SENSOR-BASED AUTOMATED IRRIGATION USE IN SPECIALTY CROP PRODUCTION AND ROOT DISEASE SUPPRESSION

By

WILLIAM DREXEL WHEELER

(Under the Direction of MATTHEW CHAPPELL)

ABSTRACT

The use of soil moisture sensor-based automated irrigation has been utilized to effectively control irrigation in both research and commercial settings. These studies sought to explore the possible benefits of sensor-based automated irrigation for commercial producers and the potential of these types of irrigation systems to reduce the incidence and severity of oomycete root pathogen infection. In commercial nursery production use of senor-based irrigation cut irrigation water use in half. However, reductions in water usage were not noted with sensor-based irrigation in commercial floriculture production. Historic grower irrigation practices and existing precision irrigation methods are thought to have resulted in the disparities in water savings between the two operations. In commercial floriculture trials sensor-based irrigation was judged to produce equal market quality plants while allowing for reallocation of labor away from irrigation management. In trials conducted at the commercial nursery in 2015 *Rhododendron catawbiense* irrigated with the sensor-based irrigation system experienced significant (>50%) crop losses. High mortality is thought to be the result of canopy structure that obstructed irrigation water capture to a greater degree than the other species within the irrigation group. It may be necessary to rethink irrigation groups around more accurate understanding of species daily water use when using more precise irrigation applications. Soil moisture sensor-based automated irrigation reduced infection rates in petunias grown with consistently low substrate water contents after inoculation with *Pythium aphanidermatum*. Reductions in root infection however were not correlated to reductions in plant mortality or improvements in marketability. Future studies could focus on the disruption of pathogen establishment (pre-inoculation) within the root zone by maintaining consistently low substrate water contents with sensor-based automated irrigation.

INDEX WORDS: Soil moisture sensors, automated irrigation, capacitance sensors, *Pythium*, ornamental plant production, technology transfer, outreach, education, precision irrigation, petunia, *Petunia* x *hybrida*, poinsettia, *Euphorbia* x *pulcherrima*, geranium, *Pelargonium* x *hortorum, Pieris Japonica* D. Don ex G. Don 'Prelude', *Hydrangea quercifolia* W. Bartram 'Jet Stream', *Rhododendron catawbiense* Michx. 'Roseum Elegans', *Kalmia latifolia* L. 'Sarah'

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DEDICATION

I would like to dedicate this work to my parents Drexel and Vicki who have always supported me and inspired my love of science.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Overview

Water scarcity caused by the effects of climate change, a growing population, and increased regulation will put greater pressure on horticultural producers to effectively manage water resources (STRZEPEK and BOEHLERT, 2010). Legislation regulating water use by specialty growers already exists in California, New York, Maryland, Delaware, and Florida, and is expected to become more widely adopted in the future. In Florida alone greenhouse and nursery producers near urban centers have seen their allowed consumption drop by 40%, where as in the past, consumption was unregulated (BEESON JR et al., 2004; MAJSZTRIK and LEA-COX, 2013). Accurate irrigation management is key to not only reducing horticultural water use but also managing plant health.

Climate change is predicted to raise the mean global temperature as well as alter patterns of precipitation (JURY and VAUX, 2005). At the same time the global population is expected to increase to approximately 9.5 billion, with half of the total population residing in urban areas by 2050 (UN, 2013). With irrigated agriculture estimated to account for 70% of all freshwater used by humans, increasing demand from urban and industrial areas will create scarcity for agriculture (FISCHER et al., 2007; JURY and VAUX, 2005). In the U.S., horticultural operations were estimated by the USDA to exceed 235 billion gallons of irrigated water in 2008 (USDA, 2008). Better irrigation practices will need to be adopted by horticultural producers in the future in order to maintain and increase current levels of production while conserving the water resources. Recently developed soil moisture sensor and wireless technology can help address water management while increasing economic competitiveness and reducing disease losses in specialty crop production.

Irrigation management

The majority of production of horticultural crops is done in containers, which present unique challenges for irrigation and nutrition management. Container volumes limit the amount of rooting substrate and consequently the amount of water available to crops, which increases susceptibility to drought stress compared to soil-grown crops. Accurate assessment of irrigation timing is one of the most challenging tasks in a nursery operation, and growers frequently irrigate out of precaution when in doubt of plant water needs (MILLION et al., 2007). Inappropriate application of irrigation water can contribute to run off, excessive water consumption, and increased disease pressure (CHAPPELL et al., 2013; INCROCCI et al., 2014). Soil moisture extremes, either flooding or drought events, can predispose a crop's root system to infection from many pathogens. These events do not have to be exceptionally severe to cause predisposition, and are within the range of growing conditions common to nursery environments (BLAKER and MACDONALD, 1981).

A number of irrigation methods are employed in nursery and greenhouse operations including: impact sprinklers, drip irrigation, and micro-sprinklers. Impact sprinklers offer the advantages of requiring little labor to operate and maintain once installed, however actual application of water can be affected by wind and canopy cover. Drip irrigation allows for more precise application of water at a lower pressure but requires greater input of maintenance and installation. Micro sprinklers improve upon the drip technology by increasing coverage of the root zone while still precisely applying irrigation, but require the greatest labor and maintenance investments (FERERES et al., 2003). All of these application methods can be successfully integrated to automated irrigation systems.

Current methods for regulating irrigation timing are based on individual grower experience and intuition with crops and weather conditions. Automating irrigation in commercial settings has largely been limited to the use of timers to turn irrigation on and off at set periods independent of plant water needs. Current crop water consumption modeling uses evapotranspiration rates derived from nearby weather stations and crop coefficients specific to individual crops and growing conditions. Nursery and greenhouse growers often cultivate a large variety of species for market, each with unique optimal growing requirements. Crop coefficients do not currently exist for the majority of specialty crops cultivated in horticulture and are unlikely to become available in the near future. This limits the application of evapotranspirative modeling in controlling irrigation in horticultural applications (BEESON JR et al., 2004).

Plant water need-based irrigation

A number of recent studies have utilized sensor-based wireless networks to automate irrigation in both research and commercial settings. In these networks capacitance sensors are monitored by a data logger in the field, which then wirelessly transmits an average of the readings to a computer located nearby. Capacitance sensors take advantage of the high dielectric of water when compared to the low dielectric of soil and are able to convert the dielectric reading into a volumetric water content (VAN IERSEL et al., 2013). While cheap and easy to use, most capacitance sensors require calibration to the soil or substrate that they are reading. Software developed for the network at Carnegie-Melon University for these studies, referred to as Sensorweb, allows users to configure irrigation scheduling as well as manually irrigate crops, all over the Internet (KOHANBASH et al., 2013). Chappell et al. (2013) documented the implementation and adoption of three wireless irrigation networks in commercial nurseries to monitor and automate irrigation. Commercial producers found value in the system and cited: "shorter cropping cycles, reduced disease incidence and severity, less fungicide use, increased sense of security, and the ability to expand the production area with currently available water resources" as benefits they saw from the use of wireless sensor networks. A recent study in commercial operations in Italy reported similar findings of reduced water use, runoff, and the number of irrigation events when comparing sensor controlled irrigation to traditional timer-based irrigation. Growers surveyed for the study reportedly could not determine which irrigation treatment was applied to a sampling of the trial crops and judged crop quality to be equal between all treatments. This is significant because the crops grown using soil moisture sensors to automate irrigation achieved a 40% reduction in irrigation water use compared to traditional irrigation methods (INCROCCI et al., 2014). Economic analysis by Lichetenberg et al. (2013) reported that wireless sensor networks required greater upfront costs, but increased annualized nursery profits by 1.5 times over standard practice. Savings in labor, irrigation water, fungicides, fertilizers, lowered energy costs from pumping, and accelerated crop production times all contributed to making wireless sensor network controlled irrigation more profitable than conventional methods of irrigation. Sensor controlled irrigation has been used in two different research trials to determine water use and growth in petunias. Both studies reported that the automated networks were able to accurately control volumetric water content through increases in plant size and fluctuations in environmental conditions (KIM et al., 2011; VAN IERSEL et al., 2010).

Root disease

Irrigation is a primary factor in root disease susceptibility in horticultural crops, and proper management of soil moisture is key to reducing incidence. Root rot disease causing pathogens, including the genera *Phytophthora*, *Pythium*, *Rhizoctonia*, and *Thielaviopsis* are of major concern in the horticultural industry. *Pythium* is one of the most pervasive and economically impactful genera of root rot disease, with a wide verity of species that vary in their pathogenicity and host specificity (HENDRIX AND CAMPBELL, 1970). Drought and flooding stress, common to nursery production, have been demonstrated to reduce resistance to *Phytophthora,* a genus of oomycete plant pathogen closely related to *Pythium*, in Rhododendron (BLAKER and MACDONALD, 1981). *Pythium* spp. produce spores under a wide variety of conditions, but are thought to germinate and release mobile zoospores, which cause infection, in near-saturated, saturated, or flooded conditions (STANGHELLINI AND BURR, 1973). *Pythium* spp. differ in their resistance to the limited number of commercially available fungicides used to combat their growth (MOORMAN et al., 2004). The use of cultural practices and strict sanitation procedures can be used in place of, or conjunction with chemical controls combat the establishment of *Pythium* spp. Observations by Chappell et al. (2012) suggest that the use of sensor-based automated irrigation system resulted in a reduction of losses due to disease in *Gardenia augusta* "Heaven Scent." This may be due to a reduction in suitable root zone environmental conditions that favor plant pathogen development when using sensor-based automated irrigation.

Significance and Rationale

Conventional irrigation is based largely on grower intuition and experience with a crop, which leads many growers to irrigate out of caution when they are in doubt. Elevated soil moisture contents have been shown to predispose crops to root pathogen infection and thereby increase crop losses (BLAKER and MACDONALD, 1981; RHOADES et al., 2003). Crop losses from disease for some specialty crops can approach 30%, significantly impacting growers' bottom lines. Preliminary data and observations from case studies conducted in commercial nurseries have suggested a relation between the use of wireless sensor network controlled irrigation and a reduction in crop losses due to disease (CHAPPELL et al., 2012). To our knowledge there has been no controlled study which has explored this relationship. My research evaluated the incidence and severity of root rot diseases when using sensor-based automated irrigation to precisely control soil moisture content in studies conducted at the UGA greenhouses. In addition, several studies have demonstrated the economic feasibility of implementing wireless sensor networks in commercial nurseries (CHAPPELL et al., 2013). In all of these studies researchers controlled the soil moisture based automated irrigation system with minimal input from growers. I conducted two case studies with commercial specialty crop producers in which control of the sensor-based automated irrigation was handed over to the grower to determine if similar benefits to more controlled studies would be observed.

The potential to reduce crop losses from root rot diseases, while speeding cropping times, through the use of moisture sensor automated irrigation could significantly improve the economic competitiveness for individual growers and increase industry profits. Widespread adoption of moisture sensor technology could also be associated with environmental benefits, reducing runoff of fertilizers and chemical controls from horticultural operations, thereby reducing watershed contamination (LICHTENBERG et al., 2013).

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CHAPTER 2

SENSOR-BASED AUTOMATED IRRIGATION IMPACTS *PYTHIUM APHANIDERMATUM* INFECTION IN *PETUNIA* × *HYBRIDA*[1]

[1] Wheeler, W. Williams-Woodward, J. Chappell, M. Thomas, P. and van Iersel M. To be submitted to *Plant Disease*.

Abstract

Soil moisture sensors have been employed to monitor and control irrigation via substrate volumetric water content (θ) in container grown ornamental crops. Real-time monitoring and control afforded by these systems allows for precise θ to be maintained. This contrasts cyclic soil moisture profiles created by traditional timer-based irrigation management. Anecdotal observations in previous commercial trials have implied root disease could be reduced by employing sensor-based irrigation management. Based on these observations, trials were conducted in a controlled setting in July and September of 2015. *Petunia* × *hybrida* 'Dreams Red' were grown using a sensor-based irrigation system that maintained substrate θ at 0.2, 0.3, and 0.4 $m^3 \cdot m^{-3}$, as well as creating a cyclic soil moisture profile that underwent a 25% change in θ (0.18 to 0.43 $m^3 \cdot m^{-3}$) between irrigation events. Once established, half of the plants in each trial were inoculated with *Pythium aphanidermatum* and grown out for one month under defined irrigation regimes. The probability of root infection was lowered when θ was maintained at 0.2 $m^3 \cdot m^{-3}$ compared to 0.4 $m^3 \cdot m^{-3}$ and cyclic (0.18 to 0.43 $m^3 \cdot m^{-3}$) θ. Mortality, biomass, and aesthetic quality were unaffected by irrigation regime in both uninoculated and inoculated treatments.

Introduction

The majority of ornamental crops are container grown, which presents unique irrigation management challenges for greenhouse and nursery managers (ROUPHAEL et al., 2008). Container volumes constrict root systems and limit the amount of rooting substrate available to retain water. This restricts container grown crops' ability to withstand drought stress between irrigation or rain events (MATHERS et al., 2005). Reduced buffering capacity caused by container production places added pressure on irrigation managers to correctly judge irrigation timing and volume. Irrigation management is largely based on experience and when in doubt growers frequently irrigate out of precaution (KIM et al., 2011). Additionally, irrigation duration is often excessive, leading to prolonged saturation of the root zone, which contributes to leaching and subsequent fertilizer and pesticide runoff (LEA-COX et al., 2013). Previous studies have shown that prolonged saturating root zone conditions increases the incidence and severity of root infections in a number of crops (ELMER et al., 2012; HANCOCK, 1990; WILCOX AND MIRCETICH, 1985). Conversely, during peak growing months when temperature and light levels are the most intense, providing adequate irrigation to crops before they come under drought stress can prove difficult. Duniway (1977) found that safflower (*Carthamus tinctorius* L.) that was water stressed before inoculation with *Phytophthora cryptogea* had increased severity of visible disease symptoms and decreased root weights. Traditional irrigation management allows crops to dry down to levels that can approach drought conditions, followed by extensive periods of irrigation application similar to a flooding event. These root zone moisture extremes were shown to predispose normally resistant rhododendron cultivars to root and crown rots from

Phytophthora cinnamomi (BLAKER AND MACDONALD, 1981). It is hypothesized that the cyclic moisture profiles created by traditional timer-based irrigation management of containerized ornamental crops may introduce greater stress and reduce crop resilience to root pathogens (Biesbrock and Hendrix, 1970).

The use of soil moisture sensors has been demonstrated to be an effective means to automate irrigation in both controlled studies and commercial horticultural operations (BELAYNEH et al., 2013; CHAPPELL et al., 2013; VAN IERSEL et al., 2009). This same technology has been demonstrated to maintain θ within 3% of a programmed threshold, thereby limiting fluctuations in root zone moisture levels (NEMALI AND VAN IERSEL, 2006). Observations from case studies conducted in commercial nurseries have suggested a relationship between the use of soil moisture sensor-based automated irrigation and a reduction in crop losses due to disease (CHAPPELL et al., 2012). It is theorized that minimizing root zone moisture extremes by maintaining θ within a narrow range, using precision irrigation, may be able to reduce disease incidence and severity. Damage and control costs from root and crown rots in the state of Georgia alone were estimated to account for a 4.0% reduction in the farm gate value of ornamental crops in 2013 (MARTINEZ-ESPINOZA, 2015). Given that the market value of nursery, greenhouse and floriculture crops grown in the United States was estimated to be $18.5 billion in 2012 (USDA, 2013) similar reductions from crown and root rots could account for $740 million worth of losses nationwide. This study sought to explore the relationship between soil moisture sensor-based automated irrigation and the incidence and severity of infection of *Pythium aphanidermatum* in *Petunia* × *hybrida*, a common ornamental bedding plant.

Materials and Methods

Experimental design

Trials utilized a completely randomized design. Treatments included two inoculation treatments in combination with four irrigation regimes with each treatment combination replicated four times. A total of 128 plants were used in each trial, with each replication containing four plants in individual containers, that were treated as sub-replicates. A total of 32 irrigation lines were used (2 inoculation treatments × 4 irrigation treatments × 4 replications), each line provided water to the four sub-replicates based on the programmed irrigation regime.

Plant material

The experiment was conducted over four weeks starting on 8 July 2015 and repeated starting 1 September 2015 at the University of Georgia horticulture greenhouse complex in Athens, GA. Each trial consisted of a total of 128 *Petunia* × *hybrida* 'Dreams Red' seedlings transplanted from 128-cell plug trays into individual containers. Seedlings were purchased from C. Raker & Sons, Inc. for the trial conducted in July and produced on site for the trial conducted in September. Commercially available plastic opaque containers (10 cm diam. X 16 cm ht.) were loose filled with 1 liter of a peat and perlite based potting substrate. The trial in July utilized a substrate blend of 65% peat and 35% perlite (Fafard 1P; Sun Gro; Agawam, MA) while the trial conducted in September utilized a similar substrate blend of 80% peat and 20% perlite (Fafard 2P; Sun Gro). In both trials, the substrate was amended with 14-14-14 Osmocote Classic (Everris Inc.;

Dublin, OH) fertilizer at a rate of 5.0 $kg \cdot m^{-3}$. All containers were hand watered for 14 days after transplant to allow for individual seedling establishment within the container.

