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 ornamental nursery over the 2014-2015 growing seasons. In both years, use of the sensor-based system resulted in an approximate 50% reduction in irrigation application (volume) when compared to grower-managed irrigation. No differences in growth and equivalent or slightly reduced crop losses were noted when comparing the sensor-based irrigation system to grower-managed irrigation in production of *Pieris japonica*, *Hydrangea quercifolia*, and *Kalmia latifolia*. In 2014, *Rhododendron catawbiense* had equivalent canopy size and 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* losses. High mortality was thought to have resulted from use of averaged (across crop species) soil moisture readings to establish irrigation set points. Canopy structure of *Rhododendron* obstructed water capture to a greater degree than the other three species due to canopy architecture. This effect, combined with precision irrigation applications, resulted in persistent drought conditions within the *Rhododendron* block. Soil moisture sensor-based automated irrigation can be an effective means of automating irrigation. Support from crop consultants is highly desirable to minimize disruption and maximize adoption 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 in both highly managed research studies and adoption studies at commercial firms. 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 to adopt technology by individual operations is a balance among 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 university extension/outreach or industry experts to assist with transfer of technology and foster successful adoption. Proper training of employees at appropriate management levels and ongoing collaboration with consultants 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 in the last decade (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 other nursery crops (Chappell et al. 2013). A transdisciplinary team of land-grant universities and commercial partners have developed and trialed a robust soil moisture sensor-based automated irrigation system that has been commercialized (Mayim Inc., Pittsburgh, PA). 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 (timer-based) irrigation management. Some of the observed benefits have been reductions in water usage, losses due to disease, 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 150% increase in annualized nursery profits when compared to standard irrigation practices. Savings in labor, irrigation volume, fungicides,

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fertilizers, lowered energy costs from pumping, and accelerated crop production times compared to conventional irrigation management have been reported. In addition, increased automation in horticultural operations has been documented 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, Wheeler et al. 2018). Successful large-scale adoption of soil moisture sensor-based automated irrigation by the horticulture industry could facilitate increased economic competitiveness for commercial producers while improving environmental sustainability (Majsztrik et al. 2013).

The majority of previous studies at commercial nursery crop cooperators, trialing sensor-based irrigation in commercial settings, have relied upon researchers controlling the computer system and determining irrigation set points (Chappell et al. 2013). These set points were based on recommended best management practices for nursery production with minimal grower input. 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 sought to determine whether benefits observed in previous studies would occur 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 species. Transplant Nursery (Lavonia, GA) was selected to participate in this study based on their willingness to adopt new technology, openness to allowing research to be conducted on site, and expressed interested in automated irrigation technology. Transplant Nursery is located is located at 34°26′33.9″N by 83°04′23.6″W in USDA hardiness zone 8A with approximately 5 hectares (12.4 acres) available for production. On-farm trials were conducted on a 4,460 m^2 (48,000 ft^2) gravel pad covered with black landscape fabric that was seasonally (May- October) covered with 60% shade cloth. Plants were grown in trade size #3 (9.78 L) black plastic containers (Nursery Supply Inc., Chambersburg, PA) that were filled with 100% composted 1 cm (3/8") (fine size) pine bark (SunGro Horticulture, Agawam, MA), amended with 1.2 kg·yard^{-3} (2 lb·yard^{-3}) Micromax micronutrient mix (Scotts, Marysville, OH) and pH adjusted to 5.2 using dolomitic limestone. Trials utilized four species of woody ornamental plants: *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 owner's (at the onset of the study) experience.

Irrigation control and environmental data. A soil moisture sensor-based automated irrigation system similar to systems used to control irrigation in three container nurseries by Chappell et al. (2013) and a commercial greenhouse (Wheeler et al. 2018) was used in trials conducted at Transplant Nursery. 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 taxa (*Pieris*, *Kalmia*, and *Hydrangea*). Sensors were inserted into the middle of the pot (approximately 10 cm (3.9 in) below the rim) with the metal prongs inserted horizontally through the sidewall of the container into the substrate. Sensors generated volumetric water content (θ) using a custom calibration determined at the UGA Horticulture Physiology Laboratory ($\theta = 0.1869 \times \ln(x) - 0.1166$) for the substrate used at Transplant Nursery. 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) developed by Carnegie-Melon University (Kohanbash et al. 2013). This GUI had a website format that was deemed intuitive to 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. Initial θ set points were selected by the owner and head grower based on the observed θ sensor readings, recommendations from UGA extension specialists, and the owner's intuition with the crop. When θ values fell below the user defined set point, an irrigation event lasting 300 s would be triggered. After a triggered irrigation event, the computer would then recheck θ and trigger an additional irrigation event if θ values were still below irrigation thresholds. After the initial seven-day consultation with extension specialists on crop water status and irrigation thresholds, control of the system was turned over to nursery staff, unless staff requested assistance from researchers.

