a randomized complete block with eight treatments (substrate volumetric water content set points) and two replications for a total of 16 plots with 25 plants each. Data were analyzed separately for the two locations using linear and non-linear regression with $P = 0.05$ considered to be statistically significant. Curve fitting was done using SigmaPlot (Systat).

Results and Discussion

Substrate water content. In the greenhouse study, the automated irrigation system

used small but frequent irrigation events to maintain θ just above the thresholds throughout the course of the experiment (Fig. 1), even with changing water needs resulting from plant growth and changing environmental conditions, similar to what was observed by van Iersel et al. (2010). Drying of the substrates to the θ thresholds occurred between Days 1 and 8 of the greenhouse study (Fig. 1). Drying of substrates to their θ thresholds in the nursery studies was lengthened as a result of rain. In Tifton, it rained on 9 of the first 20 d of the experiment, delaying the drying of the substrate to the $0.10\text{-m}^3\text{-m}^{-3}$ threshold until Day 41 (Fig. 2). It rained 5 of the first 10 d in Watkinsville and the $0.10\text{-m}^3\text{-m}^{-3}$ threshold was not reached until Day 35 (Fig. 2). Drying of substrate to θ thresholds generally occurred after rain events at both locations. However, in Watkinsville, a rain event of 51 mm on Day 39, along with the small size and low water use of the plants maintained at the $0.10\text{-m}^3\text{-m}^{-3}$ threshold, prevented θ from reaching the threshold for the rest of the study and those plants did not get irrigated thereafter.

Fluctuations in θ were generally larger at the lower θ thresholds, as has been described previously (Garland et al., 2012; Nemali and van Iersel, 2006; van Iersel et al., 2010). Reduced hydraulic conductivity has been observed in peat-based substrates with low water contents (Naasz et al., 2005), which slows the movement of water throughout the substrate. This can result in irregular water distribution in the substrate, causing variability in θ (Nemali and van Iersel, 2006). Short-term fluctuations in θ were observed in both nursery experiments and with all θ thresholds. The increased fluctuations in θ in the nursery studies compared with the greenhouse study could be the result of different hydraulic characteristics of peat- vs. bark-based substrates. A strong correlation between Theta Probe measurements and θ threshold readings confirms differences in substrate θ among the various treatments

Fig. 1. Average substrate volumetric water content (θ) measurements as measured with capacitance sensors over the course of the 37-d greenhouse experiment. All θ s were reached within 8 d, after which θ was maintained slightly above the θ thresholds ($0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40$, and $0.45\text{-m}^3\text{-m}^{-3}$, indicated by the dotted lines).

(greenhouse: ThetaProbe measurement = $0.07 + 0.78 \times \theta$ threshold, $r = 0.81$, $P < 0.0001$; Tifton: ThetaProbe measurement = $-0.03 + 0.77 \times \theta$ threshold, $r = 0.86$, $P < 0.001$;

Watkinsville: ThetaProbe measurement = $0.04 + 0.62 \times \theta$ threshold, $r = 0.81$, $P < 0.001$). Soil moisture sensor readings (EC-5 and 10HS) were higher than ThetaProbe measurements.

Fig. 2. Substrate volumetric water content (lines) and rain (bars) over the course of the 57-d Tifton, GA (upper graph) and 68-d Watkinsville, GA (lower graph) nursery experiments. *Hibiscus acetosella* 'Panama Red' were irrigated when the substrate water content dropped below $0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45\text{-m}^3\text{-m}^{-3}$ thresholds. Note that for clarity only four ($0.1, 0.2, 0.3$, and $0.4\text{-m}^3\text{-m}^{-3}$) of the eight treatments are shown in these graphs. After rain events, drying of substrates to θ thresholds was generally achieved within days for both experiments. However, in Watkinsville, a rain event of 51 mm on Day 39, along with the small size and low water use of the plants maintained at the $0.10\text{-m}^3\text{-m}^{-3}$ threshold, prevented θ from reaching the threshold for the rest of the study and those plants did not get irrigated thereafter.

Fig. 3. Total irrigation volume over the course of the 37-d growing period of *Hibiscus acetosella* 'Panama Red' as affected by the volumetric water content thresholds at which irrigation occurred in the greenhouse study.

van Iersel et al. (2011) suggested that a volumetric water content gradient in the substrate from top to bottom, created by the effects of gravity and evapotranspiration on the distribution of water through the substrate, can explain the difference between the readings from the different sensors. The soil moisture sensors were deeper and therefore likely in wetter substrate than the ThetaProbe.

