

IMPROVING GROWTH AND QUALITY OF HIBISCUS ACETOSELLA AND GARDENIA
JASMINOIDES WITH EFFICIENT IRRIGATION AND FERTILIZATION FOR MORE
SUSTAINABLE CONTAINER PLANT PRODUCTION

by

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(Under the Direction of Marc van Iersel and John Ruter)

ABSTRACT

Improving water and nutrient management is a focus of sustainable container plant production. Best management practices are commonly used and although effective, these methods do not take into account actual plant water needs. Irrigating in response to substrate volumetric water content applies only the water needed by the crop to replace what is lost to evapotranspiration and plant water use. Soil moisture sensor technology can allow for precise and efficient control of irrigation in response to substrate water content. To best utilize this technology an understanding of the effect of irrigation volume and water stress on plant growth is needed. The aim of this research was to understand how plant growth is affected by substrate water content and irrigation volume. *Hibiscus acetosella* and *Gardenia jasminoides* were irrigated using an automated irrigation systems set to maintain substrate volumetric water content above various thresholds in order to quantify plant growth and irrigation volume. Experiments were conducted in Watkinsville and Tifton, GA in order to assess differences due to

environmental conditions. Growth of *Hibiscus acetosella* increased with increasing volumetric water content threshold, with plants above the $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ threshold of a salable size, which suggests that moderate irrigation volumes can be used in plant production. Growth of two *Gardenia jasminoides* cultivars responded similarly to volumetric water content threshold. Bud and bloom development was greater at the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold than the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold indicating that over-irrigation can impact bud and bloom development. Plant growth of *Gardenia jasminoides* was similar when grown with 50% and 100% of the standard bag rate of a controlled release fertilizer indicating that reduced fertilizer applications can be possible with more efficient irrigation. Efficient irrigation also reduced leachate volume. There were diurnal patterns of stem elongation of *Hibiscus acetosella* for both well-watered and water-stressed plants with elongation rates greatest after the onset of darkness. Further research with additional species will provide additional information in order to most effectively utilize sensor controlled irrigation and reduced fertilizer applications in a commercial plant production.

INDEX WORDS: automated irrigation; soil moisture sensor; datalogger; woody ornamental plants; volumetric water content; nursery production; electrical conductivity; leaching; fertilization; evapotranspiration; stem elongation; load cell; height control; circadian rhythms; diurnal growth pattern

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DEDICATION

This dissertation is dedicated to my husband AJ, who not only supported me through this process, but also gave up his free time to do such exciting things as wash gardenia roots.

I thank my parents, Stan and Vicki, for their support of this degree and also my entire academic career. You have always encouraged me to reach for my dreams and have provided the love and support I needed to do so. I also thank my in-laws, Karen and Andy, for their support.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Availability of freshwater worldwide will likely continue to decrease due to 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 have 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.

Agriculture consumes 70% of the water consumed worldwide (Fischer et al., 2007). The USDA reported that in 2008 horticultural operations, which include greenhouse, nursery, and floriculture operations, used over 235 billion gallons of irrigation water (USDA, 2008). Of the over 28,000 operations accounting for this water usage, only 5% recycled or reclaimed their water. It is vital that horticultural operations adopt more sustainable irrigation practices.

Improving water and nutrient management in container plant production is necessary for the industry to adapt to decreasing water resources and the growing number of laws and

regulations regarding nursery water use, fertilizer applications, and nutrient levels in runoff (Beeson et al, 2004; Chappell et al., 2013a). Over-irrigation commonly occurs for many reasons, including the belief that maintaining substrates near 100% container capacity is necessary for maximum growth (Beeson, 2006), inefficiencies in irrigation application and poor uniformity of irrigation systems (Fare et al., 1992), and the grower preference to over- rather than under apply water (Million et al., 2007; Yeager et al, 2010). Along with this, many growers apply large amounts of fertilizer out of concern that lower fertilizer applications could negatively impact growth (Owen et al., 2008; Tyler et al., 1996). The combination of excessive irrigation and high fertilizer rates often leads to significant leaching of fertilizers, which has a negative environmental impact as the leachate enters local ecosystems (Lea-Cox and Ross, 2001), and can lead to the need for additional fertilizer applications late in the production cycle.

Best management practices (BMPs) have been adopted by many growers in an effort to irrigate and fertilize more efficiently. Cyclic irrigation can be used to apply reduced irrigation volumes more frequently, and can reduce water and nutrient leaching (Fare et al, 1994; Ruter, 1998). Other BMPs for irrigation management include grouping plants by water requirements and inspecting irrigation systems for uniformity (Chappell et al, 2013a). These methods are effective methods of improving irrigation, but do not control irrigation based on actual crop water requirements.

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 cm/h, but actual rates ranged from 0.8 to 3.2 cm/h (Garber et al., 2002). Measured irrigation volumes varied due to 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). More efficient irrigation management has become a focus in sustainable container plant production (Chappell et al., 2013a) to improve resource utilization 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).

Nutrient use efficiency is directly related to irrigation efficiency (Bilderback, 2002). Improving irrigation practices reduces the amount of water and fertilizer lost via leaching. Leaching is both an economical and environmental issue prevalent in container nursery production. Sensor technology has the potential to improve nutrient use efficiency by reducing the fertilizer leaching by controlling irrigation runoff.

Controlling water and nutrient uptake also has the potential to control plant growth, potentially lessening the need for plant growth retardants. Soil moisture sensor automated irrigation has been used to control irrigation with a variety of nursery and greenhouse crops including *Hibiscus acetosella* (Bayer et al., 2013), *Lantana camara* (Bayer et al., 2014), *Hydrangea macrophylla* (van Iersel et al., 2009), *Gaura lindheimeri* (Burnett and van Iersel, 2008), *Petunia ×hybrida* (van Iersel et al, 2010), and *Gardenia jasminoides* (Chappell et al., 2013b). This presents the possibility of using water stress induced by automated irrigation to control plant growth as opposed to applying growth regulators.

Although sensor technology has great potential for improving irrigation in nurseries, the cost of establishing the system can be high. Another drawback to this technology is the expertise required to establish and maintain the system. Until recently most sensor controlled irrigation has been for research purposes; however, wireless sensor networks capable of

controlling irrigation are being developed for implementation in commercial production (Kohanbash et al., 2013; Lea-Cox et al., 2013).

The objective of my research was to increase water and nutrient use efficiency in nursery crop production through the use of real-time soil moisture monitoring and controlled irrigation. The first study compared growth and water use of *Hibiscus acetosella* ‘Panama Red’ maintained at various substrate volumetric water content (θ) levels using soil moisture sensor controlled, automated irrigation. The objectives of the study 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, and 3) to describe how growth of *Hibiscus acetosella* ‘Panama Red’ is affected by θ .

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

The objective of the third study was to determine how irrigation volume and fertilizer rate affect pore water EC, leachate volume, electrical conductivity (EC), and nutrient concentrations;

as well as growth of *Gardenia jasminoides* ‘MAGDA I’. Our hypothesis was that more efficient irrigation can be combined with reduced fertilizer inputs without impacting plant growth, reducing leaching and nutrient levels in leachate; with reduced leaching, more fertilizer remains in the container and available to the plant.

The objective of the final study was to quantify diurnal patterns of elongation in response to well-watered and water-stressed conditions. Understanding when elongation occurs could be useful in using drought stress as a means of plant elongation control. Water stressed plants were re-watered to determine whether nodes with reduced elongation stayed short or whether elongation resumed upon re-watering.

Water Availability

Anticipated global warming and the subsequent climate change could potentially affect both the availability of and demand on water supplies. Agricultural irrigation water uses 80% of water consumed worldwide (Jury and Vaux, 2005). The Intergovernmental Panel on Climate Change predicts that agricultural operations will be the most impacted water consumer due to climate change (Kundzewicz et al., 2007). This impact will necessitate changes in irrigation methods, as climate change will alter current management practices. Along with a reduction in water supply, increasing temperatures due to climate change will most likely increase the amount of water needed for agricultural production. The increased demands of the growing global population, along with industrial water needs, will precede those of agriculture requiring more efficient and sustainable irrigation practices.

An increasing number of laws and regulations limiting the amount of water available for use in container nurseries have been implemented in states such as California, Florida, North

Carolina, Texas, and Oregon (Beeson et al., 2004). For example, growers in Georgia withdrawing over 378,540 liters of water a day from streams and aquifers must be permitted by the Environmental Protection Division of the Georgia Department of Natural Resources (Masters et al, 2010). 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.

Irrigation Management

The most common irrigation methods used by container nurseries are overhead sprinkler and drip irrigation (Hodges et al., 2008). The advantage of overhead irrigation is the variability of plant size and container number that can be irrigated in a given area (Mathers et al., 2005). However, variability in water requirements due to plants type (deciduous, broadleaf evergreens, or conifers) as well as container size can lead to excess or deficient irrigation when plant types or container sizes are mixed (Beeson and Yeager, 2003). The uniformity and efficiency of overhead irrigation can be variable depending on container location in irrigation area, wind speed, spacing between containers, and plant canopy size (Beeson and Yeager, 2003; Mathers et al., 2005). The container location in the irrigation area is a factor due to variability in the spray from the sprinkler (decreased spray efficiency with increased distance from sprinkler). Prevalent winds can potentially alter spray patterns. Adequate spacing between containers is necessary for improved plant growth but increased spacing will likely increase the amount of water lost between containers (Beeson and Yeager, 2003). The plant canopy can potentially help increase the water reaching the substrate by “capturing” irrigation outside the container area and directing it back towards the substrate surface (Beeson and Yeager, 2003). Conversely, plant canopy can

also act like an umbrella, decreasing the amount of irrigation reaching the substrate due to water flow to canopy edges. The advantage of drip irrigation is more precise and controlled application of water to the substrate surface (Mathers et al., 2005). The disadvantage of drip irrigation is the maintenance of the system to ensure it functions properly. Filters must be cleaned, emitters must be monitored and cleaned, and water pressure must be properly regulated.

Horticultural operations have adopted best management practices to more efficiently use water supplies. These practices vary depending on the needs of a given operation, the method of irrigation used, and the availability of water resources. Best management practices include methods of more efficiently applying irrigation, methods of dealing with runoff, and methods of reducing volume of water needed by the plants.

Irrigation scheduling is the practice of irrigating based on plant water needs. Irrigation is applied only when needed and in the amount needed (Mathers et al., 2005). The difficulty of this method is that water requirements of each species to be irrigated need to be known and plants have to be grouped depending on requirements. Requirements are further complicated by method of irrigation application, spacing of containers, plant size, and plant type. Cyclic irrigation is the practice of applying the daily irrigation amount in multiple small volume irrigation events instead of one large volume irrigation event (Ruter, 1997). The crucial component of cyclic irrigation is time-averaged application rate (TAAR) (Warren and Bilderback, 2005). The components of TAAR are application rate, application duration, and the amount of time between events. Shorter but more frequent irrigation events have been successful in reducing the amount of water applied and the amount of runoff (Mathers et al., 2005).

Time of irrigation is another consideration for managing water use. The Southern Nursery Association (SNA) recommends predawn irrigation because it reduces evapotranspiration (Chappell et al., 2013a). This earlier irrigation, along with lower winds prior to sunrise, has been proven to be effective in reducing water use. Warren and Bilderback (2005) reported that water use was greatest with PM watering (between 1200 – 1800 HR), but growth was greatest as well. Therefore, they concluded that the individual grower would need to decide their main goal in controlling irrigation. An indirect method for reducing water use is managing container heat (Mathers et al., 2005). Most containers used in the nursery trade are made of black plastic that act as a heat-sink when exposed to sunlight (Ruter, 1999). Plants require greater amounts of water to deal with the added stress from container heat. Methods for managing container heat stress include shading of the growing area with larger plants, shade cloth, or retractable roofs. Reclamation of irrigation water in collection ponds and basins is beneficial for recycling runoff water. Proper site preparation is necessary to maximize the water that is reclaimed (Mathers et al., 2005).

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 (Niu 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). Leaching fraction, calculated as $\text{leachate volume} / \text{irrigation volume} * 100$, should not exceed 15% (Chappell et al., 2013a). 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 do adapt to current 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 following an irrigation event (Wells et al., 2011).

Substrate Water Based Irrigation

Approaches to irrigation control based on substrate θ and/or daily water use (DWU) apply only the water needed by the crop to replace what is lost due to evapotranspiration and can provide greater efficiency (Bayer et al, 2013; van Iersel et al, 2010; Warsaw et al, 2009a). Irrigating based on θ and DWU requires knowledge of a diversity of ornamental plant water requirements, which is currently limited (Warsaw et al, 2009a). Understanding how plant growth is affected by maintenance of different θ thresholds will allow for species-specific guidelines.

Management of irrigation water can also be beneficial for reducing the spread of soil-borne pathogens. Losses due to soil-borne pathogens can be around 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).

Recent advances in water management have been in soil moisture control. Measuring soil water content can generally be divided into three methods: the thermogravimetric method, the neutron method, and various methods that measure soil dielectric properties (Gardner et al., 2001). Methods can also be described as either being direct or indirect; direct methods actually measure soil water whereas indirect methods measure other soil properties that can be related to soil water content.

The thermogravimetric method is a direct measurement in which a soil sample is weighed, dried in a 105°C oven overnight, removed and cooled in a desiccator, and then reweighed. The water content of the sample is determined by subtracting the dry soil mass from the wet soil mass and dividing the difference by the dry soil mass. Advantages of this method are simplicity, reliability, affordability, and that it is truly a direct measurement of soil water. Disadvantages include problems during transit (soil loss, drying, and water adsorption from the atmosphere), soil disruption during sampling, need for replication to determine variance, time required for measurements, and labor and resources to sample, store, and measure multiple samples.

The neutron method is an indirect measurement that involves the slowing of neutrons by hydrogen in water. Hydrogen slows fast moving neutrons more effectively than other components of the soil solution. Most hydrogen in the soil is in water molecules, and therefore changes in hydrogen concentrations correspond to changes in soil water content. The neutron method uses a probe with a radioactive source that releases fast moving neutrons and a slow neutron detector. Slow neutron count rates are recorded and converted to soil water content using a calibration curve. Disadvantages of the neutron method include the large volume of soil necessary for installation and measurement (Nemali et al., 2007), various safety issues involving

transport, use, storage, and disposal of the probe, and the need for installation of access tubes for all soils of interest (Gardner et al., 2001).

Tensiometers measure soil matric potential, which is the soil moisture tension of an unsaturated soil (Kirkham, 2005). A tensiometer uses a pressure sensor connected to a porous cup via a water-filled tube to measure the matric potential. Pressure sensors differ depending on the manufacturer of the tensiometer and include mercury manometers, vacuum dial gauges, and current transducers. It is difficult to obtain accurate measurements with tensiometers in a nursery setting due to the use of soilless substrates (Nemali et al., 2007). Soilless substrates are generally porous which increases the likelihood of large areas of the sensor being exposed to air instead of substrate. Exposure to air can result in inaccurate measurements due to cavitation.

Many types of sensors and probes use the relationship between the dielectric properties of the soil and the water content of the soil. Dielectric methods include time domain reflectometry, impedance, and capacitance.

Time domain reflectometry (TDR) consists of a TDR instrument, soil probes, a coaxial cable and cables to connect the TDR instrument to the probes (Kirkham, 2007). The TDR instrument is composed of a pulser, a sampling receiver, a timing device, and a data display. TDR measures an electromagnetic pulse sent through the soil between metal probes creating a waveguide. Time between initiation of the pulse and reflectance of the pulse is recorded. The propagation of the pulse is varied by the water content of the soil. Measurements using TDR probes are generally reliable; however, the expense and amount of components involved in measurements, as well as the knowledge required for equipment use has impeded their utilization (Nemali et al., 2007).

ThetaProbes measure the permittivity at 100 MHz (Gardner et al., 2001). The impedance of a part of a fixed transmission line is compared to that of a stainless steel electrodes inserted into the soil. The electrode's impedance varies with soil water content. The probe produces a voltage output which is converted to volumetric water content. Calibrations must be performed for every soil type. The ThetaProbe has been evaluated for measurement accuracy in soilless substrates and was found to be accurate with little variation due to instrument or user (Hansen et al., 2006). ThetaProbes have also been evaluated for sensitivity to EC, temperature, and fertilizer salts with the probe being sensitive to fertilizer salts and EC but less sensitive to temperature (Nemali et al., 2007).

Capacitance sensors measure high-frequency capacitance in the soil between two electrodes (Gardner et al., 2001). Measurements must be performed at high frequency (greater than 50MHz) to compensate for impurities in the substrate. These sensors must be calibrated and are influenced by soil temperature, composition, and EC. Soil moisture sensors such as Decagon Device's EC-5 and 10HS use capacitance and frequency domain technologies to estimate volumetric water content and are both affordable and compact giving growers the ability to use these sensors in a variety of containers (Burnett and van Iersel, 2008); Decagon Device Inc., 2011). New sensors, which measure the bulk dielectric, temperature, and bulk EC (GS3, Decagon Devices; Pullman, WA), can be used to estimate pore water EC using with the Hilhorst model (Hilhorst, 2000; van Iersel et al., 2013). These sensors are affordable and provide real-time information about the growing conditions that can be used on a day-to-day basis to make irrigation and fertilization decisions.

Plant Growth and Irrigation

Capacitance soil moisture sensors can accurately measure volumetric water content (θ) in peat- and bark-based substrates (van Iersel et al., 2009, van Iersel et al., 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 \times hybrida* (van Iersel et al., 2010) and *Antirrhinum spp.* (Lea-Cox et al., 2009).

The accuracy of the soil moisture sensors along with the automated irrigation system developed by Nemali et al. (2006) allows for the maintenance of soil water contents (van Iersel et al. 2010) which allows for examination of plant growth and plant physiology as affected by substrate water content and 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), *Lantana camara* (Bayer et al, 2014), and *Gardenia jasminoides* (Chappell et al, 2013b). Along with showing the accuracy of soil moisture sensors, these studies have been used to gain an understanding of plant water requirements (Burnett and van Iersel, 2008; van Iersel et al., 2009; van Iersel et al., 2010) and can be used to further develop sensor controlled irrigation technology.

A commercially available twelve-node wireless irrigation system (Decagon Devices Inc.; Pullman, WA) was used to monitor *Acer rubrum* ‘Franksred’ Red Sunset® and *Cornus florida* ‘Cherokee Princess’ on an ornamental tree farm in Maryland (Lea-Cox et al., 2008a). These species were chosen due to large water requirement of *A. rubrum* and the lower requirements of *C. florida*. Sensors were placed at 15, 30, and 45 cm depths in order to understand variability of soil moisture throughout the root zone. The data from the soil moisture sensors were used to make decisions about irrigation. Sensors were calibrated using soil-specific calibrations to ensure accuracy of soil moisture readings. The sensors at the 15 cm depth had the most variability with much less variability at the 45 cm depth showing the importance of sensor placement. Environmental data was collected in order to give the grower additional information for making irrigation and nutrient application decisions (Lea-Cox et al., 2008b).

Lea-Cox et al. (2008b) have also employed networks using Decagon ECH2O moisture sensors to monitor container grown *Rhododendron spp.* In a nursery setting and *Antirrhinum* (snapdragon) species in a cut-flower greenhouse using a closed-system hydroponic (perlite) system. Both networks have proven to work well and have provided precise information used to control irrigation (Lea-Cox et al., 2009). Environmental data including soil and air temperature, relative humidity, rain, and light levels (photosynthetically-active radiation) are also monitored and recorded using sensors. Irrigation amounts as well as runoff are collected from the Azalea study in order to compare sensor controlled irrigation to other best management practices.

MoistureClick irrigation controllers (IL200-MC, Dynamax, Houston, TX) were used in a commercial nursery setting to compare water use of hydrangea irrigated according to substrate volumetric water content to the regular irrigation routine used at the nursery (van Iersel et al., 2009). The MoistureClick controllers were set to irrigate when substrate water content dropped

below $0.20 \text{ m}^3 \cdot \text{m}^{-3}$. Soil moisture sensors were connected to dataloggers (EM50, Decagon) and were used to monitor substrate water content. A comparison of total irrigation volumes at the conclusion of the experiment showed a water savings of 83% using sensor controlled irrigation compared to the regular nursery irrigation practices. Plant dry weights were also compared at the conclusion of the experiment with no differences observed.

Growth and physiological responses of *Catharanthus roseus* (annual vinca) maintained at varying substrate water contents to see if plant growth, as represented by shoot dry weight, was correlated to substrate water content (van Iersel et al., 2007). Plant growth and size of the uppermost fully-expanded leaf were found to be strongly correlated to substrate water content. Leaf water potential and osmotic potential as well as stomatal conductance and transpiration were found to relate to irrigation treatment. Leaf photosynthesis and turgor pressure were unaffected. This study shows that reduced growth can be observed when plants are water stressed.

Petunia ×hybrida growth and water use in response to automated irrigation control of substrate water content (θ) thresholds was examined by van Iersel et al. (2010). The effect of daily light integral on water use and plant growth was also studied. EC-5 moisture sensors (Decagon Devices Inc., Pullman, WA) were used to maintain θ just above the thresholds by applying small but frequent irrigation events. The number of irrigation events per treatment was recorded allowing for determination of total irrigation volume applied per treatment. Plant age and daily light integral were found to be positively correlated with daily irrigation volume allowing for creation of a model to predict daily water use based on plant age and the daily light integral. Total irrigation volume increased with increasing θ threshold with a water use efficiency of 2.54 g/L. There was a quadratic relationship between shoot dry weight and

irrigation volume for *P. ×hybrida* and a linear relationship between irrigation volume and shoot dry weight. Other than the lowest θ threshold ($0.05 \text{ m}^3 \cdot \text{m}^{-3}$) plants were visually considered salable. However, plants at θ thresholds of 0.10 and $0.15 \text{ m}^3 \cdot \text{m}^{-3}$ were smaller and flowered poorly.

Additional studies have looked at growth at different θ thresholds. Burnett and van Iersel (2008) reported that total irrigation volume increased with increasing θ threshold. Shoot dry weight and height of *Gaura lindheimeri* 'Siskiyou Pink' increased with increasing θ thresholds. Reduced leaf area with drought stress has been reported for *G. lindheimeri* (Burnett and van Iersel, 2008). Fulcher et al. (2012) determined shoot length of *Hibiscus rosa-sinensis* 'Cashmere Wind' was greatest for intermediate treatments rather than high or low θ treatments. There was less root growth 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 ($0.30, 0.41, 0.49 \text{ m}^3 \cdot \text{m}^{-3}$). 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. Van Iersel and Nemali (2004) found drought stress treatments produced smaller, but not more compact, marigold (*Tagetes erecta*). Drought stress reduced elongation. Reduced leaf area of *T. erecta* under drought was the result of fewer leaves and reduced leaf size.

The impact of reduced irrigation volumes on growth has been reported for multiple species. A quadratic relationship between shoot dry weight and irrigation volume has been reported for *Cotoneaster dammeri* 'Skoghom', *Rudbeckia fulgida* 'Goldstrum' (Groves et al., 1998),. 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. 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. Height increased with increasing θ threshold. Flowering of *C. citrinus* was not reduced from the control with moderate deficit irrigation ($\theta \approx 40\%$) but was reduced for the severe deficit treatment ($\theta \approx 20\%$).

Greater allocation of resources to root development vs. shoot growth in water-limited conditions has been reported as a plant adaptation for survival (Kozlowski 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.

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; Lea-Cox et al, 2013) and have been trialed in nurseries (Chappell et al, 2013b; Belayneh et al, 2013). 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 due to disease, and reduced fertilizer and fungicide applications which resulted in a 156% increase in profits (Lichtenberg et al, 2013).

Fertilization and Leaching

Fertilization and nutrient leaching BMPs have also been adopted, including using controlled release fertilizers that last throughout the production period and monitoring substrate nutrient levels (Yeager et al., 2010). Less leaching can help reduce nutrient runoff, but there is concern that this may result in the buildup of salts in the substrate, which can damage roots (Bilderback, 2002). Irrigating to have a moderate or high leaching fraction (volume of water leached/volume of water applied) is commonly used to avoid fertilizer salt buildup in substrates. Monitoring EC can ensure that salt levels do not become excessive. The pour-through method of EC measurement is commonly used by growers (Chappell et al., 2013a; Bilderback 2002). This method produces reliable results, but is labor intensive and can be inconvenient if samples are sent to a laboratory for analysis. In situ methods are instantaneous and provide continuous measurements allowing for a clearer picture of the impact of fertilization and irrigation, but most sensors measure the bulk EC of the soil or substrate, which is a combination of substrate/soil particles, air spaces, and substrate/soil solution. The bulk EC depends on substrate water content (Scoggins and van Iersel, 2006) and is not a reliable measurement of nutrient levels in the substrate. New sensors, which measure the bulk dielectric, temperature, and bulk EC (GS3, Decagon Devices; Pullman, WA), can be used to estimate pore water EC using with the Hilhorst model (Hilhorst, 2000; van Iersel et al., 2013). These sensors are affordable and provide real-time information about the growing conditions that can be used on a day-to-day basis to make irrigation and fertilization decisions. The effects of reduced fertilizer rates and irrigation application have been examined (Fare et al., 1994; Million et al., 2007; Tyler et al., 1996; Owen et al, 2008); however, the effects of reduced irrigation volume based on plants water use and fertilizer rate have not been adequately studied.

Reducing irrigation volume of *Ilex crenata* 'Compacta' from 13 mm to 8 mm per day reduced leachate by around 50% (Fare et al., 1994). Cyclic irrigation reduced leachate volume by 34% with fertilizer treatment having no effect on leachate volume. $\text{NO}_3\text{-N}$ leached was 53% less with 6 mm/day irrigation compared to 13 mm/day at the high fertilizer rate ($9.5 \text{ kg}\cdot\text{m}^{-3}$) and 64% less for the low fertilizer rate ($7.1 \text{ kg}\cdot\text{m}^{-3}$). Cyclic irrigation reduced $\text{NO}_3\text{-N}$ leached by 53% and 16% for the high and low leaching fractions compared to one 13 mm irrigation application. Growth index was higher with cyclic irrigation than one daily irrigation and plants receiving higher fertilizer rate had a higher growth index than plants with low fertilizer rates.