Environmental conditions in the experimental area and water use by the two irrigation treatments were recorded using two additional nodes (nR5-DC, Decagon Devices). Solar radiation was monitored with a PYR solar radiation sensor (Decagon Devices), wind direction and speed were 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 an ECRN-50 tipping rain gauge (Decagon Devices). Irrigation water use was monitored using two Netafim IRT flow meters (36IRT3F-MPE, Netafim, Fresno, CA).

Data collection. Data collection began midway through the growing season in 2014 and at the start of the growing season in 2015. Once plants were potted and placed on the gravel production pad data was collected on a monthly interval in 2014 and shortened to a three-week interval in 2015. In 2015, the *Hydrangea* were terminated early because of a late frost that was judged to compromise marketability. Growth indices were calculated from 25 randomly selected plants per block by averaging measures of 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 ((Ht+W1+W2)/3). Direct stick 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) calibrated to the bark substrate used by the grower. Flow meter readings were taken at every sampling period and also continuously logged by the computer throughout the trial. Plant mortality was recorded 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 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 two-year study, whereby the owner was asked for opinions and feedback on the system.

Experimental design and statistics. Side by side comparisons of sensor-based irrigation system and grower-managed irrigation were conducted in 2014 and repeated in 2015. Irrigation for both treatments consisted of five lines of rotating impact sprinklers (2045-PJ, Rain Bird, Azusa, CA) on 1.2 m (3.9 ft) risers spaced 3 m (9.8 ft) apart. Sampling blocks within each irrigation management zone consisted of 125 plants per species (500 plants per irrigation treatment) and were surrounded by a buffer crop to mitigate edge effects. Trials began once the sampling blocks were established and the sensor-based system was initiated. In 2014, the trial was initiated on August 25, 2014 and continued through November 14, 2014, while in 2015 the trial began on April 23, 2015 and ran until November 5, 2015. Growth indices, plant quality ratings and electrical conductivity readings were analyzed using multivariate analysis of variance (MANOVA) over the course of each trial. Experimental setup 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 reduced by approximately 50% in both 2014 and 2015 when comparing sensor-based to grower-controlled irrigation (Fig. 1). On average, the sensor-based system used 29,004 L per d (7,662 gal per d) in 2014 and 45,387 L per d (11,990 gal per d) in 2015. In contrast the grower-controlled system used an average of 56,312 L per d (14,876 gal per d) in 2014 and 88,166 L per d (23,291 gal per d) in 2015. This resulted in a savings of 2,157,306 L (569,900 gal) or approximately 4,850 L per m^2 (119 gal per ft^2) of irrigation water over approximately 2.5 months in 2014 and 8,385,065 L (2,215,100 gals) or approximately 18,740 L per m^2 (460 gal per ft^2) over approximately 6.5 months in 2015. These savings are roughly equivalent to the cumulative annual water usage of