Irrigation control and environmental data

Three irrigation treatments maintained soil moisture contents near threshold θ's of 0.2, 0.3, and 0.4 $m^3 \cdot m^{-3}$ (corresponding to dry, moderate, and wet substrates) and one irrigation treatment cycled between 0.18 and 0.43 $m^3 \cdot m^{-3}$, a change of 25% in θ between irrigation events (Fig. 1.1). Irrigation was controlled by a soil moisture sensor-based automated irrigation system similar to one constructed by Nemali and van Iersel (2006). A total of 32 irrigation lines were used, each with a corresponding soil moisture sensor (EC-5, Decagon Devices, Pullman, WA) that was inserted in the center of the container, at a 45° angle into one representative container per irrigation line. Soil moisture sensors were connected to a multiplexer (AM16/32B, Campbell Scientific, Logan, UT) that was in turn connected to a data logger (CR10X, Campbell Scientific) that recorded voltage output readings from the soil moisture sensors every 10 s. The data logger converted voltage readings to θ using a substrate specific calibration equation [$\theta = 1.13 \text{ x } (\text{voltage})^2 - 0.612 \text{ x voltage} + 0.0889$]. Two relay drivers (SDM-CD16AC/DC, Campbell Scientific) were connected to the data logger to control 32 solenoid irrigation valves (075-DV ¾ inch Rain Bird, Azusa, CA), one for each irrigation line. When sensor readings fell below θ thresholds, the relay driver powered the corresponding solenoid valve, irrigating the crop until θ readings exceeded the programmed threshold. Each container was irrigated with dribble rings (DR6, Dramm, Manitowoc, WI) that were approximately 10 cm in diameter. Dribble rings were connected to pressure compensated drip emitters rated at 2 l/h (PCJ, Netafim USA, Fresno, CA). Air temperature and relative humidity within the greenhouse were measured with a VP3 probe (Decagon Devices). In July, the average daily maximum temperature and relative humidity were 27.6 ± 0.6 °C (±SE) and 87.5 ± 0.5% while the average daily minimum temperature and relative humidity were 17.5 ± 0.6 °C and 57.9 ± 1.6%. In September average daily maximum temperature and relative humidity were 23.6 ± 0.3 °C and 86 ± 1.0% while the average daily minimum temperature and relative humidity were 15.8 ± 0.6 °C and 62.8 ± 2.0%. Daily light integral was calculated using photosynthetic photon flux readings measured with a quantum sensor (SQ-110; Apogee Instruments, Logan, UT) and ranged from 10.0 to 41.4 mol/m^2/day with an average of 32.5 mol/m^2/day in July, and ranged from 6.5 to 35.7 mol/m^2/day with an average of 22.1 mol/m^2/day in September.

Inoculum production and inoculation procedure

Pythium aphanidermatum (Edson) Fitzp. (isolate 'M15D') originally recovered from symptomatic *Euphorbia pulcherrima* cultivated in Georgia and previously determined to be pathogenic on petunia (WILLIAMS-WOODWARD, Unpublished data), was used in this study. The isolate was maintained under diffuse light at 22°C on V8-PARP medium (15 g Bacto agar [Becton, Dickerson and Co., Sparks, MD]; 50 ml clarified V8 juice [Campbells, Camden, NJ]; 400 µl pimaricin [Sigma-Aldrich, St. Louis, MO]; 250 mg ampicillin [Sigma-Aldrich]; 10 mg rifampicin [Sigma-Aldrich]; 67 mg pentachloronitrobenzene (PCNB) [Terraclor; Chemtura, Middlebury, CT]; in 950 ml of deionized water) (JEFFERS AND MARTIN, 1986). Inoculum was prepared by filling 1000-ml Erlenmeyer flasks with 500 cc vermiculite mixture comprised of 500 cc fine vermiculite (Sta-Green, SunGro horticulture Distribution Inc., Agawan, MA.); 25 g of plain yellow corn meal (House-Autry, Four Oaks, NC); and 250 ml V8 broth (200 ml V8 juice, 2 g CaCO3, and 800 ml deionized water). Flasks were plugged with a foam stopper, covered with tin foil and autoclaved twice for 60 min at 121°C over two consecutive days. Ten 5-mm diameter mycelial plugs from 1-week-old *P. aphanidermatum* cultures were aseptically transferred to each flask and gently shaken to distribute the plugs within the vermiculite mixture. Flasks were incubated under diffuse light at room temperature (22 °C) for 2 days, gently shaken to break up and distribute mycelium, and incubated for an additional 5 days prior to use in greenhouse trials. In the greenhouse, a glass rod was used to create two, 5 cm deep holes in the rooting substrate of each plant to be inoculated. A total of 18 cc of colonized vermiculite mixture was distributed between the two holes in each container and re-covered with substrate. All containers were maintained at saturation for 24 hr to assure colonization of *P. aphanidermatum* in the substrate prior to re-instituting irrigation treatments.

Data collection

Plant quality was assessed weekly using a standardized 1-5 scale, where 1 = a dead plant; 2 = severely inhibited growth, wilting, widespread chlorosis and necrosis; 3 = impacted growth, poor habit, slight wilting, minor chlorosis and necrotic tissue; 4 = good growth and habit, possible weak foliar tone; 5 = a plant with vigorous growth, attractive habit and good foliar tone. Marketability of the crop was assessed at the end of the trial by analyzing the number of plants per irrigation treatment that had plant quality ratings of 4 and 5, which were judged to be of an aesthetic quality suitable for commercial sales.

Mortality was tracked for each treatment combination and percent mortality was calculated based on the number of plants that died in each treatment combination over the course of both trials. At the end of each trial, all plants were cut at the soil line and dried for 72h at 85 °C then weighed to determine dry shoot weight. Roots were washed to remove as much substrate as possible, dried for 72 h at 85 °C and weighed to determine dry root weight. Fresh root samples were collected from each treatment combination prior to root washing and stored in a refrigerator at 5 °C until processing within 1-2 weeks. The root sub-samples were gently washed under running water and 20 1-cm root sections were randomly excised and embedded into V8 PARP medium. Embedded root sections were then incubated under diffuse fluorescent light at room temperature (22 °C) for 48 h before being examined microscopically for the presence of *P. aphanidermatum* hyphal structures. Infection rate was determined by comparing the total number of root pieces from which *P. aphanidermatum* growth was observed from to the total number of root pieces plated. Observed hyphal growth was subcultured onto V8 PARP medium and incubated at room temperature (22 °C) for seven days prior to pathogen confirmation.

Pathogen confirmation

The presence of *P. aphanidermatum* from cultured root sections was confirmed through amplification of the internal transcribed spacer (ITS) region using primers ITS1 and ITS4. A protocol modified from the Barber Ecology and Evolutionary Biology Laboratory at UCLA, CA (2004) was used for extraction. A sterile 20 µl pipette tip was used to remove a small amount of aerial hyphae that was then dipped in a sterile tube containing 300 µl 10% Chelex (Bio-Rad, Hercules, CA). Extraction protocol was followed and after final centrifuging, 1 µl of supernatant was removed and added to a PCR tube containing a PuReTaq Ready-To-Go™ PCR Bead (GE Healthcare, Pittsburgh, PA), 1 µl of 100 µM ITS-1 primer (TCCGTAGGTGAACCTGCGG-3') and 1 µl of 100 µM ITS-4 primer (5'-TCCTCCGCTTATTGATATGC-3') (White et al. 1990), and 22 µl of sterile PCR-grade water for a total reaction volume to 25 µl. PCR reaction was performed in a Thermal Cycler (Mastercycler gradient, Eppendorf, Hamburg, Germany) under the following parameters: initial denaturation at 94 °C for 5 min; 34 cycles at 94 °C for 1 min; 1 cycle at 53 °C for 1 min; 1 cycle at 72 °C for 1 min; final extension at 72 °C for 5 min; and a 4 °C hold (White et al. 1990). DNA amplification was confirmed using 1.0% agarose gel electrophoresis. Samples were run on the gel alongside a 100 bp ladder (New England Biolabs, Ipswich, MA) and bands with a range of 400 – 600 bp were visualized on a transilluminator. Amplified DNA was purified using a QIAquick Purification Kit (Qiagen, Inc., Valencia, CA) and stored at -20 °C. DNA concentration was measured using a Nanodrop 2000 spectrophotometer (Thermo Fisher Scientific, Waltham, MA) and vacuufuged (Vacufuge plus, Eppendorf) for 45 min. DNA was then resuspended to a concentration of 40 ng/µl and submitted to Eurofins Genomics (Louisville, KY) for sequencing using the ITS1/ITS4 primers. Sequences were manually edited and aligned using Geneious software (Biomatters Ltd., Auckland, New Zealand). Consensus sequences were BLAST analyzed using NCBI GenBank (National Center for Biotechnology Information, Bethesda, MD).

Statistical analysis

Experimental parameter measurements were taken on all plants every seven days after inoculation. Parameter measurements from sub-replicates were averaged and used for statistical analysis. No statistically significant differences in parameter measurements were noted between trials with the exception of infection rate. Root infection rate was less in the September trial than the July trial and it is hypothesized that this is due temperature differences between the two trials. The *P. aphanidermatum* isolate M15D has optimal growth at 35 °C (data not shown), and inoculation occurred before a large spike in temperatures in July while temperatures in September remained relatively cooler. Data from both trials were combined and analyzed utilizing R statistical software (R Foundation for Statistical Computing, Vienna, Austria). All analyses treated trial replicates as a random effect while irrigation and pathogen inoculation were treated as fixed effects. Shoot and root dry weights were analyzed using a two-way analysis of variance (ANOVA) to compare the effects of inoculation and irrigation treatment. Plant quality ratings at 7, 14, 21, and 28 days after inoculation were analyzed utilizing two way repeated measures multivariate analysis of variance (MANOVA). Infection rate, mortality and marketability among irrigation treatments were analyzed using a two-way ANOVA and means separation with Tukey's HSD test to determine differences between treatments.

Results

Root infection and mortality

Root infection and whole plant mortality were noted only in inoculated treatments. Within inoculated treatments, plants maintained at a θ of 0.2 $m^3 \cdot m^{-3}$ had average root infection rates of 16.25 ± 4.30% (SE). This was significantly lower than plants maintained at 0.4 $m^3 \cdot m^{-3}$ (p = 0.02) and under cyclic θ (p = 0.03) that had infection rates of 30.00 ± 10.30% and 29.19 ± 9.70%, respectively (Fig. 2.2). The root infection rates of plants grown at consistent θ of 0.3 $m^3 \cdot m^{-3}$ was 21.25 ± 6.40%, which did not differ from infection rates in any other treatment. Differences in plant mortality, while not significant (p = 0.88), had the opposite trend seen for root infection. Inoculated plants grown at 0.2, 0.3, and 0.4 $m^3 \cdot m^{-3}$ incurred 28.1 ± 10.00%, 25.0 ± 9.40%, 25 ± 6.70%, mortality respectively, while inoculated plants grown with cyclic irrigation incurred 18.8 ± 6.30% mortality. Consequently, there was no correlation between infection rate and plant mortality (p = 0.19).

Dry weight

Inoculation with *P. aphanidermatum* reduced dry root and shoot weight (p < 0.01) across all irrigation treatments by an average of 2.37 ± 0.79 g and 2.50 ± 0.29 g, respectively (Fig. 2.3). No interactive effect between irrigation treatment and inoculation was noted in either root (p = 0.29) or shoot (p = 0.72) dry weight. Irrigation treatments had no effect on dry root weights within the uninoculated (p = 0.90) and inoculated treatments (p = 0.76). Dry root weights ranged from 6.70 ± 1.47 g to 8.34 ± 1.95 g in the uninoculated treatments and 4.17 ± 0.79 g to 5.82 ± 1.32 g in the inoculated treatments.

Similarly shoot dry weight was unaffected by irrigation treatment in both the uninoculated ($p = 0.56$) and inoculated treatments ($p = 0.54$). Dry shoot weights ranged from 8.99 ± 0.98 g to 10.99 ± 1.30 g in the uninoculated treatments, and from 6.36 ± 0.61 g to 7.80 ± 0.85 g in inoculated treatments.

Plant quality

Inoculation with *P. aphanidermatum* caused a reduction of plant quality over time in all irrigation treatments ($p < 0.01$). The average plant quality ratings at the completion of both trials ranged from 3.31 ± 0.40 to 3.69 ± 0.35 in inoculated treatments and 4.44 ± 0.16 to 4.94 ± 0.04 in Uninoculated treatments. (Table 2.1). Irrigation treatments did not differ in their ability to mitigate reductions in overall quality caused by inoculation ($p = 0.76$). Within both the uninoculated ($p = 0.17$) and inoculated ($p = 0.88$) treatments plant quality did not differ as a result of irrigation treatments. No interactive effects were noted between irrigation treatment and inoculation ($p = 0.70$).

Marketability

Across all treatments inoculation with *P. aphanidermatum* reduced the average probability of producing a marketable crop by 27 ± 11% (±SE) ($p < 0.01$) (Fig. 2.4). Irrigation treatments were not effective at mitigating the reduction in marketability caused by inoculation ($p = 0.74$). No interactive effects were noted between irrigation and inoculation treatments ($p = 0.96$). In uninoculated treatments, irrigation regime had no effect on marketability with 0.2, 0.3, 0.4 $m^3 \cdot m^{-3}$ and cyclic θ having 93.75 ± 6.25%, 96.88 ± 3.13%, 100.00 ± 0.00%, and 93.75 ± 4.09% probability of producing plants greater than the marketable threshold. In inoculated treatments, no differences in marketability were noted in plants grown at 0.2, 0.3, 0.4 $m^3 \cdot m^{-3}$ and cyclic θ which produced 62.50 ± 10.56%, 71.88 ± 9.95%, 71.88 ± 8.76%, and 68.75 ± 10.30% of plants above the marketable threshold.

Discussion

Use of sensor-based automated irrigation systems has previously been shown to accurately control irrigation, reduce water usage, minimize crop shrinkage, and shorten the cropping cycle of nursery and floriculture crops (CHAPPELL et al., 2012; BELAYNEH et al., 2013; CHAPPELL et al., 2013). In this study, we sought to explore the relationship between precise irrigation control afforded by these systems and the incidence and severity of infection by *Pythium aphanidermatum* in an inoculated crop. Previous research has shown that both abundant soil moisture and cyclic drying and wetting of substrate can promote root pathogen proliferation, growth and subsequent primary and secondary infections (BLAKER AND MACDONALD, 1981; MARTIN AND LOPER, 1999). Conversely, *P. aphanidermatum* oospore germination and germ tube growth is reduced in consistently dry soil conditions (STANGHELLINI AND BURR, 1973). Based on these previous studies, we hypothesized that by maintaining dry root zone conditions with recently developed automated irrigation technology, it would be possible to inhibit *P. aphanidermatum* growth and oospore germination. Data indicated that in inoculated treatments, by maintaining a consistently dry root zone (0.2 $m^3 \cdot m^{-3}$), root infection was reduced when compared to substrates maintained near saturation (0.4 $m^3 \cdot m^{-3}$) and those undergoing cyclic wetting and drying (0.18 – 0.43 $m^3 \cdot m^{-3}$). This is consistent with other research that showed disease incidence in soybean (*Glycine max* [L.] Merr.) correlated to the number of days with high soil water matric potential (SCHLUB AND LOCKWOOD, 1981). It is also consistent with findings of increased root necrosis caused by *Pythium* spp. on holly (*Illex crenata* var. *helleri*) grown with cyclic soil water availability (BIESBROCK AND HENDRIX JR, 1970). However, a reduction in root infection rates did not correspond to a decrease in plant mortality, which averaged 24 ± 8% over all inoculated irrigation treatments in this study (Fig. 2.2).

Within the inoculated treatments, the driest irrigation regime (0.2 $m^3 \cdot m^{-3}$) led to an overall reduction in infection rate in the root system, likely as a result of mitigating secondary infection. However, the combination of drought stress and pathogen presence likely contributed to crop mortality in the driest treatment in this study. The inoculation method used could account for this result. To ensure infection, all treatments were irrigated to near field capacity following inoculation. Doing so ensured the pathogen's distribution from the vermiculite carrier into the soil column. This likely led to primary infection of plants in all irrigation regimes. In the driest treatment, where plants were under water stress, the combined pressure of primary *P. aphanidermatum* infection degrading the root system and drought stress may have led to higher levels of plant mortality than expected similar to results summarized by Schoeneweiss (1978). This resulted in no notable difference in mortality between cyclic or steady state soil moisture profiles in inoculated treatments.

While these results are somewhat confounding, focusing on the combination of growth and infection rates between inoculated and uninoculated treatments points to the potential for reduced secondary infection in the driest irrigation treatment (0.2 $m^3 \cdot m^{-3}$), while maintaining similar growth rate and quality regardless of θ. Implementation of consistently dry rooting substrates before the introduction of the pathogen could disrupt its establishment, a fact that is alluded to in reduced secondary infection witnessed in the current study at the lowest θ (0.2 $m^3 \cdot m^{-3}$) of inoculated treatments. Looking at uninoculated treatments, the lowest θ (0.2 $m^3 \cdot m^{-3}$) did not impact plant growth compared to higher θ levels. Specifically, no difference in mortality, plant quality, marketability, or biomass among the four irrigation regimes was noted in uninoculated treatments. Concurrently analyzed, a conclusion can be drawn that the best non-chemical method of mitigating pathogen damage in commercial production of petunia species would combine strict sanitation practices to prevent the introduction of inoculum while maintaining dry root zone conditions to prevent pathogen proliferation and infection. However, even in the presence of inoculum, establishment and infection of root rot pathogens could be mitigated by growing at a low θ, as seen in the θ treatment of 0.2 $m^3 \cdot m^{-3}$ in this study. The data points to a window of θ in which pathogen germination and subsequent infection is reduced, and yet plant growth is not reduced by drought stress. This window of θ would need to be determined based on soil properties and species grown, however this study indicates that by using recent advances in automated irrigation technology, strict θ control is now feasible for commercial growers that could reduce disease pressure without sacrificing growth and/or quality. Based on results presented in this study, integrated pest management recommendations could be expanded to include maintaining consistently dry, yet stable θ to prevent the establishment and spread of *Pythium* spp. This, combined with sanitation practices, could significantly reduce disease incidence and severity in many floriculture and nursery crops. This study represents the first use of a sensor-based automated irrigation system to reduce *Pythium* spp. root infection and disease development.