Million et al. (2007) reported a 6% reduction in shoot dry weight of *Viburnum odoratissimum* irrigated at a rate of 2 cm/day vs. 1 cm/day, showing that over irrigation can negatively impact plant growth. Shoot dry weight of *V. odoratissimum* was reduced by 32% with a lower fertilizer rate (15 vs. 30 g/plant). Height was 15% greater with increased fertilizer application and was not affected by irrigation volume. Growth index increased by 11% with increased fertilizer rate but was unaffected by additional irrigation volume. Runoff from *V. odoratissimum* was more than doubled with increased irrigation volume from 1 to 2 cm daily irrigation, while fertilizer rate did not affect runoff volume. Leaching fraction increased from 49 to 69% with increased irrigation rate. Increasing irrigation rate from 1 to 2 cm/day increased $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ losses by 21 and 28% at the high fertilizer rate (30g/container) and by 34% and 38% for P at the 50% fertilizer rate (15g/plant) with amount leached varying weekly due to rainfall.

Tyler et al. (1996) found a reduction of only 8% of maximum shoot dry weight for *Cotoneaster dammeri* 'Skogholm' with a leaching fraction of 0.0-0.2 instead of 0.4-0.6 fraction and reducing fertilizer rate by 50% reduced shoot dry weight by 26%. Root dry weight of

Cotoneaster dammeri ‘Skogholm’ was not affected by irrigation volume. Cumulative leachate volume of *Cotoneaster dammeri* ‘Skogholm’ was decreased by 63% by maintaining a low (0.0-0.2) instead of high leaching fraction (0.4-0.6) with no effect of 50% reduced fertilizer rate on leachate volume. $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ quantity in effluent were higher for the high fertilizer rate (3.5 g N/container) at both high and low leaching fractions, with low leaching fraction reducing $\text{NO}_3\text{-N}$ quantity by 66% and $\text{PO}_4\text{-P}$ by 57%. $\text{NO}_3\text{-N}$ quantity was less for the 50% fertilizer rate (1.75 g N/container) than the high rate; however, $\text{PO}_4\text{-P}$ was not reduced by the 50% fertilizer rate.

Warsaw et al. (2009a) reported increased or no effect on plant growth index and shoot dry weight 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 to the control of 19 mm/day. Runoff volume was reduced by using DWU replacement, compared to applying 19 mm/day, considered to be the standard industry practice (Warsaw et al., 2009b). $\text{NO}_3\text{-N}$ quantities in the leachate were reduced by an average of 38 and 59% for the 100 and 75% DWU irrigation treatments compared to the control of 19 mm/day. 100 and 75% DWU treatments resulted in 46 and 74% reduced losses in $\text{PO}_4\text{-P}$ than the control.

Ruter et al. (1998) found that cyclic irrigation reduced leachate volume by 50% and that cyclic irrigation compared to single application irrigation did not affect $\text{NO}_3\text{-N}$ quantity leached. Ruter et al. (1998) found that root to shoot ratios decreased with use of cyclic irrigation. Bayer et al. (2014) found that leachate volume of *Lantana camara* ‘Sunny Side Up’ increased with increasing irrigation duration, regardless of fertilizer rate (25 – 150% of the labeled rate of 17.71 g/plant). Shoot dry weight of *L. camara* increased from 14 g at 25% fertilizer rate to 35 g with

150% fertilizer rate with plants grown with 50% fertilizer and greater were considered salable, with no effect due to irrigation volume.

Drought Stress for Elongation Control

Controlling plant elongation is common in ornamental plant production. Growth control is necessary to meet industry standards for target plant height (Fisher and Heins, 1995), to increase plant aesthetics by creating more compact plants (van Iersel and Nemali, 2004), and because more compact plants are less expensive to ship (Burnett and van Iersel, 2008). Plant growth regulators (PGR) are commonly used (Currey and Lopez, 2011, Berghage and Heins, 1991), but are not always desirable as there is growing concern about the use of agrochemicals in production and their presence in nursery runoff (Kaufmann et al., 2000). Selection of cultivars with shorter internodes and smaller growth habits can be used to produce smaller plants (Ecke et al., 2004).

Environmental conditions can also be altered to manipulate plant growth, including alteration of day and night temperatures (Kaufmann et al., 2000), changing the daily light integral, and increasing plant spacing (Liu and Heins, 2002). Alteration of temperature and light conditions are not always possible depending on what other crops are growing in the greenhouse or when plants are grown outdoors. Plant spacing may not be able to be increased if there is not enough space available and can increase overall production costs with fewer plants per hectare. Deficit irrigation or drought stress can also limit elongation; however many growers are reluctant to expose their plants to drought stress because they do not want it to negatively affect overall plant quality (Bailey and Whipker, 1998).

Drought stress has been used to reduce elongation in many species, including *Gaura lindheimeri* ‘Siskiyou Pink’ (Burnett and van Iersel, 2008), *Rhododendron catawbiense* ‘Boursault’ and ‘Old Port’ (Koniarski and Matysiak, 2013), *Tagetes erecta* ‘Queen Sophia’ (van Iersel and Nemali, 2004), and *Salvia splendens* ‘Bonfire’ (Burnett et al, 2005). Reduced leaf area with drought stress has been reported for *Rhododendron* (Koniarski and Matysiak, 2013), *S. splendens* (Burnett et al, 2005), and *T. erecta* (van Iersel and Nemali, 2004). Leaf area is a responsive indicator of drought stress due to the sensitivity of leaf cell elongation to low soil water potential (Lambers et al., 2008). It is possible that stem growth, similar to leaf expansion, is reduced by water stress due to reduced cell division and expansion (Taiz and Zeiger, 2010). Reduced leaf size contributes to decreased plant growth under drought because of reduced canopy light interception and photosynthesis (Burnett and van Iersel, 2008).

Circadian and Diurnal Rhythms of Plant Growth

Circadian and diurnal rhythms of stem elongation rates have been reported (Nozue and Maloof, 2006) for plants grown under constant temperature and light as well as light and dark cycles (Lecharny and Wagner, 1984; Dowson-Day and Millar, 1999). Inflorescence stem elongation of *Arabidopsis thaliana* (Jouve et al.1998) and stem elongation of *Chenopodium rubrum* (Lecharny and Wagner, 1984) have circadian rhythms even in constant light. Dowson-Day and Millar (1999) reported a diurnal pattern with maximum hypocotyl elongation rates of *A. thaliana* at dusk with reductions in growth rate at dawn. Neily et al. (1997) reported stem elongation rate of snapdragon declined at night and increased during the day. Patterns of stem elongation rate of zinnia changed with developmental stage with elongation rate was greatest early in the day during early development and at night as plants matured (Neily et al., 1997). This suggests that stem elongation patterns are species and developmentally dependent.

Similarly, leaf elongation rates have been reported to show growth patterns with maximum elongation occurring around dawn or at night depending on species (Ruts et al., 2012).

Circadian rhythms interact with environmental conditions and result in changes in elongation. Stomatal conductance and transpiration are also controlled by the plant circadian clock (Farré, 2012). Stomata also open in anticipation of dawn (Hotta et al., 2007) indicating circadian control. Diurnal changes in transpiration could be due to changes in ABA levels which are influenced by the circadian clock (Tallman, 2004). Environmental factors can influence the amount of growth but not the pattern (Ruts et al., 2012). Knowing how and when stem elongation is affected by water availability will help to increase our understanding of how elongation can be controlled through controlled drought stress without reducing plant quality.

A greater understanding of the effects of reduced irrigation volume based on plants water use and fertilizer rate will allow us to make recommendations for more efficient irrigation and fertilization practices for more sustainable plant production.

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. *Scientia Hort.* 156:54-62.
- Bailey, D. and B. Whipker. 1998. Height control of commercial greenhouse flowers. N.C. Coop. Ext. Serv. Hort. Info. Lflt. 528.

- 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. (ISHS)*: 1034:477-484
- Beeson, R.C., Jr. and T.H. Yeager. 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. *HortScience* 38:1373-1377.
- 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.
- Beeson, R.C., Jr. 2006. Relationship of plant growth and actual evapotranspiration to irrigation frequency based on management allowed deficits for container nursery stock. *J. Amer. Soc. Hort. Sci.* 131:140-148.
- 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.

- Berghage, R. D. and R. D. Heins. 1991. Quantification of temperature effects on stem elongation of poinsettia. *J. Amer. Soc. Hort Sci.* 116:14-18.
- Bilderback, T.E. 2002. Water management is key in reducing nutrient runoff from container nurseries. *HortTechnology* 12: 541-544.
- Burnett, S., P. Thomas, and M. van Iersel. 2005. Post-germination drenches with PEG-8000 reduce growth of saliva and marigolds. *HortScience* 40:675-679.
- 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: T. Yeager, 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 April. 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.
- Currey, C.J. and R.G. Lopez. 2011. Early flurprimidol drench applications suppress final height of four poinsettia cultivars. *HortTechnology*. 21:35-40.

- 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/>>
- Ecke, P., III, J.E. Jaust, J. Wiggins, and A. Higgins. 2004. Height control, p. 51-72. In: The Ecke poinsettia manual. Ball Publishing, Batavia, IL.
- Fare, D. C., C. H. Gilliam, and G .J. Keever. 1992. Monitoring irrigation at container nurseries. *HortTechnology*. 2:75-78.
- Fare, D.C., C.H. Gilliam, G.J. Keever, and J.W. Olive. 1994. Cyclic irrigation reduces container leachate nitrate-nitrogen concentration. *HortScience* 29:1514-1517.
- Farré, E.M. 2012. The regulation of plant growth by the circadian clock. *Plant Biol.* 14:401-410.
- Fischer, G., F.N. Tubiello, H. van Velthuisen, and D.A. Wiberg 2007. Climate change impacts on irrigation water requirements: Effects on mitigation, 1990-2080. *Technol. Forecast. Soc. Change* 74:1038-1107.
- Fisher, P.R. and R.D. Heins. 1995. A process-control approach to poinsettia height control. *HortTechnology* 5:57-63.
- Fulcher, A., J. Buxton, and R. Geneve. 2012. Developing a physiological-based, on-demand irrigation system for container production. *Scientia Hort.* 138:221-226.
- Garber, M.P., J.M. Ruter, J.T Midcap, and K. Bodari. 2002. Survey of container nursery irrigation practices in Georgia. *HortTechnology* 12:727-731.

- Gardner C.M.K, D. Robinson, K. Blyth, and J.D. Cooper. 2001. Soil water content, p. 1-64. In Smith K.A. and C. Mullins (eds.). Soil and environmental analysis: Physical methods, 2nd edn. Marcel Dekker, New York.
- 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.
- Hansen, R.C., J.C. Chistman, and R.C. Derksen. 2006. Statistical evaluation of instruments designed to measure volumetric water content of soilless container media. Applied Engineering in Agriculture 22:753-763.
- Hilhorst, M.A. 2000. A pore water conductivity sensor. Soil Sci. Soc. Amer. J. 64:1922-1925.
- Hodges, A.W., C.R. Hall, B.K. Behe, and J.H. Dennis. 2008. Regional analysis of production practices and technology use in the U.S. nursery industry. HortScience 43:1807-1812.
- Hotta, C.T., M.J. Gardner, K.E. Hubbard, S.J. Baek, N. Dalchau, D. Suhita, A.N. Dodd, and A.A.R. Webb. 2007. Modulation of environmental responses of plants by circadian clocks. Plant, Cell, Environ. 30:333-349.
- Jouve, L., H. Geppin, and R.D. Agosti. 1998. *Arabidopsis thaliana* floral stem elongation: Evidence for an endogenous circadian rhythm. Plant Physiol. Biochem. 36:469-472.
- Jury, W.A, and H. Vaux. 2005. The role of science in solving the world's emerging water problems. Proc. Natl. Acad. Sci. USA. 102:15715-15720.

- Kaufmann, P.H., R.J. Joly, and P.A. Hammer. 2000. Influence of day and night temperature differentials on root elongation rate, root hydraulic properties, and shoot water relations in chrysanthemum. *J. Amer. Soc. Hort. Sci.* 125:383-389.
- Kirkham, M.B. 2005. Principles of soil and plant water relations. Elsevier Academic Press. Burlington, MA.
- Knox, G.W. 1989. Water use and average growth index of five species of container grown woody landscape plants. *J. Environ. Hort.* 7:126-139.
- 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.
- Koniarski, M. and B. Matysiak. 2013. Growth and development of potted *Rhododendron* cultivars ‘Catawbiense Boursault’ and ‘Old Port’ in response to regulated deficit irrigation. *J. Hort. Research* 21:29-37.
- Kozlowski, T.T. and S. G. Pallardy. 2002. Acclimation and adaptive responses of woody plants to environmental stresses. *Bot. Rev.* 68:270-334.
- Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov, 2007. Freshwater resources and their management. P. 173-210. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, Cambridge, UK.

- Lambers, 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.
- Lea-Cox, J.D., S. Black, A. Ristvey, and D.S. Ross. 2008a. Towards precision scheduling of water and nutrient applications, utilizing a wireless sensor network on an ornamental tree farm. Proc. Southern Nursery Assn. Res. Conf. 53:32-37
- Lea-Cox, J.D., G.F. Kantor, and A.G. Ristvey. 2008b. Using wireless sensor technology to schedule irrigation and minimize water use in nursery and greenhouse production systems. Comb. Proc. Int. Pl. Prop. Soc. 58:1-7.
- Lea-Cox, J.D., A.G. Ristvey, D.S. Ross, and G.F. Kantor. 2009. Deployment of wireless sensor networks for irrigation and nutrient management in nursery and greenhouse operations. Proc. Southern Nursery Assn. Res. Conf. 54:28-34.
- Lea-Cox, J.D., W.L. Bauerle, M.W. van Iersel, G.F. Kantor, T.L. Bauerle, E. Lichtenberg, D.M. King, and L. Crawford. 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: an overview. HortTechnology 23:717-724.
- Lichtenberg, E., J. Majsztrik, and M. Saavoss. 2013. Profitability of sensor-based irrigation in greenhouse and nursery crops. HortTechnology 23:770-774.

- Liu, B. and R.D. Heins. 2002. Photothermal ratio affects plant quality in 'Freedom' poinsettia. J. Amer. Soc. Hort Sci. 127:20-26.
- Majsztrik, J., A. G. Ristvey and J. D. Lea-Cox. 2011. Water and Nutrient Management in the Production of Container-Grown Ornamentals. In: *Hort. Reviews* J. Janick (Ed.). John Wiley and Sons, NJ. Hort. Rev. 38:253-297.
- Masters, M., M. Risse, and S. Wells. 2010. National Environmentally Sound Production Agriculture Laboratory. Water use for Georgia's nurseries and greenhouses. 10 November 2010. <http://www.nespal.org/SIRP/waterinfo/State/AWD/AgWaterDemand_NurseryIndustry.htm>
- Mathers, H.M., T.H. Yeager, and L.T. Case. 2005. Improving irrigation water use in container nurseries. HortTechnology 15:8-12.
- Million, J., T. Yeager, and J. Albano. 2007. Consequences of excessive overhead irrigation on runoff during container production of sweet viburnum. J Environ. Hort. 25:117-125.
- Neily, W.G., P.R. Hicklenton, and D.N. Kristie. 1997. Temperature and developmental stage influence diurnal rhythms of stem elongation in Snapdragon and Zinnia. J. Amer. Soc. Hort. Sci. 122:778-783.
- Nemali, K.S. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. Scientia Hort. 110:292-297.
- 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. Scientia Hort. 112: 227-234.

- Nozue, K. and J. N. Maloof. 2006. Diurnal regulation of plant growth. *Plant, Cell, and Environ.* 29:396-408.
- Niu, G., D.S. Rodriguez, R. Cabrera, C. McKenney, and W. Mackay. Determining water use and crop coefficients of five woody landscape plants. 2006. *J. Environ. Hort* 24:160-165.
- Owen, J.S., S.L. Warren, T.E. Bilderback, and J.P. Albano. 2008. Phosphorus rate, leaching fraction, and substrate influence on influent quantity, effluent nutrient content, and response of a containerized woody ornamental crop. *HortScience*. 24:906-912.
- Ruter, J.M. 1997. Cyclic irrigation and pot-in-pot production affect the growth of 'Okame' Cherry. *Proc. Southern Nursery Assn. Res. Conf.* 42:423-425.
- Ruter, J.M. 1998. Pot-in-pot production and cyclic irrigation influence growth and irrigation efficiency of 'Okame' cherries. *J. Environ. Hort.* 16:159-162.
- Ruter, J.M. 1999. Fiber pots improve survival of 'Otto Luyken' Laurel. *Proc. Southern Nursery Assn. Res. Conf.* 44:37-38.
- Ruts, T., S. Matsubara, A. Wiese-Klinkenberg, and A. Walter. 2012. Diel patterns of leaf and root growth: endogenous rhythmicity or environmental response? *J. Exp. Bot.* 63:3339-3351.
- Scoggins, H.L. and M.W. van Iersel. 2006. In situ probes for measurement of EC of soilless substrates: Effects of temperature and substrate moisture content. *HortScience* 41:210-214.

- Seager, R., A. Tzanova, and J. Nakamura. 2009. Drought in the southeastern United States: causes, variability over the last millennium, and the potential for future hydroclimatic change. *J. Climate* 22:5021-5045.
- 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.
- Taiz, L. And E. Zeiger. 2010. *Plant physiology*. 5th ed. Sinauer Associates, Sunderland, MA.
- 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.
- U.S. Department of Agriculture. 2008. 2008 Farm and Ranch Irrigation Survey. U.S. Dept. Agr., Washington, D.C. 22 September 2010. <<http://agcensus.usda.gov>>.
- 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., J.G. Kang, and S. Burnett. 2007. Making greenhouse irrigation more efficient: effects of substrate water content on the growth and physiology of vinca (*Catharanthus roseus*). *Proc. Southern Nursery Assn. Res. Conf.* 52: 92-96.
- 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. Res. Conf.* 54: 17-21.
- van Iersel, M.W., S. Dove, J.G. Kang, 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., M. Chappell, and J.D. Lea-Cox. 2013. Sensors for improved efficiency of irrigation in greenhouse and nursery production. *HortTechnology* 23:735-746.
- Warren, S.L. and T.E. Bilderback. 2005. More plant per gallon: getting more out of your water. *HortTechnology* 15:14-18.
- Warsaw, A.L., R.T. Fernandez, and B.M. Cregg. 2009a. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. *HortScience* 44:1308-1318.
- Warsaw, A.L., R.T. Fernandez, B.M. Cregg, and J.A. Andresen. 2009. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. *HortScience*. 44:1573-1580.
- Wells. S., M. Chappell, J. Ruter, P. Thomas, and M. van Iersel. 2011. Monitoring substrate water content in nurseries: More efficient irrigation and reducing leaching and runoff. ASABE Paper No. 1111254.
- Yeager, T., J. Million, C. Larsen, and B. Stamps. 2010. Florida nursery best management practices: past, present, and future. *HortTechnology* 20:82-88.

CHAPTER 2

WATER USE and GROWTH of *HIBISCUS ACETOSELLA* ‘PANAMA RED’ GROWN with a SOIL MOISTURE SENSOR CONTROLLED IRRIGATION SYSTEM¹

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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 utilized 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 to 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.

Additional index words: volumetric water content, container plants, nursery production, woody ornamentals, automated irrigation

Introduction

Availability of freshwater worldwide will likely continue to decrease due to 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 have 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 cm/h, but actual rates ranged from 0.8 to 3.2 cm/h. Measured irrigation volumes varied due to 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 following an irrigation event (Wells et al., 2011).

Capacitance soil moisture sensors can accurately measure volumetric water content (θ) in peat- and bark-based substrates (van Iersel et al., 2009, van Iersel et al., 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 \times 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 to 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 (Niu 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 do 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, 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 June 17, 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 datalogger (CR10, Campbell Scientific, Logan, UT) using two multiplexers (AM16/32, Campbell Scientific). The datalogger excited the sensors with 2.5 VDC and measured the resulting voltage output from the sensors every 10 minutes. 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 datalogger opened an irrigation valve for 20 s, using a relay driver (SDM-CD16AC, Campbell Scientific). Plants were irrigated using pressure compensated drip emitters (8 L/h, 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 datalogger 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 datalogger. These sensors were measured

every 20 s and the datalogger recorded the daily minimum, maximum and average. In addition, the datalogger calculated the vapor pressure deficit (VPD) from the air temperature and relative humidity and the daily light integral (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, UK), 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), daily light integral (DLI), average temperature, vapor pressure deficit (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 as 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 August 19 to October 26, 2010 and at the University of Georgia Tifton

Campus in Tifton, GA from August 10 to October 5, 2010. The studies were conducted at two locations in different USDA 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 m³. 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 datalogger (CR10; Campbell Scientific).

The datalogger 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 datalogger 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 minutes using dribble rings (Dramm; Manitowoc, WI) connected to pressure-compensated drip emitters (2L/h, 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 datalogger. Vapor pressure deficit was calculated by the datalogger using temperature and relative humidity data.

At the conclusion of the experiment, a representative group of 10 plants from each plot were 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 VWC set points) and two replications for a total of sixteen 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. 2.1), even with changing water needs due to 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. 2.1). Drying of substrates to their θ thresholds in the nursery studies was lengthened due to rain. In Tifton, it rained on 9 of the first 20 d of the experiment, delaying the drying of the substrate to the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ threshold until day 41 (Fig. 2.2). It rained 5 of the first 10 d in Watkinsville and the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ threshold was not reached until day 35 (Fig. 2.2). 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 $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ 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 to the greenhouse study could be due to 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 (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. 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 (Nemali and van Iersel, 2006; Burnett and van Iersel, 2008; Kim and van Iersel, 2009; and van Iersel et al., 2010). In the greenhouse study, total irrigation volumes increased from an average of 1.9 L/plant in the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ treatment to 41.6 L/plant for the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ treatment (Fig. 2.3). Daily water use generally increased over the course of the greenhouse experiment due to increasing plant size, but DWU was low on days with low DLI (Fig. 2.4), as previously reported by van Iersel et al. (2010) and Garland et al. (2012). Stepwise regression analysis of the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ 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. 2.5). The importance of DLI in determining DWU of ornamental plants has been previously reported (Baille 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 are difficult to separate from DLI. Pearson correlation analysis (Table 2.1) 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. As 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 $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ treatment to 33.6 L/plant for the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ treatment (Fig. 2.6), while in Watkinsville irrigation volume increased from 0.06 L per plant for the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ treatment to 23.0 L/plant for the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ treatment (Fig. 2.5). Increasing total irrigation volume with increasing θ threshold was expected. Total irrigation volumes do not include water from rainfall, as 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. 2.2) and rain thus provided more water to plants in relatively dry substrates. Average daily irrigation volume increased from 4.21 mL/plant for the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ treatment to 580 mL/plant for the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ treatment in the

Tifton study and from 0.87 mL/plant for the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ treatment to 334 mL/plant for the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ treatment in the Watkinsville study. Average irrigation volume use likely differed between the two locations due to 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 to the nursery studies can be explained by the different growing 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. 2.8)]. 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. 2.7). 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 to $0.45 \text{ m}^3 \cdot \text{m}^{-3}$.

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. 2.7). 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 g/L for *Petunia ×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 to 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 that 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 ×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 to 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/day vs. 1 cm/day, showing that over irrigation 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 θ threshold (Fig. 2.7). Plant height increased from \approx 46 cm with the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ threshold to 125 cm for the $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ 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 $0.41 \text{ m}^3 \cdot \text{m}^{-3}$) were taller than the wettest and driest treatments (0.49 and $0.22 \text{ m}^3 \cdot \text{m}^{-3}$). There was a linear relationship between plant height and θ threshold in nursery studies (Fig. 2.8). Height increased from an average of 26.5 cm ($0.10 \text{ m}^3 \cdot \text{m}^{-3}$) to 89.5 cm ($0.45 \text{ m}^3 \cdot \text{m}^{-3}$) in the Tifton study and from 27.8 cm ($0.10 \text{ m}^3 \cdot \text{m}^{-3}$) to 69.0 cm ($0.45 \text{ m}^3 \cdot \text{m}^{-3}$) in the Watkinsville study (Fig. 2.8).

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. 2.7) and nursery studies (Fig. 2.8). 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 due to 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 due to 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 due to reduced cell division and expansion (Taiz and Zeiger, 2010). This would explain the shorter height and reduced internode length at lower thresholds (< 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 threshold ($0.35 \text{ m}^3 \cdot \text{m}^{-3}$). In both greenhouse and nursery settings, maintaining plants at a threshold of $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ instead of $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ 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 Tifton study, and 8 L/plant savings with 8 g/plant dry weight difference in 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 $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ θ threshold show the potential for using sensor controlled irrigation systems in commercial nursery settings. The irrigation system generally reestablished the θ thresholds after significant rainfall events, with the exception of the $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ 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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Literature Cited

- Baille, M, A. Bialle, and J.C. Laury. 1994. A simplified model for predicting evapotranspiration rate of nine ornamental species vs. climate factors and leaf area. *Sci. Hort.* 59:217-232.
- 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.
- 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. 2012. Irrigation Management Practices. IN T. Yeager, T. Bilderback, D. Fare, C. Gilliam, J. Lea-Cox, A. Niemiera, J. Ruter, K. Tilt, S. Warren, T. Whitwell and R. Wright (eds.) *Best Management Practices: Guide for Producing Nursery Crops*. 3rd edition Southern Nursery Association, Atlanta, GA.
- Fare, D. C., C. H. Gilliam, and G .J. Keever. 1992. Monitoring irrigation at container nurseries. *HortTechnology*. 2:75-78.

- Fulcher, A., J. Buxton, and R. Geneve. 2012. Developing a physiological-based, on-demand irrigation system for container production. *Scientia Hort.* 138:221-226.
- Garland, K. F., S. E. Burnett, M. E. Day, M. W. van Iersel. 2012. Influence of substrate water content and daily light integral on photosynthesis, water use efficiency, and morphology of *Heuchera americana*. *J. Amer. Soc. Hort. Sci.* 137:57-67.
- 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.
- Jury, W.A, and H. Vaux. 2005. The role of science in solving the world's emerging water problems. *Proc. Natl. Acad. Sci.* 102:15715-15720.
- Kim, J. and M.W. van Iersel. 2009. Daily water use of abutilon and lantana at various substrate water contents. *Proc. Southern Nursery Assn.* 54:12-16.
- Knox, G.W. 1989. Water use and average growth index of five species of container grown woody landscape plants. *J. Environ. Hort.* 7:126-139.
- Lambers, 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.