Irrigation volume. Total irrigation volume increased with increasing θ threshold in all three studies, as previously described (Burnett and van Iersel, 2008; Kim and van Iersel, 2009; Nemali and van Iersel, 2006; van Iersel et al., 2010). In the greenhouse study, total irrigation volumes increased from an average of 1.9 L/plant in the $0.10\text{-m}^3\text{-m}^{-3}$ treatment to 41.6 L/plant for the $0.45\text{-m}^3\text{-m}^{-3}$ treatment (Fig. 3). Daily water use generally increased over the course of the greenhouse experiment as a result of increasing plant size, but DWU was low on days with low DLI (Fig. 4), as previously reported by Garland et al. (2012) and van Iersel et al. (2010). Stepwise regression analysis of the $0.45\text{-m}^3\text{-m}^{-3}$ treatment data indicated that the $\text{DLI} \times \text{day}$ interaction was the only significant term explaining DWU [daily water use (mL/plant) = $-6.279 + 1.369 \times \text{DLI} \times \text{day}$, $r^2 = 0.95$, $P < 0.0001$] (Fig. 5). The importance of DLI in determining DWU of ornamental plants has been previously reported (Baile et al., 1994; Kim and van Iersel, 2009; Löfkvist et al., 2009; van Iersel et al., 2010). The results of our regression analysis suggest the DLI was the only environmental factor influencing DWU; however, the correlation of other factors to DLI means their effects is difficult to separate from DLI. Pearson correlation analysis (Table 1) showed correlations between DWU and temperature ($r = 0.87$) as well as VPD ($r = 0.52$). However, both temperature and VPD were correlated with DLI ($r = 0.45$ and 0.84 , respectively) and temperature also was correlated with VPD ($r = 0.62$). The vapor pressure gradient from leaf to air is the driving force for transpiration; higher air temperature increases the gradient and leads to higher transpiration, which increases DWU. Higher DLI levels are usually associated with higher temperatures, and therefore a greater VPD, than days with low DLI. Like in the greenhouse study, DWU for the outdoor studies was low on days with a low DLI (results not shown).

In Tifton, total irrigation volume increased from 0.24 L/plant for the $0.10\text{-m}^3\text{-m}^{-3}$ treatment to 33.6 L/plant for the $0.45\text{-m}^3\text{-m}^{-3}$ treatment (Fig. 6), whereas in Watkinsville, irrigation volume increased from 0.06 L per plant for the $0.10\text{-m}^3\text{-m}^{-3}$ treatment to 23.0 L/plant for the $0.45\text{-m}^3\text{-m}^{-3}$ treatment (Fig. 5). Increasing total irrigation volume with increasing θ threshold was expected. Total irrigation volumes do not include water from rainfall, because neither rainfall volume received nor leached was quantified. Rainfall increased θ more in treatments with a low θ threshold than in treatments with a high θ threshold (Fig. 2) and rain thus provided more water to plants in relatively dry substrates. Average

Fig. 4. Daily light integral (DLI, top) and daily water use (DWU) of *Hibiscus acetosella* ‘Panama Red’ irrigated at different substrate water contents (θ) ($0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45\text{ m}^3\text{-m}^{-3}$) (bottom) over the course of the Athens, GA, greenhouse experiment. Note that for clarity, only four of the eight treatments are shown. Decreases in DLI on Days 15, 21, 24, 29, and 34 correspond with reductions in DWU in most treatments. The reduction of DLI on Day 6 did not correspond with a reduction in DWU because θ had not yet reached the θ thresholds for irrigation in all plots, the stage of growth of the plants, and low water use of the plants at that time.

Fig. 5. Measured and modeled daily water use (DWU) of *Hibiscus acetosella* ‘Panama Red’ grown at a substrate water content (θ) of $0.45\text{ m}^3\text{-m}^{-3}$ in a 37-d greenhouse experiment (left). Modeled vs. measured DWU of plants irrigated at the $0.45\text{-m}^3\text{-m}^{-3}$ θ threshold (right). Modeled DWU = $-6.3 + 1.369 \times \text{daily light integral} \times \text{day}$ ($r^2 = 0.952$, $P < 0.0001$).