Tables and Figures

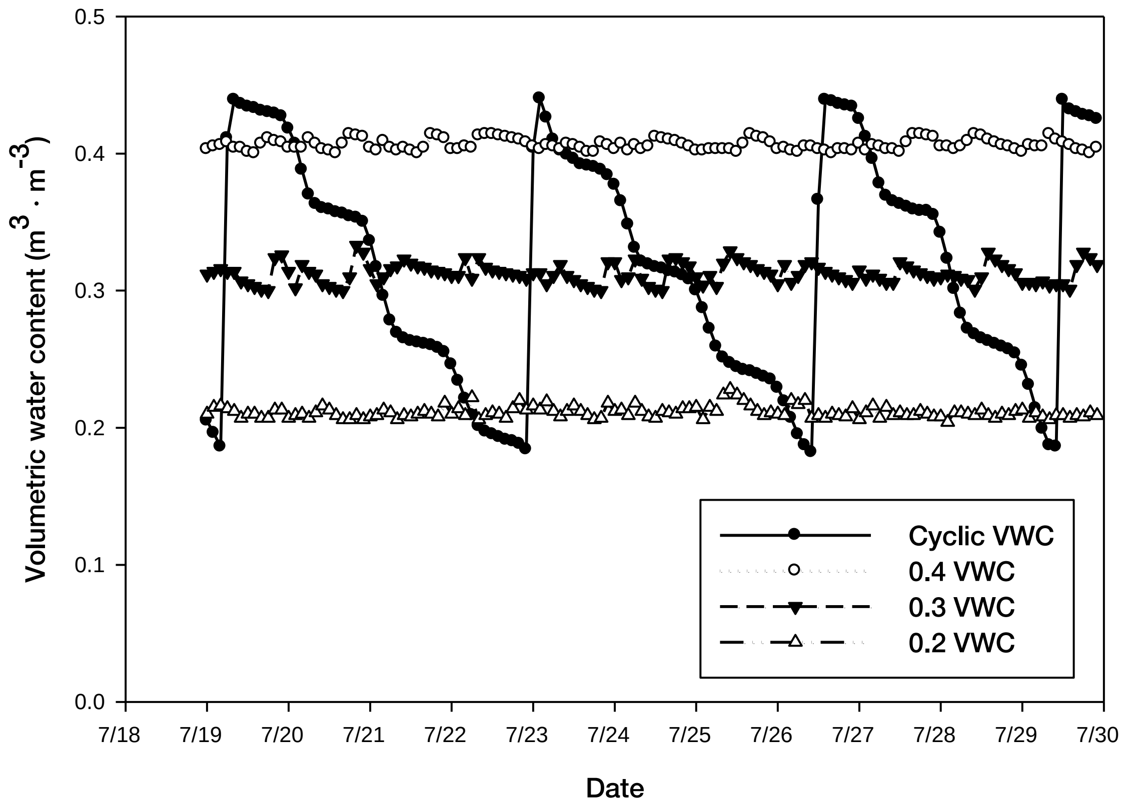
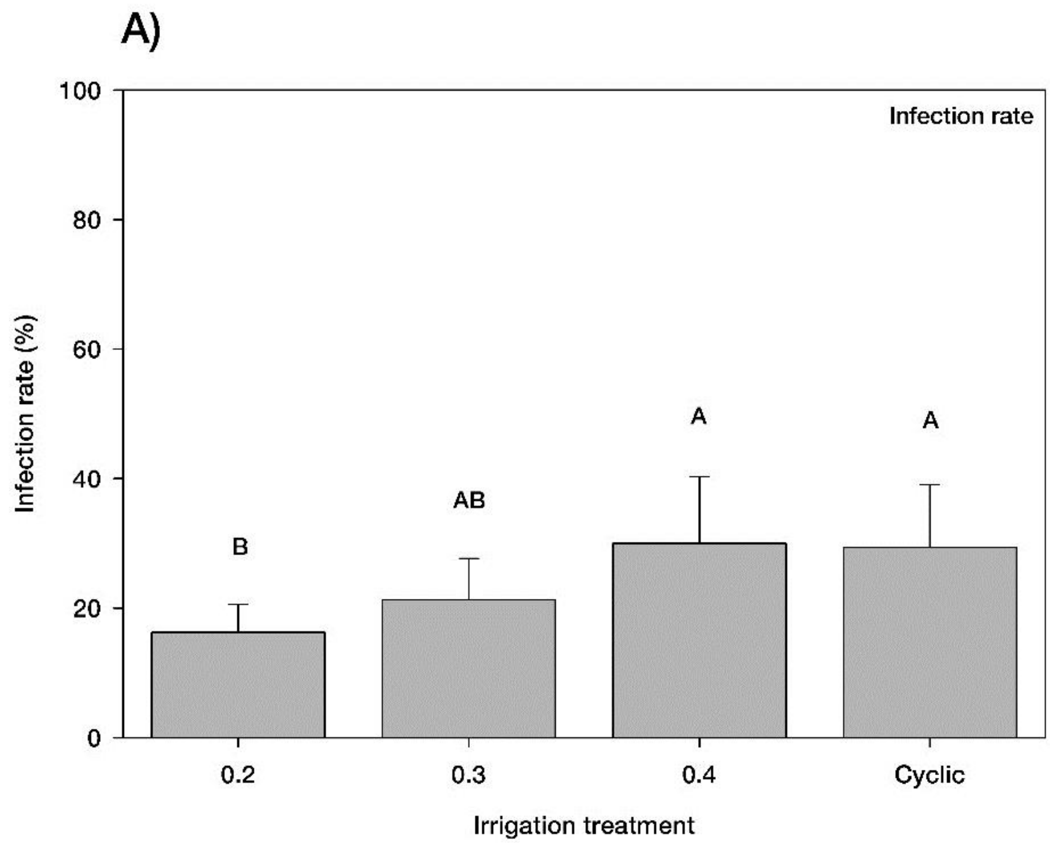


Figure 2.1. Soil moisture sensor readings over a 12-day period from 19 Jul 2015 to 30 Jul 2015 for a sensor-based automated irrigation system. The sensor-based automated irrigation system maintained substrate volumetric water content (VWC) at 0.2, 0.3, and 0.4 $m^3 \cdot m^{-3}$ as well as creating a cyclic soil moisture profile, allowing irrigation to dry down to 0.18 $m^3 \cdot m^{-3}$ before irrigating to 0.43 $m^3 \cdot m^{-3}$. The automated irrigation system received readings from soil moisture sensors every 10 s and opened or closed the corresponding solenoid valve depending if readings fell above or below the programmed threshold.


A)
Infection rate
Infection rate (%)
100
80
60
40
20
0
B
AB
A
A
0.2
0.3
0.4
Cyclic
Irrigation treatment

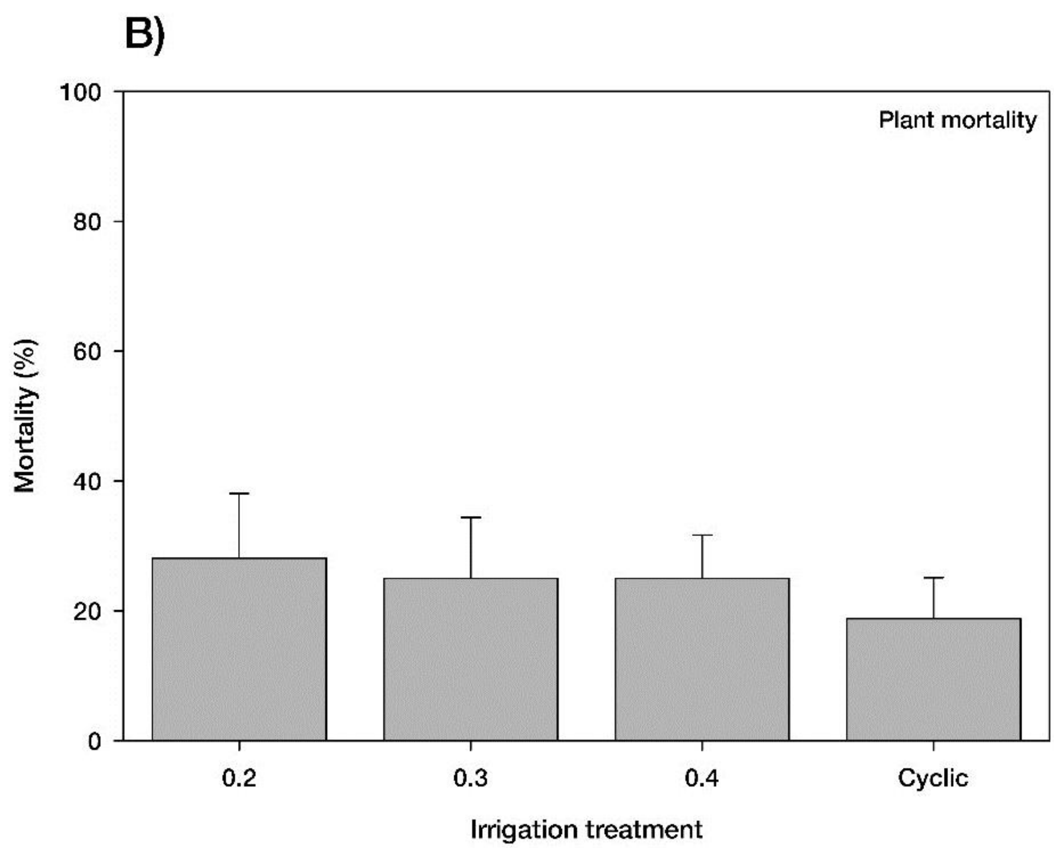
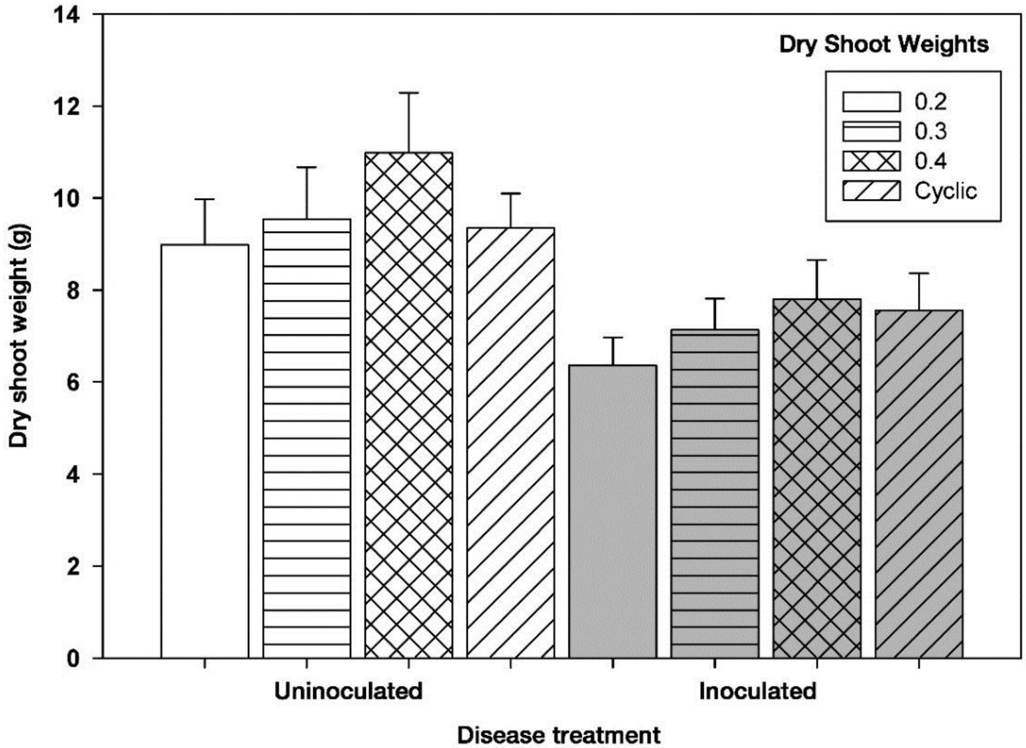

B)
Plant mortality
Mortality (%)
100
80
60
40
20
0
0.2
0.3
0.4
Cyclic
Irrigation treatment

Figure 2.2. *Pythium aphanidermatum* root infection rate (A) and plant mortality (B) in inoculated *Petunia* × *hybrida* 'Dreams Red' irrigation treatments. Plants maintained at consistently dry (0.2 $m^3 \cdot m^{-3}$) soil moisture contents had reduced probability of infection compared to those maintained at near saturation (0.4 $m^3 \cdot m^{-3}$) ($p = 0.02$) and those grown with cyclic ($p = 0.03$) soil moisture profiles. Plants grown under consistently moist root zone conditions (0.3 $m^3 \cdot m^{-3}$) did not differ in probability of root infection from any of the other irrigation treatments. Plants grown at consistent soil moisture profiles (0.2, 0.3, 0.4 $m^3 \cdot m^{-3}$) and those undergoing cyclic change (0.18 to 0.43 $m^3 \cdot m^{-3}$) had no significant differences ($p = 0.88$) in mortality rate when inoculated.

A)


Dry Shoot Weights
0.2
0.3
0.4
Cyclic
Dry shoot weight (g)
0
2
4
6
8
10
12
14
Uninoculated
Inoculated
Disease treatment

B)

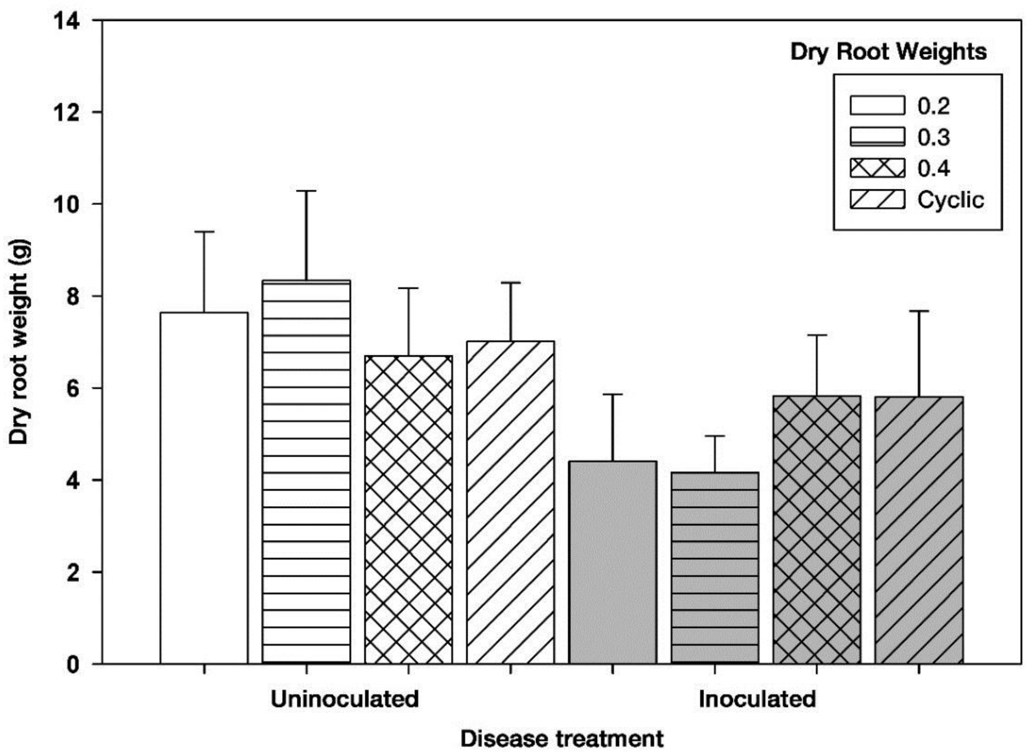
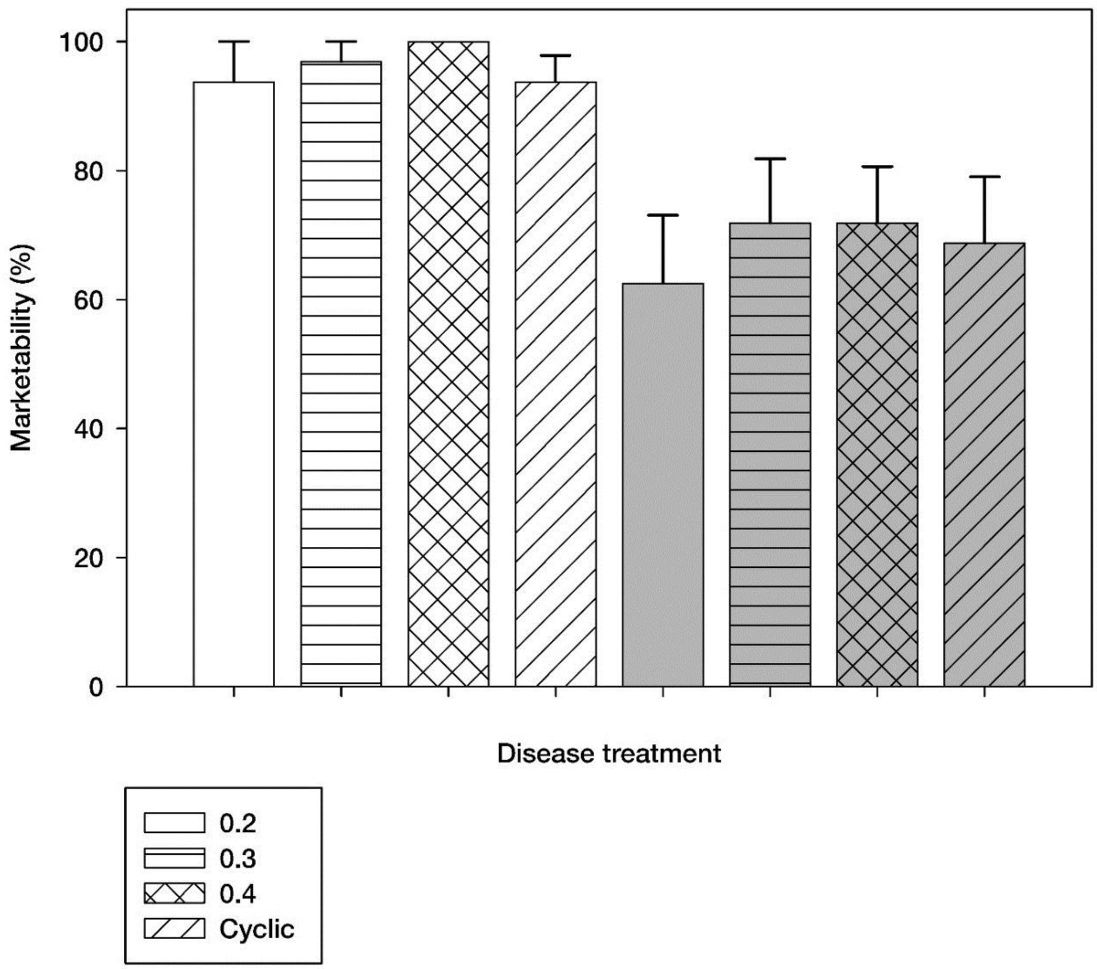

