University of Tennessee, Knoxville

Trace: Tennessee Research and Creative Exchange

Masters Theses

Graduate School

8-2013

Use of Capacitance Sensors for Development of Conservative Irrigation Regimes

Ethan Daniel Hagen

University of Tennessee - Knoxville, ehagen1@utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Ethan Daniel Hagen entitled "Use of Capacitance Sensors for Development of Conservative Irrigation Regimes." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

Amy Fulcher, Major Professor

We have read this thesis and recommend its acceptance:

Dean A., Kopsell, Brian G. Leib, John C. Sorochan

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Use of Capacitance Sensors for Development of Conservative Irrigation Regimes

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ethan Daniel Hagen

August 2013

Abstract

Several experiments were conducted to further develop capacitance sensor-based automated irrigation systems. The first experiment tested whether the photosynthetic response to decreasing volumetric water content (VWC) differed among four species tested. A sigmoidal curve best described the relationship for all species (r^2 [r-squared]>0.86). The VWC that maintained maximum photosynthesis at 90% was selected as a potential conservative irrigation set point and values were not different between species, nor were 100% container capacity values. This indicates that a single set point is adequate to initiate irrigation and that a common upper threshold for VWC can be used for this group of taxa. This research also examined which of five sensor placements best estimates VWC and the effect of low VWC on sensor reading variability. Five sensor placements were tested; three sensors were horizontally inserted into the sidewall at 5 cm, 10 cm and 15 cm from the base of the container. The other two placements, vertical and diagonal, were inserted into the substrate surface. All positions showed a strong linear relationship (r^2[r-squared]>0.92) making them all appropriate models of container substrate moisture. No placement proved better than the others, but choosing a vertical placement is most practical for sensor calibration, installation, and removal. Other trials were conducted to test two container nursery irrigation regimes on oakleaf hydrangea (*Hydrangea quercifolia* 'Alice') in both nursery and greenhouse environments. Plants were automatically irrigated by one of two substrate moisture sensor-based regimes: 1) a daily water use (DWU) system that delivered the exact amount of water lost in the previous 24 h and 2) an on-demand (OD) irrigation system based on the relationship between substrate moisture level and photosynthetic rate. In this system, irrigation was applied when the substrate moisture level fell below 33% container capacity, which corresponded to 90% maximum predicted photosynthetic rate. Both treatments used significantly less water than the industry standard of 2.5 cm/day. This research demonstrated that automating irrigation based on the relationship between photosynthesis and VWC may be practical for multiple species in a nursery setting and can attenuate water use to meet crop demands.

Keywords: nursery crops, soil moisture sensors, substrate water content, photosynthesis

Table of Contents

List of Tables

List of Figures

Chapter 1
Literature Review

Nursery Industry

The "Green Industry" as defined by Hall (2005) is comprised of wholesale nursery and sod growers, landscape architects, designers/builders, contractors and maintenance firms, retail garden centers, home centers and mass merchandisers with lawn and garden departments, and marketing intermediaries such as brokers and horticultural distribution centers. This industry has very substantial economic importance, valued at $147.8 billion nationwide (Hall, 2005). The green industry is very important for the state of Tennessee worth about $3.85 billion and employing 50,812 people (Hall, 2005). Of vital importance to maintaining the industry is the availability of water. The Tennessee River watershed is the fifth largest watershed in the United States draining over 10.6 million hectares and spanning seven states including a large portion of East Tennessee (Bohac and McCall, 2008). Irrigation for agriculture draws nearly 162.7 million liters of water per day from the watershed accounting for almost 10% of total consumption (Bohac and McCall, 2008). Better management and conservation practices could help reduce the demand for this precious resource and ease strains on water reserves allowing the industry to continue to prosper.

Correct water management is crucial to the success of a nursery. A healthy balance of irrigation must be maintained to obtain premium plants. Too much, or too little irrigation can have negative effects on plants. Under watering has traditionally been the greater concern to growers because of more immediate and obvious consequences to plant growth and development. Too little irrigation can cause stunted growth leading to irregular and undesirable growth forms, smaller plants, and a longer production time required to achieve marketable plants. Efforts to avoid under irrigation lead to very wasteful over-watering practices in the nursery industry. In addition to the wasted water, too much irrigation fosters a good environment for disease proliferation, makes plants less resilient to stress, and creates a smaller, less robust root system.