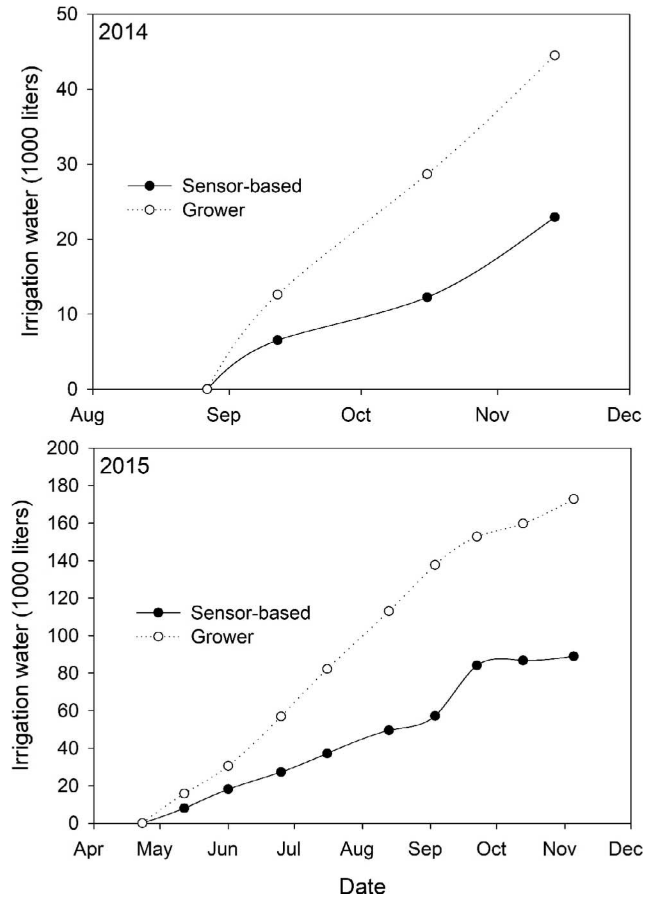

Fig. 1. Cumulative irrigation water usage in 2014 and 2015 for a soil moisture sensor-based automated irrigation system compared to grower-managed irrigation in container production. In 2014 trials were initiated on August 25, 2014 and continued through November 14, 2014 when irrigation lines where drained for the winter. The following year trials were initiated on April 23, 2015 and completed on November 11, 2015.

19 single family homes in the U.S. (EPA 2016). Comparative growth indices and plant quality ratings (data not shown) at $P \leq 0.05$ were observed in the *Pieris*, *Kalmia*, and *Hydrangea* between the sensor-based and grower-managed irrigation sections in both 2014 and 2015 (Fig. 2). In these same three species, direct comparisons of plant mortality resulted in equivalent or slightly reduced losses in sensor-based irrigated crops when compared to those produced under grower-managed irrigation. In 2014, similar trends were seen in *Rhododendron* grown with the sensor-based system, which had slightly lower comparative mortality and equivalent average growth indices and plant quality ratings to those produced by the grower. However, in 2015 greater than 50% mortality was noted in *Rhododendron* produced with the sensor-based system by the end of the production cycle (Fig. 2). Growth indexes of plants grown with the sensor-based system dipped slightly mid-season, because plants which had begun to die back were still included in the index. Sensor-based growth indexes recovered by the end of the season as dead plants were rogued from the block and the index reflected a subsample of the remaining plants. High mortality in the crop