Dry Root Weights
0.2
0.3
0.4
Cyclic
Dry root weight (g)
0
2
4
6
8
10
12
14
Uninoculated
Inoculated
Disease treatment

Figure 2.3. Shoot (a) and root (b) dry weights of *Petunia* x *hybrida* 'Dreams Red' in uninoculated and inoculated treatments (with *Pythium aphanidermatum*). Soil moisture sensor-based automated irrigation was used to control irrigation at constant (0.2, 0.3, 0.4 $m^3 \cdot m^{-3}$) and cyclic (0.18 to 0.43 $m^3 \cdot m^{-3}$) volumetric water contents. Irrigation treatments inoculated with *P. aphanidermatum* experienced a reduction in both root and shoot dry weights ($p < 0.01$). Plants grown at consistent soil moisture profiles and those undergoing cyclic change had no significant differences in dry shoot or root weights in both uninoculated and inoculated treatments.



100
80
60
40
20
0
Marketability (%)
Disease treatment
0.2
0.3
0.4
Cyclic

Figure 2.4. Marketability of *Petunia* × *hybrida* 'Dreams Red' was reduced by inoculation with *Pythium aphanidermatum*. Marketable crops were those judged to have a plant quality rating of 4 or 5 on a standardized 1 to 5 scale at the end of the experiment, where 1 = a dead plant and 5 = a vigorously growing plant with good foliar tone. Irrigation was maintained at multiple steady state (0.2, 0.3, 0.4 $m^3 \cdot m^{-3}$) and one cyclic (0.18 to 0.43 $m^3 \cdot m^{-3}$) volumetric water contents had no effect at mitigating marketability losses due to disease. Probability of producing a marketable crop was unaffected in both uninoculated ($p = 0.66$) and inoculated ($p = 0.90$) treatments by the different irrigation regimes.

[1] Plant quality rating based on a 1 to 5 scale, where = 1 a dead plant and 5 = a vigorously growing plant with good foliar tone.

[2] dai = days after inoculation

Average Plant Quality Over Time

Irrigation Treatment (VWC)	Disease Treatment	Plant Quality Rating[1]			
		7 dai[2]	14 dai	21 dai	28 dai
0.2	Uninoculated	4.91 ± 0.07[a]	4.91 ± 0.07[a]	4.81 ± 0.09[ab]	4.44 ± 0.16[ab]
0.3	Uninoculated	4.84 ± 0.08[a]	4.91 ± 0.09[a]	4.81 ± 0.08[ab]	4.72 ± 0.07[ab]
0.4	Uninoculated	4.94 ± 0.04[a]	4.94 ± 0.06[a]	4.94 ± 0.04[a]	4.94 ± 0.04[a]
Cyclic	Uninoculated	4.91 ± 0.05[a]	4.97 ± 0.03[a]	4.81 ± 0.06[a]	4.72 ± 0.10[ab]
0.2	Inoculated	4.91 ± 0.05[a]	3.78 ± 0.45[b]	3.34 ± 0.42[c]	3.31 ± 0.40[c]
0.3	Inoculated	4.88 ± 0.07[a]	4.06 ± 0.27[a]	3.81 ± 0.36[bc]	3.59 ± 0.33[bc]
0.4	Inoculated	4.91 ± 0.05[a]	3.97 ± 0.25[a]	3.78 ± 0.25[bc]	3.47 ± 0.29[bc]
Cyclic	Inoculated	4.84 ± 0.07[a]	4.41 ± 0.28[a]	3.78 ± 0.34[bc]	3.69 ± 0.35[bc]

Letter assignment based on Tukey's post hoc analysis for $p < 0.05$ by measurement date

Table 2.1. Average plant quality ratings for *Petunia* × *hybrida* 'Dreams Red' at 7, 14, 21, and 28 days after inoculation with *Pythium aphanidermatum*. Plants were grown at three consistent soil moisture profiles (0.2, 0.3, 0.4 $m^3 \cdot m^{-3}$) and one undergoing cyclic change (0.18 to 0.43 $m^3 \cdot m^{-3}$).

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CHAPTER 3

IMPLEMENTATION OF SOIL MOISTURE SENSOR-BASED AUTOMATED IRRIGATION IN COMMERCIAL FLORICULTURE PRODUCTION[1]

[1] Wheeler, W. Chappell, M. Thomas, P. and van Iersel M. To be submitted to *HortTechnology*

Abstract

A newly developed soil moisture sensor-based automated irrigation system has been trialed in a number of woody ornamental nurseries with a number of observed production benefits. For this study a similar sensor-based automated irrigation system was installed in a commercial floriculture greenhouse to determine what benefits these types of systems may offer herbaceous annual producers. In this study, water use, crop quality and growth along with grower behavior toward adoption of this new technology was monitored. Two cultivars of *Euphorbia* × *pulcherrima* Willd. ex Klotzsch and three cultivars of *Pelargonium* × *hortorum* L.H. Bailey were produced in side by side trials over the course of two years comparing sensor-based irrigation with grower managed irrigation. Plant quality was equivalent between irrigation treatments across all five trials. Differences in average plant size were noted in four of the six trials between irrigation treatments, but in all instances these differences were not judged by the commercial grower to impact marketability of the crop. Irrigation water use by the sensor-based system exceeded or matched water use in the grower managed irrigation sections. Over the course of two years the number of plants for which sensor-based irrigation was scaled up at the request of the grower. Managers at the facility determined that sensor-based irrigation facilitated reallocation of labor away from irrigation management, which was valuable during peak production periods.

Introduction

Agricultural water scarcity resulting from climate change, a growing population and increased environmental regulation is expected to become more pervasive in the future (STRZEPEK and BOEHLERT, 2010). Water scarcity has the potential to significantly impact floriculture production, which is valued at approximately $4 USD billion annually (U.S. Dept. Ag., 2015). State and federal regulations are already in place in many areas of the U.S. that limit water consumption and runoff for floricultural and specialty crop production (FULCHER et al., 2016). These regulations are expected to increase in stringency and prevalence as urban centers continue to expand, and public understanding of the value of ecosystem function grows (COSTANZA et al., 2014). Regulatory and environmental pressures will create greater incentives for floriculture producers to effectively manage limited water resources (FERERES et al., 2003). Commercial horticulture producers also face persistent challenges from the cost of labor, and effective employee management, retention and training. Mathers et al. (2010) noted that labor accounts for 40% of nursery production costs, while labor retention rates were more than 51% after five years. The horticulture industry is facing critical shortfalls in labor with tightening regulations regarding migrant workers and an increasingly competitive domestic labor market (BELLENGER et al., 2008). Greenhouse and nursery jobs are typically lower paying, averaging $19,330 annually, making worker acquisition and retention difficult (BUREAU OF LABOR STATISTICS, 2015; US CENSUS BUREAU, 2015).

Automation and mechanization is one means by which horticultural producers are overcoming these challenges (POSADAS, 2012). Automation has a number of potential benefits for specialty crop producers including: improving production quality, reducing production costs, increasing market value, reducing hazardous working conditions, and improving professional esteem (LING, 1994). Automated irrigation through soil moisture sensing has been shown to be an efficient means of regulating irrigation application (MAJSZTRIK et al., 2013). While a number of different moisture sensors exist, capacitance sensors that track volumetric water content (θ) have been used in commercial nursery trials in conjunction with wireless networks to produce a number of observed benefits (BELAYNEH et al., 2013; CHAPPELL et al., 2013; VAN IERSEL et al., 2009). Significant reductions in irrigation water use, as well as reductions in crop production times and crop shrinkage due to disease have been noted (CHAPPELL et al., 2012). Economic analysis by Lichtenberg et al. (2013) reported that sensor-based automated irrigation systems required greater upfront costs, but increased annualized nursery profits by 1.5 times over standard irrigation practices. Savings in labor, irrigation volume, fungicides, fertilizers, lowered energy costs from pumping, and accelerated crop production times all contributed to making soil moisture senor based automated irrigation more profitable than conventional methods of irrigation. Kim et al. (2014) documented the effects of sensor-based automated irrigation on *Antirrhinum majus* L. hydroponic cut flower production. The study found a 24% reduction in water use when employing a sensor-based automated irrigation but noted an 18% lower harvest yield. Reductions in yield were attributed to selection of lower than optimal θ set points by researchers (KIM et al., 2014). Growers who participated in the study readily adopted the system, using it to track soil moisture contents and further optimize their manual irrigation scheduling based on system readings. Additionally, sensor-based automated irrigation systems have been used in a number of controlled studies in university greenhouses. Species trialed in these studies have included *Petunia* × *hybrida* E. Vilm. (VAN IERSEL et al., 2010), *Euphorbia pulcherrima* (ALEM et al., 2015a), and *Catharanthus roseus* (L.) G. Don (KIM AND VAN IERSEL, 2011). To our knowledge the study by Kim et al. (2014) is the only investigation into the adoption and implementation of sensor-based automated irrigation in commercial production of floriculture crops. It is thought that many of the benefits of soil moisture sensor-based automated irrigation observed in nursery crop production will also be observed in commercial floricultural production. This study sought to determine what advantages these types of systems could offer commercial floriculture producers and observe grower behavior with regards to adoption of the new technology. We hypothesized that soil moisture sensor-based automated irrigation would readily be adopted by the participating grower. Additionally, we hypothesized that soil moisture sensor-based automated irrigation would reduce the volume of irrigation water being applied while producing equal size and quality plants when compared to traditional irrigation management.

Materials and Methods

Commercial partner and plant material

A medium sized commercial floricultural greenhouse was selected to participate in the study based on willingness to adopt new technology, openness to allowing research to be conducted on site, and expressed interested in automated irrigation technology. The floriculture producer utilizes gutter-connected, polyethylene-covered houses and produces primarily finished annuals and both rooted and unrooted cuttings for the wholesale market. The greenhouse is located in Elebert County, Georgia in USDA hardiness zone 8A. Five separate trials (e.g. production cycles) were carried out in 2014 and 2015 to compare sensor-based automated irrigation to traditional irrigation management. All trials took place in two bays of a greenhouse with each bay measuring 44 m × 21 m × 4 m (L × W × H). Plants were produced within the greenhouse either on a ground level pad covered with landscaping cloth or on elevated wooden benches 1 m wide by 20 m long. Species trialed included three cultivars of geranium (*Pelargonium* × *hortorum*), and two different cultivars of poinsettia (*Euphorbia* × *pulcherrima*). Geranium and poinsettia cultivars were grown in 20.0 cm diameter and 16.5cm diameter containers, respectively. All containers were consumer grade opaque plastic that were loose filled with commercially available peat-perlite based growing media (Metro-Mix 360, Sun Gro Horticulture, Agawam, MA).

Irrigation control and environmental data

A soil moisture sensor-based automated irrigation system and similar to systems employed to control irrigation in commercial nursery settings by Chappell et al. (2013), was used in these trials. Five soil moisture sensors (GS3; Decagon Devices; Pullman, WA) were distributed evenly throughout each crop and inserted with the metal prongs aligned vertically downward through the surface of the media. Sensors were connected to wireless nodes (nR5-DC; Decagon Devices) and provided readings of θ, bulk electrical conductivity and soil temperature. Each wireless node was also capable of controlling a 12 V DC latching solenoid valve (075-DV ¾ in.; Rain Bird; Azusa, CA) that regulated the flow of irrigation water. Over the course of the 2 years, a total of 4 nodes were used to monitor and control θ for 300 - 450 plants per node. One additional node was deployed as a dedicated weather station, monitoring environmental conditions within the greenhouse. Light levels were monitored using a PYR solar radiation sensor (Decagon Devices) and air movement through the house was measured utilizing a cup anemometer (Decagon Devices). Temperature and relative humidity were monitored using an EHT sensor (Decagon Devices) and cumulative irrigation volume was monitored over the course of 2 years using eight flow meters (DLJ SJ50; Daniel L. Jerman Co.; Hackensack, NJ). Nodes collected readings every minute and transmitted the averages back to a centrally located computer station every 20 min using a 900-MHz radio (XSC; Digi; Minnetonka, MN). Sensorweb software, previously developed by Carnegie-Melon University (KOHANBASH et al., 2013), was installed on the computer station and provided monitoring and control capabilities. The software utilized a web based graphical user interface (GUI) that should be intuitive to most users and provided access both directly at the computer station and remotely over the internet. The GUI allowed growers to schedule irrigation and view data collected by the network, and is capable of extensive customization to meet business specific growing conditions, irrigation methods, and grower preferences. After 7 d of monitoring, growers would establish irrigation thresholds based on sensor readings from the monitoring period, their experience with the crop and guidance from University of Georgia Extension Specialists. When average θ readings fell below the programmed threshold, an irrigation event lasting 300 s was triggered. All plants were placed under drip tape rated at 1.36 L/h at 38 cm spacing (Space-It; Netafim; Fresno, CA). Fertilization for the sensor-based irrigation system was specific to each crop and was managed by the section grower to reflect fertilization rates of the grower irrigated section. Fertilizer used for geraniums was 12-2-14 Cal Mag + P

(Plantex; Master Plant-Prod Inc.; Brampton, ON) at 200 ppm N. For poinsettia production, 300 ppm N of 20-20-20 (J.R. Peters Inc.; Allentown, PA) was used from transplant until first bract color. Once bracts had colored fertigation was changed to 200 ppm N of 17-5-17 (Plantex; Master Plant-Prod Inc.). Plants were fertilized at every irrigation event triggered by the sensor-based system utilizing dedicated injectors (DM14Z2; Dosatron; Clearwater, FL) set to a 1 to 128 injection ratio.

Initial setup of the sensor-based irrigation system occurred on week 14 of 2014 and was used to monitor but not control irrigation in a ‘Fantasia Scarlet Improved’ geranium crop. This initial monitoring period allowed growers to become familiar with the functioning of the system, and note soil moisture trends generated by their irrigation management practices. Irrigation was first controlled by the sensor-based irrigation system starting week 35 of 2014 in ‘Prestige Red’ poinsettias. Following the initial trial with poinsettias in the fall, three cultivars of geranium were trialed in the spring of 2015 staring on week 6. Poinsettia trials were scaled up and repeated in the fall of 2015 starting on week 35.

Data collection

Growth indexes were calculated by taking the height of the canopy from top of the media and multiplying it by the width of the plant at its widest point and the width perpendicular to that point. Plant quality was assessed on a standardized 1-10 scale that was established at each sampling date, with 1 being a completely dead plant and 10 being a plant with vigorous growth, an attractive symmetrical habit and good foliar tone. Flow meter readings were taken at each sampling period and back calculated to determine total water use. For dry weights, shoots were cut at the soil line at the end of each trial and dried at 85 °C for 72 h and then weighed. For geranium trials, when plants were determined to be market ready by the grower, the number of flower stalks per plant was counted and used to determine the average number of flowers per plant. When poinsettias were deemed market ready, anthocyanin content index was sampled using an ACM-200 plus meter (Opti-Sciences, Inc., Hudson, NH). Bract area was determined at the sale date by selecting three of the largest colored bracts per plant and measuring the leaf area using a leaf area index meter (LI-3000C, LI-COR, Lincoln, NE).