Table 1. Pearson’s correlation coefficients for daily water use (DWU) of *Hibiscus acetosella* ‘Panama Red’, day (days from onset of treatments), daily light integral (DLI), vapor pressure deficient (VPD), and temperature from the greenhouse study.

Variables	DWU	DLI	VPD
Day	0.921**		
DLI	0.479*		
VPD	0.525*	0.84**	
Temperature	0.871**	0.45*	0.62*

** and * indicate significance of $P < 0.0001$ and $P \leq 0.01$.

daily irrigation volume increased from 4.21 mL/plant for the $0.10\text{-m}^3\text{-m}^{-3}$ treatment to 580 mL/plant for the $0.45\text{-m}^3\text{-m}^{-3}$ treatment

in the Tifton study and from 0.87 mL/plant for the $0.10\text{-m}^3\text{-m}^{-3}$ treatment to 334 mL/plant for the $0.45\text{-m}^3\text{-m}^{-3}$ treatment in the Watkinsville study. Average irrigation volume likely differed between the two locations as a result of differences in environmental conditions, specifically rainfall total (Tifton: 128.8 mm, Watkinsville 224.5 mm), but also temperature, photosynthetic photon flux (PPF), and VPD (Tifton had higher average daily temperature, PPF, and VPD). Higher light levels and temperature would increase VPD and the need for evaporative cooling, which in turn could increase DWU. Higher cumulative irrigation volume in the greenhouse study compared with the nursery studies can be explained by the different growing

Fig. 6. Cumulative irrigation volume for the production of *Hibiscus acetosella* as a function of the threshold substrate water content (0.10 to $0.45 \text{ m}^3 \cdot \text{m}^{-3}$) at which the plants were irrigated. Plants were grown outdoors on nursery pads in Watkinsville or Tifton, GA, over the course of a 57- (Tifton) or 68- (Watkinsville) period Tifton: $r^2 = 0.90$, $P < 0.0001$; Watkinsville: $r^2 = 0.93$, $P < 0.0001$.

environments with more controlled conditions for the greenhouse experiment as well as the time of the year in which the experiments were conducted (summer for greenhouse vs. fall for nursery studies).

Plant growth. A strong correlation was observed between shoot dry weight and θ [greenhouse: $r = 0.83$, $P < 0.001$ (Fig. 7); Tifton: $r = 0.90$, $P < 0.001$; Watkinsville: $r = 0.95$, $P < 0.001$ (Fig. 8)]. In the greenhouse study, shoot dry weight increased from 7.3 to 58.8 g/plant (0.10 - to $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds); shoot dry weight in the Tifton and Watkinsville studies increased from 3.9 to 35.9 g/plant and 8.0 to 50.6 g/plant with increasing θ thresholds.

The relationship between plant growth and water is further demonstrated by the quadratic relationship between shoot dry weight and total irrigation volume ($r^2 = 0.85$, $P = 0.001$) in the greenhouse study (Fig. 7).

Fig. 7. Shoot dry weight (top), height (middle), and compactness (bottom) of greenhouse-grown *Hibiscus acetosella* 'Panama Red' as affected by the substrate water content threshold at which the plants were irrigated (left) or total irrigation volume (right). Error bars indicate SE. The slope of the linear regression in the total irrigation volume vs. shoot dry weight graph is the water use efficiency (grams shoot weight produced per liter of water applied) for thresholds from 0.10 to $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ with water use efficiency greatly reduced at higher thresholds.

Fig. 8. Shoot dry weight (top), shoot height (middle), and compactness (bottom) of *Hibiscus acetosella* 'Panama Red' as affected by the substrate water content threshold at which the plants were irrigated (left) or total irrigation volume (right). Plants were grown on nursery pads in Watkinsville or Tifton, GA. Error bars indicate SE. Cumulative irrigation volume does not include water received through rainfall as rainfall volume intercepted and leaching volumes were not recorded. Substrate volumetric water content readings before and after rain events indicate that more water was incorporated in soils maintained at lower thresholds.

Little additional shoot weight was gained as irrigation volume increased from 22.7 to 41.6 L (θ thresholds of 0.35 to 0.45 $\text{m}^3 \cdot \text{m}^{-3}$). The 0.35- $\text{m}^3 \cdot \text{m}^{-3}$ θ threshold would equate to 18 L/plant savings (45% reduction in irrigation) with only a 4 g per plant difference (8% reduced shoot growth) compared with 0.45 $\text{m}^3 \cdot \text{m}^{-3}$.