- Lea-Cox, J.D., S. Black, A. Ristvey, and D.S. Ross. 2008a. Towards precision scheduling of water and nutrient applications, utilizing a wireless sensor network on an ornamental tree farm. *Proc. Southern Nursery Assn.* 53:32-37.
- Lea-Cox, J.D., G.F. Kantor, and A.G. Ristvey. 2008b. Using wireless sensor technology to schedule irrigation and minimize water use in nursery and greenhouse production systems. *Comb. Proc. Int. Pl. Prop. Soc.* 58:1-7.
- Lea-Cox, J.D., A.G. Ristvey, D.S. Ross, and G.F. Kantor. 2009. Deployment of wireless sensor networks for irrigation and nutrient management in nursery and greenhouse operations. *Proc. Southern Nursery Assn.* 54:28-34.
- Löfkvist, K., R. Larsen, J.-E. Englund, and B.W. Alsanius. 2009. Light integral as an indicator of water use in commercial greenhouse nurseries. *Acta Agric. Scandinavica* 59:326-334.
- Majsztrik, J., A. G. Ristvey and J. D. Lea-Cox. 2011. Water and Nutrient Management in the Production of Container-Grown Ornamentals. In: *Hort. Reviews* J. Janick (Ed.). John Wiley and Sons, NJ. *Hort. Rev.* 38:253-297.
- Million, J., T. Yeager, and J. Albano. 2007. Consequences of excessive overhead irrigation on runoff during container production of sweet viburnum. *J Environ. Hort.* 25:117-125.
- Naasz, R., J.-C. Michael, and S. Charpentier. 2005. Measuring hysteretic hydraulic properties of peat and pine bark using a transient method. *Soil Sci. Soc. Amer. J.* 69:13-22.
- Nemali, K.S. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. *Scientia Hort.* 110:292-297.

- Nemali, K.S., F. Montesano, S.K. Dove, M.W. van Iersel. 2007. Calibration and performance of moisture sensors in soilless substrates: ECH₂O and Theta probes. *Scientia Hort.* 112:227-234.
- Nui, G., D.S. Rodriguez, R. Cabrera, C. McKenney, and W. Mackay. Determining water use and crop coefficients of five woody landscape plants. 2006. *J. Environ. Hort* 24:160-165.
- Owen, J.S., S.L. Warren, T.E. Bilderback, and J.P. Albano. 2008. Phosphorus rate, leaching fraction, and substrate influence on influent quantity, effluent nutrient content, and response of a containerized woody ornamental crop. *HortScience*. 24:906-912.
- Seager, R., A. Tzanova, and J. Nakamura. 2009. Drought in the southeastern United States: causes, variability over the last millennium, and the potential for future hydroclimatic change. *J. Climate* 22:5021-5045.
- Taiz, L. and E. Zeiger. 2010. *Plant physiology*. 5th ed. Sinauer Associates, Sunderland, MA.
- 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.
- Van Iersel, M.W., S. Dove, J.G. Kang, 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., S. Dove, and S.E. Burnett. 2011. The use of soil moisture probes for improved uniformity and irrigation control in greenhouses. *Acta Hort.* 893: 1049-1056.

- 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.
- Wells. S., M. Chappell, J. Ruter, P. Thomas, and M. van Iersel. 2011. Monitoring substrate water content in nurseries: More efficient irrigation and reducing leaching and runoff. ASABE Paper No. 1111254.
- Welsh, D., J. Zajicek, C. Lyons Jr. 1991. Effect of seasons and irrigation regimes on plant growth and water-use of container-grown *Photinia x fraseri*. J. Environ. Hort. 9:79-82.

Table 2.1. 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 $P \leq 0.01$

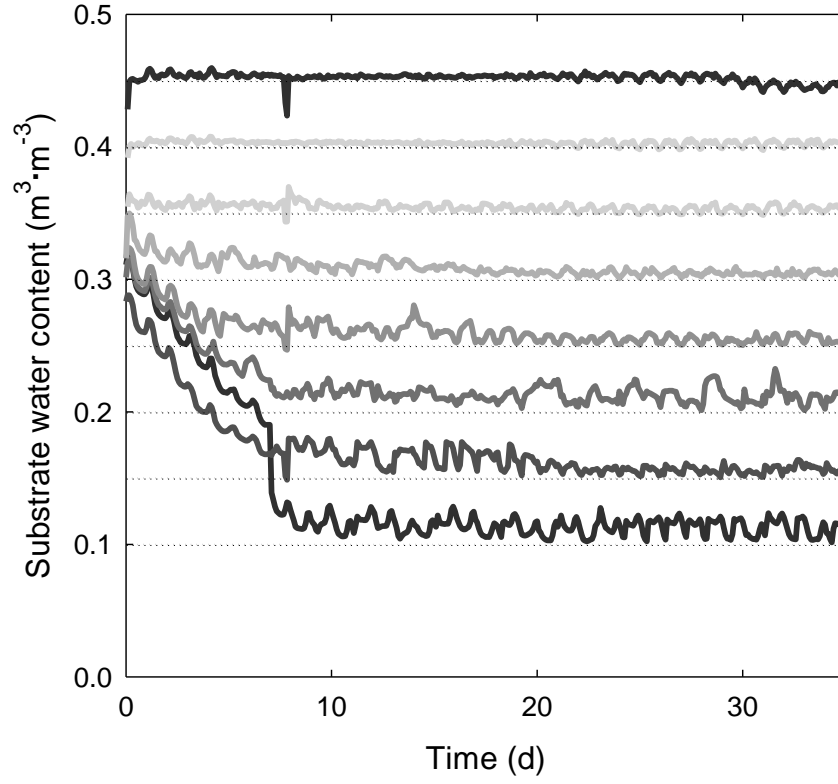


Figure 2.1. Average substrate volumetric water content (θ) measurements as measured with capacitance sensors over the course of the 37 d greenhouse experiment. All θ s were reached within 8 d, after which θ was maintained slightly above the θ thresholds (0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, and 0.45 $\text{m}^3 \cdot \text{m}^{-3}$, indicated by the dotted lines).

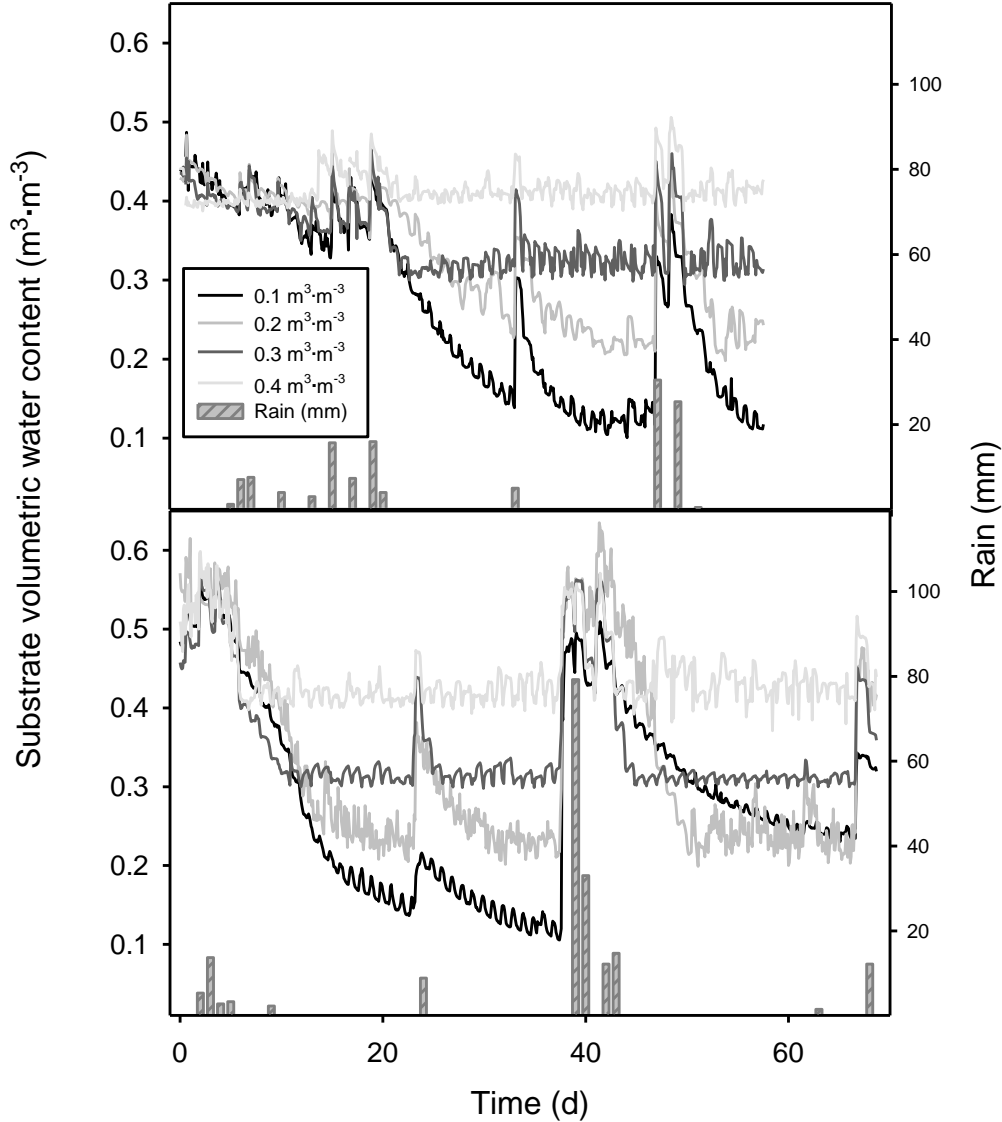


Figure 2.2. Substrate volumetric water content (lines) and rain (bars) over the course of the 57d Tifton, GA (upper graph) and 68d Watkinsville, GA (lower graph) nursery experiments.

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 $\text{m}^3 \cdot \text{m}^{-3}$ thresholds. Note that for clarity only four (0.1, 0.2, 0.3, and 0.4 $\text{m}^3 \cdot \text{m}^{-3}$) 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 $0.10 \text{ m}^3 \cdot \text{m}^{-3}$ threshold, prevented θ from reaching the threshold for the rest of the study and those plants did not get irrigated thereafter.

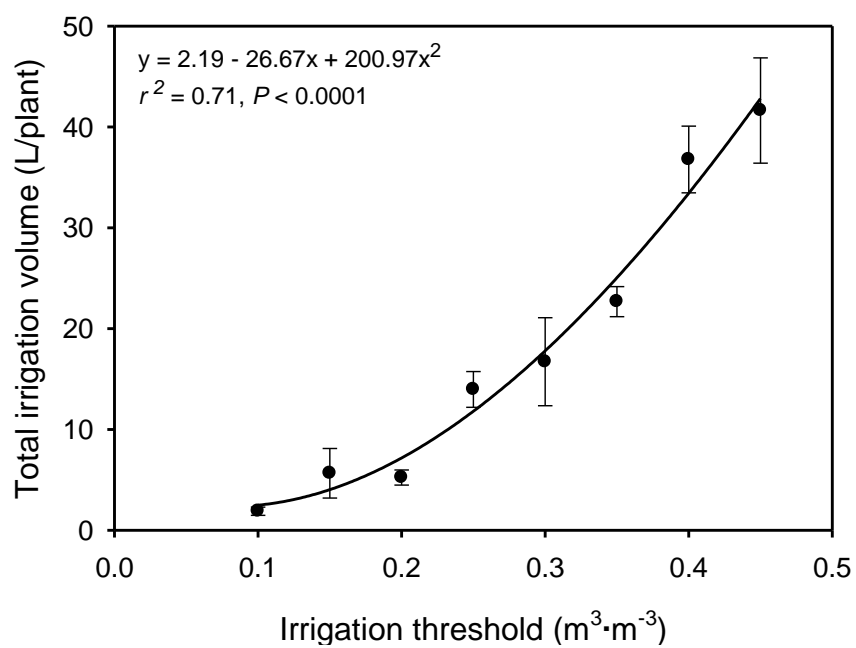


Figure 2.3. Total irrigation volume over the course of the 37-d growing period of *Hibiscus acetosella* 'Panama Red' as affected by the volumetric water content thresholds at which irrigation occurred in the greenhouse study.

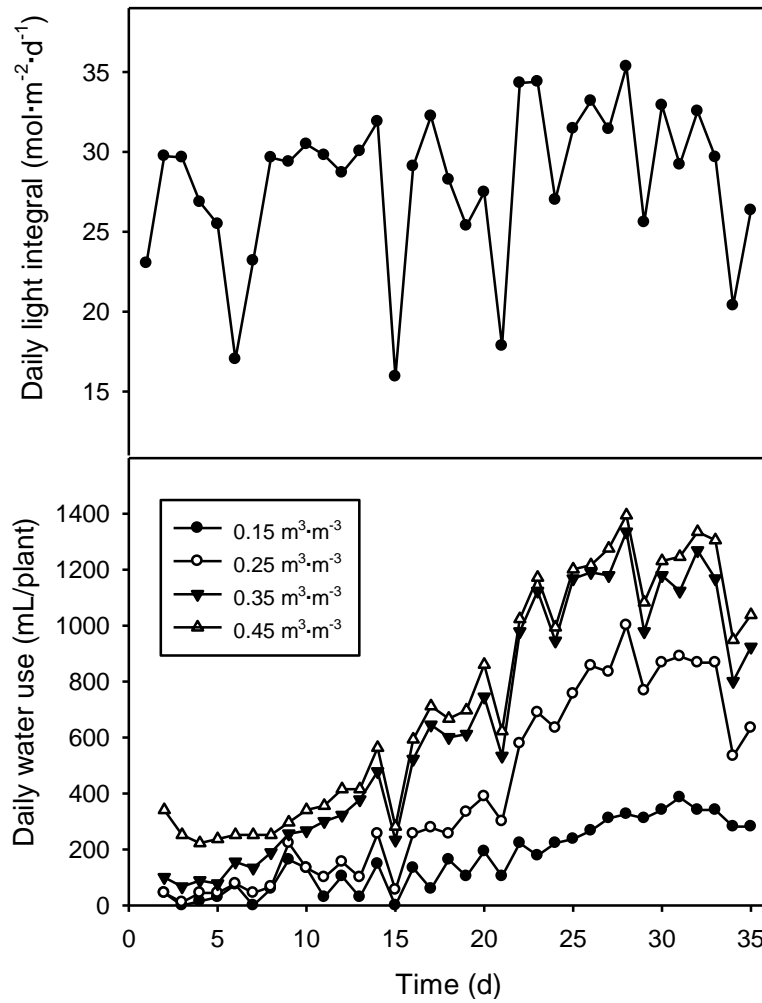


Figure 2.4. Daily light integral (DLI, top) and daily water use (DWU) of *Hibiscus acetosella* ‘Panama Red’ irrigated at different substrate water contents (θ) (0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 m³·m⁻³) (bottom) over the course of the Athens, GA greenhouse experiment. Note that for clarity 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.

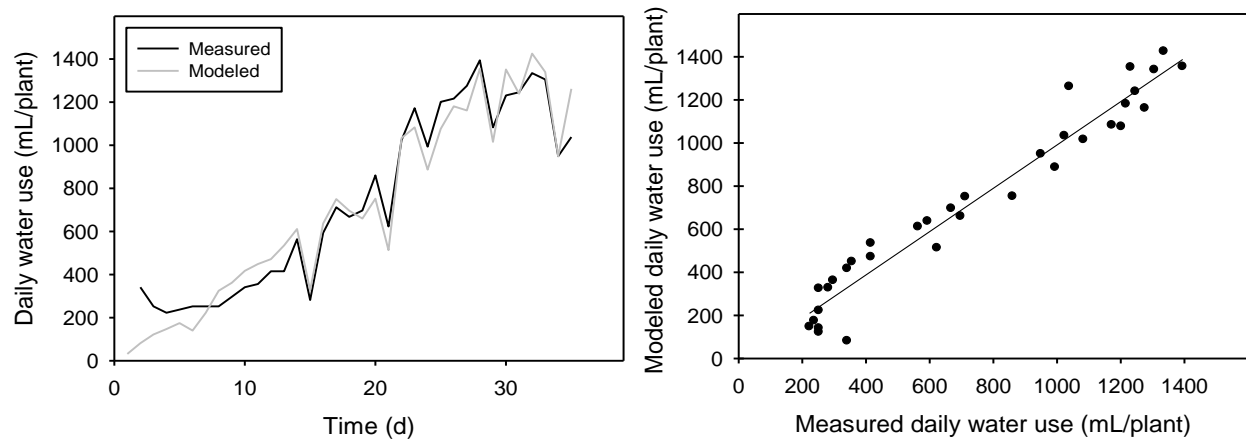


Figure 2.5. Measured and modeled daily water use (DWU) of *Hibiscus acetosella* ‘Panama Red’ grown at a substrate water content (θ) of $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ in a 37-d greenhouse experiment (left). Modeled vs. measured DWU of plants irrigated at the $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ θ threshold (right). Modeled DWU = $-6.3 + 1.369 \times \text{daily light integral} \times \text{day}$ ($r^2 = 0.952$, $p < 0.0001$).

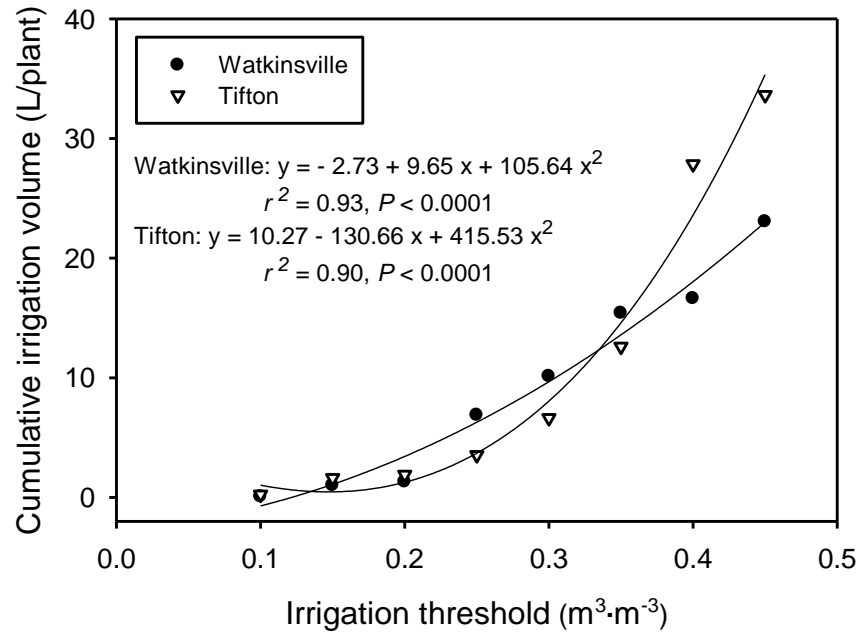


Figure 2.6. Cumulative irrigation volume for the production of *Hibiscus acetosella* as a function of the threshold substrate water content ($0.10 - 0.45 \text{ m}^3 \cdot \text{m}^{-3}$) at which the plants were irrigated. Plants were grown outdoors on nursery pads in Watkinsville or Tifton, GA over the course of a 57- (Tifton) or 68-d (Watkinsville) period Tifton: $r^2 = 0.90$, $P < 0.0001$; Watkinsville: $r^2 = 0.93$, $P < 0.0001$.

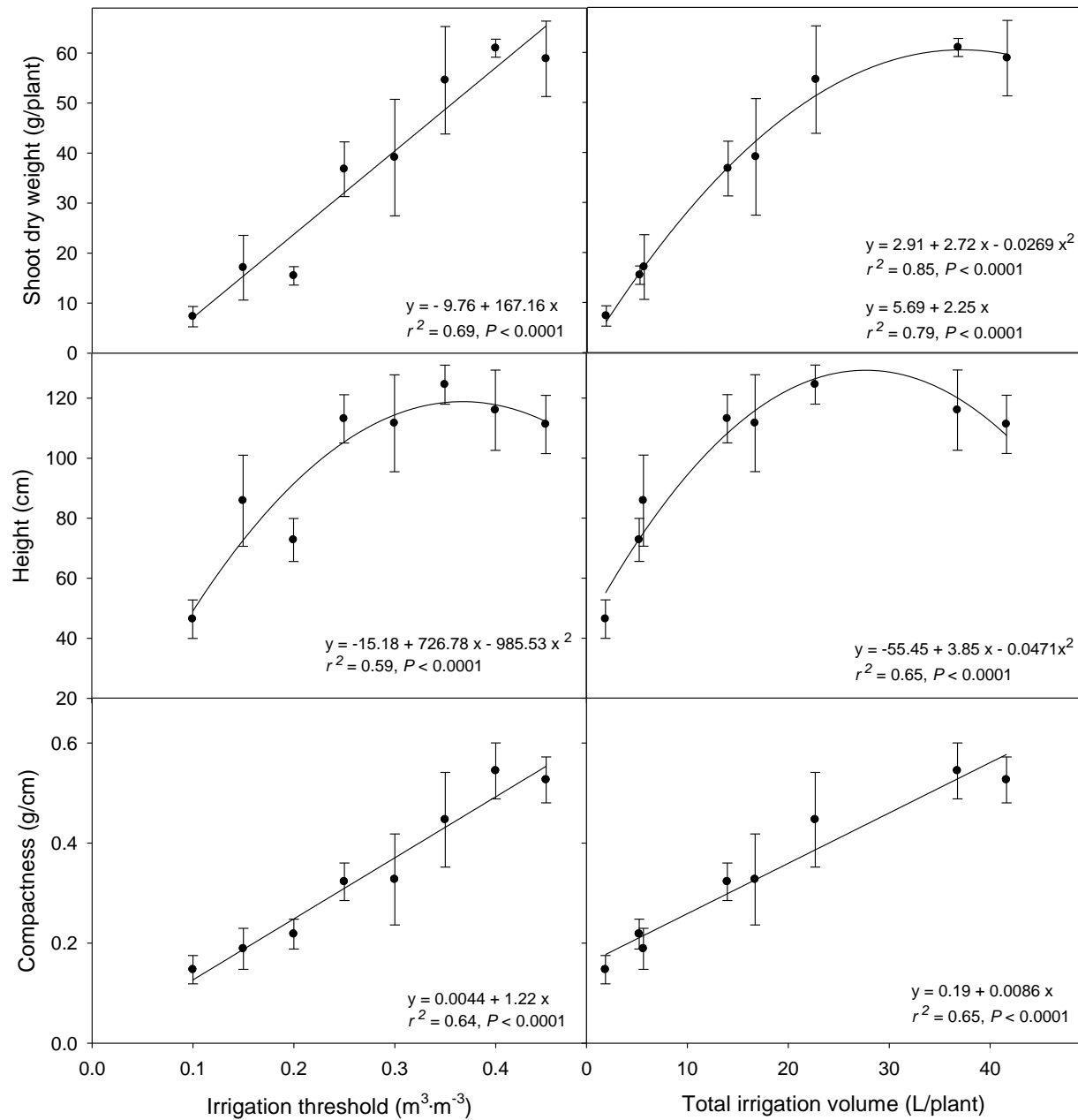


Figure 2.7. Shoot dry weight (top), height (middle), and compactness (bottom) of greenhouse-grown *Hibiscus acetosella* 'Panama Red' as affected by the substrate water content threshold at which the plants were irrigated (left) or total irrigation volume (right). Error bars indicate standard error. The 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.

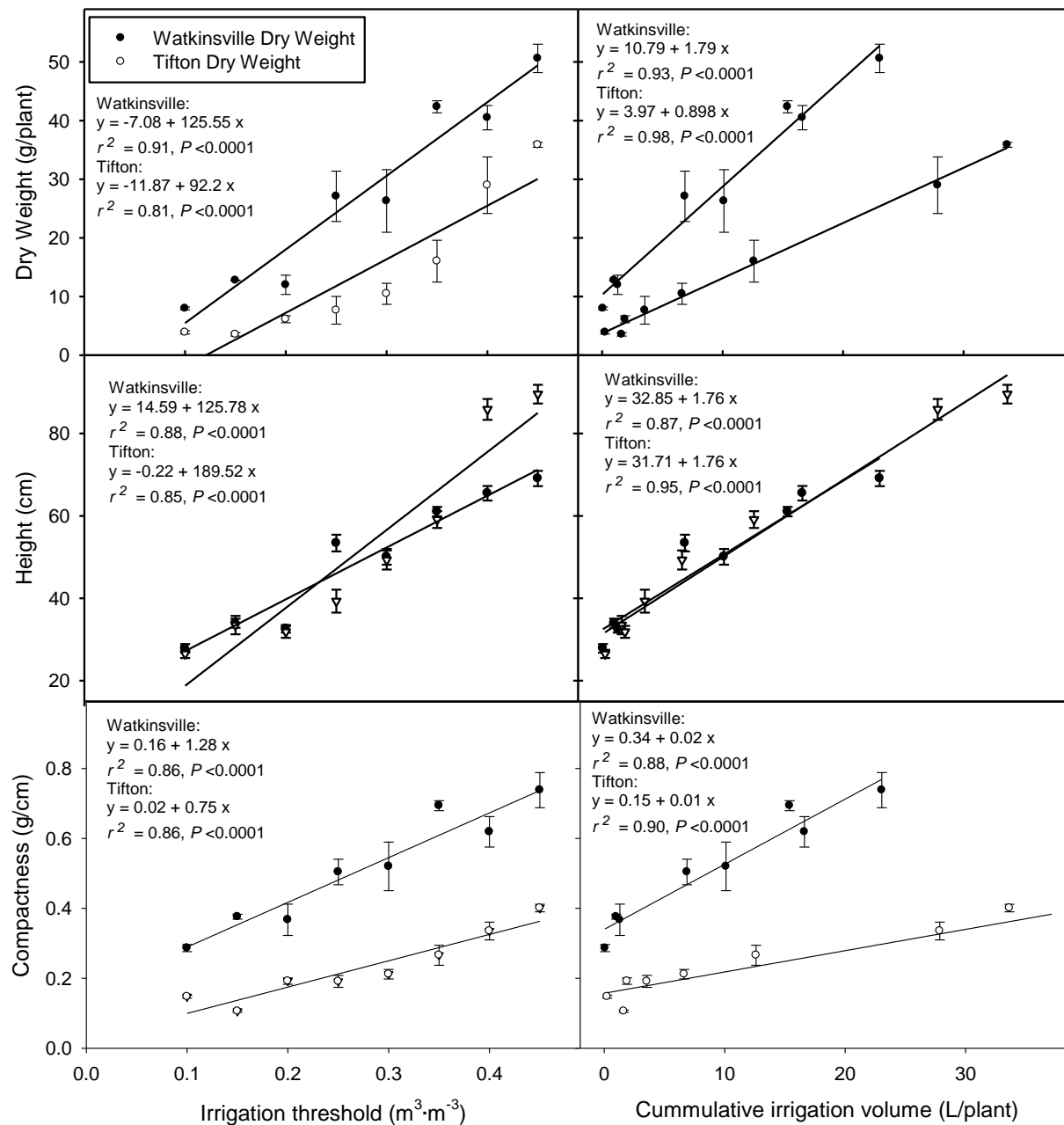


Figure 2.8. Shoot dry weight (top), shoot height (middle), and compactness (bottom) of *Hibiscus acetosella* 'Panama Red' as affected by the substrate water content threshold at which the plants were irrigated (left) or total irrigation volume (right). Plants were grown on nursery pads in Watkinsville or Tifton, GA. Error bars indicate standard error. Cumulative irrigation volume

does not include water received via 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.