Grower interviews

Throughout the course of the 2-year study, greenhouse staff behavior and opinions of the sensor-based irrigation system were documented. Semi-structured interviews were conducted at each sampling date with the owner, head grower, and section grower in which their impressions and comments about the system were noted. Two annual presentations were given in which results from the studies conducted that year were discussed and growers were formally asked for their input on the performance of the system. Grower use of the system, including establishment and re-assignment of irrigation thresholds during trials, was tracked. Informal conversations about the sensor-based automated irrigation system and occasional trouble shooting were carried out on an as needed bases.

Experimental design and statistics

All trials utilized side by side comparisons of sensor-based irrigation to that of grower managed irrigation. Irrigation treatments were treated as fixed effects when analyzing for treatment differences. For all trials, sample plots consisting of 125 plants were established in each irrigation treatment, from which 20 were randomly selected for evaluation for plant quality and growth indexes throughout the trial. Evaluations were performed every 14 d after the start of each trial. When plants were deemed market ready twenty plants were randomly selected for additional quality (anthocyanin content index, bract area, and flower count) and dry weight measurements. R statistical software (R Foundation for Statistical Computing, Vienna, Austria) was used to analyze all data collected. Geranium flower counts, poinsettia bract size and anthocyanin content index readings, as well as dry canopy weights in all trials were examined using a two-way analysis of variance (ANOVA) comparing irrigation methods. Plant quality ratings and growth indexes were analyzed utilizing two way repeated measures multivariate analysis of variance (MANOVA) over the course of the trials. Irrigation setup was such that single flow meters were used to track water use in each irrigation treatment for all geranium trials and the 2014 trial of poinsettia so that only direct comparisons of readings could be made. In 2015, expansion of poinsettia trials allowed instillation of additional flow meters and replication of water use data which was examined using MANOVA analysis.

Results

Geranium

In all three trials conducted with geraniums in the spring of 2015, irrigation volume (gallons of water applied to a crop) as well as growth indexes were greater with sensor-based irrigation when compared to grower managed irrigation (Figs. 3.1, 3.2). In the first trial of 2015, a ‘Fantasia Cardinal Red’ crop was produced from week 6 to week

12. In this trial, the greatest differences in irrigation volume applied and growth indexes ($p < 0.01$) were observed. By the end of the first trial, the sensor-based system applied an additional 266.78 gal of total irrigation water, or 0.89 gal per plant (Fig. 3.1). Growth indexes at the market ready stage averaged 35,134 ± 1701 (± SE) cm^3 in sensor-based irrigated treatments, compared to 23,253 ± 1281 cm^3 in grower irrigated treatments (Fig. 3.2). Flowering was also reduced as a result of irrigating with sensor-based irrigation (p = 0.02), with 0.9 ± 0.18 flowers per pot produced with the sensor-based irrigation system and 1.7 ± 0.27 flowers per pot in grower irrigated crops (Fig. 3.3).

Based on results from the first geranium crop, the grower reduced the initial irrigation set point in subsequent crops (Fig. 3.1). An additional 85.76 gal of total irrigation water, or 0.28 gal per plant, were used by the sensor-based irrigation system to produce the cultivar ‘Fantasia Salmon’ while an additional 86.26 gal, or 0.29 gal per plant, was used to produce the cultivar ‘Fantasia Shocking Pink’. In cultivar ‘Fantasia Salmon’ (week 15 to week 20) plants grown under sensor-based irrigation had larger (p = 0.04) growth indexes, averaging 11,687 ± 404 cm^3 at market ready compared to grower irrigated plants that averaged 10,245 ± 313 cm^3. Growth indexes were also larger (p = 0.01) at market ready with sensor-based irrigation in the ‘Fantasia Shocking Pink’ (week 15 to week 21), averaging 16,747 ± 745 cm^3 while grower-irrigated crops averaged and 13,047 ± 633 cm^3. Flower counts were equivalent between the two irrigation treatments in both the ‘Fantasia Salmon’ (p = 0.49) and ‘Fantasia Shocking Pink’ (p = 0.72) (Fig. 3.3).

Poinsettia

Poinsettia production was trialed in both 2014 and 2015, with ‘Prestige Red’ used in both years and ‘Christmas Day Red’ added in 2015. In 2014, the sensor-based irrigation system used 0.12 additional gal of irrigation water per plant, or 43 gal total, when compared to grower managed irrigation. In 2015, the trial size and number of flow meters was expanded that allowed for statistical analysis of water use between the two irrigation treatments. The sensor-based irrigation system did not differ in its average water use on a per plant basis (3.10 ± 0.34 gal) (±SE) when compared to the grower managed section (3.57 ± 0.27 gal) (fig. 3.4). In both 2014 ($p = 0.74$) and 2015 ($p = 0.79$) ‘Prestige Red’ poinsettias received equivalent plant quality ratings when comparing irrigation control by the sensor-based system and the grower. Plant quality ratings were also equivalent in ‘Christmas Day Red’ poinsettias produced in 2015 ($p = 0.34$). Equivalence of plant quality ratings were consistent with bract anthocyanin content index readings, that ranged from 45.5 to 112.5 across all three cultivar and year combinations, but were comparable between irrigation treatments (data not shown). Growth indexes were similar between irrigation treatments for the cultivar ‘Christmas Day Red’ in 2015 ($p = 0.43$) (Fig. 3.5). However, in both 2014 ($p < 0.01$) and 2015 ($p < 0.01$) average growth indexes of cultivar ‘Prestige Red’ irrigated with the sensor-based system differed from those irrigated by the grower. In 2014, ‘Prestige Red’ grown with sensor-based irrigation had higher growth indexes at sale averaging 143,237 ± 6,084 (±SE) while grower irrigated plants averaged 119,847 ± 4,084. In 2015, sensor-based irrigation resulted in ‘Prestige Red’ plants with an average growth index at sale of 107,367 ± 3,852 cm^3, while grower irrigated plants averaged 134,509 ± 5,208 cm^3. The difference in growth indexes was also reflected in dry weight measurements and bract sizes (data not shown).

Discussion

Water use and plant growth

Increased water use by the sensor-based system observed in trials conducted with geranium and the 2014 poinsettia trial, as well as equivalent water use in the 2015 poinsettia trial, was thought to be the result of the approach that the grower took to managing irrigation. Initial selection of irrigation thresholds and subsequent adjustment throughout crop development were observed to maintain substrate moisture levels in abundance or, in some cases, close to saturation. Interviews with greenhouse personnel suggest that threshold management practices were the consequence of a combination of historical grower production preferences and a lack of awareness of how the sensor-based irrigation operated. Historical preferences for production were to maintain high levels of substrate moisture to act as a buffer against drought stress and to push crop growth. Grower perceptions of the sensor-based system were such that they believed irrigation thresholds needed to be gradually increased to match plant growth. This perception resulted in the continual upward adjustment of irrigation thresholds by the section grower throughout crop production in all trials (Fig. 3.1). This management strategy makes intuitive sense based on historical behaviors when using timer-based automated irrigation systems. In these systems, the only method of applying more irrigation is to increase the run-time. The same behavior is not necessary when setting soil-moisture sensor-based automated irrigation. Nemali and van Iersel (2006) demonstrated that a similar soil moisture based irrigation system was able to maintain irrigation control as plants developed and their water usage changed without modification of irrigation thresholds. In previous studies employing sensor-based irrigation, researchers controlled irrigation thresholds that were established based on best management practices, substrate physical properties and grower input. Once irrigation thresholds were established they would remain in place for the duration of the production cycle (Chappell, personal communication, 2016). High irrigation thresholds observed in this study may have contributed to results observed in the first geranium trial, in which increased growth indexes and reduced flowering were observed in the crop grown with sensor-based irrigation. Increasing θ has been correlated with increased dry shoot weight and a reduction in flowers when combined with high fertility in petunia (*Petunia* × *hybrida*), (ALEM et al., 2015b; KIM et al., 2011; VAN IERSEL et al., 2010). Despite reductions in flowering in 'Fantasia Cardinal Red' and increased water use and growth indexes in all geranium cultivars, marketability of the crops produced with sensor-based irrigation was not impacted and plants were sold alongside those produced with grower managed irrigation. Similarly, poinsettias produced in 2014 and 2015 by the sensor-based system were pulled for sale at the same time as grower irrigated plants. Differences in the average growth indexes, in both 2014 and 2015, between the sensor-based system and grower irrigated crops in 'Prestige Red' were judged not to impact marketability. Alem et al. (2015b) demonstrated that water deficit imposition utilizing a sensor-based automated irrigation system could be used to regulate poinsettia height in a controlled setting. Findings from the study indicated that water deficit imposition could be a potential alternative to plant growth regulator (PGR) applications. Precise control of soil moisture contents afforded by the sensor-based system allow for selection of irrigation thresholds so that mild drought stress could be imposed throughout crop development. In this study, growers established irrigation thresholds based on intuition and experience with the crop. In conversations with the owner, head grower and section grower, researchers explained the mechanisms of control of sensor-based irrigation and how low irrigation thresholds could be used for water savings. However, adjustments to the irrigation thresholds continued throughout all trials conducted at the greenhouse. This is a significant difference in how the system had been used by researchers and how production managers may choose to use the sensor-based system for irrigation management. This points to the need for an education and/or consulting component to sensor-based automated irrigation setup and operation. Some steps have been taken to provide grower-based knowledge on soil moisture sensor-based irrigation systems through the USDA Specialty Crops Research Initiative funded Smart-Farms project (CHAPPELL et. al., 2015).

Grower perspectives

At the request of the owner, greater implementation of the system occurred over the course of the 2 years. In 2014 the sensor-based system controlled irrigation to 300 poinsettias and in 2015 control expanded to 1800 plants. This same trend was seen in the geraniums, with the initial trial controlling irrigation for 300 plants and later concurrent trials controlling irrigation for 900 plants. This greater reliance on the system to control irrigation was seen as strong evidence of acceptance and successful technology transfer. In interviews with the owner, he conveyed that the real value to the company of sensor-based automated irrigation was the ability to free up labor during peak spring production periods. Water usage, while a consideration, was not a management priority due to the relatively low cost of water in the region. Moreover, the greenhouse employed a number of efficient irrigation practices prior to this study (e.g. producing crops under drip lines). He commented that section growers were often overwhelmed during peak production and “dry” growing practices that were historically observed were more often the result of neglect than good horticultural practice. Sensor-based irrigation provided a mechanism to automate irrigation, a task normally requiring frequent grower input and observation, allowing for greater distribution of labor throughout the operation. Posadas et. al (2008) reported a similar result when looking at increased automation in horticultural production practices, finding that automation did not lead to a reduction in labor force but instead more efficient allocation of that labor.

Conclusion

Sensor-based automated irrigation was able to produce equal quality plants with no differences in marketability. Despite no observed reduction in water use, unlike previous studies working with woody ornamental production, adoption of this emerging technology by the grower took place because of its utility as a labor saving device. Reduced labor hours associated with irrigation management allowed for reallocation of that labor toward other production and shipping related activities, which was especially important during peak production periods when labor shortages are commonly observed.

Tables and Figures

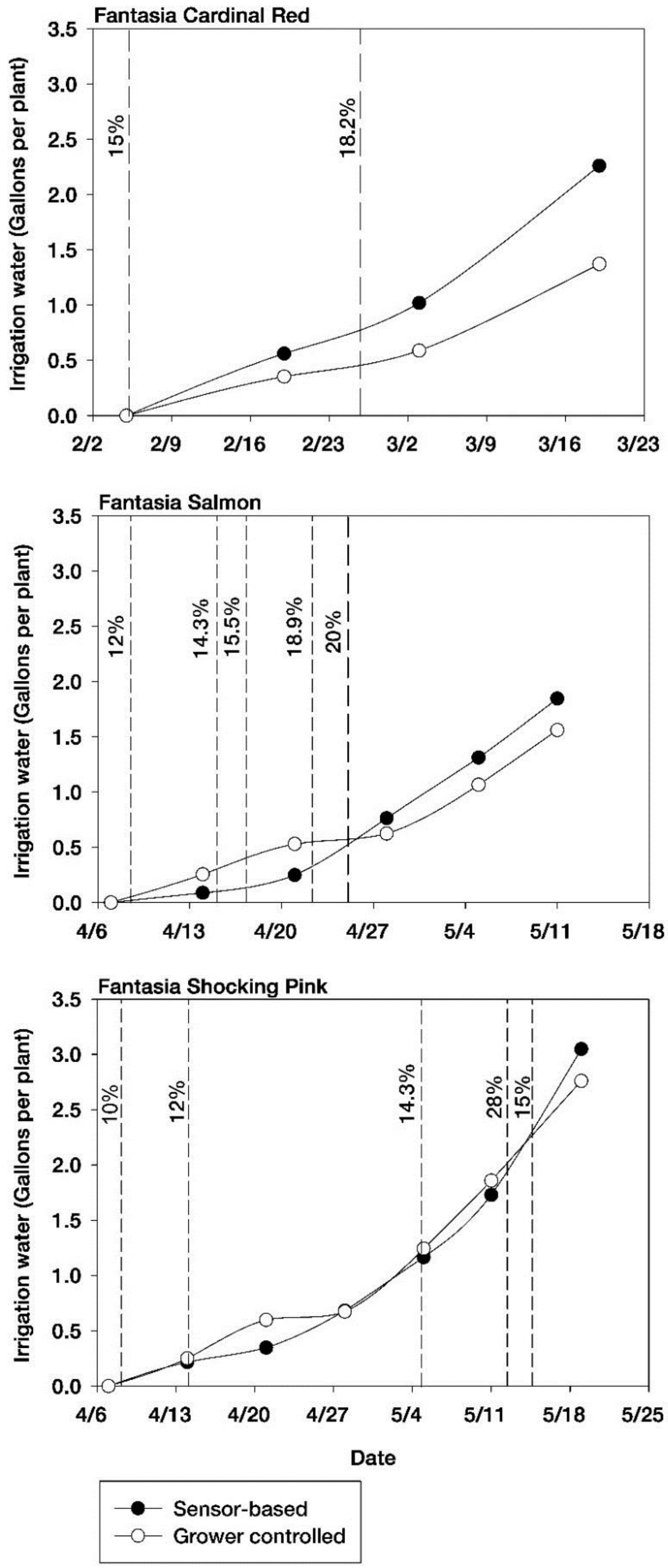
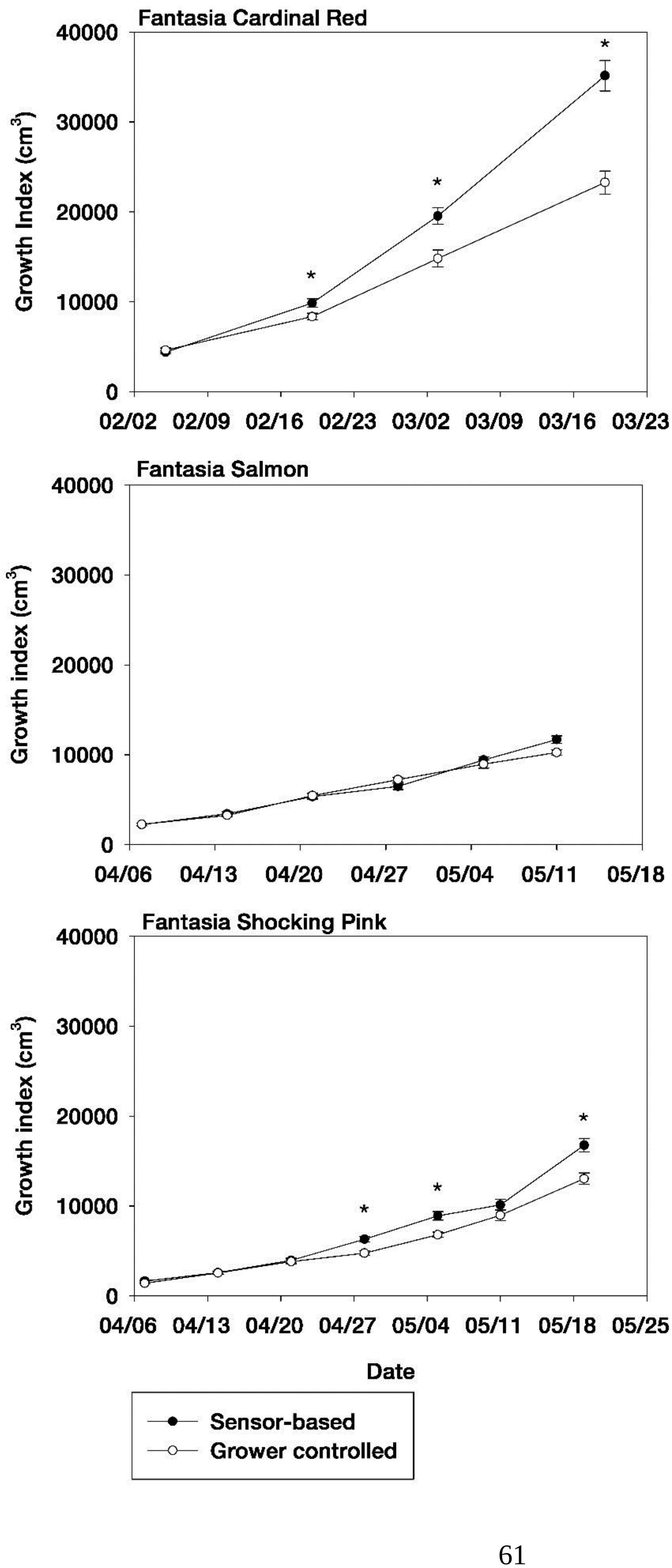


Figure 3.1.