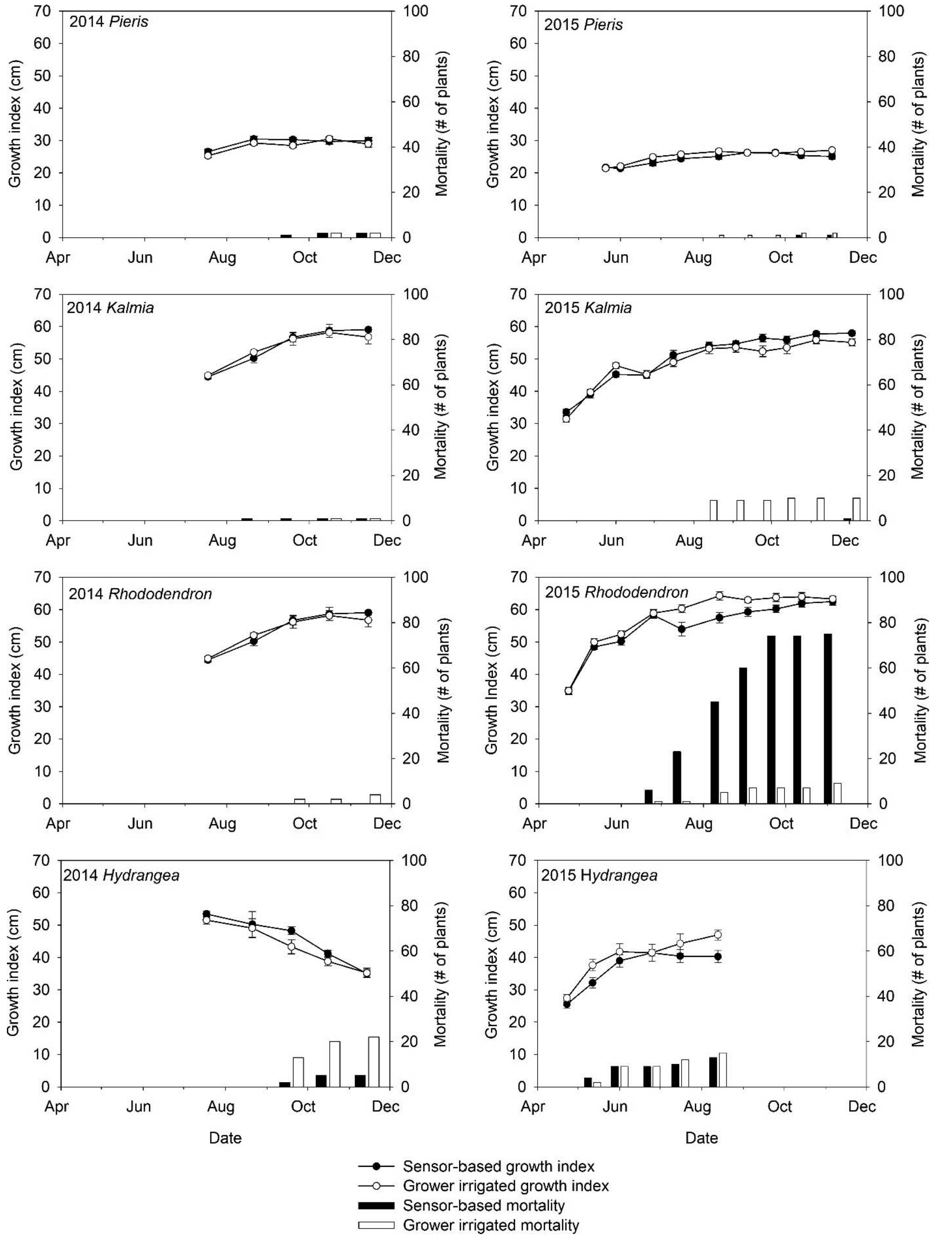

Fig. 2. Comparative growth indices and mortality rates for four crops produced with grower-managed irrigation and a soil moisture sensor-based automated irrigation system in container production. Growth indices were calculated by averaging measures of canopy height from the media surface, the width of the widest point of the canopy, and the width of the canopy 90° from that measure. Measurements were randomly taken from twenty-five plants out of each species block. Averaged distributed soil moisture readings were used to trigger irrigation events with the sensor-based system.