Water

Water is essential to the survival of all types of plants. In plants, water is used as a solvent to transport nutrients to cells and remove waste, maintain turgor pressure for physical structure, foster growth, and drive photosynthetic reactions. Plants growing on land have the difficult task of getting water to all cells throughout the organism. Vascular plants are able to obtain and transport this water from the soil through capillary action. Transpiration, the loss of water vapor from above ground parts of the plant, creates a difference in water potential that provides the driving force that pulls water up through the xylem and to the distant portions of the plant. The amount of energy a plant must expend to transport the water from the ground is largely dependent on the physical properties of the soil. When the matric potential becomes too great for the plant to effectively move water, the plant experiences water stress. Water stress elicits a number of physiological responses in plants in an effort to conserve water. These include closing of stomata and arresting cellular growth (Kulac et al., 2012). If water stress is not alleviated, the plant will shut down photosynthesis, stop carbon assimilation, and normal metabolism is disrupted (Kulac et al., 2012). These responses mean that plants experiencing water stress will end up smaller and look less appealing resulting in lower revenue or a longer growing period in a nursery setting (Jones and Tardieu, 1998).

Irrigation

For thousands of years since the beginning of domesticated plants, agriculture has been intrinsically linked with water and its availability. Nowadays, clean water is all too often taken for granted. In 2005, it was estimated that 1.55 trillion liters of water are drawn each day from United States water reserves (Kenny et al., 2005). As populations increase, so does demand for water and many sources of our freshwater are at risk of depletion. Conservation of freshwater is becoming increasingly important as a result of this trend. One of the largest draws on water supplies is agriculture with 37% of all United States freshwater withdrawals going into irrigation systems (Kenny et al., 2005). The increasing demand and cost of irrigation has created the need for newer, more efficient strategies for irrigation. The nursery industry does not draw a large portion of the total water used but is highly irrigated and extremely inefficient. Regan (1997) stated that 75-85% of water is wasted on common practice container set up.

Traditionally, irrigation strategies have aimed to keep containers wet for as long as possible with the goal of having the greatest amount of water available to the plants. Overhead irrigation is the cheapest and most effective method of accomplishing that goal and has become the most widely used system in nursery settings. In a paper by Beeson and Knox (1991), the average amount of water captured from an overhead system was only 37% even when containers were placed pot-to-pot. The amount of irrigation applied has not been calculated or managed due to the low cost and availability of water. The cost of fresh water is rising with demand and this type of system is already unsustainable in the driest parts of the country. There are many strategies ranging in cost and complexity from very low to very high that can improve efficiency and decrease use.

One of the simpler strategies involves cyclic irrigation. Dividing the irrigation into three separate events throughout the day allows the water time to soak in, decreasing water use by

25% and preventing run-off (Sneed, 1996). Another strategy involves proper plant placement and spacing of plant material. With overhead irrigation, wider spacing leads to greater amounts of water directly hitting the ground and becoming runoff instead of the hitting the container surface. Zinati (2005) estimates that 50-75% of overhead irrigation does not even hit the container surface, and instead falls in between the containers. Simply decreasing space between containers can drastically reduce water missing the containers and becoming run-off.

Grouping plants with similar water need in the same area and scheduling irrigation accordingly can also help efficiency (Zinati, 2005). This can be done two ways. Crop coefficients can be used to categorize the plants into groups of similar water needs. When this information is not available or sufficient, the direct method involves weighing a plant 1 h after irrigation and then again 24 h later to determine water lost in one day (Mathers et al., 2005). Irrigation scheduling can then be customized to fit the needs of the plants in each zone. Watering plants in the morning reduces water loss due to evaporation (Mathers et al., 2005). Wind increases as the day progresses which reduces overhead irrigation accuracy thus increasing required irrigation. Watering in the morning is not always the best choice, however. If water savings is the goal morning is the best time, but Warren and Bilderback (2002) have shown that evening water is the best time to maximize growth. These are a few strategies that are cheap and simple and nursery operators can implement with the equipment they currently own.