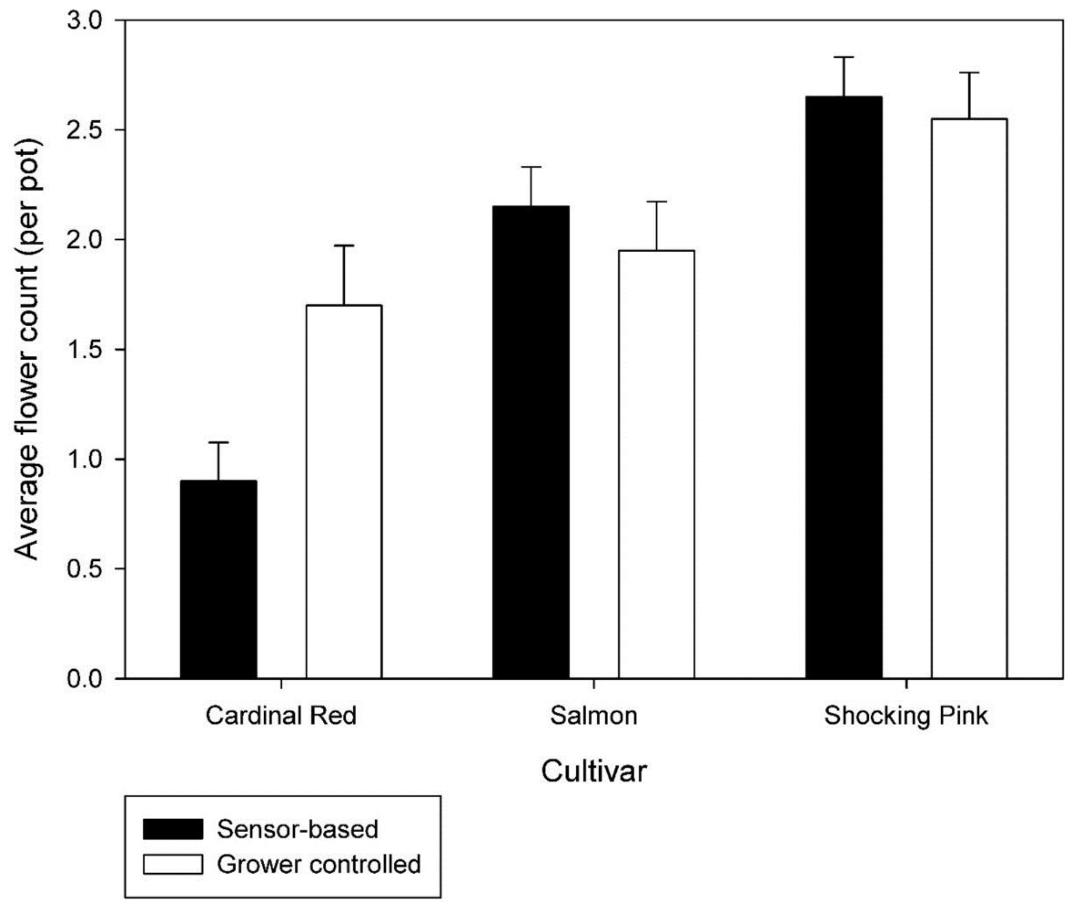
Comparative cumulative irrigation water use in the production of three cultivars of *Pelargonium* × *hortorum* by a soil moisture sensor-based automated irrigation system and traditional manual irrigation. Cultivars ‘Fantasia Cardinal Red’ and ‘Fantasia Shocking Pink’ were grown over 42 d periods while ‘Fantasia Salmon’ was produced over a 34 d period. Dotted vertical lines represent irrigation thresholds established by the grower.



Fantasia Cardinal Red
Growth Index (cm3)
40000
30000
20000
10000
0
02/02 02/09 02/16 02/23 03/02 03/09 03/16 03/23
Fantasia Salmon
Growth index (cm3)
40000
30000
20000
10000
0
04/06 04/13 04/20 04/27 05/04 05/11 05/18
Fantasia Shocking Pink
Growth index (cm3)
40000
30000
20000
10000
0
04/06 04/13 04/20 04/27 05/04 05/11 05/18 05/25
Date
Sensor-based
Grower controlled

Figure 3.2.

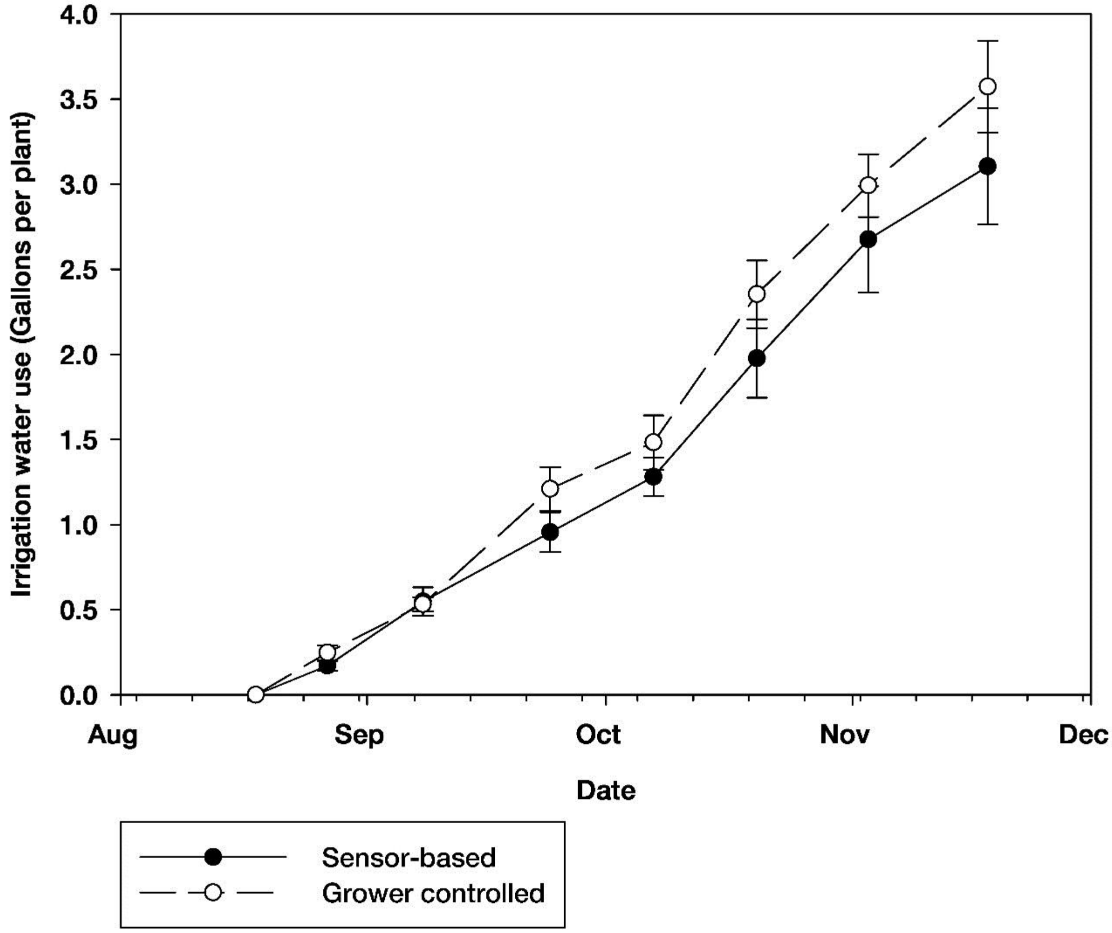
Average growth indexes of *Pelargonium* × *hortorum* cultivars 'Fantasia Cardinal Red', 'Fantasia Salmon', and 'Fantasia Shocking Pink'. Cultivars 'Fantasia Cardinal Red' and 'Fantasia Shocking Pink' were grown over 42 d periods while 'Fantasia Salmon' was produced over a 34 d period.



Average flower count (per pot)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Cardinal Red
Salmon
Shocking Pink
Cultivar
Sensor-based
Grower controlled

Figure 3.3.

Average number of flowers per pot for three geranium species grown with a soil moisture sensor-based automated irrigation system as compared to grower managed irrigation. Cultivars ‘Fantasia Cardinal Red’ and ‘Fantasia Shocking Pink’ were grown over 42 d periods while ‘Fantasia Salmon’ was produced over a 34 d period.



Irrigation water use (Gallons per plant)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Aug
Sep
Oct
Nov
Dec
Date
Sensor-based
Grower controlled

Figure 3.4.

Average cumulative irrigation water usage calculated on a per plant basis in the production of *Euphorbia pulcherrima* ‘Prestige Red’ and ‘Christmas Day Red’ by a soil moisture sensor-based automated irrigation system and grower managed irrigation.

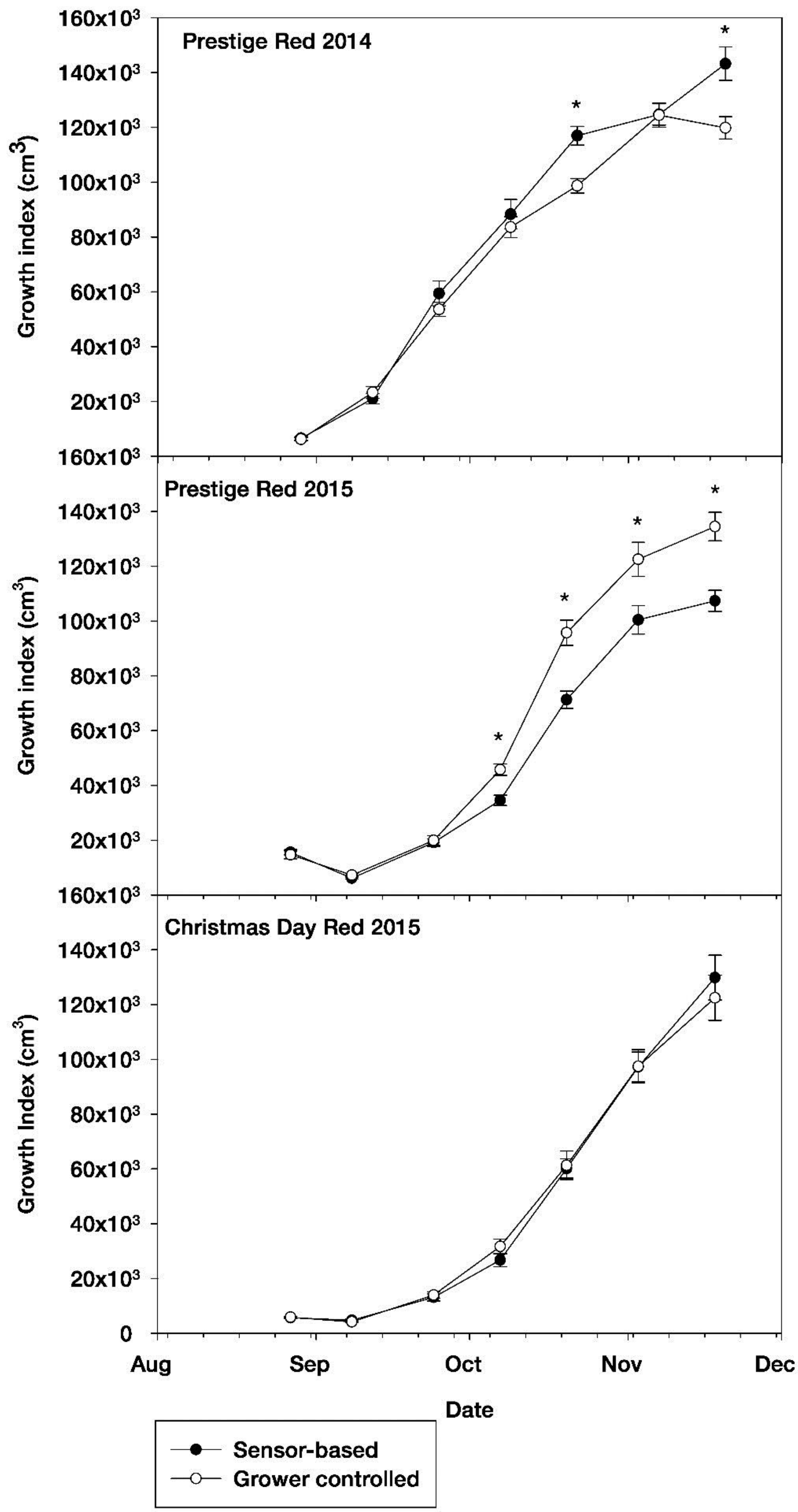

Prestige Red 2014
Prestige Red 2015
Christmas Day Red 2015
Growth index (cm3)
Growth Index (cm3)
160x103
140x103
120x103
100x103
80x103
60x103
40x103
20x103
0
Aug
Sep
Oct
Nov
Dec
Date
Sensor-based
Grower controlled

Figure 3.5.

Average growth indexes of *Euphorbia pulcherrima* ‘Prestige Red’ and ‘Christmas Day Red’ in 2014 and 2015 grown with a soil moisture sensor-based automated irrigation system and traditional section grower controlled irrigation. Growth indexes were calculated finding the product of the height of the canopy from the soil line, width of the canopy at its widest point and the width ninety degrees from that point.

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CHAPTER 4

IMPLEMENTATION OF SOIL MOISTURE SENSOR-BASED AUTOMATED IRRIGATION IN WOODY ORNAMENTAL PRODUCTION[1]

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Abstract

A soil moisture sensor-based automated irrigation system was trialed in a commercial woody ornamental nursery in both 2014 and 2015. Over the course of both years, use of the sensor-based system resulted in an approximate 50% reduction of irrigation water use when compared to grower managed irrigation. Equivalent or slightly reduced crop losses were noted when comparing sensor-based irrigation to grower managed irrigation in the production of *Pieris japonica*, *Hydrangea quercifolia*, and *Kalmia latifolia* in both 2014 and 2015. Similarly, in 2014 *Rhododendron catawbiense* had reduced mortality when comparing sensor-based irrigation to grower managed irrigation. However, in 2015 irrigation control with the sensor-based system resulted in significant (>50%) *Rhododendron* crop losses. High mortality is thought to be the result of canopy structure that obstructed irrigation water capture to a greater degree than the other three species. This effect combined with precision irrigation applications and the use of soil moisture readings averaged across all four species to establish irrigation set points resulted in persistent drought conditions in the *Rhododendron*. Soil moisture sensor-based automated irrigation can be an effective means of automating irrigation; however, support from extension specialists and industry representatives is highly desirable to minimize disruption during implementation.

Index words

Pieris Japonica D. Don ex G. Don 'Prelude', *Hydrangea quercifolia* W. Bartram 'Jet Stream', *Rhododendron catawbiense* Michx. 'Roseum Elegans', *Kalmia latifolia* L. 'Sarah', irrigation groupings, automation, canopy structure, irrigation capture, technology transfer, outreach, education, precision irrigation

Species used in this study

Japanese andromeda 'Prelude' (*Pieris Japonica* D. Don ex G. Don); Oakleaf hydrangea 'Jet Stream' (*Hydrangea quercifolia* W. Bartram); Rhododendron 'Roseum Elegans' (*Rhododendron catawbiense* Michx.); Mountain laurel 'Sarah' (*Kalmia latifolia* L.)

Significance to the Horticulture Industry

The use of soil moisture sensors to automate irrigation in commercial nurseries and greenhouses has proven an effective means of reducing water use. A number of additional benefits have been observed with the use of these systems including: reduced losses from disease, faster crop cycling, reductions in pumping and labor costs, and reductions in chemical applications. Adoption of novel technology is not without risk and the decision whether or not to adopt a new technology by individual operations is a balance between the perceived risks, benefits and opportunity costs. While soil moisture sensing is an effective way to automate irrigation, it is important that growers have access to extension or industry experts to assist with the transfer of technology. Proper training of all employees and ongoing collaboration with extension experts can ensure effective use and rapid implementation of these types of systems without significant disruption to operations.