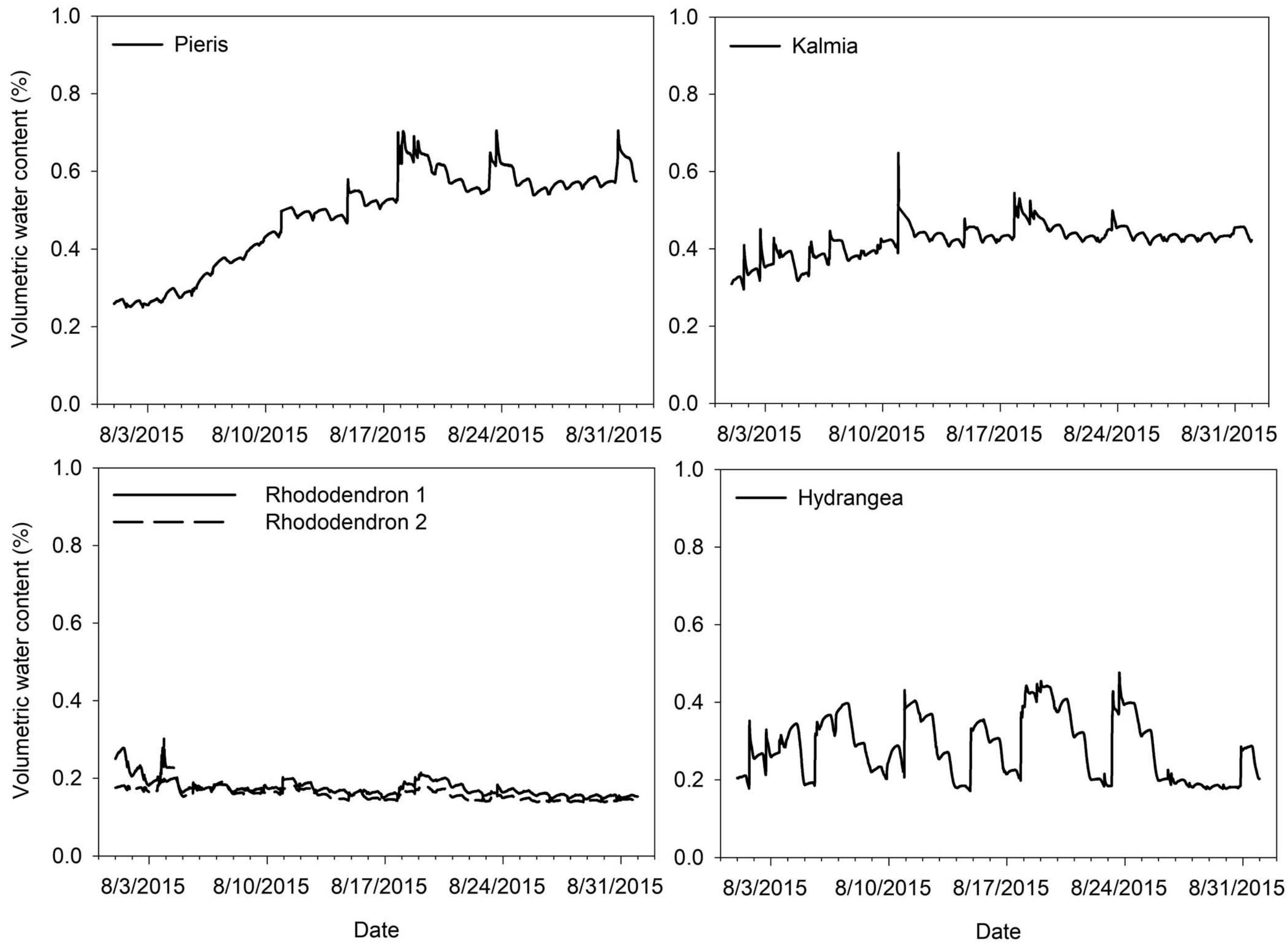

Fig. 3. Select soil moisture readings from a soil moisture sensor-based automated irrigation system in container production. Averaged irrigation thresholds were used to trigger irrigation events with one sensor placed in the *Pieris*, *Kalmia*, and *Hydrangea* while two sensors were placed in the *Rhododendron*.

grown with the sensor-based system was thought to be the result of persistent drought stress throughout most of the 2015 trial, which was an abnormally hot and dry growing season. Water capture from overhead irrigation application is inversely related to leaf area and canopy density (Beeson and Knox 1991, Beeson and Yeager 2003). Both *Pieris* and *Kalmia* had high canopy densities, smaller leaf areas and leaf orientation that tended to channel water towards the root ball meant both crops had greater irrigation water capture. This same channeling quality was observed in the *Hydrangea* leaves, which had the greatest leaf area but lowest canopy density. In contrast the *Rhododendron* combined relatively large leaf areas with high canopy densities that extended beyond the diameter of the container. Leaf orientation was such that it shed water away from the root ball, reducing the amount of water reaching the roots. This was confirmed by visual observation of the growing medium and direct stick soil moisture measurements immediately after irrigation was completed. We noted that the VWC of randomly selected *Rhododendron* with direct stick measurements was approximately 20% and the rootball had surface level wetting but was dry to the touch below approximately 5 cm (2 in). This was in contrast to the *Kalmia,* which had similar growth indices but, due to the canopy density, leaf area and orientation, had well-watered root balls with VWC's around 40%. While canopy structure helped create conditions that reduced irrigation water capture within the *Rhododendron*, the use of averaged soil moisture sensor readings across all four crops to trigger irrigation allowed for drought conditions to persist (Fig. 3). The *Pieris*, *Kalmia*, and *Hydrangea* were consistently maintained at average or luxury soil moisture levels for the majority of the trial, skewing the average soil moisture readings, while *Rhododendron* did not receive adequate water. In addition, *Rhododendron* had large canopy volumes (Fig. 2) and likely high transpiration rates and daily water use requirements. We hypothesize that these combined factors created drought conditions in *Rhododendron* that subsequently contributed to the higher mortality numbers observed 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. However, our selection of the four taxa was solely based upon the original owner's perception, based upon nearly 40 years of growing experience, that all four had similar water use. Historical irrigation applications at the operation consisted of one to two-hour long events that saturated all crops within the irrigation zone. The composted bark media used by the grower had high porosity allowing for quick drainage, limiting prolonged saturating conditions and allowing frequent long irrigation applications. This in turn facilitated grouping of the four species used in the study together without detrimental effects to any one species. By implementing a precision irrigation regime, traditional grower perceptions related to crop water use may need to be first addressed. It may be necessary to rework traditional irrigation groupings employed at the nursery and take greater account of daily water use and water use efficiencies on a crop-by-crop basis.