Irrigating at a water deficit is a strategy of improving water efficiency that requires more attention and regulation but has lower equipment costs than other methods of water conservation such as installing drip systems or retention ponds. Container capacity is defined as the water held in a substrate when completely saturated and after all free water has been allowed to drain (Jones and Tardieu, 1998). Deficit irrigation means intentionally replenishing only a portion of all the water a container has lost from container capacity. Depending on how well the irrigation system is managed, water is conserved and there is negligible or no effect on the final plant size. This strategy reduces the threat from plant pests and increases hardiness, both of particular significance to the nursery industry.

If truly efficient water use is going to be obtained, then accurate, controllable irrigation systems are needed. The easiest method is drip irrigation but this method is restricted by the costs of installation and maintenance of the individual emitters (Beeson and Knox, 1991). Currently only larger nursery containers such as 27, 57, and 95 L are irrigated with individual emitters (Mathers et al., 2005). Drip irrigation is efficient because it provides a slow, steady flow over longer periods of time preventing leaching and ensuring that 100% of the water reaches the container surface. However, the system requires maintenance to ensure filters are working properly, the irrigation lines are not clogged, and they are running at expected rates (Mathers et al., 2005).

Measuring Plant Water Requirements

If precise irrigation application systems are being used, then this allows for greater efficiency through accurate measures of plant water requirements. To determine those requirements, three main types of models are used: environmental, substrate moisture, and plant-based measurement models. The first method attempts to determine container water loss using environmental measurements. There are a number of equations used to determine water loss that depend on a variety of environmental measurements to make their calculations. The Penman-Monteith is widely accepted as the traditional standard, but equations such as Blaney-Criddle or Priestly-Taylor are two of the newer models used to predict evapotranspirational loss (Xu and Singh, 2002). A simpler but less accurate method is the pan evaporative method. This method is much more practical for a nursery setting requiring a grower simply to set out a pan with a measured amount of water on it. The evaporative loss in the pan can then be extrapolated to determine the water lost by nursery containers. The pan method is very inaccurate and does not take into account a few factors that impact evaporative loss including the plant. Using environmental modeling equations such as the Penman-Monteith is also problematic because it relies on crop specific measures which must be predetermined and can change with the age, developmental stage, and size of the plant (Jones, 2004).

The second method to estimate plant water status is to use substrate moisture measurements. Both substrate moisture content and water potential in the soil are measured to calculate water status. Tensiometers are used to measure the substrate water potential and are quite accurate at measuring available water. The disadvantage to using these devices is inconsistent contact with substrates resulting in inaccurate substrate moisture calculations, which is especially a problem in the coarser substrates commonly used in nursery production. Tensiometers also require regular maintenance especially when exposed to dry conditions. The other measure of substrate water is volumetric water content which is measured using capacitance sensors or gravimetric techniques. Gravimetric values are determined by watering a plant to and letting it drain to container capacity before weighing it. The plant is again measured 24 h later and the difference in weight used to determine the water lost in one day. Volumetric water content can also be determined by measuring the dielectric constant of the substrate, or the ability of molecules in the surrounding substrate to hold a charge when an electric field is projected into the soil. Like the tensiometers, these sensors are hampered by the heterogeneous substrates used in a nursery. Large particles that become wedged between the two electrical field emitting tines and air pockets in the substrate can cause inaccurate capacitance readings. Capacitance sensors are only able to measure the water content of the substrate, which does not account for the amount of water actually available to the plant and therefore must be calibrated for each substrate used. Plant available water depends mostly on the physical properties of the substrate but can also be affected by atmospheric conditions such as vapor pressure (Fulcher, 2010).

Plant-based systems are the third approach that attempts to determine irrigation rates for nursery production. There is a wide range of measurements that researchers have attempted to use to determine the water conditions of a plant. These methods are still in developmental stages, but have the potential to be the most accurate estimators of plant water stress (Jones, 2004). One issue with using these measurements is that they do not quantify the amount of irrigation required by the plants so this method must be used in conjunction with other measures to ensure parsimonious watering. The other major issue these measures have is they are measuring a plant’s response to stress so irrigation cannot be timed before the plant experiences water stress but can only resolve the issue after the plant has already been stressed. The plant based systems fall into one of two categories; measuring the tissue water status or the physiological responses of the plant.