Introduction

Innovations in technology have made capacitance sensors, used for monitoring soil moisture, more reliable and inexpensive (VAN IERSEL et al., 2013). As a result, capacitance-based soil moisture sensors have been used to automate irrigation in research and in commercial settings growing both herbaceous annual (ALEM et al., 2015; VAN IERSEL et al., 2010) and nursery crops (CHAPPELL et al., 2013). A transdisciplinary team of universities and commercial partners have developed and trialed a robust soil moisture sensor-based automated irrigation system that will soon be commercially available for use in greenhouse and nursery production. As part of this effort, sensor-based irrigation systems have been trialed in Tennessee (BELAYNEH et al., 2013), Maryland (KIM et al., 2014), Ohio (BARNARD AND BAUERLE, 2015), and Georgia (CHAPPELL et al., 2013). These studies have reported a number of production and environmental benefits when comparing sensor-based automated irrigation to that of traditional irrigation management. Some of the benefits observed have been reductions in: water usage, losses due to diseases, chemical control applications, and irrigation costs, as well as a shortening of crop cycling times (BELAYNEH et al., 2013; CHAPPELL et al., 2012; LICHTENBERG et al., 2013). Economic analysis of sensor-based automated irrigation by Lichtenberg et al. (2013) reported greater upfront costs to establish these types of systems, but a 1.5-fold increase in annualized nursery profits when compared to standard irrigation practices. Savings in labor, irrigation volume, fungicides, fertilizers, lowered energy costs from pumping, and accelerated crop production times all contributed to making sensor- based automated irrigation more profitable than conventional irrigation management. In addition, increased general automation in horticultural operations has been reported to increase efficiency of labor allocation, improve production quality, improve professional esteem, and reduce production costs and hazardous working conditions (LING, 1994; POSADAS et al., 2008). Successful large scale adoption of soil moisture sensor-based automated irrigation by the horticulture industry would mean increased economic competitiveness for commercial producers while improving environmental sustainability (MAJSZTRIK et al., 2013).

In previous studies trialing sensor-based irrigation in commercial settings, researchers have largely controlled irrigation set points throughout the trail. These set points were established by the researchers with minimal grower input, established best management practices for nursery production, and analysis of growing substrate physical properties (CHAPPELL, Personal communication, 2016). In this study, we sought to turn over control of the soil moisture sensor-based automated irrigation system to the grower and observe behaviors regarding irrigation management and adoption of new technology. In addition, we wanted to determine whether similar benefits, observed in previous studies, would be seen when the growers, rather than researchers, were managing the system. We hypothesized that many of the benefits that have been previously reported would be observed in this study and that the grower would successfully adopt the technology.

Materials and Methods

Commercial partner and plant material.

A medium sized commercial woody ornamental nursery was selected to participate in this study based on willingness to adopt new technology, openness to allowing research to be conducted on site, and expressed interested in automated irrigation technology. The nursery is located is located in Hart county, Georgia in USDA hardiness zone 8A, with approximately 5 hectares available for production. On-farm trials were conducted on a 4460 m^2 pad which was seasonally covered with 60% shade cloth. Plants were grown in trade size #3 (9.78L) black plastic containers that were filled with 100% composted pine bark (SunGro Horticulture, Agawam, MA), amended with Micromax micronutrient mix (Scotts, Marysville, OH) and pH adjusted for each crop using dolomitic limestone. Trials utilized four different species of woody ornamental plants including: *Hydrangea quercifolia* 'Jet Stream', *Pieris Japonica* 'Prelude', *Rhododendron catawbiense* 'Roseum Elegans', and *Kalmia latifolia* 'Sarah'. These species were selected for similar water use requirements based on the grower's experience.

Irrigation control and environmental data.

A soil moisture sensor-based automated irrigation system (Decagon Devices, Pullman, WA), and similar to systems used to control irrigation in three container nurseries by Chappell et al. (2013) was used in these trials. Five soil moisture sensors (GS3, Decagon Devices, Pullman WA) were distributed throughout the sampling block with two sensors placed in the *Rhododendron* crop and one sensor placed in each of the three remaining species. Sensors were inserted with the metal prongs inserted horizontally through the side of the pot and into the media. Soil moisture sensors generated volumetric water content (θ), bulk electrical conductivity, and soil temperature readings. Sensors were connected to a wireless node (nR5-DC, Decagon Devices) that could control irrigation through a 12 – V DC latching solenoid valve (075-DV, 3 in., Rain Bird, Azusa, CA) Sensor readings were taken every minute and the average was transmitted to a centrally located computer base station every 20 min using a using a 900-MHz radio (XSC; Digi, Minnetonka, MN). The base station utilized a web-based graphical user interface (GUI), referred to as Sensorweb, developed by Carnegie-Melon University (KOHANBASH et al., 2013). This GUI had a website format which would be intuitive to most users and allowed for graphical display of data collection, establishment of irrigation set points, and extensive customization of irrigation scheduling. Irrigation set points were established after an initial monitoring period of 7 d, in which average θ were observed. Based on the observed θ sensor readings, recommendations from UGA extension specialists, and experience and intuition with the crop, initial set points were established by the grower. When θ values fell below the user defined set point an irrigation event lasting 300 s was triggered.

Environmental conditions in the experimental area and water usage by the two irrigation treatments were recorded using two additional nodes. Solar radiation was monitored with a PYR solar radiation sensor (Decagon Devices), wind direction and speed was monitored using a Davis cup anemometer (Decagon Devices), and temperature and relative humidity were monitored using an EHT sensor (Decagon Devices). Rainfall and overhead irrigation were monitored using a ECRN-50 tipping rain gauge (Decagon

Devices). Irrigation water use was monitored using two Netafim IRT 3 inch flow meters (36IRT3F-MPE, Netafim, Fresno, CA).

Data collection.

Growth indexes were calculated by taking the product of the canopy height from the media surface, the width of the widest point of the canopy, and the width of the canopy 90° from that measure. Plant quality was evaluated on a standardized 1-10 scale that was established at each sampling date for each species, with 1 being a completely dead plant and 10 being a plant with vigorous growth, good foliar tone, and a symmetrical habit. Direct measures of electrical conductivity within the rooting substrate were taken utilizing a HH2 meter with attached WET-2 Sensor (Delta-T Devices Ltd., Cambridge, UK). Flow meter readings were taken at every sampling period and also continuously logged on the computer throughout the trial. Plant mortality was noted at every sampling date and dead plants removed from the experimental block at that time. Semi-structured interviews were conducted with the section grower and head grower about the performance of the sensor-based irrigation system at each sampling period. Grower attitudes and perspectives on the system were documented throughout the trial and a formal interview was conducted at the end of the 2-year period in which the owner was asked for his opinions and feedback on the system.

Experimental design and statistics.

Side by side comparisons of sensor-based irrigation and grower managed irrigation were conducted in 2014 and repeated in 2015. Irrigation zones were established, each consisting of five lines of rotating impact sprinklers (1/2 inch, 2045-PJ, Rain Bird) on 1.2 m risers spaced 3 m apart. Sampling blocks, made up of 125 plants per species (500 plants per irrigation treatment), were established within each irrigation zone and surrounded by a buffer crop. Trails were initiated once the sampling blocks were established and the sensor-based irrigation system was turned on. In 2014 the trial was initiated on 25 Aug. 2014 and continued through 14 Nov. 2014, while in 2015 the trial began on 23 April 2015 and ran until 5 Nov. 2015. Data was collected on a monthly basis in 2014 and every three weeks in 2015. Growth indexes, plant quality rantings and electrical conductivity readings were analyzed using multivariate analysis of variance (MANOVA) over the course of each trial. Experimental set up was such that a single flow meter was used to track water usage in each experimental treatment in both years. Direct comparisons were made of total water usage and mortality numbers over the course of both trials.

Results and discussion

Irrigation water use was cut by approximately 50% in both 2014 and 2015 when comparing sensor-based to grower controlled irrigation (Fig. 3.1). This resulted in a savings of 569,900 gals of irrigation water in 2014 and 2,215,100 gals in 2015, roughly the annual water usage of 19 family homes in the US (EPA, 2016). Comparative *Pieris japonica* growth indexes were observed between irrigation treatments in both 2014 and 2015 (Fig. 3.2). In 2014 2% *Pieris japonica* mortality was noted in both irrigation treatments. In 2015 the grower irrigated *Pieris japonia* again experienced a 2% mortality rate compared to 1% in the sensor-based irrigation section. *Hydrangea quercifolia* had comparative growth indexes in 2014 during which time the grower irrigated section had a higher mortality rate (18%) compared to the sensor-based section (4%). Declining growth indexes were observed in 2014 as the plants began to harden off and defoliate for winter. In 2015 a late frost compromised the quality and vitality of all of the *Hydrangea quercifolia* used in the study. The decision was made by the nursery owner to discard the entirety of the crop in late August as it was not judged to be salvageable for market. Before the crop was discarded in 2015 the grower controlled section produced *Hydrangeas* with larger growth indexes ($p = 0.03$) averaging 106,720 ± 10,661 cm^3 (±SE) while *Hydrangeas* produced with sensor-based irrigation averaged 69,926 ± 8,623 cm^3 (±SE). *Hydrangea* losses before discarding of the crop in 2015 were greater in the grower section with 12% mortality observed compared to 10% mortality in the sensor-based section. Growth indexes of *Kalmia latifolia* in 2014 were greater in plants irrigated with sensor-based irrigation ($p < 0.01$). However, this observation is hypothesized to be an artifact of selection from the grower irrigated section to accommodate end of year sales at the nursery. *Kalmia latifolia* grown in 2015 with sensor-based irrigation had larger growth indexes ($p = 0.04$) averaging 191,994 ± 7,414 cm^3 (±SE) by the end of the trial while grower irrigated plants averaged 168,554 ± 9,285 cm^3 (±SE). *Kalmia latifolia* mortality was less than 1% in 2014 in both irrigation treatments. Mortality was again less than 1% in the sensor controlled irrigation section in 2015, however the grower irrigated *Kalmia* experienced an 8% crop loss. In 2014 *Rhododendron catawbiense* had equivalent growth indexes and higher mortality in the grower section (3%) when compared to the sensor-based section (0%). However, in 2015 greater than 50% mortality was noted in the sensor-based irrigation by the end of the production cycle (Fig. 3.2). High mortality in the crop was thought to be the result of persistent drought stress that was observed in the *Rhododendron* irrigated with sensor-based irrigation throughout most of the 2015 trial. Water capture from overhead irrigation application is inversely related to leaf area and canopy density (Beeson and Knox, 1991; Beeson and Yeager, 2003). We hypothesize that while observationally both the *Pieris* and *Kalmia* had high canopy densities, we believe leaf orientation may have channeled water towards the root ball creating conditions of greater irrigation water capture. This same channeling quality was also observed in the leaf orientation of the *Hydrangea,* which also appeared to have the greatest leaf area but the lowest canopy density. In contrast, the *Rhododendron*, based on casual observation combined relatively large leaf areas with high canopy densities that extended beyond the diameter of the container and leaf orientation that tended to shed water away from the root ball. It is hypothesized that this canopy structure reduced the amount of water reaching the roots. We hypothesize that while canopy structure helped create conditions that reduced irrigation water capture within the *Rhododendron*, the use of averaged soil moisture sensor readings to trigger irrigation allowed for drought conditions to persist (Fig. 3.3). Soil moisture readings for August of 2015 averaged 48.84 ± 0.26 $m^3 \cdot m^{-3}$ (±SE) for *Pieris*, 42.08 ± 0.08 $m^3 \cdot m^{-3}$ for *Kalmia*, and 28.18 ± 0.17 $m^3 \cdot m^{-3}$ for *Hydrangea*. Comparatively sensor readings averaged 17.47 ± 0.05 and 15.99 ± 0.04 $m^3 \cdot m^{-3}$ for the two sensors monitoring the *Rhododendron* crop. These values suggest *Pieris*, *Kalmia*, and *Hydrangea* were maintained at adequate or luxury soil moisture levels while *Rhododendron* were under persistent drought stress. In addition, *Rhododendron,* with the largest canopy volumes (Fig. 3.2), are thought to have had higher transpiration rates and daily water use requirements than the other three species.

We hypothesize that these combined factors created drought conditions that contributed to the higher mortality numbers seen in 2015. Fernandez et al. (2009) recommend grouping nursery crop species by their daily water use requirements for maximization of water use efficiency while minimizing overwatering. Grower managed irrigation at this nursery had previously allowed for grouping of the four species used in the study and it is hypothesized that plants were able to adapt to high irrigation volumes. Greater precision irrigation applications afforded by the sensor-based irrigation system may mean reworking traditional irrigation groupings employed at the nursery and take greater account of daily water use and water use efficiencies.

Grower adoption

Ownership of the nursery was transferred from one generation to the next within the same family in August of 2014. Experiments continued through the transfer with the consent of the new owner. However, the challenges of new ownership meant that there was less interaction with extension efforts and diverted interest in the trials by upper management at the nursery. High mortality numbers in the *Rhododendron* crop produced with sensor-based irrigation generated concern from the new owner and head grower about the ability of the system to meet plant water needs and flush accumulated salts from the media. No significant differences were noted in electrical conductivity readings between sensor-based and grower irrigated *Rhododendron* in 2014 ($p = 0.84$) though they were significant in 2015 ($p < 0.01$) (Fig. 3.4). However, readings in both irrigation treatments in 2015 were not observed above 2.0 mS cm^{-1}, levels not typically sufficient to generate crop damage (FORNES et al., 2007). While the system did face challenges meeting the water needs of the *Rhododendron* in 2015, we believe this could have been avoided with greater understanding, experience, and involvement of the grower or section grower with the system. A number of preventative measures could have been undertaken such as re-positioning the sensors, increasing irrigation set points, or sending manual irrigation commands to address the disparities in water usage. Additional challenges to grower adoption that occurred over the course of the study involved the dynamic of irrigation management that evolved as a result of access and understanding of system by nursery staff. The head grower and owner received training on how to make irrigation changes with the sensor-based system and had access to the computer station in the central office. Experimental plots however were managed primarily by the section grower, who did not have training or access to the Sensorweb software, and could not make changes to the system. Any necessary changes to irrigation set points were made by the researcher after semi-structured interviews with the section grower and head grower about the performance of sensor-based irrigation system. However, this dynamic limited the functionality of the system and ultimately may have hindered adoption of the technology. Ultimately this arrangement was closer to those employed in previous studies in which researchers controlled irrigation set points. This also may have contributed to the mortality observed in the *Rhododendron* in 2015 as the person who had the greatest interaction with the experimental plot also had the least control over the system.

Greater education and experience have been shown to increase the likelihood of early adoption. Scale of production also has an impact, with greater opportunity costs associated with larger scales of production (WOZNIAK, 1987). Interviews with the owner and head grower suggest that they were unlikely to adopt technology during the earliest stages of diffusion, and in many cases preferred to avoid automation in general, as it in their view promoted neglect of routine maintenance. Growers also commented that reductions in irrigation water usage were not a management priority given the accessibility and low cost of water regionally. Interest in the system was initiated with the previous owner and related to a lack of well-trained irrigators at the facility and the potential to reduce crop losses. The transfer of ownership early in the study reduced the institutional experience and introduced a great deal of volatility within the organization. Transfer of ownership also limited availability and access to upper management which in turn limited education and outreach opportunities to facilitate technology transfer. Shortfalls in technology transfer, coupled with initial challenges associated with inappropriate irrigation grouping, increased resistance to early adoption. This study demonstrates the need of sustained grower interest and education to overcome the perceived risks of new technology and ensure its successful adoption. Equally important is ensuring proper access and training are provided ultimate end user of the system and consideration is given to how institutional organization of labor management might impact the viability of implementation. Incentives to adopt precision irrigation systems may come in the future in the forms of greater regulation associated with water management or from environmental pressures in the form of drought. However, at present the reductions in irrigation water usage alone, coupled with the perceived risks of implementing precision irrigation through soil moisture sensing have limited adoption at this facility. Adoption of novel technology will ultimately depend on the individual institution and whether risks and costs associated with new technology out weight the perceived benefits.

Tables and Figures

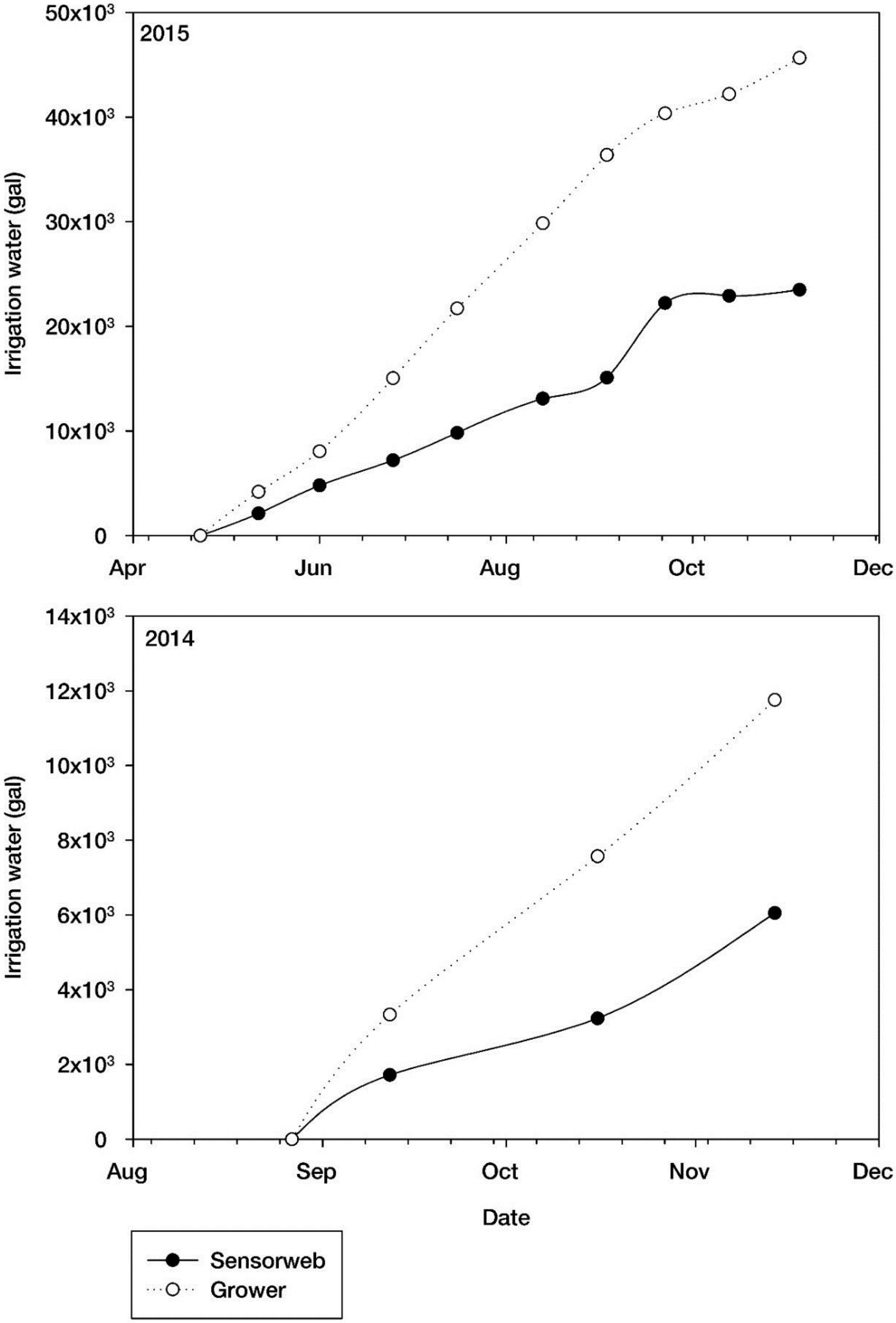

Figure 4.1.