CHAPTER 3

AUTOMATED IRRIGATION CONTROL for IMPROVED GROWTH and QUALITY of *GARDENIA JASMINOIDES* ‘RADICANS’ and ‘AUGUST BEAUTY’²

² Bayer, A., J. Ruter, and M.W. van Iersel. Submitted to HortScience, 8/12/14.

Abstract

Sustainable use of water resources is of increasing importance in container plant production due to 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 due to 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 over-irrigation 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 $\text{m}^3 \cdot \text{m}^{-3} \theta$ thresholds show that more efficient irrigation can be used without negatively impacting growth.

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

Introduction

More efficient irrigation management has become a focus in sustainable container plant production (Chappell et al., 2013a) to improve resource utilization 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 (θ) and/or daily water use (DWU) apply only the water needed by the crop to replace what is lost due to 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 (Chappell et al., 2013b; Belayneh et al., 2013).

Management of irrigation water can also be beneficial for reducing the spread of soil-borne pathogens. Losses due to soil-borne pathogens can be around 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 due to 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 (Kozlowski 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 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 April 5, 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 two or four 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 18-20 plants. Soil moisture sensors (10HS; Decagon Devices, Pullman, WA) were inserted into two pots in each of the 16 plots at approximately a 45° 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 datalogger (CR10; Campbell Scientific). The datalogger excited the sensors with 2.5 VDC and measured the resulting voltage output from the sensors every 20 minutes.

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 datalogger 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 minutes 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 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), and a rain gauge (ECRN-50; Decagon Devices) connected to the datalogger.

On August 11, 2011 two to three plants from each plot at the Watkinsville location were inoculated with 5 g of *Phytophthora cinnamomi* colonized rice grains produced via method for inoculum production described by Holmes et al. (1994). Inoculated plants were kept on the same irrigation line but were physically separated from other plants to avoid pathogen spread via 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). 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 to be statistically significant. Treatment means were separated using either 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 1. 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 (30-34 d in Tifton and 23 d in Watkinsville) due to 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. 3.1), 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 , 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. 3.2), as previously described for other species (Bayer et al., 2013; Burnett and van Iersel 2008; and van Iersel et al., 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 including, specifically rainfall (Tifton: 599 mm, Watkinsville: 387 mm), but also temperature and vapor pressure deficit (Table 3.1). 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 $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold is likely due to the difficulty in maintaining the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ 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 which could result in irrigation (Decagon Devices, 2014). 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 $\text{m}^3 \cdot \text{m}^{-3}$ 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 33g for increasing θ threshold. Shoot dry weight was lower with 0.20 and 0.30 $\text{m}^3 \cdot \text{m}^{-3}$ thresholds than with 0.40 and 0.50 $\text{m}^3 \cdot \text{m}^{-3}$ thresholds (Fig 3.3), but not affected 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 et al., 2008) and *Hibiscus acetosella* ‘Panama Red’ (Bayer et al., 2013), with salable plants produced at moderate thresholds (0.25 – 0.35 $\text{m}^3 \cdot \text{m}^{-3}$ and 0.35-0.40 $\text{m}^3 \cdot \text{m}^{-3}$ 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 0.0-0.2 instead of 0.4-0.6. Applying 6-75% less water than the control treatment of 19 mm per day 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 $\text{m}^3 \cdot \text{m}^{-3}$

threshold similar to those grown at the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ 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. 3.3). The small root systems of plants grown at the 0.20 and $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ 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 $0.20 \text{ m}^3 \cdot \text{m}^{-3}$ threshold (72% in Tifton and 79% in Watkinsville). The $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ 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 not affected by irrigation volume. The variability in root dry weight with irrigation volume may be due to natural variability in root growth responses to θ among species or due to substrate 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 to the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold (Fig. 3.4). Dry weight increased linearly with increasing irrigation volume for the $0.20 - 0.40 \text{ m}^3 \cdot \text{m}^{-3}$ 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. 3.4). Extrapolating the linear relationship for the $0.20 - 0.40 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds (dashed lines, Fig. 3.4) 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 $0.20 - 0.40 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds is an estimation of leaching, which was 19 to 335 L (horizontal arrows, Fig. 3.4). 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. 3.5). 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).

Average height of the two cultivars responded differently to θ thresholds ($P = 0.0115$, Fig. 3.6), with θ having a greater effect on ‘August Beauty’ than ‘Radicans’. ‘August Beauty’

was smaller at the $0.20 \text{ m}^3 \cdot \text{m}^{-3}$ threshold and larger at the $0.40 \text{ m}^3 \cdot \text{m}^{-3}$ threshold. 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. 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. 3.6). 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. 3.6) 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’ (Álvarez 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 over the observation period ($P < 0.0001$). 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 (Fig. 3.7). There was poor bud development at the 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 due to the excessive irrigation applied at the $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ threshold. A flush of growth was observed for the $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ plants after more frequent rains in October. Flowering of those plants occurred at that time (delayed compared the 0.40 and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ 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 over-irrigation.

Conclusions

Gardenia jasminoides ‘August Beauty’ and ‘Radicans’ had similar growth responses to θ thresholds. θ thresholds reduced height, width, shoot dry weight, root dry weight, and leaf size at the 0.20 and $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ θ thresholds compared to the 0.40 and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ θ thresholds.

The $0.20 \text{ m}^3 \cdot \text{m}^{-3}$ 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 $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ 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 $\text{m}^3 \cdot \text{m}^{-3}$ θ thresholds suggests that the additional irrigation applied by maintaining a high θ threshold leads to over-irrigation and leaching with little additional growth. Bud and flower numbers of ‘Radicans’ with the 0.40 and 0.50 $\text{m}^3 \cdot \text{m}^{-3}$ θ thresholds shows that over-irrigation can reduce flowering.

There was little or no difference in growth between the 0.40 and 0.50 $\text{m}^3 \cdot \text{m}^{-3}$ θ thresholds for either cultivar. Irrigation was more efficient at the 0.40 $\text{m}^3 \cdot \text{m}^{-3}$ θ thresholds with little leaching observed. These results show that cultivars with different growth habits respond similarly to θ thresholds. This shows 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.

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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. *Scientia 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. (ISHS)*: 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: T. Yeager, 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 April. 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. Scientia Hort. 138:221-226.
- Graham, J.H. and J.A. Menge. 1999. Root health: Fungal diseases. p. 126-135. In: L.W. Timmer 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.
- 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. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. Scientia Hort. 110:292-297.
- Nemali, K.S., F. Montesano, S.K. Dove, M.W. van Iersel. 2007. Calibration and performance of moisture sensors in soilless substrates: ECH2O and Theta probes. Scientia Hort. 112:227-234.
- Niu, G., D.S. Rodriguez, and W. Mackay. 2008. Growth and physiological responses to drought stress in four Oleander clones. J. Amer. Soc. Hort. Sci. 133:188-196.

- 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., 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.
- Van Iersel, M.W., S. Dove, J.G. Kang, S. E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45:277-282.
- 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.

Table 3.1. Average temperature, relative humidity, vapor pressure deficit, and rainfall over the course of the 191 and 190 d experiments in Tifton and Watkinsville, GA.

	Average temperature (°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

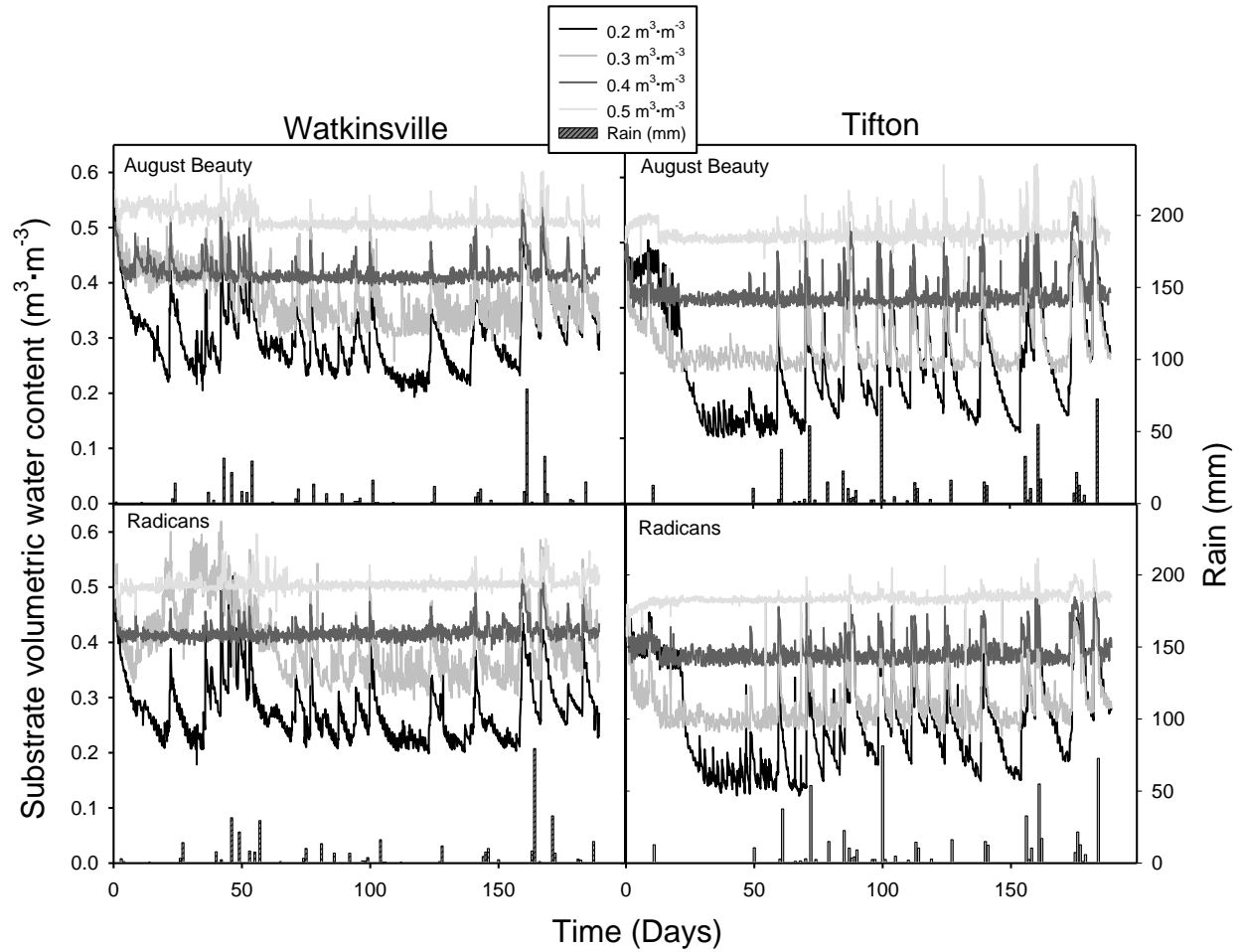


Figure 3.1. Substrate volumetric water content (lines) and rain (bars) over the course of the 191 d Tifton (right graphs) and 190 d Watkinsville (left graphs) experiments. *Gardenia jasminoides* ‘August Beauty’ (upper graphs) and ‘Radicans’ (lower graphs) were irrigated when substrate volumetric water 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.

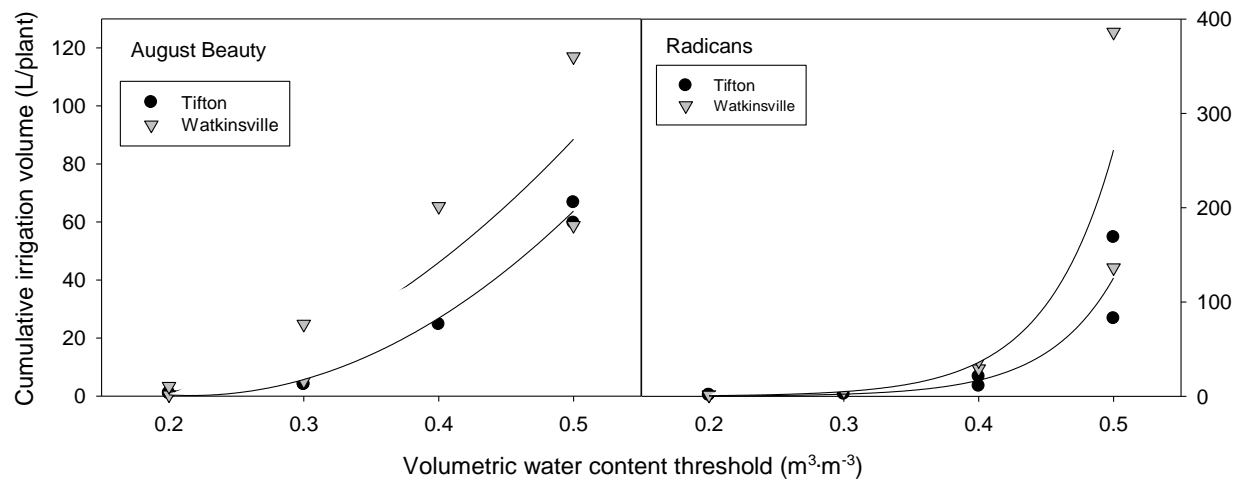


Figure 3.2. Cumulative irrigation volume for the production of *Gardenia jasminoides* 'August Beauty' and 'Radicans' as a function of the volumetric water content thresholds at which irrigation occurred over the course of the 191 (Tifton) or 190 d (Watkinsville) period.

Cumulative irrigation volume increased with increasing volumetric water content threshold ($P = 0.0001$). Data was 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'.

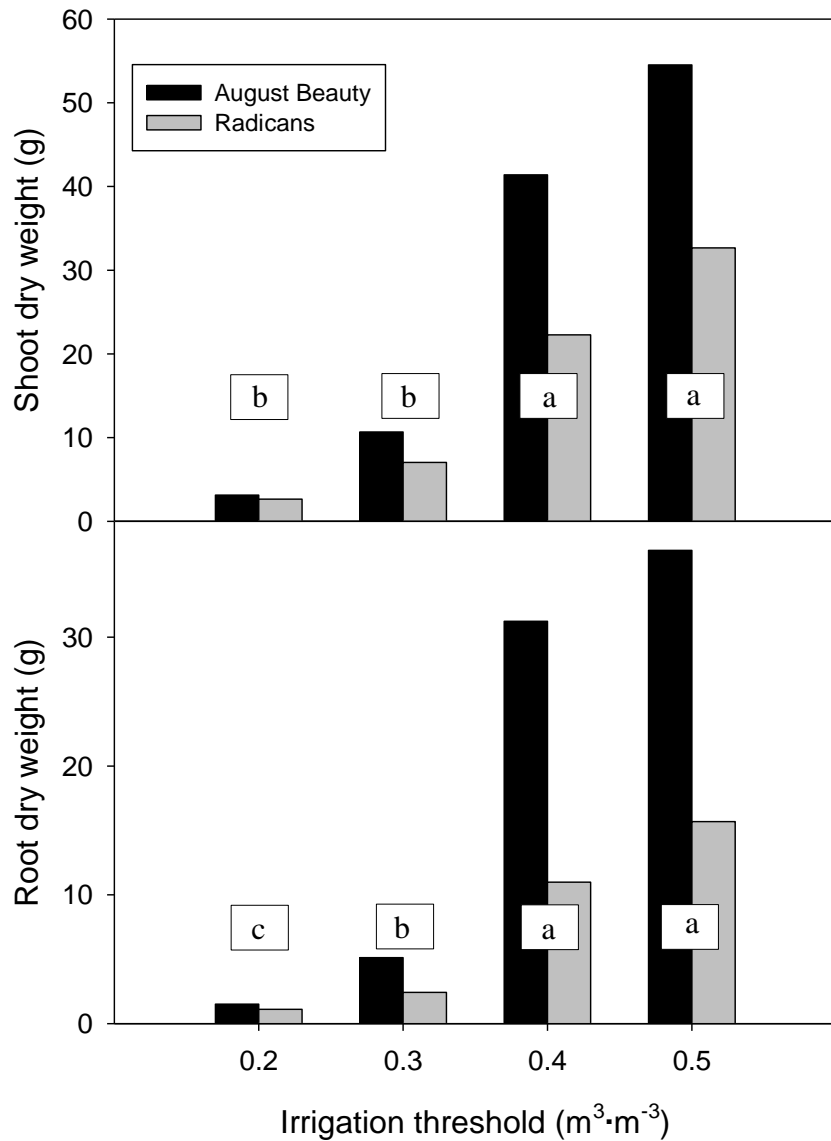


Figure 3.3. Shoot dry weight (top) and root dry weight (bottom) of *Gardenia jasminoides* ‘August Beauty’ and ‘Radicans’ as affected by irrigation thresholds (θ) (0.20, 0.30, 0.40, and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$) for irrigation. Data were normalized before analysis by dividing all data by 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 not significant ($P \leq 0.05$). There were no location effects or cultivar by θ interaction effects.

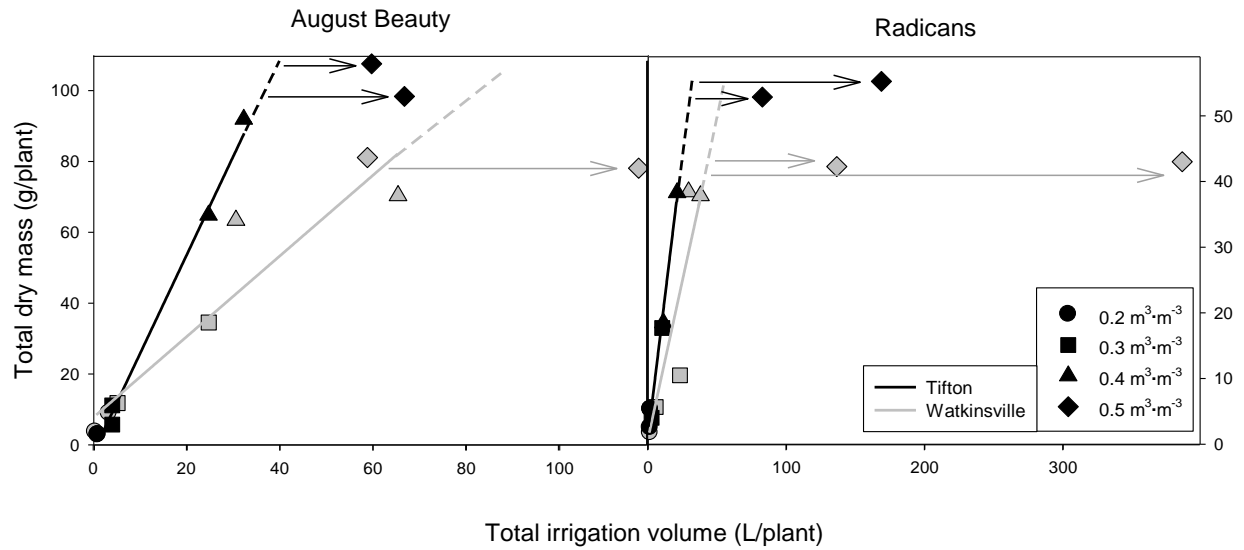


Figure 3.4. Total dry weight as a function of the total volume of irrigation water applied. Dry weight increased linearly with increasing irrigation volume (indicated by solid lines) for the 0.20 to 0.40 $\text{m}^3 \cdot \text{m}^{-3}$ thresholds (Tifton, ‘August Beauty’: $y = 8.188 + 1.6533x$, $R = 0.94$; 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.

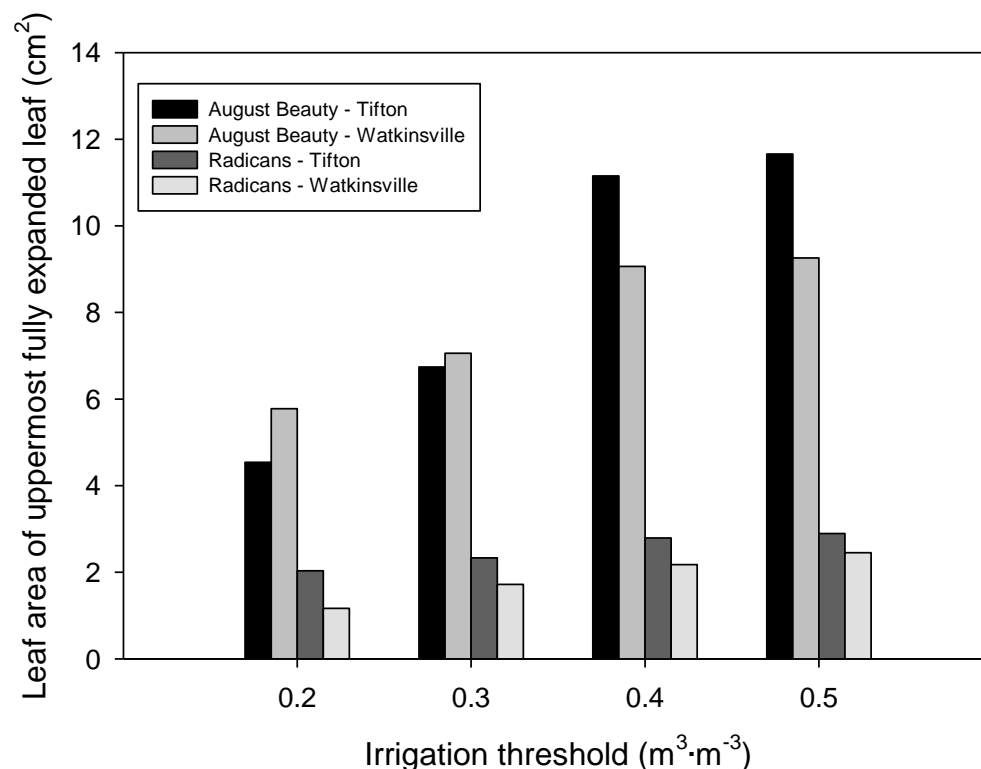


Figure 3.5. Area of the uppermost fully expanded leaf of *Gardenia jasminoides* ‘August Beauty’ and ‘Radicans’ as affected by irrigation threshold. Data were normalized before analysis by cultivar averages to account for natural differences in growth habit among cultivars. Leaf size was lower with the 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.

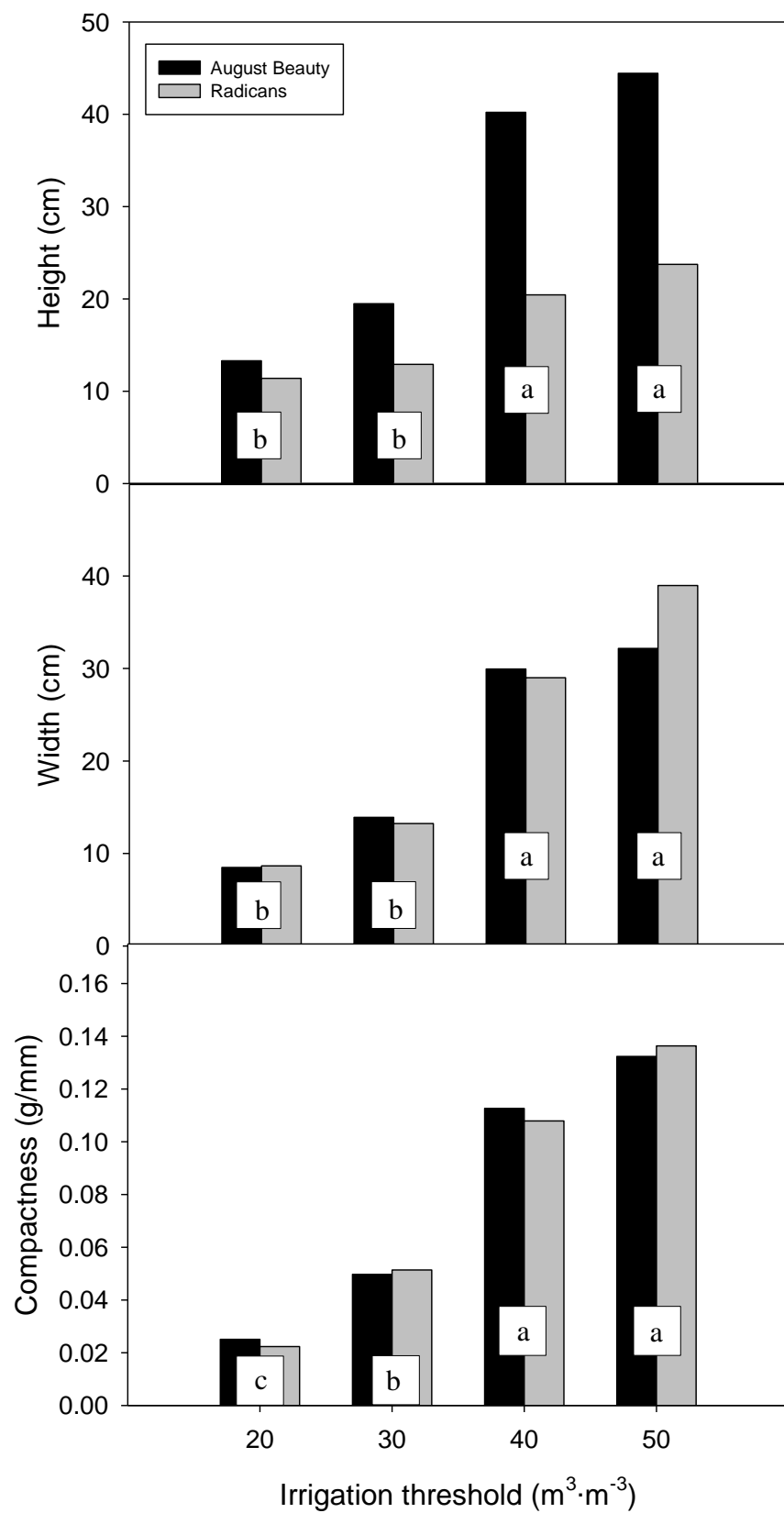


Figure 3.6. Height (top) and width (middle) and compactness (bottom) of *Gardenia jasminoides* ‘August Beauty’ and ‘Radicans’ as affected by irrigation threshold. Data was normalized by cultivar averages before analysis to account for differences in growth habit between cultivars. Irrigation thresholds with the same letter indicate that the main effect of irrigation, averaged over both cultivars, is not significant ($P \leq 0.05$).