One strategy used to determine tissue water status is to measure actual water potential in the plant. Water potential can be measured using a pressure chamber. A pressure chamber is a very accurate way to measure stem water potential and is therefore a very accurate method to measure water stress (Jones, 2004). This method is problematic to apply to a nursery system because the process requires destruction of leaves, is very time consuming, and cannot be automated. A tool that does not require excision of leaves is a psychrometer. Psychrometers enclose a part of the plant such as a leaf within a sealed chamber. A thermometer is placed in the chamber with a drop of known liquid standard with a known solute concentration. The change in temperature is reflected in the amount of condensation or evaporation caused by diffusion of water from the plant to the droplet or vice-versa. However, this method involves a high level of skill and sophisticated equipment and can also be unreliable (Jones, 2004). A third and the most accurate method to measure water potential is the pressure probe. A microcapillary is inserted into a single cell and the pressure required to keep cytoplasm from entering the microcapillary equals the turgor pressure of the cell (Kramer and Boyer, 1995). While this method is currently confined to the laboratory, if adapted to field use this device would be extremely accurate at measuring water potential at a cellular level.

Tissue water content, as opposed to water potential, can also be a good indicator of plant water stress. Water content is determined by measures of leaf thickness or dilation of stem and fruit diameter. Both of these methods are plagued by the issues of complex and expensive equipment, inaccurate measures due to low variability, and constant recalibration needed due to growth (Jones 2004). Tissue water status can also be guessed by observing visible wilting and xylem cavitation but both of these occur too late, only after the plant has been adversely affected by a water deficit, and are therefore impractical for use in a nursery setting.

Physiological responses of plants are frequently used as accurate indicators of plant water stress. Porometers measure stomatal conductance and are the industry standard to determine water stress (Jones, 2004). Portable photosynthesis systems such as the LI-COR 6400, directly measure whether photosynthetic processes are being inhibited, normally due to water stress. Both will reliably indicate whether a plant’s growth is inhibited by water stress, but they can also respond to other stresses and require multiple replications due to leaf-to-leaf and plant-to-plant variability. They are not automatable and therefore would require a high cost in labor. Sap flow sensors are a very accurate way to measure how quickly water is flowing through the xylem by applying heat and then measuring the temperature at another point further up the stem. While it is accurate, this method does not account for the environmental influences on sap flow, it needs to be installed and calibrated at night on a tree by tree basis, and will only work with tree crops of sufficient stem size. These problems mean xylem flow is inapplicable to a majority of nursery crops.

Species Used in this Study

Acer rubrum 'Red Sunset' is a medium to fast growing native tree. These trees are planted as shade trees and for their fall color. They are hardy from zones 3-9 but show a significant degree of regional hardiness (Dirr, 2009). This cultivar is extremely popular and is considered one of the best shade trees with good winter tolerance.

Cercis chinensis 'Don Egolf' is a small, multi-stemmed ornamental shrub hailing from central China and introduced before 1850. It can be grown in zones 6 through 9 (Dirr, 2009). This shrub is a popular ornamental and is selected for its showy flowers blooming in March and April.

Deutzia gracilis 'Nikko' is a ground cover shrub often used as a facer or in shrub borders. This Japanese native can survive in zones 5-8. *D. gracilis* is known for its pure white flowers in May.

Hibiscus moscheutos 'Pink Elephant' is a deciduous, perennial shrub native to the Eastern United States. It is hardy in zones 5-9. This species is useful for landscape planting in swampy wet soil but will thrive in any full sun environment with consistent soil moisture (Armitage, 1989). This species grows vigorously, producing large, colorful flowers throughout the summer, and is a suspected high water user.

Hydrangea quercifolia 'Alice' is a perennial, deciduous shrub native to the Southeast United States. It is hardy in USDA zones 5-9 (Dirr, 2009). This plant was selected because it is a common landscape plant grown in many nurseries, desired for its colorful panicles of flowers and fall color. This plant is also a suspected high water user, which would make it more susceptible to midday water stress and therefore stands to benefit the most from more frequent irrigation.

Viburnum dentatum 'Ralph Senior' is a very resilient ornamental shrub. The dark green foliage, fall colors and cream to white flowers are what make this shrub attractive. Its versatility and usefulness has been shown in hedges, as screens, and in groupings. This species can grow on almost any type of soil and is grown in zones 3-8.