Cumulative irrigation water usage in 2014 and 2015 for a soil moisture sensor-based automated irrigation system compared to grower managed irrigation. In 2014 trials were initiated on 25 - Aug - 2014 and continued through 14 – Nov. – 2014 when irrigation lines where drained for the winter. The following year trials were initiated on 23 - April – 2015 and completed on 11 – Nov. – 2015.

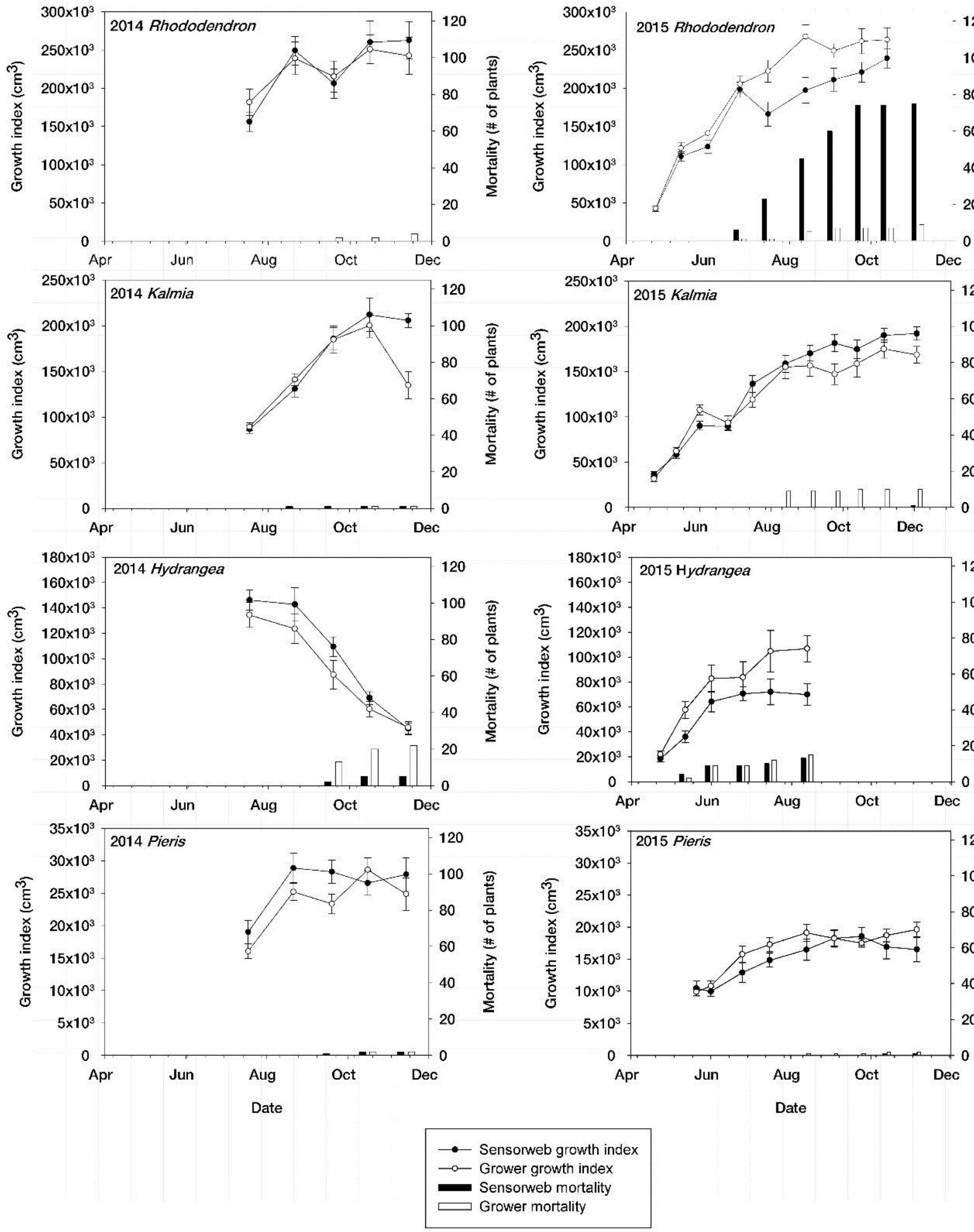
2014 Rhododendron
2015 Rhododendron
2014 Kalmia
2015 Kalmia
2014 Hydrangea
2015 Hydrangea
2014 Pieris
2015 Pieris
Growth index (cm3)
Mortality (# of plants)
Date
Apr
Jun
Aug
Oct
Dec
Sensorweb growth index
Grower growth index
Sensorweb mortality
Grower mortality

Figure 4.2.

Comparative growth indexes and mortality rates for four crops produced with grower managed irrigation and a soil moisture sensor-based automated irrigation system. Averaged distributed soil moisture readings were used to trigger irrigation events with the sensor-based irrigation system.

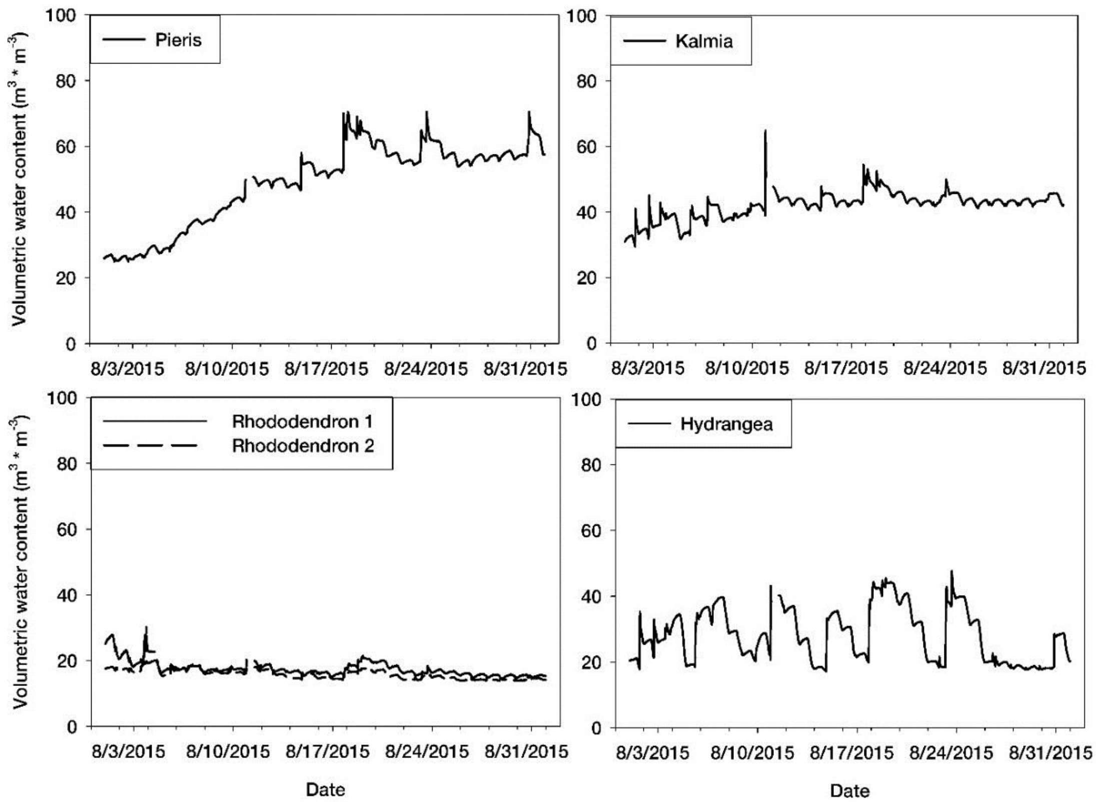
Pieris
Kalmia
Rhododendron 1
Rhododendron 2
Hydrangea
Volumetric water content (m^3 * m^{-3})
100
80
60
40
20
0
8/3/2015
8/10/2015
8/17/2015
8/24/2015
8/31/2015
Date

Figure 4.3.

Select soil moisture readings from a soil moisture sensor-based automated irrigation system. High mortality numbers in the Rhododendron were noted in the sensor-based irrigation block. It is thought that the Rhododendron were under persistent drought stress due to inappropriate irrigation groupings with greater precision irrigation application employed by the sensor-based system. Canopy structure of the Rhododendron was such that it shed irrigation water away from the root ball, while other species within the irrigation grouping had canopies which allowed for greater overhead irrigation water capture. Averaged irrigation thresholds were used to trigger irrigation events, which allowed for the *Rhododendron* to be maintained under drought conditions while the other three species in the study were maintained at adequate or luxury water consumption irrigation application rates.

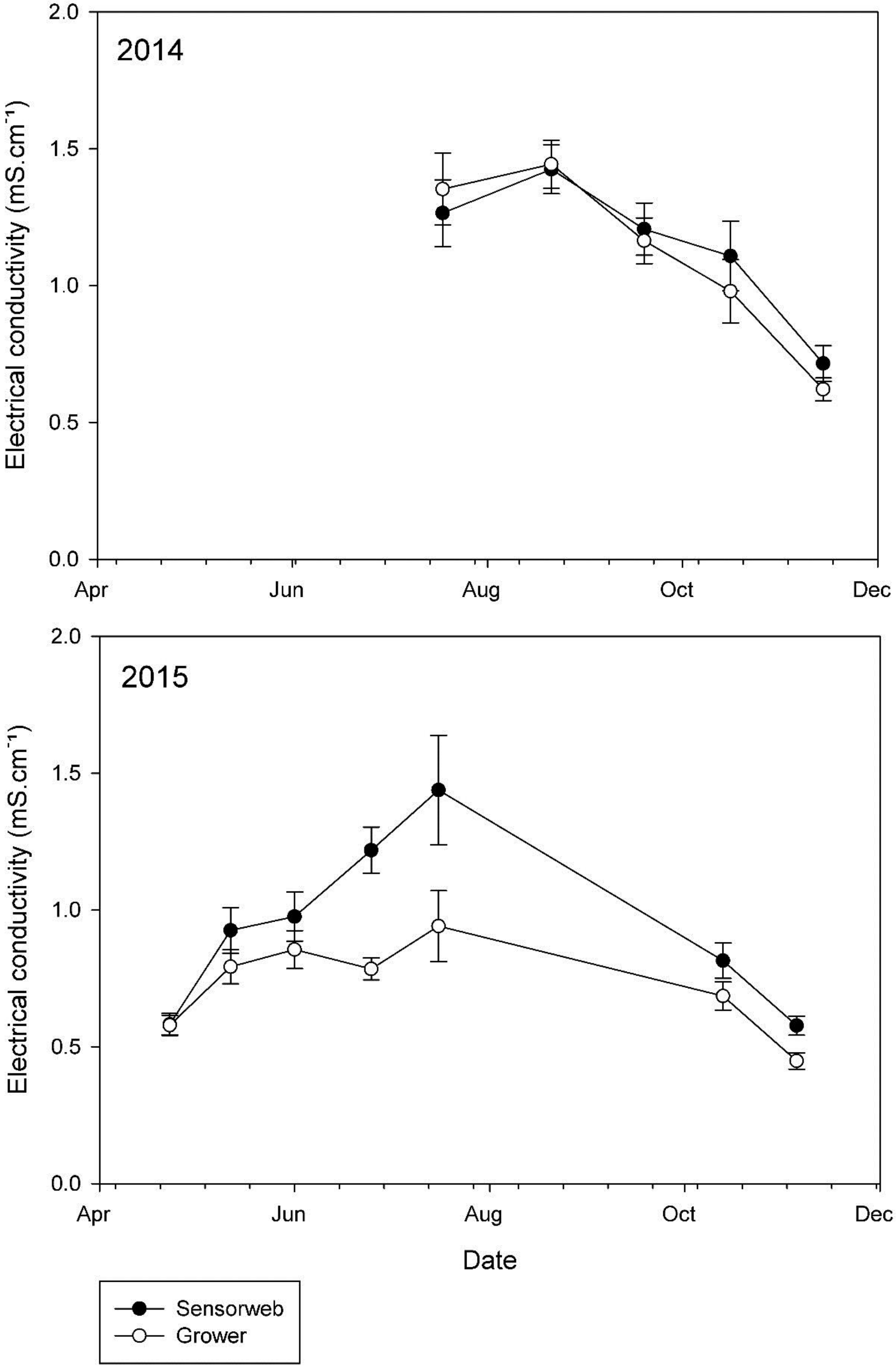
2014
2015
Electrical conductivity (mS.cm-1)
2.0
1.5
1.0
0.5
0.0
Apr
Jun
Aug
Oct
Dec
Date
Sensorweb
Grower

Figure 4.4. Discrete electrical conductivity readings using a HH2 WET2 meter from *Rhododendron catawbiense* ‘Roseum Elegans’ grown using a soil moisture sensor-based automated irrigation system and grower managed irrigation.

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CHAPTER 5

CONCLUSIONS

The use of soil moisture sensors is an effective means of automating irrigation in commercial production of both woody and herbaceous ornamental crops. Numerous studies have shown the capacity of the sensor-based irrigation to reduce the amount of water being applied in nursery settings with overhead irrigation. Similar findings were observed over the course of 2014 and 2015 in studies conducted at a woody ornamental nursery. However, this was in contrast with studies conducted at the commercial greenhouse grower, where it was noted that sensor-based irrigation did not reduce the amount of irrigation water used to produce herbaceous annual crops. Observations over the course of the study at commercial greenhouse suggest that additional water use was the result of a combination of historical grower production preferences and the need for greater education about how soil moisture systems operate. The grower however did find the system useful by allowing reallocation of labor away from irrigation management. The need for greater outreach and education was also evident at the woody ornamental nursery where *Rhododendron catawbiense* irrigated with the sensor-based system experienced significant losses in 2015. High mortality observed in the 2015 trial was thought to be the result of inappropriate irrigation groupings that were based on traditional irrigation management. Moving forward, re-structuring of these groups to take into greater consideration daily water use needs and overhead irrigation capture is necessary with the greater precision irrigation afforded by sensor-based irrigation.

Excluding the 2015 *Rhododendron,* both the nursery and greenhouse crops irrigated using sensor-based irrigation were of equivalent market size and quality to those grown with traditional grower managed irrigation. Previous studies have found a number of other benefits including reductions in: water usage, losses due to diseases, chemical control applications, and irrigation costs, as well as a shortening of crop cycling times. Based on our findings and observations in both the nursery and greenhouse, we feel that appropriate education on these new systems is vital in their adoption. Support from extension agents and industry professionals to educate growers and their staff can minimize disruption and risk when adopting this new technology.

The precision afforded by sensor-based automated irrigation may also allow for specific soil moisture contents to be maintained which would inhibit root pathogen establishment while still allowing for plant growth and development. Data from our experiments looking at the interactions of soil moisture and *Pythium aphanidermatum* infection in petunia noted a reduction in infection rates at the lowest irrigation threshold. However, the reductions in infection rates did not correspond to reductions in mortality or marketability in the infected treatments. Plant growth data from the driest treatments was not statically significant from wetter treatments trialed in the study, suggesting they may still be viable for use in commercial production. Inoculation methods for the study most likely allowed for the establishment of the pathogen and primary infection across all irrigation treatments. It is hypothesized that the primary infection accounted for the mortality and declines in marketability across all treatments even though fewer infected roots were found in petunia grown in the driest treatment. Future studies could explore the use of sensor-based irrigation to maintain specific soil moisture contents, that allow for comparable plant growth while inhibiting the establishment of plant pathogens.

The use of sensor-based irrigation has already demonstrated many economically and environmentally advantageous benefits for growers. Studies conducted over the course of 2014 and 2015 show the potential for these types of systems to not only reduce disease losses in production but also free up labor and reduce water usage. Adoption of new technology is not without challenges and risks and growers will need to work to assure they have the appropriate training and understanding of any new technology they may take on.