There is a linear relationship between shoot dry weight and irrigation volume for thresholds between 0.10 $\text{m}^3 \cdot \text{m}^{-3}$ and 0.35 $\text{m}^3 \cdot \text{m}^{-3}$ (Fig. 7). The slope of this regression line (2.25 g of shoot dry weight produced per liter) is the water use efficiency. van Iersel et al. (2010) reported a water use efficiency of 2.54 $\text{g} \cdot \text{L}^{-1}$ for *Petunia $\times$ hybrida*. The quadratic relationship between irrigation volume and shoot dry weight in the greenhouse study shows the potential benefit of irrigating at a moderate threshold (0.35 $\text{m}^3 \cdot \text{m}^{-3}$) compared with a high threshold (0.45 $\text{m}^3 \cdot \text{m}^{-3}$). For the nursery experiments, the relationship between shoot dry weight and irrigation volume was linear

[Tifton: $r^2 = 0.98$, $P < 0.001$; Watkinsville: $r^2 = 0.93$, $P < 0.001$ (Fig. 8)]. Water use efficiency in the nursery experiments could not be determined because we did not quantify how much rain water the plants received.

Plants grown with a θ threshold of 0.35- $\text{m}^3 \cdot \text{m}^{-3}$ threshold were considered to be a salable size for all experiments. This indicates the possibility for using irrigation control as a means of controlling growth. In Tifton, maintaining irrigation at the 0.35- $\text{m}^3 \cdot \text{m}^{-3}$ instead of the 0.45- $\text{m}^3 \cdot \text{m}^{-3}$ threshold resulted in a 21 L/plant difference in irrigation (66% reduction in irrigation) with a 19.8 g per plant difference in shoot dry weight (55% reduction in shoot growth). In Watkinsville, maintaining irrigation at the 0.35- $\text{m}^3 \cdot \text{m}^{-3}$ instead of the 0.45- $\text{m}^3 \cdot \text{m}^{-3}$ threshold equaled a 8 L/plant difference in irrigation (33% reduction in irrigation) with a 8.3 g per plant difference in shoot dry weight (15% reduction in shoot growth). The higher shoot dry weight with the 0.40- or 0.45- $\text{m}^3 \cdot \text{m}^{-3}$ thresholds suggests the

possibility of producing a salable crop in less time. This could reduce water use as well as production costs, but this was not quantified in these experiments.

A quadratic relationship between shoot dry weight and irrigation volume has been reported for *Cotoneaster dammeri* 'Skoghom', *Rudbeckia fulgida* 'Goldstrum' (Groves et al., 1998), and *Petunia $\times$ hybrida* (van Iersel et al., 2010). Groves et al. (1998) reported that 90% of maximum dry weight could be produced with 40% less irrigation volume than that needed to produce the maximum dry weight. Others have reported little to no change in shoot dry weight with reduced irrigation volumes. Warsaw et al. (2009) reported increased or no effect on plant growth index for 23 common container-grown woody ornamental species by irrigating based on replacement of 100% DWU or less (that reduced total irrigation applied by 6% to 75% depending on treatment and species) compared with the control of 19 mm per irrigation. Welsh et al.

(1991) reported little or no difference in shoot dry weight of *Photinia × fraseri* irrigated to replace 100%, 75%, and 50% of actual water use. Million et al. (2007) reported a 6% reduction in shoot dry weight of *Viburnum odoratissimum* irrigated at a rate of 2 cm·d⁻¹ vs. 1 cm·d⁻¹, showing that overirrigation can negatively impact plant growth. These studies, along with the current research, support the idea that salable plants can be produced using moderate irrigation amounts.

Results for plant height were similar to those for shoot dry weight. Plant height in the greenhouse also responded quadratically to the θ threshold (Fig. 7). Plant height increased from ≈ 46 cm with the 0.10-m³·m⁻³ threshold to 125 cm for the 0.35-m³·m⁻³ threshold with no additional increase at higher θ thresholds. This is similar to the findings of Fulcher et al. (2012), which determined with *Hibiscus rosa-sinensis* 'Cashmere Wind' that intermediate treatments (0.30 and 0.41 m³·m⁻³) were taller than the wettest and driest treatments (0.49 and 0.22 m³·m⁻³). There was a linear relationship between plant height and θ threshold in nursery studies (Fig. 8). Height increased from an average of 26.5 cm (0.10 m³·m⁻³) to 89.5 cm (0.45 m³·m⁻³) in the Tifton study and from 27.8 cm (0.10 m³·m⁻³) to 69.0 cm (0.45 m³·m⁻³) in the Watkinsville study (Fig. 8).