Substrates

Plants will halt growth, wilt, and eventually die if subjected to enough water stress. The key to water conservation in a nursery setting is to apply the least amount of water without the plant experiencing sufficient water stress to stunt its growth and extend the production cycle. Detrimental water stress is experienced when the water content gradient from the soil to the air is not great enough to facilitate water movement through the plant. The water available to the plant is determined by two factors. The first factor is substrate water content at container capacity, which is the amount of water that is held by a substrate after being soaked and allowed to drain freely (Jones and Tardieu, 1997). The second factor is the minimum water potential value at which plants are able to take up water from the substrate. Water potential is a measure of the energy required to remove water from substrate pores. The difference between these two points determines plant available water (Jones and Tardieu, 1997). The minimum value varies from species to species, but at that minimum water potential, a plant is unable to draw up water from the substrate. Both of these factors are highly influenced by the physical properties of a substrate. The type of substances included and their ratios in the substrate mix determine both the soil's container capacity and also the plant available water.

Many different types of substances are mixed to create substrates for the horticultural industry including tree bark, sand, and sphagnum moss. Water status in a substrate is affected by amount of pore space, size of pores, substrate structure, and attraction between water and the substrate. Pore space volume can range from around 50% in a soil based container substrate up to 90% in a sphagnum based substrate (Drzal et al., 1999). Pores can be divided into four types; macropores, mesopores, micropores, and ultramicropores. Macropores are air filled after free drainage, mesopores are considered the pores with water available to plants, micropores are filled with water that is only available to plants under high water stress, and ultramicropores contain unavailable water (Drzal et al., 1999). The variation between substrates in the quality of pore space means the water available to plants can vary significantly. Selection of a substrate with higher volumes of water available to plants allows for less frequent watering and decreased threat of water stress, both properties are very helpful in practical conservation of water. A substrate with too high of unavailable water does not allow for proper aeration of the roots and will encourage disease.

Literature Cited

Ackerman, F. and E.A. Stanton. 2011. The last drop: climate change and the southwest water crisis. Stockholm Environment Institute-U.S. Center. Somerville, MA. January 25, 2013. <http://sei-us.org/Publications_PDF/SEI-WesternWater-0211.pdf>.

Armitage, A. M. 1989. Herbaceous perennial plants: A treatise on their identification, culture, and garden attributes. 3rd ed. Varsity, Athens, GA.

Beeson Jr., R.C. 2012. Development of a Simple Reference Evapotranspiration Model for Irrigation of Woody Ornamentals. HortScience 47(2):264-268.

Beeson Jr., R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in ten year. J. Environ. Hort. 22(2):113-115.

Beeson Jr., R.C. and J. Brooks, 2008. Evaluation of a model based on reference crop evapotranspiration (ETo) for precision irrigation using overhead sprinklers during nursery production of *Ligustrum japonica*. Acta Hortic. 792, 85–90.

Beeson Jr., R.C. and G.W. Knox 1991. Analysis of efficiency of overhead irrigation in container production. HortScience 26(7):848-850.

Bir, R.E. 1988. Water and container nurseries. Mountain Nursery Newsletter. Mar. 1988:1.

Bohac, C. E. and M. J. McCall. 2008. Water use in the Tennessee Valley for 2005 and projected use in 2030. Tennessee Valley Authority River Operations and U.S. Geological Survey.

Bush, E. A., C. Hong, and E.L. Stromberg. 2003. Fluctuations of *Phytopthera* and *Pythium* spp. in components of a recycling irrigation system. Plant Dis. 87(12):1500-1506.

Caron, J. 2005.Defining critical capillary rise properties for growing media in nurseries. Soil Sci. Soc. of Amer. J. 69(3):794-806.

Dirr, M.A. 2009. Manual of woody landscape plants. Stipes, Champaign, IL.

Drzal, M.S., W.C. Fonteno., and K.D. Casse 1999. Pore fraction analysis: A new tool for substrate testing. Acta Hort. 481.

Forrai, M., M. Sutorine Dioszegi, M. Ladanyi, P. Hofni, and K. Hrotko. 2012. Studies on estimation of leaf gas exchange of ornamental woody plant species. Appl. Ecol. and Environ. Res. 10(2):195-206.