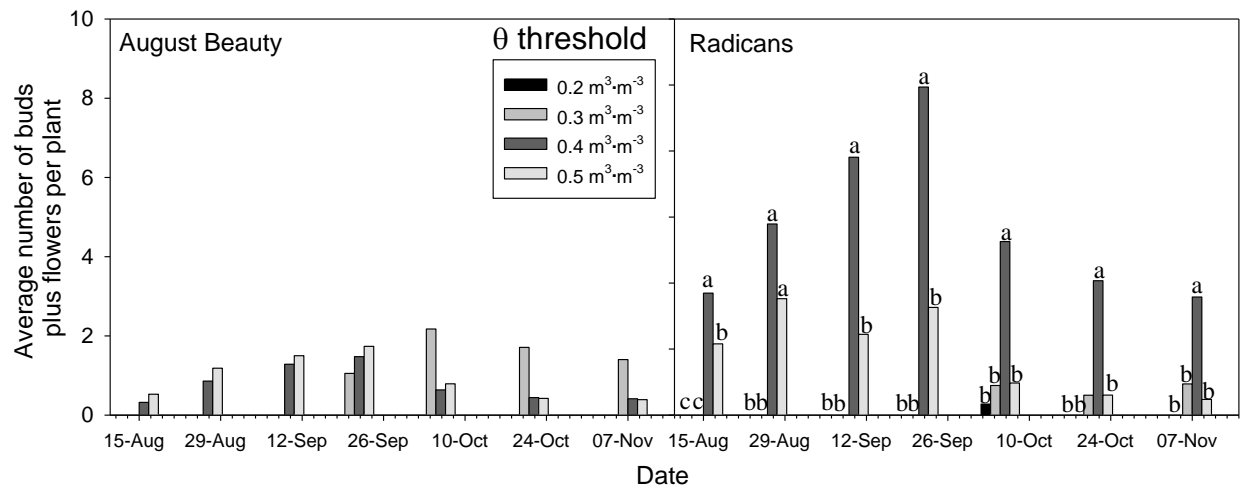


Figure 3.7. Average number of buds plus blooms per plant from August to November 2011 for the Watkinsville, GA location. Irrigation threshold did not significantly affect the number of buds and blooms of ‘August Beauty’ at any time. For ‘Radicans’, there was a significant interactive effect of date and θ threshold on the number of buds and blooms. Means with the same letter within a specific date are not significantly 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.

CHAPTER 4

OPTIMIZING IRRIGATION AND FERTILIZATION OF *GARDENIA JASMINOIDES* FOR GOOD GROWTH AND MINIMAL LEACHING³

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Abstract

Excessive irrigation and leaching are of increasing concern in container plant production.

Fertilizer leaching has a negative environmental impact as the leached nutrients enter into local ecosystems. It can also necessitate multiple fertilizer applications, which is costly for growers.

More efficient irrigation can reduce the leaching of fertilizers, potentially reducing fertilizer requirements while benefitting the environment. Our objective was to determine the effect of fertilizer rate and irrigation volume on pore water EC, leachate volume, electrical conductivity (EC), and nutrient concentrations, as well as growth of *Gardenia jasminoides* 'MAGDA I'.

Treatment combinations included fertilizer rates of 100 (40 g/plant), 50 (20 g/plant), and 25% of bag rate (10 g/plant) and irrigation volumes of 66, 100, 132, or 165 mL per irrigation event for a total of 12 treatment combinations. Soil moisture sensor-controlled, automated irrigation was used to irrigate when the control treatment (66 mL irrigation treatment, 100% fertilizer treatment) reached a volumetric water content of $0.35 \text{ m}^3 \cdot \text{m}^{-3}$. All irrigation events for a replication occurred at this time with the 66, 100, 132, and 165 irrigation volume treatments being applied with 2, 3, 4, and 5 minute irrigation intervals. Fertilizer rate had a greater effect on growth of *Gardenia jasminoides* 'MAGDA I' than irrigation volume with the 25% fertilizer rate resulting in significantly lower shoot dry weight (18.7 g/plant) than the 50 and 100% rates (25.3, and 27.3 g/plant respectively). Growth index was also higher for the 50% and 100% fertilizer rates. Leachate volume varied greatly over the course of the growing season due to rainfall.

Irrigation volume effects were the most evident in the 3rd, 8th, and 9th biweekly leachate collections, in which there was minimal or no rainfall. For these collections there was less than 130 mL of leachate for the 66 mL irrigation treatment with leachate volume increasing by 56%, 58%, and 48% from the 66 to 100, 100 to 132, and 132 to 165 mL irrigation treatments,

respectively. Pore water EC, leachate EC, NO₃-N quantities, and PO₄-P quantities were all highest with the 100% fertilizer rate, with the 66 mL irrigation treatment having the highest leachate EC for all fertilizer treatments. Cumulative leachate volume for the 66 and 100 mL irrigation treatments were not affected by fertilizer rate while the 132 and 165 mL had greater leaching at the 25% fertilizer rate. Lower irrigation volumes resulted in reduced water and nutrient leaching and higher leachate EC. The higher leachate EC was the result of higher concentration of fertilizers in less volume of leachate. The results of this study suggest that reduced fertilizer rates up to 50% and more efficient irrigation can be used to produce salable plants with reduced leaching and thus less environmental impact.

Additional index words: nursery production, volumetric water content, electrical conductivity, woody ornamentals, container plants

Introduction

Improving water and nutrient management in container plant production is necessary for the industry to adapt to decreasing water resources and the growing number of laws and regulations regarding nursery water use, fertilizer applications, and nutrient levels in runoff (Beeson et al, 2004; Chappell et al., 2013). Over-irrigation commonly occurs for many reasons, including the belief that maintaining substrates near container capacity is necessary for maximum growth (Beeson, 2006), inefficiencies in irrigation application and poor uniformity of irrigation systems (Fare et al., 1992), and the grower preference to over- rather than under apply water (Million et al., 2007; Yeager et al, 2010). Along with this, many growers apply large amounts of fertilizer out of concern that lower fertilizer applications could negatively impact growth (Owen et al., 2008; Tyler et al., 1996). The combination of excessive irrigation and high fertilizer rates often leads to significant leaching of fertilizers, which has a negative

environmental impact as the leachate enters local ecosystems (Lea-Cox and Ross, 2001), and can lead to the need for additional fertilizer applications late in the production cycle.

Best management practices (BMPs) have been adopted by many growers in an effort to irrigate and fertilize more efficiently. Cyclic irrigation can be used to apply reduced irrigation volumes more frequently, and can reduce water and nutrient leaching (Fare et al, 1994; Ruter, 1998). Other BMPs for irrigation management include grouping plants by water requirements and inspecting irrigation systems for uniformity (Chappell et al, 2013). More recently, soil moisture sensor automated irrigation has been used to control irrigation with a variety of nursery and greenhouse crops, including *Hibiscus acetosella* (Bayer et al., 2013a), *Lantana camara* (Bayer et al., 2014), *Hydrangea macrophylla* (van Iersel et al., 2009), *Gaura lindheimeri* (Burnett and van Iersel), and *Gardenia jasminoides* (Chappell et al., 2013). Until recently most sensor controlled irrigation has been for research purposes; however, wireless sensor networks capable of controlling irrigation are being developed for implementation in commercial production (Kohanbash et al., 2013; Lea-Cox et al., 2013).

Fertilization and nutrient leaching BMPs have also been adopted, including using controlled release fertilizers that last throughout the production period and monitoring substrate nutrient levels (Yeager et al., 2010). Less leaching can help reduce nutrient runoff, but there is concern that this may result in the buildup of salts in the substrate, which can damage roots (Bilderback, 2002). Irrigating to have a moderate or high leaching fraction (volume of water leached/volume of water applied) is commonly used to avoid fertilizer salt buildup in substrates. Monitoring electrical conductivity (EC) can ensure that salt levels do not become excessive. The pour-through method of EC measurement is commonly used by growers (Chappell et al., 2013; Bilderback 2002). This method produces reliable results, but is labor intensive and can be

inconvenient if samples are sent to a laboratory for analysis. In situ methods are instantaneous and provide continuous measurements allowing for a clearer picture of the impact of fertilization and irrigation, but most sensors measure the bulk EC of the soil or substrate, which is a combination of substrate/soil particles, air spaces, and substrate/soil solution. The bulk EC depends on substrate water content (Scoggins and van Iersel, 2006) and is not a reliable measurement of nutrient levels in the substrate. New sensors, which measure the bulk dielectric, temperature, and bulk EC (GS3, Decagon Devices; Pullman, WA), can be used to estimate pore water EC using with the Hilhorst model (Hilhorst, 2000; van Iersel et al., 2013). These sensors are affordable and provide real-time information about the growing conditions that can be used on a day-to-day basis to make irrigation and fertilization decisions.

The effects of reduced fertilizer rates and irrigation application have been examined (Fare et al., 1994; Million et al., 2007; Tyler et al., 1996; Owen et al., 2008); however, the effects of reduced irrigation volume based on plants water use and fertilizer rate have not been adequately studied. Using soil moisture sensors to irrigate based on substrate water content allows for efficient irrigation based on plant water use. The effect of sensor controlled irrigation along with reduced fertilizer application rates on plant growth and leaching will provide further information about the potential for reducing fertilizer inputs with efficient irrigation. Our objective was to determine how irrigation volume and fertilizer rate affect pore water EC, leachate volume, electrical conductivity (EC), and nutrient concentrations, as well as growth of *Gardenia jasminoides* ‘MAGDA I’. Our hypothesis was that more efficient irrigation can be combined with reduced fertilizer inputs without impacting plant growth, reducing leaching and nutrient levels in leachate; with reduced leaching, more fertilizer remains in the container and available to the plant.

Materials and Methods

Plant Material. The experiment was conducted at the University of Georgia horticulture farm in Watkinsville, GA from April 27 to November 8, 2012. Rooted cuttings of *Gardenia jasminoides* ‘MADGA I’ (PP#19988) Heaven Scent® were obtained from McCorkle Nurseries (Dearing, GA). Plants were grown in 5.4 L black plastic containers in a pine bark-based substrate with $1.97 \text{ kg}\cdot\text{m}^{-3}$ lime, $0.74 \text{ kg}\cdot\text{m}^{-3}$ Micromax (Everris, Dublin, OH), and $0.74 \text{ kg}\cdot\text{m}^{-3}$ gypsum incorporated. Controlled release fertilizer (Florikan 18-6-8 9-10 month release; 18.0 N- 2.6P- 6.6K; Florikan E.S.A LLC, Sarasota, FL) was incorporated into the upper part of the substrate on May 1, and plants were kept well watered for 8 weeks to allow for root establishment.

Treatments and Data Collection. Treatment combinations included fertilizer rates of 100 (40 g/plant), 50 (20 g/plant), and 25% of bag rate (10 g/plant) and irrigation volumes of 66, 100, 132, or 165 mL per irrigation event for a total of 12 treatment combinations. There were four irrigation lines per replication to apply the four irrigation volume treatments and four plants receiving each fertilizer treatment on each irrigation line for a total of 12 plants per irrigation line and 48 plants per replication (Fig. 1). Irrigation was controlled using a soil moisture sensor automated irrigation system similar to that described by Nemali and van Iersel (2006). Soil moisture sensors (10HS; Decagon Devices) were inserted into two pots in each experimental unit receiving the 100% fertilizer rate for all irrigation volume treatments at approximately a 45° angle so that the entire sensor was in the substrate. Thirty two sensors were connected to a multiplexer (AM416; Campbell Scientific, Logan, UT) which was connected to a datalogger (CR10; Campbell Scientific). The datalogger measured sensor voltage output every 20 minutes. The voltage readings from the sensors were converted to θ using our own calibration [$\theta = -0.4009 + 1.0124 \times \text{output (V)}$] using the method described by Nemali et al. (2007). When both

sensors within the same experimental unit (100% fertilizer, 66 mL irrigation treatment) were below the θ threshold of $0.35 \text{ m}^3 \cdot \text{m}^{-3}$, the datalogger signaled the relay driver (SDM16AC/DC controller; Campbell Scientific) to open all four solenoid valves (sprinkler valve; Orbit, Bountiful, UT) in a replication to apply irrigation to all four irrigation treatments. Plants in the different irrigation treatments were irrigated for 2, 3, 4, or 5 minutes using dribble rings (Dramm; Manitowoc, WI) connected to pressure-compensated drip emitters (Netafim USA, Fresno, CA), thus applying 66, 100, 132, or 165 mL/plant in the different irrigation treatments. All plots within a replication were watered the same number of times, but for different duration in order to apply the different irrigation volumes.

Soil moisture readings from each sensor were averaged and stored every 2 h and the number of irrigation events in each replication was recorded daily. The daily and total irrigation volume for a plot was calculated from the number of irrigation events and the volume of water applied per irrigation event. Twenty four GS3 soil moisture, temperature, and electrical conductivity sensors (Decagon Devices; Pullman, WA) connected to five data loggers (EM50, Decagon Devices; Pullman, WA) were installed in one plant per treatment in two replications. Sensors were installed by cutting a slit in the side of the pot and inserting the sensor into the substrate. Data from the GS3 sensors was used to calculate solution (pore water) EC, using the Hilhorst model with an offset of 4.1 (Hilhorst, 2000).

Pots containing plants were placed in another identical pot secured into the lid of 38 L leachate collection containers. Trash bags were placed over the collection container before the pots containing plants were inserted to exclude rainwater from the collection container, so that only rainwater that had moved through the pot and substrate was included in the leachate. Plant height and width as well as leachate volume and electrical conductivity (EC) (Horiba Twin

Conductivity Tester) were measured biweekly. A leachate sample was also collected biweekly for later NO_3^- and PO_4^- analysis. Samples were stored frozen at -9°C until analysis. NO_3^- was analyzed using an ion selective electrode (Cole-Parmer Combination Ion Selective Electrode; Cole-Parmer, Vernon Hills, IL). PO_4^- analysis was conducted at the University of Georgia Soil, Plant, and Water Analysis Laboratory using the continuous flow colorimetric method. Irrigation volumes and rainfall were measured daily throughout the experiment. At the conclusion of the experiment shoots were cut off at the substrate surface and dried at 80°C , after which dry weight was determined. Growth index was calculated as $(\text{height} + \text{width}_1 + \text{width}_2)/3$. Leaching fraction was calculated as $\text{leachate volume} / (\text{irrigation volume} + \text{rainfall volume})$. Rainfall volume per plant was calculated as $\text{rain amount} \times \text{pot surface}$. Environmental conditions were measured using a temperature and relative humidity sensor (HMP50, Vaisala, Woburn, MA), a quantum sensor (SQ-110, Apogee Instruments), and a rain gauge (ECRN-100; Decagon Devices) connected to the datalogger.

Experimental design and data analysis. The experimental design was a split-plot with 4 replications with main plots being irrigation treatments and splits being fertilizer rates. Each experimental unit consisted of four plants. Data were analyzed using the PROC MIXED procedure of SAS (SAS Version 9.2; SAS Institute, Cary, NC), with $P = 0.05$ considered to be statistically significant. Treatment means were separated using either the SLICE or PDIFF option of PROC MIXED. Curve fitting was done using SigmaPlot (Systat, San Jose, CA).

Results and Discussion

Irrigation and Leachate. Cumulative irrigation volumes were 6.6, 10.0, 13.2, and 16.5 L/plant in the 66, 100, 132, and 165 mL irrigation treatments, respectively (Fig. 2). Including

rainfall, total water volume was 20.95, 24.33, 27.52, and 30.81 L/plant. The irrigation volume varied on a bi-weekly basis due to the impact of rainfall, because rainfall increased the VWC, reducing the need for irrigation (Fig. 3). The inverse relationship between rainfall and irrigation volume was demonstrated during the 2nd bi-weekly collection in which rainfall was 109.5 mm during the two week period and irrigation volume ranged from 0.03 to 0.08 L/plant. For the last bi-weekly collection, there was no rain during the two week period and irrigation volume ranged from 0.91 to 2.27 L/plant.

Leachate volume also differed among the various collection periods due to rainfall. The large amount of rain during the 2nd collection period resulted in similar leachate volumes for all treatments (Fig. 3), because most of the leachate was the result of rainfall. Leachate volume increased with increasing irrigation treatments ($P < 0.0001$) for all but the 2nd collection period ($P < 0.0005$). Irrigation treatment effects are the most evident during the 3rd, 8th, and 9th collection periods, during which rainfall was less than 20 mm. For these collections, leachate volume increased by 56%, 58%, and 48% from the 66 to 100, 100 to 132, and 132 to 165 mL irrigation treatments, respectively, with less than 130 mL of leachate in the 66 mL treatment (Fig 3). There was no effect due to fertilizer rate on leachate volume for any collection date. The low leaching volumes (126 mL, 59 mL, and 12 mL) in the 100% fertilizer, 66 mL irrigation treatment during the 3rd, 8th, and 9th collections (periods with little rain) shows that this control treatment was successful in producing little leachate in the absence of rain.

Cumulative leachate volumes ranged from 9.01 to 15.22 L for the 66 to 165 mL irrigation treatments respectively (Fig. 2). Leachate volume increased with increasing irrigation treatment ($P = 0.0013$) with the 100 and 132 mL treatment resulting in similar leachate volumes. The effect of fertilizer rate differed for the irrigation treatments, with no fertilizer effect in the 66 and 100

mL irrigation treatments. For the 132 and 165 mL irrigation treatments the 25% fertilizer treatment resulted in more leachate than the 50% and 100% treatments. This could be the result of the smaller plants produced with the 25% fertilizer treatment not using as much water as plants produced with the 50% and 100% treatments.

Leaching fraction varied by collection period due to the influence of rainfall and changes in irrigation volumes ($P < 0.0001$). The 25% fertilizer rate resulted in higher leaching fractions than the 50 and 100% fertilizer rates ($P = 0.0005$), possibly because of reduced water use of the smaller plants. Irrigation treatment did not affect leaching fraction for the 1st, 2nd, 6th, and 7th collection periods. There was significant rainfall during the 2nd and 6th collection periods, resulting in fewer irrigations and no irrigation treatment effect on leaching fraction. Much of the rainfall during the 6th collection occurred during the final days of the collection period leading to high substrate water content at the start of the 7th collection period, lessening the effect of irrigation treatment on leaching fraction during that collection period as well. Leaching fractions increased with increasing irrigation volumes during the 3rd, 4th, 5th, 8th, and 9th collection periods ($P < 0.0001$). Leaching fractions increased with increasing irrigation treatment ($P = 0.0002$) with leaching fractions for the 66 and 100 mL irrigation treatments not different.

Runoff from *Viburnum odoratissimum* was more than doubled with increased irrigation volume from 1 to 2 cm daily irrigation, while fertilizer rate did not affect runoff volume. Leaching fraction increased from 49 to 69% with increased irrigation rate (Million et al., 2007). Similarly, reducing irrigation volume of *Ilex crenata* 'Compacta' from 13 mm to 8 mm per day reduced leachate by around 50% (Fare et al., 1994). Cyclic irrigation reduced leachate volume from *Ilex crenata* 'Compacta' by 50% (Fare et al., 1994) and from *Prunus xincamp* 'Okame' by 34% (Ruter, 1998). Fare et al. (1994) also found that fertilizer treatment had no effect on

leachate volume. Cumulative leachate volume of *Cotoneaster dammeri* ‘Skogholm’ was decreased by 63% by maintaining a low (0.0-0.2) instead of high leaching fraction (0.4-0.6) with no effect of 50% reduced fertilizer rate on leachate volume (Tyler et al., 1996). Leachate volume of *Lantana camara* ‘Sunny Side Up’ increased with increasing irrigation duration, regardless of fertilizer rate (25 – 150% of the labeled rate of 17.71 g/plant) (Bayer et al., 2014). Runoff volume was reduced by 66 – 79% by replacing the amount of water used on a daily basis, compared to applying 19 mm/d, considered to be the standard industry practice (Warsaw et al., 2007). This is similar to our results, in which the 66 mL irrigation treatment, with VWC maintained near $0.35 \text{ m}^3 \cdot \text{m}^{-3}$, had low leaching and larger irrigation volumes applied in other treatments resulted in more leachate and higher volumetric water contents (data not shown).

There were significant main effects of fertilizer rate ($P < 0.0001$), irrigation volume ($P = 0.0015$), and collection period ($P < 0.0001$) and interactive effects of fertilizer rate \times irrigation volume ($P = 0.0443$), fertilizer rate \times collection period ($P < 0.0001$), and irrigation volume \times collection period ($P < 0.0001$) on leachate EC. The fertilizer rate \times irrigation volume \times collection period interaction was not significant (Fig.4). In general, leachate EC decreased with decreasing fertilizer rate. At the 50% and 100% fertilizer rates, leachate EC decreased with increasing irrigation volume, but at the 25% fertilizer rate leachate EC was not affected by irrigation volume.

Collection period effects and collection by irrigation volume and fertilizer rate interactions are due to variable rainfall amounts (Fig. 3) and less remaining fertilizer to be leached as the experiment progressed. The large amount of rain during the 2nd collection interval apparently leached out much of the released nutrients, resulting in low leachate EC during the 3rd collection period. The gradual decrease in the amount of fertilizer left in the substrate, caused by

both plant nutrient uptake and fertilizer leaching, is reflected in the steady decrease in leachate EC from the middle of August until the end of the study (Fig. 4).

The 66 mL irrigation volume resulted in higher leachate EC than larger irrigation volumes, because of lower leachate volumes (Fig. 3) resulting in less dilution and thus higher nutrient concentrations. Leachate EC was low ($0.11 - 0.31 \text{ dS}\cdot\text{m}^{-1}$) during the 9th collection period, suggesting that the applied fertilizer may have been largely depleted. During the 4th to 8th collection period, leachate EC for both the 100% and 50% fertilizer treatments was higher in the 66 mL irrigation treatment than with larger irrigation volumes. This shows that the lower irrigation volumes resulted in more fertilizer remaining in the container as the experiment progressed.

Pore water EC varied over the course of the experiment due to rainfall, irrigation, and depletion of fertilizer. During the 2nd collection period, with 110 mL of rain, the impact of rainfall can be seen in the rapid increases in EC and VWC (Fig. 5) During the 9th collection period the depletion of fertilizer can be seen by the decrease in pore water EC, with EC below $0.2 \text{ dS}\cdot\text{m}^{-1}$ for all but the 100% fertilizer treatments (Fig. 5). A clear decrease in pore water EC for the 100% fertilizer rate occurs over the two week period. In general pore water EC was greatest at the 100% fertilizer rate and decreased with fertilizer rate throughout the study.

The quantity of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ leached varied by collection in a pattern similar to EC, but was not affected by irrigation volume (Fig. 6). The amount of $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ leached increased with fertilizer rate for all but the 3rd, 8th, and 9th collection periods. For the 3rd collection period, quantities are low likely because of the large amount of nutrients leached due to rainfall during the second collection period. For the 8th and 9th collections quantities likely are

low as fertilizer has been used or leached as the experiment progressed as seen by the reduction in pore water EC at the end of the study (Fig. 6). With an average high temperature of 29 °C during the study, the fertilizer had an expected release period of 9 months. However, June through August had an average high temperature of 32 °C, with 38 d above 32 °C, which could have contributed to the fertilizer being depleted more quickly. Substrate temperatures of container grown plants in the southeastern United States have been reported to be as high as 57°C (Martin and Ingram, 1991) with substrate temperature higher than air temperature (Ruter, 1993), which could have also contributed to fertilizer depletions. The quantity of NO₃-N leached was 44-81% less for the 50% fertilizer treatment and 69-92% less for the 25% treatment compared to the 100% fertilizer treatment depending on collection period. The quantity of PO₄-P leached was 35-81% and 43-92 % less than the 100% fertilizer treatment for the 50% and 25% fertilizer treatments, respectively.

NO₃-N and PO₄-P quantity in effluent were higher for the high fertilizer rate (3.5 g N/container) at both high and low leaching fractions, with low leaching fraction reducing NO₃-N quantity by 66% and PO₄-P by 57% (Tyler et al., 1996). NO₃-N quantity was less for the 50% fertilizer rate (1.75 g N/container) than the high rate; however, PO₄-P was not reduced by the 50% fertilizer rate. Increasing irrigation rate from 1 to 2cm per day increased NO₃-N and PO₄-P losses by 21 and 28% at the high fertilizer rate (30g/container) and by 34% and 38% for P at the 50% fertilizer rate (15g/plant) with amount leached varying weekly due to rainfall (Million et al., 2007). NO₃-N quantities in the leachate were reduced by an average of 38 and 59% for the 100 and 75% DWU irrigation treatments compared to the control of 19 mm/d (Warsaw et al., 2007). 100 and 75% DWU treatments resulted in 46 and 74% reduced losses in PO₄-P than the control. Six mm/day irrigation compared to 13 mm/day at the high fertilizer rate (9.5 kg·m⁻³) reduced

leachate by 53% and 64% less for the low fertilizer rate ($7.1 \text{ kg}\cdot\text{m}^{-3}$) (Fare et al., 1994). Cyclic irrigation reduced $\text{NO}_3\text{-N}$ leached by 53% and 16% for the high and low leaching fractions compared to one 13 mm irrigation application (Fare et al., 1994). Conversely, Ruter (1998) found cyclic irrigation compared to single application irrigation did not affect $\text{NO}_3\text{-N}$ quantity leached. These reports support our finding that the 25% and 50% fertilizer rates reduced leached $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ compared to the 100% fertilizer rate, but unlike most previous reports, we did not find that irrigation volume treatment affects $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ leached. The reason for this difference is not clear, but it is possible that the rainfall in this study negated possible irrigation volume effects on leached $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$.