Compactness, the shoot dry mass per unit plant height, is a measure of plant density (van Iersel and Nemali, 2004) and may be a better indicator of plant quality than growth index, which merely measures the volume of the canopy. Compactness increased linearly with both increasing θ threshold and cumulative irrigation volume for the greenhouse study (Fig. 7) and nursery studies (Fig. 8). This indicates that total plant size, not just height, increased with increasing irrigation volume. This is similar to the results of van Iersel and Nemali (2004) in which drought stress treatments produced smaller, but not more compact, marigold (*Tagetes erecta*). Leaf size increased from 12.74 cm²/leaf (0.10-m³·m⁻³ treatment) to 19.45 cm²/leaf (0.40-m³·m⁻³ treatment) in the Tifton study, from 7.71 cm²/leaf (0.10-m³·m⁻³ treatment) to 20.64 cm²/leaf (0.45-m³·m⁻³ treatment) in the Watkinsville study, and from 30.19 cm²/leaf (0.10-m³·m⁻³ treatment) to 60.69 cm²/leaf (0.40-m³·m⁻³ treatment) in the greenhouse study. There was a quadratic relationship between leaf size and θ threshold for all experiments (greenhouse: $y = 0.89 + 377.08x - 561.00x^2$, $r^2 = 0.70$, $P < 0.0001$; Tifton: $y = 8.59 + 40.97x - 40.55x^2$, $r^2 = 0.50$, $P = 0.01$; Watkinsville: $y = 3.16 + 50.12x - 21.51x^2$, $r^2 = 0.77$, $P < 0.001$). Leaf area is a responsive indicator of drought stress as a result of the sensitivity of leaf cell elongation to low soil water potential (Lambers et al., 2008). The large difference in leaf size between the greenhouse and nursery studies could be the result of the different environmental conditions, including less wind in the greenhouse.

Internode length in the greenhouse increased from 4.25 cm in the 0.10-m³·m⁻³ treatment to 7.15 cm in the 0.35-m³·m⁻³ treatment and no further increase at higher

θ thresholds (quadratic, $y = 2.82 + 20.00x - 24.29x^2$, $r^2 = 0.50$, $P < 0.0001$; results not shown). It is possible that stem growth, similar to leaf expansion, is reduced by water stress as a result of reduced cell division and expansion (Taiz and Zeiger, 2010). This would explain the shorter height and reduced internode length at lower thresholds (less than 0.35 m³·m⁻³). The reduced leaf size, height, and internode length of the plants at thresholds under 0.25 m³·m⁻³ gave the plants an appearance of being stunted.

Conclusions

Growth of *Hibiscus acetosella* 'Panama Red' increased with increasing θ threshold in both greenhouse and nursery settings. Production of salable plants can be achieved by growing plants at moderate θ thresholds (0.35 m³·m⁻³). In both greenhouse and nursery settings, maintaining plants at a threshold of 0.35 m³·m⁻³ instead of 0.45 m³·m⁻³ resulted in significant water savings (18 L/plant savings with a 4 g/plant dry weight difference in the greenhouse study, 21 L/plant savings with 20 g/plant dry weight difference in the Tifton study, and 8 L/plant savings with 8 g/plant dry weight difference in the Watkinsville study). The effect of θ threshold on dry weight, plant height, and compactness shows the potential for using precision irrigation as a means of controlling plant growth, potentially reducing the need for pruning and/or plant growth retardants.

The control of θ thresholds in the outdoor studies and the salability of plants produced at or above the 0.35-m³·m⁻³ θ threshold show the potential for using sensor-controlled irrigation systems in commercial nursery settings. The irrigation system generally re-established the θ thresholds after significant rainfall events with the exception of the 0.10-m³·m⁻³ θ threshold; however, this θ threshold was not adequate in supporting sufficient plant growth for the production of salable plants anyway. Along with reduced water use and growth control, more efficient soil moisture sensor-controlled irrigation could greatly reduce leaching, allowing for reductions in fertilizer applications. Measuring leachate volume and nutrient content will help quantify the environmental benefits of precision irrigation.

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