Fulcher, A.F., 2010. Modeling water use in nursery crops. Univ. of Kent., Lexington PhD Diss. Abstr. 121.

Fulcher, A.F., J.W. Buxton, and R.L. Geneve. 2012. Developing a physiological-based, on-demand system for container production. Sciencia Hort. 138:221-226.

Fulcher, A.F. and R.L. Geneve. 2011. Relationship between photosynthesis and substrate moisture for container-grown *Hibiscus* and *Cornus.* Acta Hort. (ISHS) 922:183-186.

Grant, O.M., M.J. Davies, H. Longbottom, and C.J. Atkinson. 2009. Irrigation scheduling and irrigation systems: optimizing efficiency for container ornamental shrubs. Irr. Sci. 27:139-153.

Griffin, J., T.G. Ranney, and D.M. Pharr. 2004. Heat and drought influence photosynthesis, water relations, and soluble carbohydrates of two ecotypes of redbud (*Cercis Canadensis*). J. Amer. Soc. Hort. Sci. 129(4):497-502.

Hall, C.R., A.W. Hodges, and J.J. Haydu. 2005. Economic impacts of the green industry in the United States: Final report to the national urban and community forestry advisory committee. Uni. of Tenn. Coop. Ext. Serv.

Jones, H.G and F. Tardieu. 1997. Modelling (sic) water relations of horticultural crops: a review. Sciencia Hort. 74:21-46.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. J. of Expt. Bot. 55(407):2427-2436.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin. 2009. Estimated use of water in the United States in 2005. U.S. Geological Survey, Reston, VA. Circular 1344:52.

Kramer, P.J. and J.S. Boyer. 1995. Water relations of plants and soils. Academic Press, Inc. London.

Kulac, S., P. Nzokou, D. Guney, B.M. Cregg, and I. Turna. 2012."Growth and physiological response of Fraser Fir [*Abies fraseri* (Pursh) Poir.] seedlings to water stress: Seasonal and diurnal variations in photosynthetic pigments and carbohydrate concentration. HortScience 47(10):1512-1519.

Mathers, H.M., T.H. Yeager, and L.T. Case. 2005. Improving irrigation water use in container nurseries. HortTechnology 15(1):8-12.

MacDonald, J.D., M.S. Ali-Shtayeh, J. Kabashima, and J. Stites. 1994. Occurrence of *Phytophthora* species in recirculated nursery irrigation effluents. Plant Dis. 78:607-611.

Miralles-Crespo, J. and M.W. van Iersel. 2011. A calibrated time domain transmissometry soil moisture sensor can be used for precise automated irrigation of container-grown plants. HortScience 46(6):889-894.

Regan, R. 1997. Grouping Container-Growth Plants by Water Use. The Digger. June.

Sneed, R. 1996. Pumps, pipes and consultations. Amer. Nurseryman. June:45-46.

Turral, H., J. Burke, and J.M. Faurès. 2011. Climate change, water, and food security. Water Reports, No. 36. Food and Agriculture Organization of the United Nations, Rome. <http://www.fao.org/docrep/014/i2096e/i2096e.pdf>. (accessed 01.23.13).

U.S. Salinity Laboratory Staff, 1954. Diagnosis and Improvement of Saline and Alkali Soils. USDA Agric. Hand. No. 60, U.S. Government Printing Office, Washington, D.C.

Van Iersel, M.W., S. Dove, J. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45(2):277-282.

Warsaw, A.L., R.T. Fernandez, and B.M. Cregg. 2009. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. HortScience 44(5):1308-1318.

Warren, S. and W. Bilderback. 2005. More plants per gallon: getting more out of water. HortTechnology 15(1):14-18.

Xu, C.-Y. and V.P. Singh. 2002. Cross-comparison of mass-transfer, radiation and temperature based evaporation models. Water Resource Mgt, 16:197–219.

Zinati, G. 2005. Irrigation Management Options for Containerized-Grown Nursery Crops. Rutgers Coop. Res. and Ext., Rutgers University, New Brunswick, NJ.