Plant Growth. There was a significant main effect of fertilizer rate and a fertilizer rate by irrigation volume interactive effect on shoot dry weight. Shoot dry weight was lower with the 25% fertilizer rate (18.1 to 19.9 g/plant) than with the 50 and 100% rates (22.7 to 27.1 and 23.8 to 30.4 g/plant respectively) ($P < 0.0001$). Only at the 100% fertilizer rate did increasing irrigation volumes increase shoot dry weight ($P = 0.02$; Fig. 7). There was no fertilizer or irrigation treatment effect on plant height, with final height ranging from 191 to 212 mm (data not shown). Compactness, calculated as shoot dry mass per unit plant height, is a measure of plant quality (van Iersel and Nemali, 2004). The 25% fertilizer rate produced less compact plants ($0.096 \text{ g}\cdot\text{mm}^{-1}$) than the 50 and 100% rates ($P < 0.0001$; 0.126 and $0.136 \text{ g}\cdot\text{mm}^{-1}$), with no effect of irrigation volume. Final growth index of plants fertilized at the 50% and 100% rates were greater than at the 25% rate ($P < 0.0001$; Fig. 7). There was a fertilizer rate by irrigation volume interaction ($P = 0.0073$). At the 50% and 100% fertilizer rates, growth index was affected by irrigation volume, but not at the 25% fertilizer rate. Similar shoot dry weight and growth index at

the 50% and 100% fertilizer rates suggests that fertilizer rate can be reduced to 50% without reducing plant size or quality.

Shoot dry weight of *Cotoneaster dammeri* 'Skogholm' was reduced by 8% by maintaining a low leaching fraction and reducing fertilizer rate by 50% reduced shoot dry weight by 26% (Tyler et al. 1996). Million et al. (2007) found that shoot dry weight of *Viburnum odoratissimum* was reduced by 32% with a lower fertilizer rate (15 vs. 30 g/plant) and that the 2 cm irrigation application reduced shoot dry weight by 6% compared to the 1 cm irrigation application. Plant height of *Viburnum odoratissimum* was 15% greater with increased fertilizer application and was not affected by irrigation volume (Million et al, 2007). Shoot dry weight of *Lantana camara* 'Sunny Side Up' increased from 14 g at 25% fertilizer rate to 35 g with 150% fertilizer rate with plants grown with 50% fertilizer and greater were considered salable, with no effect due to irrigation volume (Bayer et al., 2014). Cabrera (2003) also reported that moderate fertilizer applications can be used without reducing plant quality. The results of these studies along with this study suggest that fertilizer rate has a greater impact on plant growth than irrigation volume. Although many of these studies found reduced shoot dry weight with reduced fertilizer applications, irrigation applications may not have been as efficient as the method used in this study. These results suggest that decreased fertilizer rates may affect species differently, but there is potential for using reduced fertilizer rates.

Growth index of *Viburnum odoratissimum* was increased by 11% with increased fertilizer rate but was unaffected by additional irrigation volume (Million et al., 2007). Warsaw et al. (2009) found that final growth index measurements for plants irrigated based on daily water use was the same or greater than the control of 19mm per daily irrigation, with the effect on growth index varying by species and measurement date. Fare et al. (1994) found that growth index was

higher with cyclic irrigation than one daily irrigation and that plants receiving higher fertilizer rate had a higher growth index than plants with low fertilizer rates. The results of these studies along with ours suggest that efficient irrigation applications are beneficial in optimizing plant growth.

Conclusions

Fertilizer rate had a greater effect on growth of *Gardenia jasminoides* 'MAGDA I' than irrigation volume with both shoot dry weight and growth index being higher for the 50% and 100% fertilizer rates than the 25% rate. Biweekly leachate volume generally increased with increasing irrigation volume, with no effect of fertilizer rate. Cumulative leachate volume for the 66 and 100 mL irrigation treatments were not affected by fertilizer rate while the 132 and 165 mL had greater leaching at the 25% fertilizer rate, presumably because of the smaller plant size. Leaching fraction was greatest for the 25% fertilizer treatment for all irrigation volume treatments, likely because the smaller plants grown with the 25% fertilizer rate use less water. Leachate EC, NO₃-N quantities, and PO₄-P quantities were all highest with the 100% fertilizer rate, with the 66 mL irrigation treatment having the highest leachate EC for all fertilizer treatments. These results show the possibility of reducing fertilizer rates up to 50% without negatively impacting plant growth or quality. Lower irrigation volumes resulted in reduced water and nutrient leaching and higher leachate EC. The higher leachate EC was the result of higher concentration of fertilizers in less volume of leachate. These findings support our theory that reduced fertilizer applications can be utilized with more efficient irrigation to produce salable plants with reduced water and nutrient leaching. Further research investigating fast vs. slow growing species, high vs. low fertilizer requirements, and high vs. low water use would give a

clearer picture of how irrigation and fertilization can be altered in a production environment to reduce inputs while producing salable plants.

Acknowledgements

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Literature Cited

- 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. (ISHS): 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.
- Beeson, R.C. Jr. 2006. Relationship of plant growth and actual evapotranspiration to irrigation frequency based on management allowed deficits for container nursery stock. J. Amer. Soc. Hort. Sci. 131:140-148.

- 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.
- Cabrera, R.I. 2003. Nitrogen balance for two container-grown woody ornamental plants. *Sci. Hort.* 97:297-308.
- Chappell, M., J. Owen, S. White and J. Lea-Cox. 2013. Irrigation Management Practices. IN T. Yeager, T. Bilderback, D. Fare, C. Gilliam, J. Lea-Cox, A. Niemiera, J. Ruter, K. Tilt, S. Warren, T. Whitwell and R. Wright (eds.) *Best Management Practices: Guide for Producing Nursery Crops*. 3rd edition Southern Nursery Association, Atlanta, GA.
<<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.
- Fare, D. C., C. H. Gilliam, and G.J. Kever. 1992. Monitoring irrigation at container nurseries. *HortTechnology* 2:75-78
- Fare, D.C., C.H. Gilliam, G.J. Kever, and J.W. Olive. 1994. Cyclic irrigation reduces container leachate nitrate-nitrogen concentration. *HortScience* 29:1514-1517.
- Hilhorst, M.A. 2000. A pore water conductivity sensor. *Soil Sci. Soc. Amer. J.* 64:1922-1925.

- 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.
- 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.
- Lea-Cox, J.D., W.L. Bauerle, M.W. van Iersel, G.F. Kantor, T.L., Bauerle, E. Lichtenberg, D.M. King, and L Crawford. 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: An overview. *HortTechnology* 23:717-724.
- Martin, C.A. and D. L. Ingram. 1991. Evaluation of thermal properties and effect of irrigation on temperature dynamics in container media. *J. Environ. Hort.* 9:24-28.
- Million, J., T. Yeager, and J. Albano. 2007. Consequences of excessive overhead irrigation on runoff during container production of sweet viburnum. *J. Environ. Hort* 25:117-125.
- Nemali, K.S. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. *Scientia Hort.* 110:292-297.
- Owen, J.S., Jr., S.L. Warren, T.E. Bilderback, and J.P. Albano. 2008. Phosphorus rate, leaching fraction, and substrate influence on influent quantity, effluent nutrient content, and response of a containerized woody ornamental crop. *HortScience* 43:906-912.
- Ruter, J.M. 1993. Growth and landscape performance of three landscape plants produced in conventional and pot-in-pot production systems. *J. Environ. Hort.* 11:124-127.

- Ruter, J.M. 1998. Pot-in-pot production and cyclic irrigation influence growth and irrigation efficiency of 'Okame' cherries. *J. Environ. Hort.* 16:159-162.
- Scoggins, H.L. and M.W. van Iersel. 2006. In situ probes for measurement of EC of soilless substrates: Effects of temperature and substrate moisture content. *HortScience* 41:210-214.
- 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.
- Warsaw, A.L., R.T. Fernandez, B.M. Cregg, and J.A. Andresen. 2009. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. *HortScience* 44:1573-1580.
- 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.
- Van Iersel, M.W., M. Chappell, and J.D. Lea-Cox. 2013. Sensors for improved efficiency of irrigation in greenhouse and nursery production. *HortTechnology* 23:735-746.
- Yeager, T., J. Million, C. Larsen, and B. Stamps. 2010. Florida nursery best management practices: past, present, and future. *HortTechnology* 20:82-88.

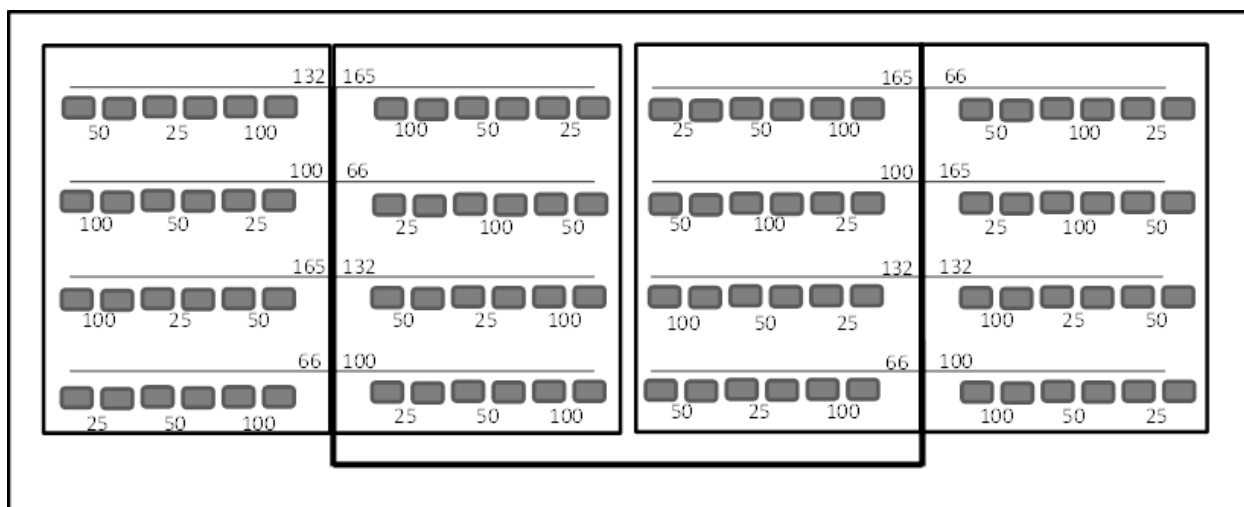


Figure 4.1. Experiment layout. The experiment was setup as a split plot with four replications. Main plots are irrigation volume treatments (66, 100, 132, and 165 mL) and splits are fertilizer rates (25%, 50%, and 100% of bag rate).

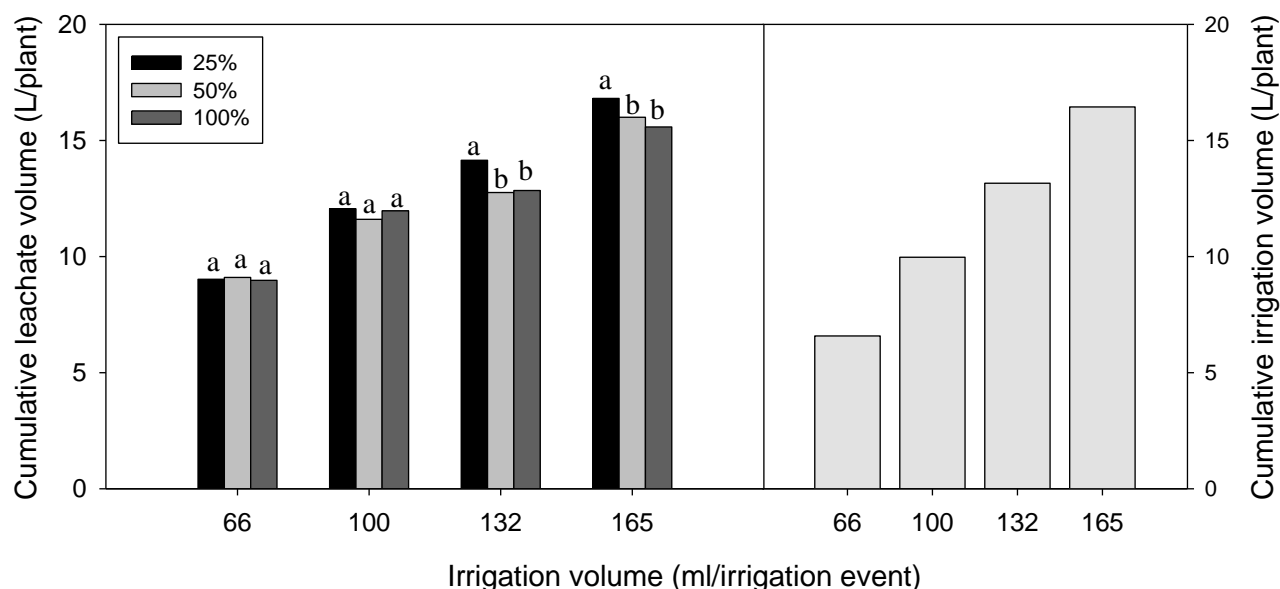


Figure 4.2. Cumulative irrigation volume (right) and cumulative leachate volume (left) to produce *Gardenia jasminoides* ‘MAGDA I’ over the course of the 137-d study. Irrigation was initiated for all treatments when the volumetric water content of the control (66 mL irrigation volume) dropped below the 0.35 m³•m⁻³ threshold. Irrigation was applied for 2, 3, 4, or, 5 min, applying 66, 100, 132, and 165 mL of irrigation water to the different treatments. Cumulative irrigation volumes were 6.6, 10.0, 13.2, and 16.5 L for the 66-165 mL treatments, respectively. Leachate volume increased with increasing irrigation volume ($P = 0.0013$) with the 100 and 132 mL treatments resulting in similar leachate volumes. The effect of fertilizer rate differed for the irrigation treatments, with no fertilizer effect for the 66 and 100 mL irrigation treatments. For the 132 and 165 mL irrigation treatments the 25% fertilizer treatment resulted in more leachate than the 50% and 100% treatments. Irrigation treatment main effects are indicated by capital letters. Lower case letters indicate fertilizer rate effect within an irrigation treatment.

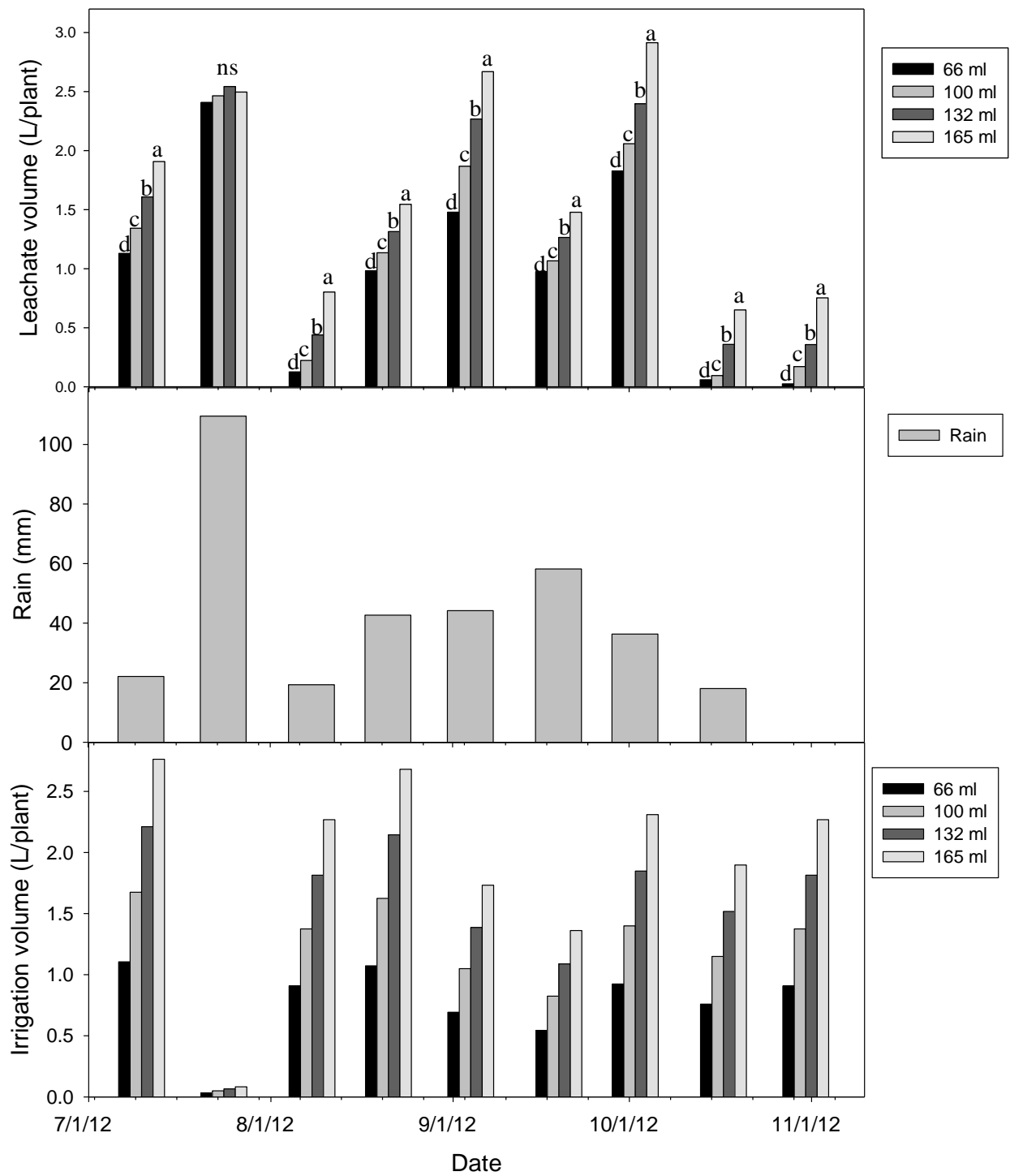


Figure 4.3. Biweekly leaching volume (top), rainfall volume (middle), and irrigation volume over the course of the 137 d study. Irrigation volume was inversely related to rainfall because rainfall would increase the volumetric water content reducing the need for irrigation. Leachate volume varied biweekly due to rainfall and irrigation volume ($P < 0.001$). Large rainfall volumes, such as the 109.5 mm volume during the second collection period, resulted in similar leachate volumes for all treatments. There was no influence due to fertilizer rate so fertilizer rates were averaged by irrigation treatment. Leachate volume increased with increasing irrigation volumes ($P < 0.0001$) for all but the 2nd collection period. There was an irrigation volume by collection period interaction ($P < 0.0004$) due to reduced irrigations with rainfall.

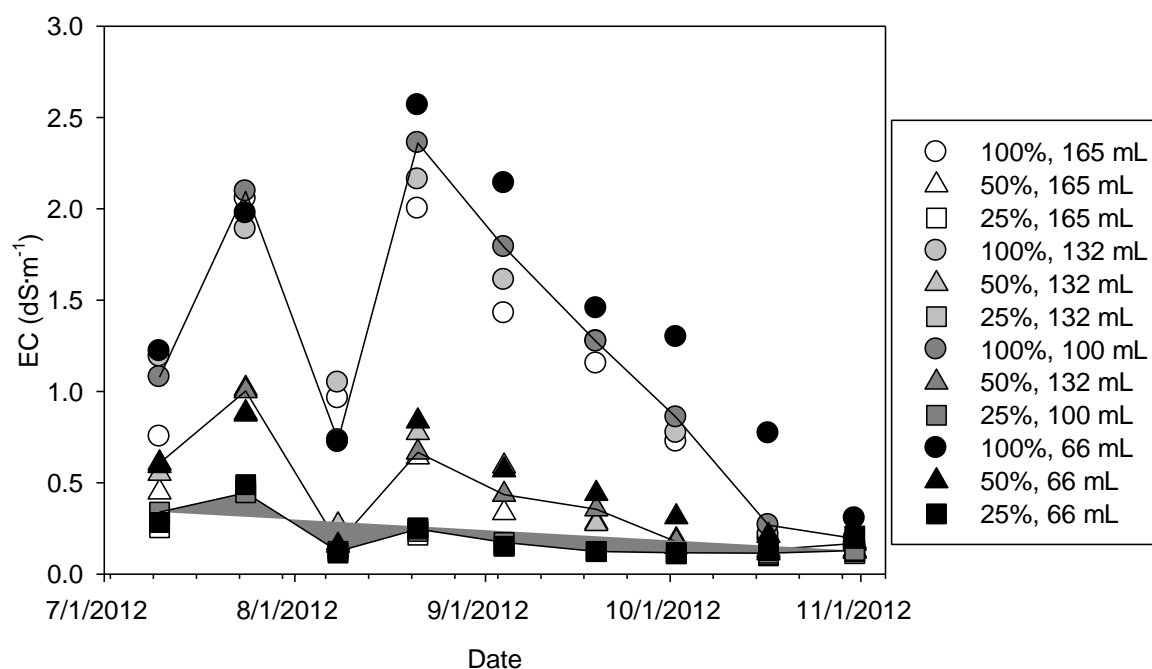


Figure 4.4. Leachate electrical conductivity (EC) for the nine biweekly collection periods.

There was an irrigation volume by fertilizer rate interaction ($P = 0.0443$). At the 50% and 100% fertilizer rates, leachate EC was affected by irrigation volume, but not at the 25% fertilizer rate.

The 66 mL irrigation treatment having higher leachate EC because of higher nutrient concentrations due to lower leachate volume. Collection effects and collection by irrigation volume and fertilizer rate interactions are due to varied rainfall volumes and less available fertilizer to be leached as the experiment progressed. Lines indicate the main effect of fertilizer rate over time.

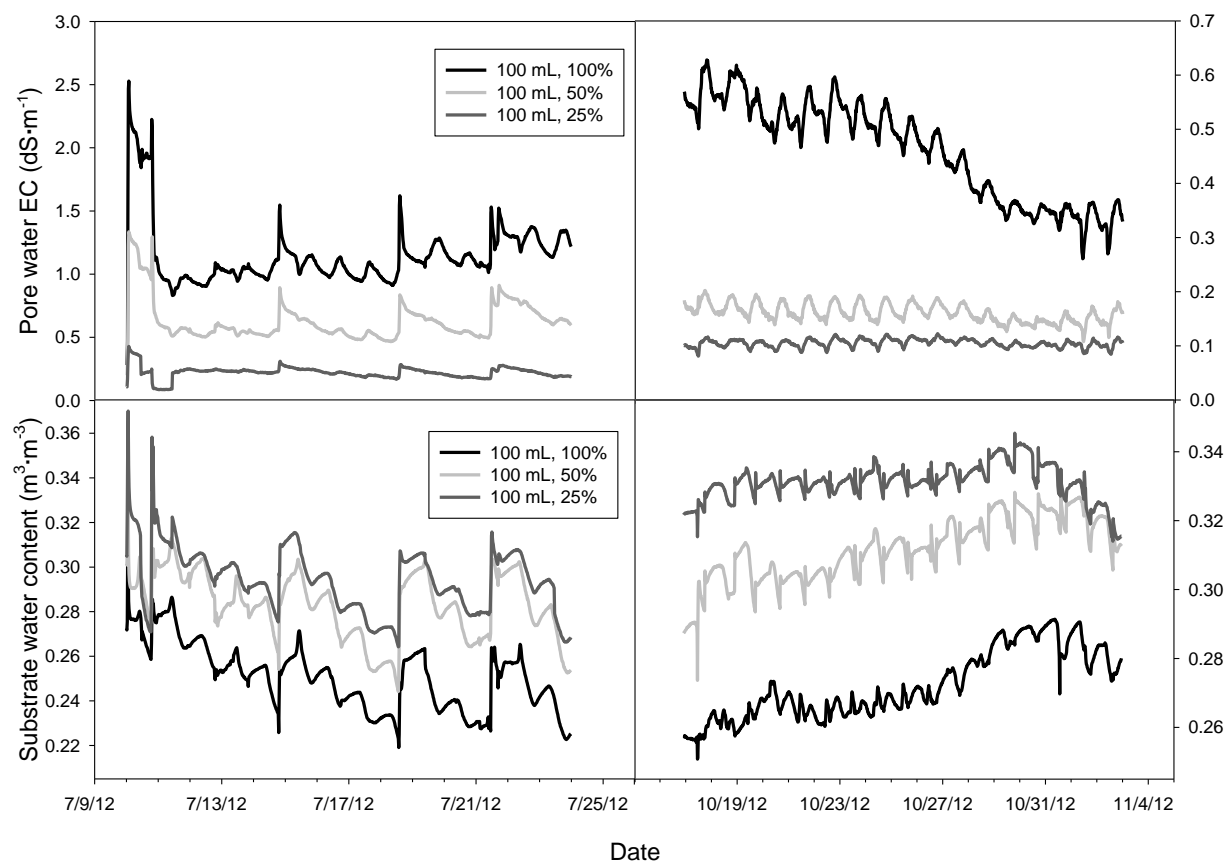


Figure 4.5. Pore water EC and substrate water content for the 100 mL irrigation volume treatment during the 2nd collection period (left) and 9th collection period (right) as determined from the GS3 sensors. There was a trend of decreasing EC with decreasing fertilizer rate and increasing irrigation volume. Pore water EC ranged from 0.1 to 2.5 dS·m⁻¹ during the 2nd collection (left) and from 0.1 to 0.6 dS·m⁻¹ during the 9th collection period (right).