Grower adoption. Ownership of the nursery was transferred from one familial generation to another at the onset of this trial in August 2014. Experiments continued through the transfer with the consent of the new managing owner. However, the new managing owner focused on other aspects of the business, resulting in reduced oversight of the onsite research project. High mortality numbers in the *Rhododendron* crop produced with sensor-based irrigation in 2015 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 *Rhododendron* irrigated with the sensor-based system and grower irrigated in 2014 ($P = 0.84$) though they were significant in 2015 ($P < 0.01$) (Fig. 4). We hypothesize that there were no significant differences in electrical conductivity in 2014 because control of irrigation by the sensor-based system did not occur until mid-July. Before that time plants were subjected to grower managed irrigation which consisted of long saturating irrigation events that flushed any residual salts. In 2015 control of irrigation by the sensor-based system occurred immediately after transplant. The precision irrigation events delivered by the sensor-based system allowed for salts to build up to a greater extent when compared to the grower-irrigated plants. However, readings in both sensor-based and grower treatments in 2015 were not observed above 2.0 $mS{\cdot}cm^{-1}$, 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 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 the system by nursery staff. The head grower and new owner received training on how to make irrigation changes with the sensor-based system at the onset of the study in 2014 and had access to the computer station in the central office. Yet experimental plots were managed primarily by the section grower, who did not have training or access to the GUI 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 performance of the sensor-based system. However, this dynamic limited the functionality of the system and ultimately may have hindered adoption of the technology across management levels. Ultimately, despite a desire to study grower adoption in a scenario whereby researchers did not assist in operation of the system, 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, the section grower, also had the least control over the system.

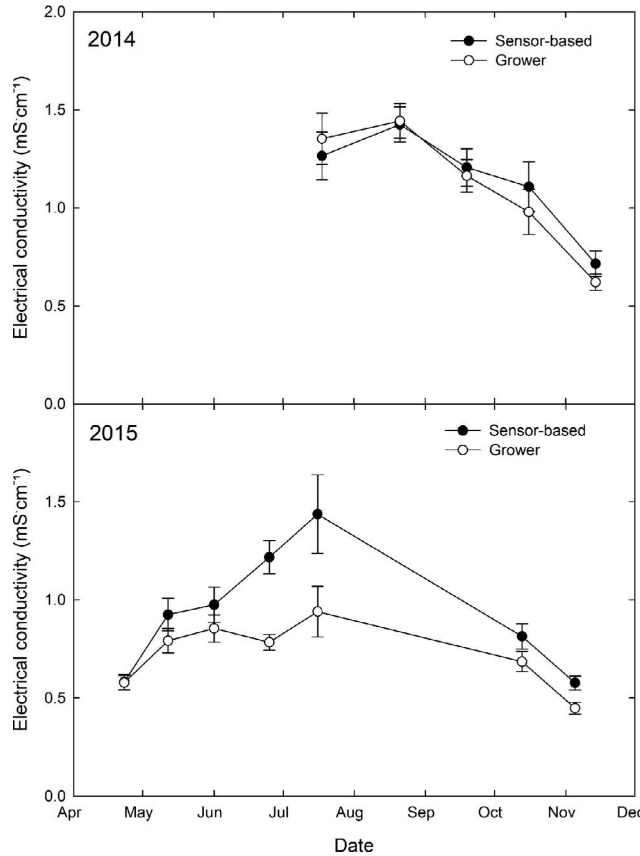

Fig. 4. Discrete direct stick electrical conductivity readings from *Rhododendron catawbiense* 'Roseum Elegans' grown using a soil moisture sensor-based automated irrigation system and grower managed irrigation in container production.

Interest in the system was initiated with the previous owner, principally due to a lack of well-trained irrigators at the facility, the potential to reduce crop losses, and maximizing water resource efficiency in times of severe drought. Interviews with the new (second-generation) owner and head grower suggest that they were unlikely to adopt technology during the earliest stages of dissemination, and in many cases preferred to avoid automation in general, as it in their view promoted neglect of routine scouting for water stress and irrigation system maintenance. Interestingly, the new owner also indicated the new management team was risk averse, despite the previous (generational) owner being an innovator. The new owner also commented that reductions in irrigation water usage were not a management priority given the accessibility and low cost of water regionally and the lack of regulations governing water use in agricultural operations in Georgia. 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 that 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. Previous research has correlated greater education and experience with increased likelihood of early adoption of technology (Wozniak 1987). This study highlights the importance of sustained grower interest as well as education to overcome perceived risks of new technology and ensure its successful adoption. Equally important is ensuring proper access and training are provided to the ultimate end user of the system, at whatever management level, and consideration given to how institutional organization of labor management might impact the viability of implementation. Future incentives to adopt precision irrigation systems may come 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 firm and whether perceived benefits associated with new technology outweigh risks and costs.

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