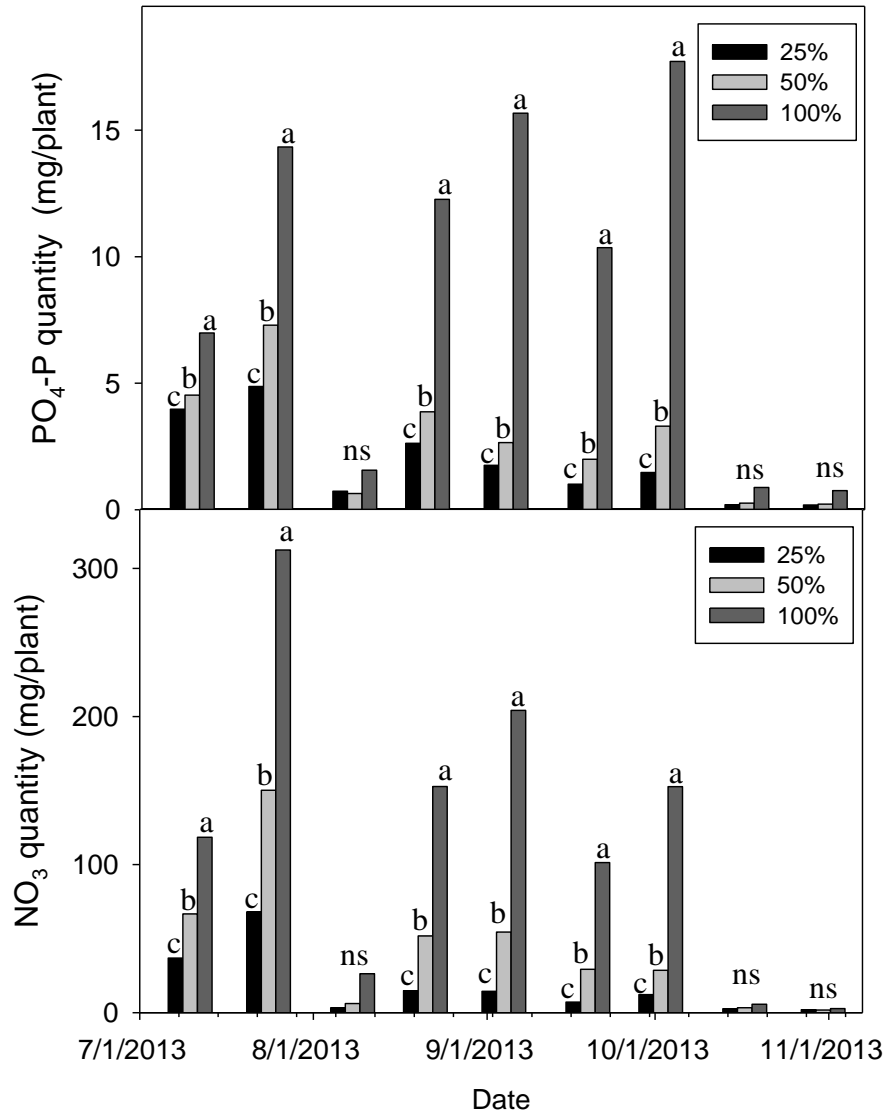


Figure 4.6. Quantity of NO₃-N and PO₄-P leached during the nine bi-weekly collection periods. . Quantity leached increased with fertilizer rate for all but the 3rd, 8th, and 9th collections. For the 3rd collection low quantities likely are the result of large quantities of nutrients leached due to rainfall during the second collection. For the 8th and 9th collections quantities are low as fertilizer has been used or leached. There was no effect of irrigation volume on NO₃-N and PO₄-P leached. Means within a collection period with different letters indicate different nutrient quantities, ns indicates no fertilizer effect on nutrient quantities.

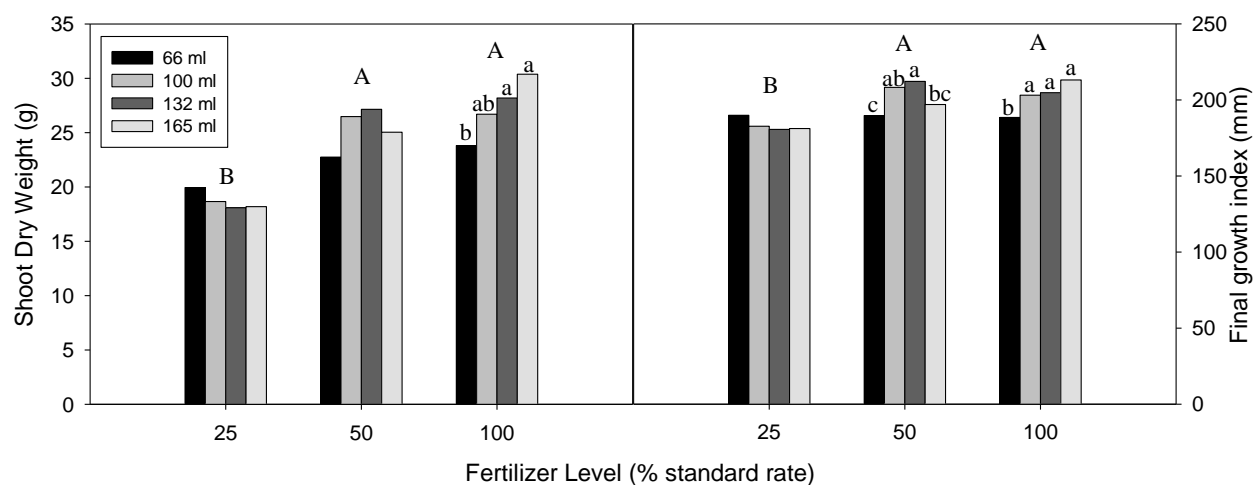


Figure 4.7. Shoot dry weight (left) and final growth index (right) of *Gardenia jasminoides* ‘MAGDA I’ at the conclusion of the 137 d study. Shoot dry weight was affected by the main effect of fertilizer rate and the interaction between fertilizer and irrigation volume. Only at the 100% fertilizer rate did irrigation volume affect shoot dry weight. Final growth index with the 50% and 100% fertilizer rates were greater than the 25% fertilizer rate. There was a fertilizer rate by irrigation volume interaction growth index was affected by the irrigation volume at the 50% and 100% fertilizer rates, but not at the 25% fertilizer rate. Upper case letters indicate fertilizer main effects and lower case letters indicate irrigation effects within a fertilizer level ($P < 0.05$).

CHAPTER 5

ELONGATION OF *HIBISCUS ACETOSELLA* ‘PANAMA RED’ UNDER WELL-WATERED AND WATER-STRESSED CONDITIONS⁴

⁴ Bayer, A., J. Ruter, and M.W. van Iersel. To be submitted to HortScience.

Abstract

Controlling the elongation of ornamental plants is commonly needed for shipping and aesthetic purposes. Drought stress can be used to limit elongation, and is an environmentally friendly alternative to plant growth regulators. However, growers can be reluctant to expose plants to drought stress because they do not want it to negatively affect overall plant quality. Knowing how and when stem elongation is affected by water availability will help to increase our understanding of how elongation can be controlled without reducing plant quality. *Hibiscus acetosella* rooted cuttings were grown in a growth chamber set to 12 h photoperiod at 25 °C. Two plants of similar size were used for each trial of the experiment to compare growth under well-watered and water-stressed conditions. For the first three trials plants were kept well watered for the first 3 to 4 d of the study, after which one plant remained well-watered while the other was allowed to become water-stressed over the remaining 6 to 11 d. For the next three runs plants were kept well watered for the first three to six d after which one plant remained well watered and the other was allowed to become water stressed by completely withholding water over the next 6 to 8 d after which it was again returned to well watered conditions for an additional 2 to 7 d in order to see if nodes with reduced elongation stayed short or whether elongation resumed upon re-watering. Time lapse photography was used to compare the diurnal patterns of elongation over the course of the experiment. Evapotranspiration was measured using load cells. Well-watered and water-stressed plants had similar diurnal patterns of elongation and evapotranspiration demonstrating that both follow circadian rhythms and are not just responding to environmental conditions. During the drought stress portion of the trials elongation of water-stressed plants was 44% less than well-watered plants. Final plant height and shoot dry weight for the water-stressed plants were 21% and 30% less, respectively. Total leaf area, number of leaves, and number of new visible internodes were greater for water stressed plants. Average

length of visible internodes and leaf size were similar for water-stressed and well-watered plants. Stem elongation was greatest at night, when evapotranspiration decreased, with greatest elongation after onset of darkness. Elongation is minimal between 800_{HR} and 1000_{HR} when evapotranspiration increases. If growers want to use drought stress for elongation control, they should ensure that plants are drought stressed before the onset of and during the dark period, when most elongation occurs.

Additional index words: Evapotranspiration, load cell, woody ornamentals, container plant production, height control

Introduction

Controlling plant elongation is common in ornamental plant production. Height control is necessary to meet industry standards for target plant height (Fisher and Heins, 1995), to increase plant aesthetics by creating more compact plants (van Iersel and Nemali, 2004), and because more compact plants are less expensive to ship (Burnett and van Iersel, 2008). Plant growth regulators (PGR) are commonly used (Currey and Lopez, 2011, Berghage and Heins, 1991), but are not always desirable as there is growing concern about the use of agrochemicals in production and their presence in nursery runoff (Kaufmann et al., 2000). Selection of cultivars with shorter internodes and smaller growth habits can be used to produce smaller plants (Ecke et al., 2004), but such cultivars are not available for many species.

Environmental conditions can also be altered to manipulate plant growth, including alteration of day and night temperatures (Kaufmann et al., 2000), changing the daily light integral, and adjusting plant spacing (Liu and Heins, 2002). Alteration of temperature and light conditions are not always possible depending on what other crops are growing in the greenhouse

or when plants are grown outdoors. Plant spacing may not be able to be increased if there is not enough space available and can increase overall production costs with fewer plants per hectare. Deficit irrigation or drought stress can also limit elongation; however many growers are reluctant to expose their plants to drought stress because they do not want it to negatively affect overall plant quality (Bailey and Whipker, 1998). Sensor controlled irrigation has been used to precisely control the timing, severity, and duration of drought stress for research application (Alem, 2014) and wireless sensor networks for commercial use being developed (Kohanbash et al, 2013; Lea-Cox et al., 2013). These sensor networks will make controlled drought for elongation control more feasible for growers. Alem (2014) controlled height of poinsettia with deficit irrigation by lowering substrate water content to $0.20 \text{ m}^3 \cdot \text{m}^{-3}$ until plant height was within tracking curve limits after which substrate water content was increased to $0.20 \text{ m}^3 \cdot \text{m}^{-3}$. This effectively lowered plant height without impacting plant quality. In a second study Alem et al. (2014) was again able to control plant height using the same method of deficit irrigation; however, in this study plants were grown to different target plant heights.

Diurnal patterns of elongation have been examined in many plant species. Circadian rhythms interact with environmental conditions to determine elongation rates. Stomatal conductance and transpiration are also controlled partly by the plant circadian clock (Farré 2012). Stem elongation has been shown to have diurnal patterns (Nozue and Maloof, 2006). Leaf growth has been reported to have maximum growth rates during the day or night depending on the species. Environmental factors can influence the amount of growth, but not the pattern (Ruts et al., 2012).

Knowing how and when stem elongation is affected by water availability will help to increase our understanding of how elongation can be controlled through controlled drought stress

without reducing plant quality. Our objective was to quantify diurnal patterns of elongation of *Hibiscus acetosella* in response to well-watered and water-stressed conditions. *H. acetosella* is a fast growing species with clear growth responses to irrigation volume and substrate water content (Bayer et al., 2013). Understanding when elongation occurs could be useful in using drought stress as a means of plant elongation control. Water stressed plants were re-watered to determine whether nodes with reduced elongation stayed short or whether elongation resumed upon re-watering. The results of this study will show if there is an optimal time for applying drought stress for elongation control.

Materials and Methods

Plant material. Research was conducted in a growth chamber at the University of Georgia in Athens, GA from February 17 to June 1, 2014. Individual trials lasted 11 to 19 d. *Hibiscus acetosella* ‘Panama Red’ (PP#20121) terminal cuttings were rooted in a peat perlite substrate (Fafard 1P, Fafard, Inc.; Agawam, MA) for 5-10 d after which the rooted cuttings were transplanted into 2.4 L containers filled with a peat perlite substrate (Fafard 1P). Cuttings were rooted every 10-14 d in order to have similar plants for each individual trial. Plants were grown in a growth chamber (E-15; Conviron, Winnipeg, Manitoba, Canada) set to 12 h photoperiod and a constant temperature of 25 °C. Plants were given 5-7 d for root establishment before onset of a trial. Fertilizer was supplied with a nutrient solution (Peters 15-5-15 Cal-Mag; Scotts, Marysville, OH; 15N-2.2P-12.45K) at 100 mg·L⁻¹ nitrogen.

Treatments and data collection. Two plants similar in size were chosen for each trial of the experiment. Axillary branches were removed so that only the central shoot remained. For the first three runs, plants were kept well watered for the first 3 to 4 d of the study, after which one plant remained well-watered which the other was allowed to become water stressed over the

remaining 6 to 11 d, only watering with approximately 200 to 400 mL after wilting occurred. For the next three runs plants were kept well watered for the first 3 to 6 d after which one plant remained well watered and the other was allowed to become water stressed by completely withholding water over the next 6 to 8 d after which it was again returned to well watered conditions for an additional 2 to 7 d in order to see if nodes with reduced elongation stayed short or whether elongation resumed upon re-watering. Well watered plants were hand-watered to above a weight of around 1.5 kg (pot with substrate + plant) which was the weight of the well-watered plants at the start of the trial. Decrease in weight (pot with substrate + plant) of water-stressed plants was between 0.71 and 0.96 kg, which is a decrease of volumetric water content of around 0.36 to 0.48 m³·m⁻³. Before the start of each run, plant height, number of internodes, internode lengths, stem diameter, and number of leaves were measured.

The weight of each plant was measured using individually calibrated load cells (LSP-10; Transducer Techniques, Temecula, CA) mounted on steel platforms with an acrylic platform on top of each load cell. Plant mass was measured every minute and averages were recorded by the data logger (CR1000, Campbell Scientific, Logan, UT) every ten minutes. Hourly evapotranspiration was determined as the change in pot weight in 1 h after correcting for irrigation when needed. Environmental conditions were measured using a temperature and relative humidity sensor (HMP50; Vaisala, San Jose, CA) and a quantum sensor (SQ-110; Apogee Instruments, Logan, UT) with measurements averaged and recorded every 10 min.

Temperature in the growth chamber fluctuated 2-3 °C between day and night with daytime temperatures ranging between 24.8 and 27 °C and night temperatures between 22.9 and 24.3 °C for the six trials. Relative humidity fluctuated both over the course an individual trial and among trials ranging between 14 and 65%. Vapor pressure deficit also varied over the course

of an individual trial and among trials ranging between 1.1 and 2.8 kPa. Average photosynthetic photon flux was $324 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Time lapse photography (Pentax WG-1; RICOH Imaging Company, Denver, CO) was used to take hourly pictures of both plants and a meter stick in the same frame. Hourly stem elongation was measured using image analysis software (Image J; U.S. National Institutes of Health; Bethesda, Maryland). Hourly elongation is the increase in elongation at the stated hour compared to height at the previous hour (i.e. stem elongation at 2000_{HR} is the elongation between 1900_{HR} and 2000_{HR}). At the conclusion of the experiment, height, number of internodes, internode lengths, stem diameter, and number of leaves were again recorded. Shoots were cut off at the substrate surface and were dried at 80 °C after which dry weight was determined. Compactness was calculated as shoot dry weight/shoot length. Leaf area was measured using a leaf area meter (LI-3100, LiCor, Lincoln, NE).

Experimental design and data analysis. The experiment was designed as a randomized complete block design with six replications with blocks being the six trials. Experimental units were individual plants. Data were analyzed using the PROC TTEST and PROC MIXED procedures of SAS (SAS Version 9.2; SAS Institute, Cary, NC), with $P = 0.05$ considered to be significant. Treatment means were separated using either the PDIFF option of PROC MIXED. Curve fitting was done using SigmaPlot (Systat, San Jose, CA).

Results and Discussion

Cumulative stem elongation was 30% less for the water-stressed plants ($P = 0.0077$) over the course of the 11- 19d trials (Fig. 5.1). During the water stressed portion of the trials, cumulative elongation of water-stressed plants was 44% less than the well-watered plants. Final

height of plants that were re-watered was 21% less than well-watered plants. Elongation rate varied by trial; likely because of fluctuations in environmental conditions between trials as well as natural variations in growth. The final number of new visible internodes was greater for well-watered plants ($P = 0.05$; Fig. 5.2). Water-stressed and then re-watered plants had 15% fewer new internodes and water-stressed only plants had 37% fewer new internodes. Average length of all visible internodes was similar among treatments ($P = 0.51$; Fig. 5.2). We hypothesize that the difference in the number of visible internodes between well-watered and drought-stressed is due to un-elongated, non-visible internodes near the growing point of the water-stressed plants. Development and differentiation in the apex is largely temperature driven (Atkinson and Porter, 1996) while elongation is water dependent (Hsiao and Xu, 2000); this would mean that new internodes could develop, while drought stress would inhibit elongation of the internodes. Shoot dry weight was less for the water-stressed plants ($P = 0.037$; Fig. 5.1). Water-stress resulted in a 30% reduction in plant dry weight.

Drought stress has been used to reduce elongation in many species including *Gaura lindheimeri* ‘Siskiyou Pink’ (Burnett and van Iersel, 2008), *Rhododendron* ‘Catawbiense Boursault’ and ‘Old Port’ (Koniarski and Matysiak, 2013), *Tagetes erecta* ‘Queen Sophia’ (van Iersel and Nemali, 2004), *Salvia splendens* ‘Bonfire’ (Burnett et al, 2005), and *Hibiscus acetosella* ‘Panama Red’ (Bayer et al, 2013). Stem elongation is reduced by drought stress due to reduced cell division and expansion (Hsiao and Xu, 2000), which could explain the lower number of internodes with water-stress. *G. lindheimeri*, *T. erecta*, and *H. acetosella* were smaller, but not more compact, with drought stress. Compactness, shoot dry weight per unit shoot length, is a measure of plant density and an indicator of quality (van Iersel and Nemali,

2004). Compactness of well-watered and water-stressed plants was not different in this study (Fig.5.1); however well-watered plants formed more axillary shoots ($P = 0.01$; data not shown).

Leaf area was 36% less for water-stressed plants. The number of leaves was also greater for well-watered plants ($P = 0.01$), but the average leaf size was not affected by drought (Fig. 5.2). Reduced leaf area with drought stress has been reported for *G. lindheimeri* (Burnett and van Iersel, 2008), *Rhododendron* (Koniarski and Matysiak, 2013), *S. splendens* (Burnett et al, 2005), and *T. erecta* (van Iersel and Nemali, 2004). Leaf size of *H. acetosella* ‘Panama Red’ was reduced with decreasing substrate volumetric water content threshold (Bayer et al., 2013). Reduced leaf area of *T. erecta* under drought was the result of fewer leaves and reduced leaf size (van Iersel and Nemali, 2004). Leaf area is reduced with drought stress due to reduced cell elongation with low soil water potential (Hsiao and Xu, 2000; Lambers et al., 2008). The lack of difference in leaf size in this study was unexpected as leaf size is normally reduced with drought stress. It is possible that the branching of the well-watered plants resulted in more new leaves that were not fully expanded, which could have biased the leaf size of well-watered plants. The increase in stem diameter was similar for water-stressed and well-watered plants ($P = 0.0645$).

Daily elongation was greater for well watered plants than stressed plants ($P < 0.0001$; Fig.5.4). Average daily elongation was 34.2 and 23.1 mm for well-watered and water-stressed plants respectively. Under well watered conditions, plant height increased by approximately 6% per day. Daily elongation rate for water-stressed plants was 13% less than well-watered plants within 2 d of the onset of water stress. During the water stressed portion of the trials, elongation rates of stressed plants were 43% less than those of well-watered plants.

Elongation rate of well watered plants was greater than the stressed plants at any time of the day ($P < 0.0001$), with both well-watered and water-stressed plants exhibiting similar diurnal patterns of elongation (Fig. 5.5). The average daytime elongation rate was 0.93 and 0.29 mm/h and nighttime elongation 2.26 and 1.54 mm/h for well-watered plants and water stressed plants, respectively. Elongation was slowest between 0800_{HR} and 10:00_{HR} at 0.44 and 0.12 mm/h and greatest around 2000_{HR} with elongation rates of 3.53 and 2.87 mm/h for well-watered plants and water stressed plants, respectively. Elongation rate was relatively steady from 1000_{HR} till 1900_{HR} and from 2100_{HR} to 0700_{HR}.

Circadian and diurnal rhythms of stem elongation rates have been reported (Nozue and Maloof, 2006) for plants grown under constant temperature and light as well as light and dark cycles (Lecharny and Wagner, 1984; Dowson-Day and Millar, 1999). Inflorescence stem elongation of *Arabidopsis thaliana* (Jouve et al.1998) and stem elongation of *Chenopodium rubrum* (Lecharny and Wagner, 1984) have circadian rhythms even in constant light. Dowson-Day and Millar (1999) reported a diurnal pattern with maximum hypocotyl elongation rates of *A. thaliana* at dusk with reductions in elongation rate at dawn. This is similar to our study with maximum elongation around 2000_{HR} with a burst of elongation occurring soon after the start of darkness and minimal elongation between 0800_{HR} and 1000_{HR}. Conversely, Neily et al. (1997) reported stem elongation rate of snapdragon declined at night and increased during the day. Patterns of stem elongation rate of zinnia changed with developmental stage, with elongation rate greatest early in the day during early development and at night as plants matured (Neily et al., 1997). This suggests that stem elongation patterns are species and developmentally dependent. Similarly, leaf elongation rates have been reported to show growth patterns with maximum elongation occurring around dawn or at night depending on species (Ruts et al., 2012).

There is an inverse relationship between elongation and evapotranspiration with evapotranspiration high during the day and low at night and elongation greatest at night (Fig. 5.5). This suggests that elongation is greatest at night due to rehydration and increasing turgor pressure of the plant, allowing for cell elongation. Sufficient turgor pressure is needed to deform the cell wall allowing for cell expansion (Passioura and Boyer, 2003; Boyer and Silk, 2004). Evapotranspiration was low when the lights were off, increasing rapidly between 0800_{HR} and 0900_{HR} after the lights were turned on and rapidly decreasing between 2000_{HR} and 2100_{HR} after the lights were turned off, indicative of stomatal opening in response to light. Elongation was greatest between 2000_{HR} and 2100_{HR} and was 59% and 82% greater at night than during the day for the well-watered and water-stressed plants, respectively. Rate of elongation began to decrease at around 0700_{HR} (before the start of the light period), suggesting that elongation is responding to a circadian pattern rather than just a response to light. Lower transpiration rates at night could mean that more water is available for cell expansion and elongation, rather than transpiration, which could explain greater nighttime elongation. A comparison of daily evapotranspiration and elongation shows the reduction in elongation rate due to water stress. Re-watering stressed plants resulted in increased evapotranspiration; however, elongation rate remained restricted. (Fig.5.6).

Evapotranspiration is influenced by environmental conditions including light, temperature, and vapor pressure deficit, but also by stomatal opening and closing, which is regulated partly by circadian mechanisms (Hotta et al., 2007). In well-watered *A. thaliana* plants, stomata close at mid-day, not in response to water status but due to circadian control of the guard cells (Dodd et al., 2005). Stomata also open in anticipation of dawn (Hotta et al., 2007) indicating circadian control. Diurnal changes in transpiration could be due to changes in ABA levels which are influenced by the circadian clock (Tallman, 2004). Environmental influences

can alter the intensity of the circadian responses (Hotta et al., 2007). Reduced leaf area surface of water-stressed plants contributes to reduced transpiration. The combination of ABA levels, reduced leaf area, and water stress could explain reduced evapotranspiration in water-stressed plants.

Conclusions

Both water-stressed and well-watered plants followed a similar diurnal pattern of elongation, agreeing with previous research that elongation is a circadian rhythm and not just a response to environmental conditions. Well-watered plants elongated $10 \text{ mm} \cdot \text{d}^{-1}$ more than water-stressed plants. Cumulative elongation showed that as the degree of water stressed increased over the course of the study the rate of elongation of the water stressed plants continued to decrease. The results of this study show that controlling stem elongation and growth of plants is possible with irrigation management. Increased elongation rate after stressed plants were re-watered suggests that elongation restriction with water-stress is negated with re-watering. In this study, diurnal patterns show that elongation of *H. acetosella* is greatest at night, with greatest elongation following the onset of darkness when evapotranspiration decreased. Elongation is minimal between 0800_{HR} and 1000_{HR} when evapotranspiration increases. If growers want to use drought stress for elongation control, they should ensure that plants are drought stressed before the onset of and during the dark period, when most elongation occurs.

Literature Cited

Alem, P. 2014. Irrigation, fertilization, and non-chemical plant growth regulation in greenhouse production. Univ. of Georgia., Athens, PhD. Diss.

- Atkinson, D. and J.R. Porter. 1996. Temperature, plant development and crop yields. *Trends in Plant Sci.* 1:119-124.
- Bailey, D. and B. Whipker. 1998. Height control of commercial greenhouse flowers. N.C. Coop. Ext. Serv. Hort. Info. Lflt. 528.
- 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.
- Berghage, R. D. and R. D. Heins. 1991. Quantification of temperature effects on stem elongation of poinsettia. *J. Amer. Soc. Hort Sci.* 116:14-18.
- Boyer, J.S. and W.K. Silk. 2004. Hydraulics of plant growth. *Functionall Plant Biol.* 31:761-773.
- Burnett, S., P. Thomas, and M. van Iersel. 2005. Post-germination drenches with PEG-8000 reduce growth of saliva and marigolds. *HortScience* 40:675-679.
- Burnett, S.E. and M.W. van Iersel. Morphology and irrigation efficiency of *Gaura lindheimeri* grown with capacitance sensor-controlled irrigation. *HortScience* 43:15555-1560.
- Currey, C.J. and R.G. Lopez. 2011. Early Flurprimidol drench applications suppress final ehight of four poinsettia cultivars. *HortTechnology* 21:35-40.
- Dodd, A. N., N. Salathia, A. Hall, E. Kévei, R. Tóth, F. Nagy, J.M. Bibberd, A.J. Millar, and A.A.R. Webb. 2005. Plant circadian clocks increase photosynthesis, growth, survival, and competitive advantage. *Science* 309:630-633

- Dowson-Day, M. and A.J. Millar 1999. Circadian dysfunction causes aberrant hypocotyl elongation patterns in *Arabidopsis*. *Plant J.* 17:63-71.
- Ecke, P., III, J.E. Jaust, J. Wiggins, and A. Higgins. 2004. Height control, p. 51-72. In: The Ecker poinsettia manual. Ball Publishing, Batavia, IL.
- Farré, E.M. 2012. The regulation of plant growth by the circadian clock. *Plant Biol.* 14:401-410.
- Fisher, P.R. and R.D. Heins. 1995. A process-control approach to poinsettia height control. *HortTechnology* 5:57-63.
- Hotta, C.T., M.J. Gardner, K.E. Hubbard, S.J. Baek, N. Dalchau, D. Suhita, A.N. Dodd, and A.A.R. Webb. 2007. Modulation of environmental responses of plants by circadian clocks. *Plant, Cell, Environ.* 30:333-349.
- Hsiao, T.C. and L.K. Xu. 2000. Sensitivity of growth of roots versus leaves to water stress: biophysical analysis and relation to water transport. *J. Expt. Bot.* 51:1595-1616.
- Jouve, L., H. Geppin, and R.D. Agosti. 1998. *Arabidopsis thaliana* floral stem elongation: Evidence for an endogenous circadian rhythm. *Plant Physiol. Biochem.* 36:469-472.
- Kaufmann, P.H., R.J. Joly, and P.A. Hammer. 2000. Influence of day and night temperature differentials on root elongation rate, root hydraulic properties, and shoot water relations in chrysanthemum. *J. Amer. Soc. Hort. Sci.* 125:383-389.
- 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.

- Koniarski, M. and B. Matysiak. 2013. Growth and development of potted *Rhododendron* cultivars ‘Catawbiense Boursault’ and ‘Old Port’ in response to regulated deficit irrigation. *J. Hort. Res.* 21:29-37.
- Lambers, H., T.L. Pons, and S. Chapin. 2008. *Plant physiological ecology*. 2nd Ed. Springer Verlag, New York, NY.
- Lea-Cox, J.D., W.L. Bauerle, M.W. van Iersel, G.F. Kantor, T.L., Bauerle, E. Lichtenberg, D.M. King, and L Crawford. 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: An overview. *HortTechnology* 23:717-724.
- Lecharny, A. and E. Wagner. 1984. Stem extension rate in light-grown plants. Evidence for an endogenous circadian rhythm in *Chenopodium rubrum*. *Physiol. Plant.* 60:437-443.
- Liu, B. and R.D. Heins. 2002. Photothermal ratio affects plant quality in ‘Freedom’ poinsettia. *J. Amer. Soc. Hort Sci.* 127:20-26.
- Neily, W.G., P.R. Hicklenton, and D.N. Kristie. 1997. Temperature and developmental stage influence diurnal rhythms of stem elongation in Snapdragon and Zinnia. *J. Amer. Soc. Hort. Sci.* 122:778-783.
- Nozue, K. and J. N. Maloof. 2006. Diurnal regulation of plant growth. *Plant, Cell, Environ.* 29:396-408.
- Passioura, J.B. and J.S. Boyer. 2003. Tissue stresses and resistance to water flow conspire to uncouple the water potential of the epidermis from that of the xylem in elongating plant stems. *Functional Plant Biol.* 30:325-334.

Ruts, T., S. Matsubara, A. Wiese-Klinkenberg, and A. Walter. 2012. Diel patterns of leaf and root growth: endogenous rhythmicity or environmental response? *J. Expt Bot.* 63:3339-3351.

Van Iersel, M.W., and K. S. Nemali. 2004. Drought stress can produce small but not compact marigolds. *HortScience* 39:1298-1301.

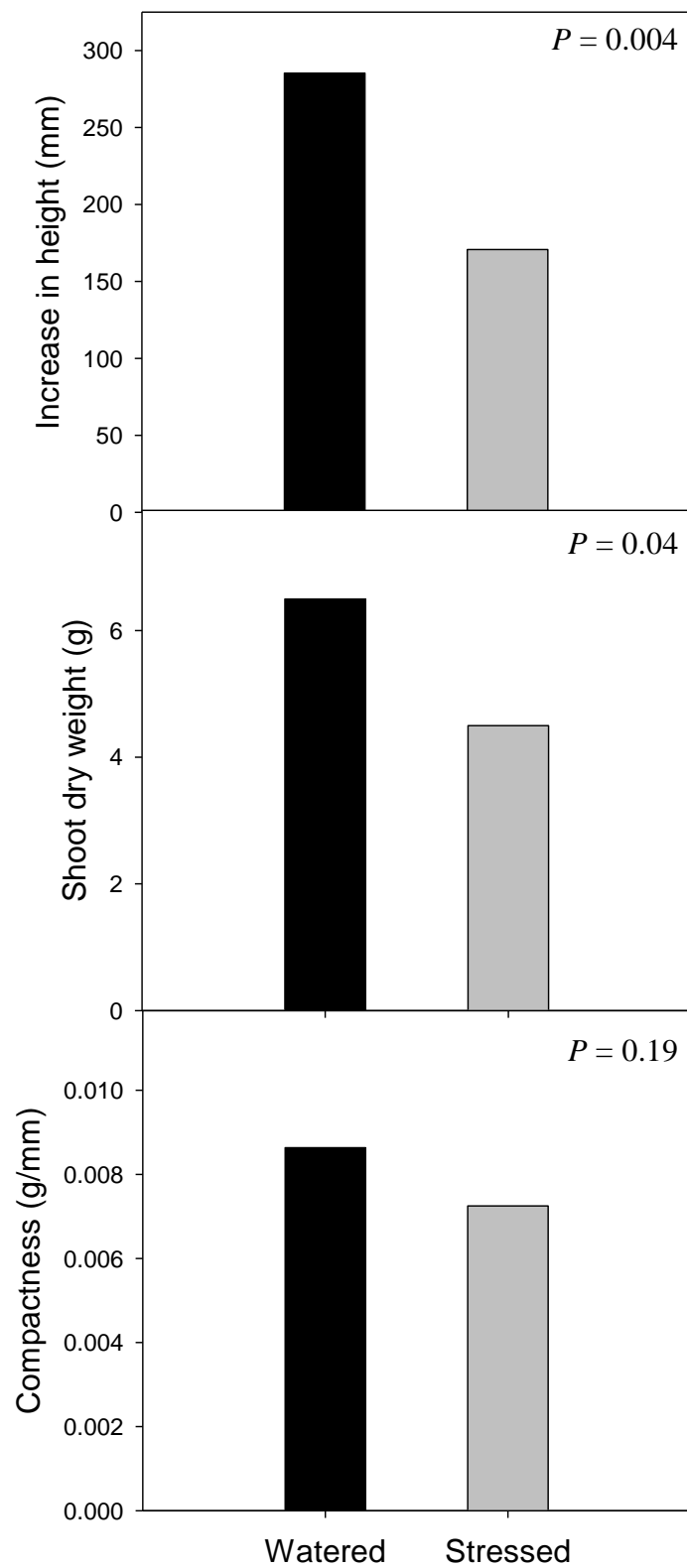


Figure 5.1. Increase in height over the course of the 7 to 11 d drought stress period (top), final shoot dry weight (middle), and compactness (bottom) for well-watered and water-stressed *Hibiscus acetosella* ‘Panama Red’. Well-watered plants had a greater increase in height and higher shoot dry weight than water-stressed plants. There was no difference in compactness (shoot dry weight per unit shoot length) between treatments.

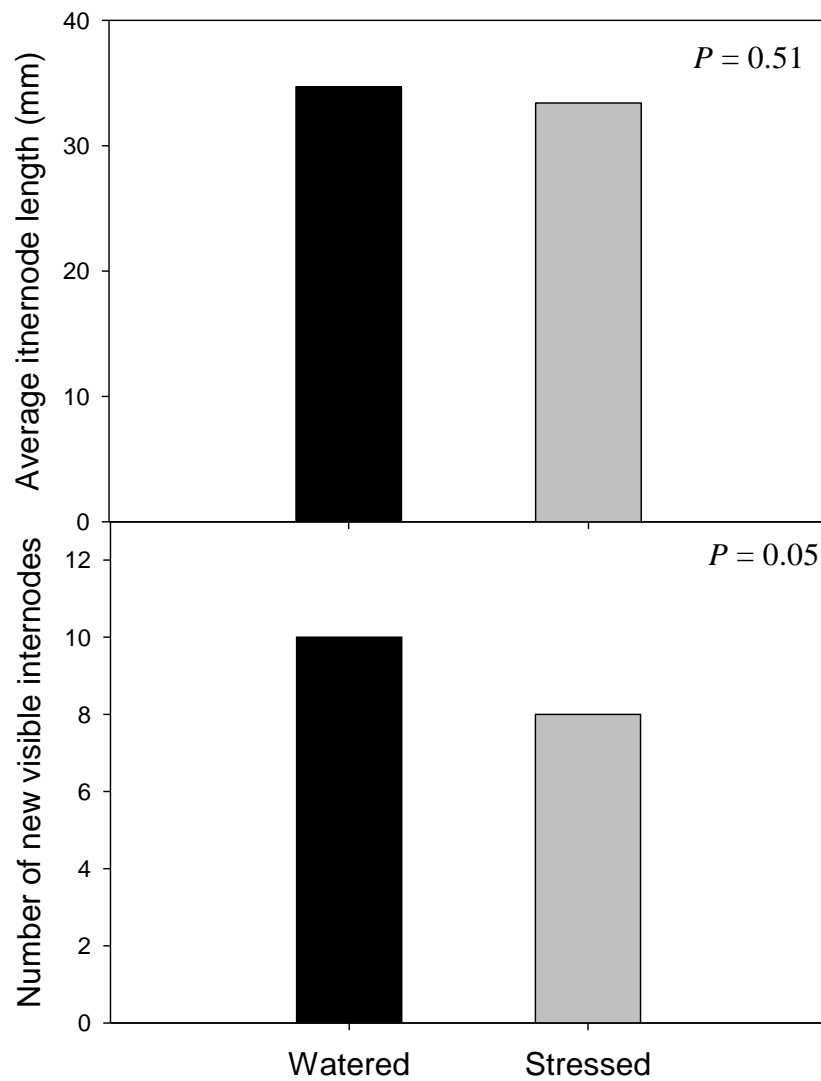


Figure 5.2. Average final internode length of all internodes on the main stem (top) and increase in number of visible internodes (bottom) for well-watered and water-stressed *Hibiscus acetosella* ‘Panama Red’ at the end of the 11-19 d trials. Average internode length was similar, but well-watered plants had a greater increase in number of visible internodes than drought stressed plants.

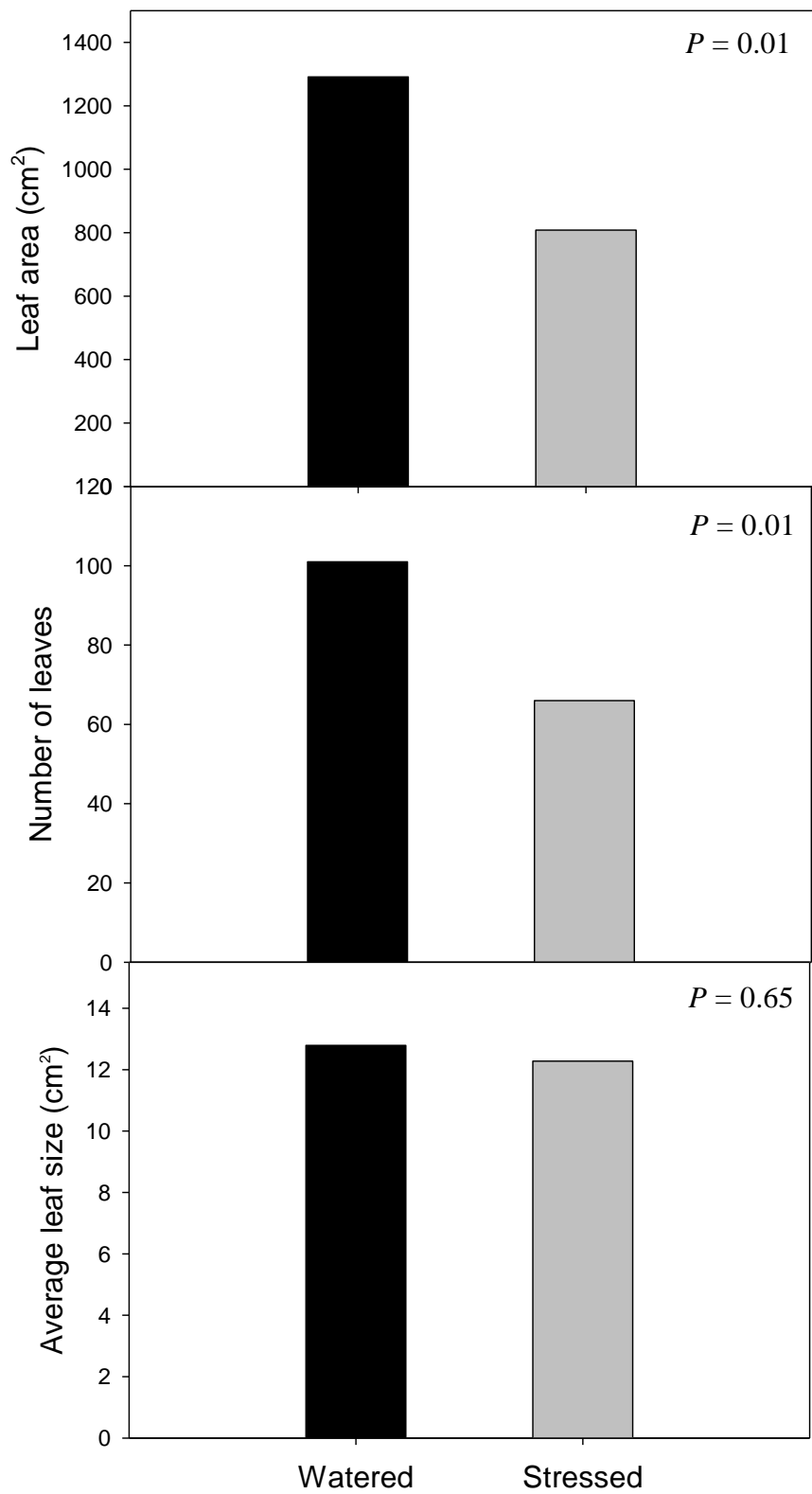


Figure 5.3. Total leaf area (top) number of leaves (middle) and average leaf size (bottom) of well-watered and water-stressed *Hibiscus acetosella* ‘Panama Red’ at the conclusion of the 11-19 d trials. Both leaf area and number of leaves were greater for the well-watered than the water-stressed plants. However, average leaf area was not different for well-watered and water-stressed plants.

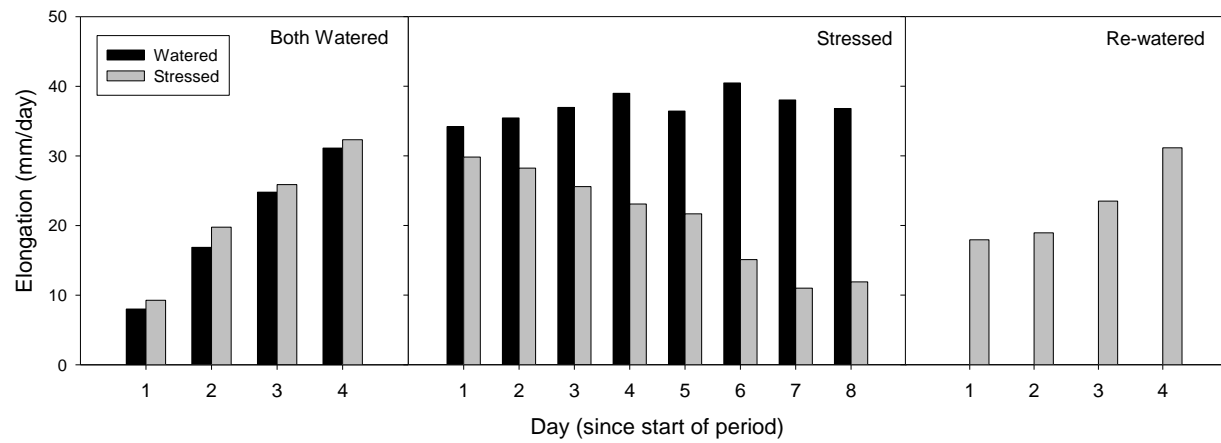


Figure 5.4. Daily elongation of *Hibiscus acetosella* ‘Panama Red’ over the course of the 11-19 d experiments. Graphs have been separated into both watered (left), watered or stressed (middle), and re-water of stressed plants (right) to show how daily elongation changed during the different periods. A clear decrease in daily elongation can be seen as water-stress becomes greater. Daily elongation increases gradually after re-watering.

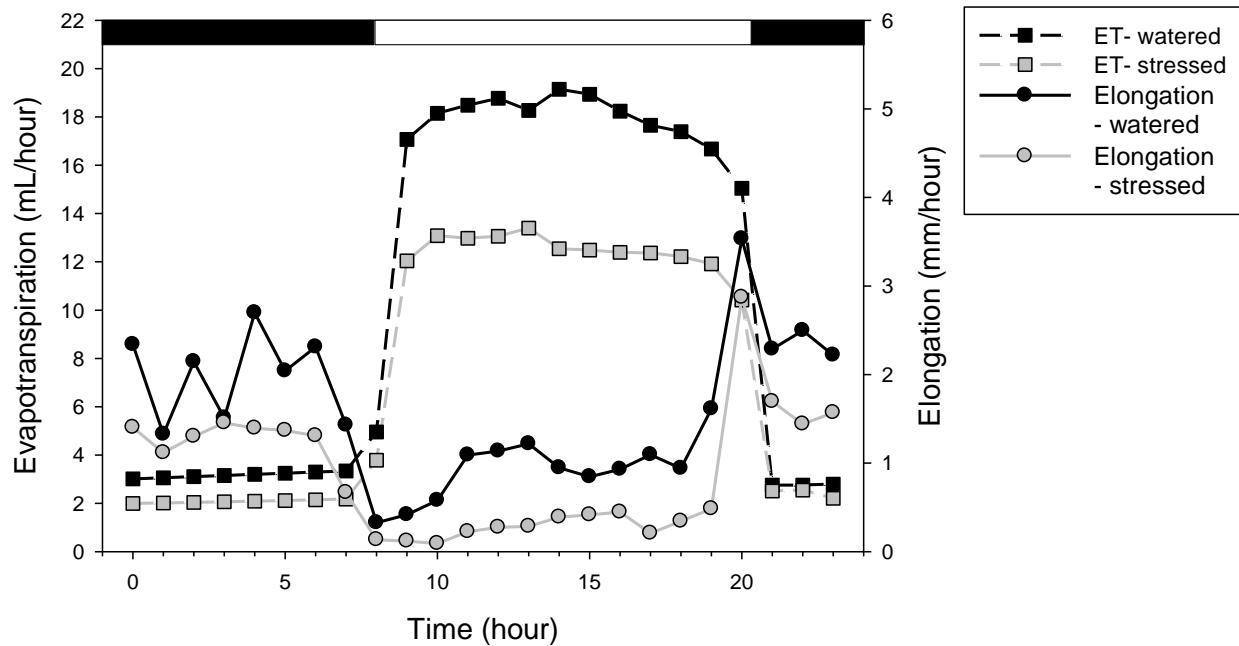


Figure 5.5. Hourly evapotranspiration (squares) and elongation (circles) of *Hibiscus acetosella* ‘Panama Red’ over the course of 24 h for the 11-19 d experiments. A diurnal pattern of evapotranspiration can be seen with increased evapotranspiration when the lights are turned on (0800_{HR}) and decreased when the lights are turned off (2000_{HR}). Elongation also exhibits a diurnal pattern with reduced elongation during the day and increased elongation at night. For both evapotranspiration and elongation, well-watered and water-stressed plants follow similar diurnal patterns with water-stressed plants having reduced evapotranspiration and elongation. Elongation and evapotranspiration data at a specific time indicate the elongation and evapotranspiration during the previous hour. Black and white boxes at the top of the graph indicate darkness and light, respectively.

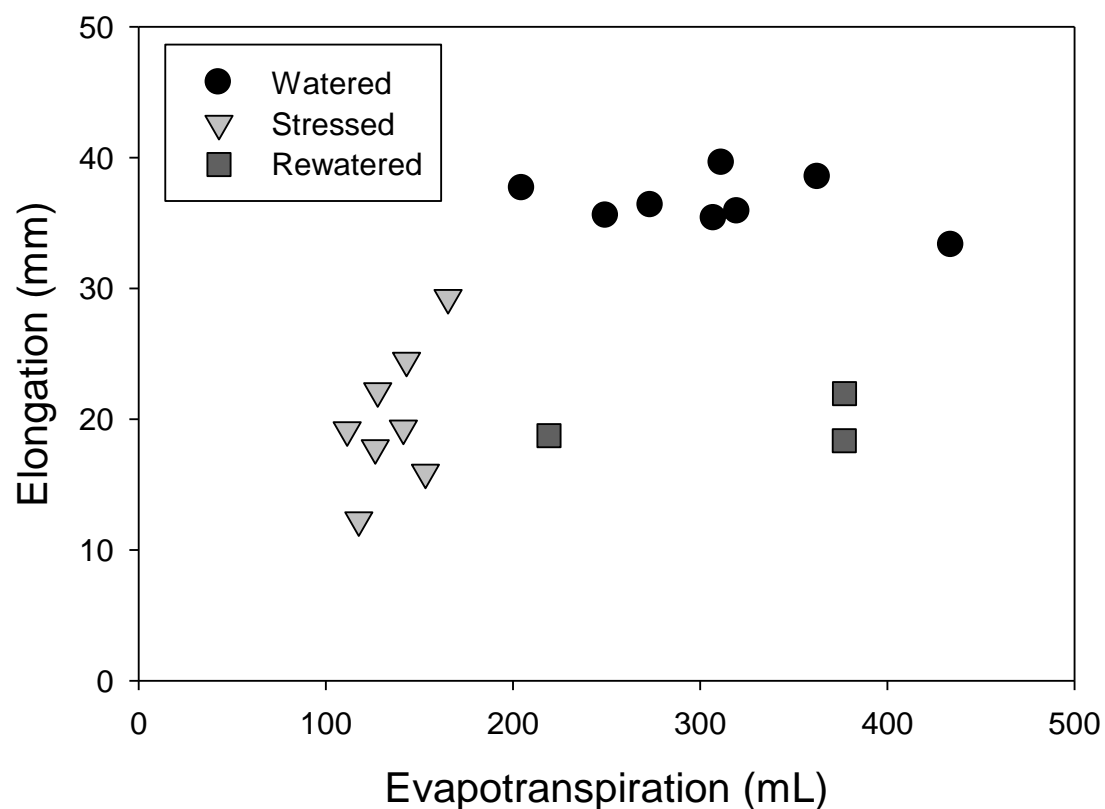


Figure 5.6. Daily elongation of well-watered (black circles), water-stressed (light gray triangles), and stressed then re-watered (dark gray squares) *Hibiscus acetosella* 'Panama Red' as a function of daily evapotranspiration. The relationship between evapotranspiration and elongation shows the reduction in elongation rate due to water stress. Re-watering stressed plants resulted in increased evapotranspiration; however, elongation rate remained restricted.

CHAPTER 6

CONCLUSIONS

Sustainable use of resources is of increasing importance in container plant production. Decreasing water availability and an increasing number of laws and regulations regarding water use and runoff are increasing the need to develop new methods for managing water in container plant production. Soil moisture sensors can allow for precise and efficient control of irrigation. Recent advancements in sensor technology have led to the development of systems that can be implemented in commercial production. To best utilize this technology an understanding of the effect of water stress on plant growth is needed. The aim of this research was to understand how plant growth is affected by substrate water content and irrigation volume.

In our first study water use and growth of *Hibiscus acetosella* ‘Panama Red’ increased with θ threshold in both greenhouse and nursery settings, with plants at the $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ threshold and greater of a salable size. 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 regulators. In both greenhouse and nursery settings, maintaining plants at a threshold of $0.35 \text{ m}^3 \cdot \text{m}^{-3}$ instead of $0.45 \text{ m}^3 \cdot \text{m}^{-3}$ resulted in significant water savings.

Gardenia jasminoides ‘August Beauty’ and ‘Radicans’ had similar growth responses to θ thresholds. Maintenance of θ above at the 0.20 and $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ thresholds resulted in reduced growth compared to the 0.40 and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ θ thresholds. The growth similarities at the 0.40 and $0.50 \text{ m}^3 \cdot \text{m}^{-3}$ θ thresholds and large difference in irrigation volume suggests that the

additional irrigation applied to maintain the high θ threshold leads to over-irrigation and leaching with little additional growth. The $0.30 \text{ m}^3 \cdot \text{m}^{-3}$ threshold was enough to maintain plants but growth was less than for higher θ thresholds, suggesting that moderately low thresholds can be utilized for growth control.

To best utilize sensor-controlled automated irrigation in a commercial nursery setting, further research comparing growth of multiple species and/or multiple container sizes is still needed. It is not uncommon in container plant production to have different species, different plant sizes, and plants with different water requirement in the same irrigation zone. A comparison of deciduous and evergreen plants would also provide additional information for mixed plot irrigation and plant water requirements. Additional studies comparing pathogen inoculated plants are needed to understand of sensor technology can be used for disease management.

Reduced fertilizer rates and efficient irrigation can be used to produce salable plants with reduced leaching. Shoot dry weight and growth index of *Gardenia jasminoides* 'MAGDA I' was similar for plants grown at 100% and 50% of the fertilizer bag rate; this shows that fertilizer rates can be reduced up to 50% without negatively impacting plant growth or quality. Reduced fertilizer applications also reduced the leachate electrical conductivity, pore water electrical conductivity, $\text{NO}_3\text{-N}$ quantities, and $\text{PO}_4\text{-P}$ quantities. Lower irrigation volumes resulted in reduced water and nutrient leaching.

In our study we used a singular fertilizer and substrate. Research using controlled release fertilizers with different fertilizer compositions, different coatings, and different release rates are needed for more detailed recommendations of reducing fertilizer applications. A comparative study of liquid fertilizers and controlled release fertilizers would also provide more information

for reducing fertilizer applications. Additional research using GS3 sensors to applying liquid fertilizer in response to substrate EC could allow for fertilization based on substrate nutrient status. Additional studies with plant with low and high nutrient requirements and low and high water use are needed to for deeper understanding of plant growth responses to reduced fertilizer rates and efficient irrigation.

Water-stressed and well-watered *Hibiscus acetosella* 'Panama Red' followed diurnal patterns of elongation and evapotranspiration. Elongation was greatest at night, with a burst of elongation soon after the onset of darkness. If growers want to use drought stress for elongation control, they should ensure that plants are drought stressed before and during when elongation is greatest.

Comparing growth of additional species is needed to see if different species have similar diurnal patterns and respond to water stress in a similar manner. A similar experiment with sensor controlled irrigation would provide more detailed information regarding substrate water content and irrigation volume when using deficit irrigation for elongation control. The response of elongation to varying degrees of water stress is also needed to be able to advise growers on the severity of drought stress to apply for growth control. Our experiment was performed in a controlled environment, comparing growth of plants in a production setting and with varied environmental conditions is needed to understand if similar growth responses are seen in a production environment. The timing of irrigation events and drought periods needs to be examined to provide further details regarding deficit irrigation for growth control.

This research has shown that soil moisture sensor controlled irrigation can be used to irrigate more efficiently. Further research investigating fast vs. slow growing species, high vs. low fertilizer requirements, and high vs. low water use would give a clearer picture of how

irrigation and fertilization can be altered in a production environment to reduce inputs while producing salable plants. Use of reduced fertilizer rates with different irrigation systems will provide additional information as well.