Chapter 2
Modeling the Relationship between Volumetric Water Content and Photosynthetic Rate for Four Woody Ornamental Species: Advances Toward a Physiologically-based Irrigation System

Abstract

Precision irrigation systems that deliver the correct volume of water at the appropriate time have great potential for water savings and efficiency. Previously, a precision, On-Demand irrigation system was developed based on the sigmoidal relationship between photosynthesis and volumetric water content (VWC). By triggering irrigation when VWC fell below a set point, the plants were irrigated just before photosynthesis was impacted, conserving water without affecting plant growth. Our research was conducted to evaluate the hypothesis that the sigmoidal relationship was representative of a small, but botanically diverse group of plants and to examine if a common irrigation set point was possible among these diverse nursery crops. Photosynthetic response curves were conducted to ensure that photosynthetic characteristics were representative of woody ornamental plants and to determine the optimum light level of subsequent experiments. The relationship between photosynthetic rates and VWC was established for each species. A sigmoidal curve best described the relationship for all species (r^2 >0.86). The VWC that maintained photosynthesis at 90% of the maximum rate was selected as a potential conservative irrigation set point for each species and were as follows: *Hydrangea quercifolia* Bartr. 'Alice' (oakleaf hydrangea) 0.35 $m^3 \cdot m^{-3}$, *Hibiscus moscheutos* L. 'Pink Elephant' (common mallow) 0.34 $m^3 \cdot m^{-3}$, *Cercis chinensis* Bunge 'Don Egolf' (eastern redbud) 0.38 $m^3 \cdot m^{-3}$, and *Viburnum dentatum* L. 'Ralph Senior' (arrowwood viburnum) 0.35 $m^3 \cdot m^{-3}$. The selected VWC set points did not significantly differ between species, nor did 100% container capacity values. This indicates that a single set point is adequate to initiate irrigation and that a common upper threshold for VWC can be used for this group of taxa. This research suggests that adapting a physiologically-based irrigation system to a diverse range of plants may be possible,

potentially increasing irrigation efficiency and reducing water consumption in container-grown crops.

Keywords: nursery crops, precision irrigation, irrigation scheduling, capacitance sensors

Introduction

World population growth has increased demand and competition for natural resources as resource availability decreases (Turral et al., 2011). Water is one of the most crucial resources to conserve. Extreme weather conditions; practices such as unsustainable levels of groundwater extraction; and competition among industry, municipalities, and agriculture have resulted in irrigation restrictions. Major nursery crop production states such as Florida, California, Texas, and Oregon now face irrigation restrictions (Ackerman and Stanton, 2011; Beeson, et al. 2004; Beeson and Brooks, 2008; Houston et al., 2003; Marella and Burndt, 2005; State of Oregon, 2013). Container nurseries are substantially affected by restrictions because of their high water use per hectare. When irrigating with a standard amount of 2.5 cm per day, 250,000 L of water are used per hectare per day (LeBude and Bilderback, 2007).

Container nurseries are often extremely inefficient with 60% to 90% of applied irrigation being lost due to lack of application uniformity, excess volume applied, deflection by the canopy, and container spacing (Beeson and Yeager, 2003; Fare et al., 1992). Increasing irrigation application efficiency, i.e. increasing the proportion of water that is intercepted and retained by containers, can drastically reduce water consumption by nurseries. A number of strategies have been proposed to increase application efficiency in nursery irrigation, such as increasing distribution uniformity by optimizing container spacing to increase interception (Beeson and Knox, 1991). Irrigation timing also impacts irrigation efficiency, and watering crops at night or early morning reduces the amount of evaporative loss from overhead irrigation systems (Mathers et al., 2005), although this may not be the best time for crop growth (Warren and Bilderback, 2005). Cyclic irrigation, or dividing a daily irrigation event into multiple shorter irrigation events can also reduce water use (Beeson and Haydu, 1995). Other strategies to increase efficiency include grouping plants according to water use, using a more appropriate irrigation system design, and cleaning and replacing nozzles (Grant et al., 2009; Warsaw et al., 2009; Zinati, 2005). However, most of these commonly used strategies are passive attempts to address gross application inefficiencies and do not account for continually changing plant and environment-specific need for water.

To more fully maximize water conservation, an irrigation system would need to be dynamic and calibrate irrigation application volume and timing to plant and environmental demand, applying only the exact amount of water needed each day, and only when needed. A number of methods have been developed to determine the optimum irrigation volume to apply on a daily basis. Researchers have successfully developed crop coefficients for use in models, such as Penman-Monteith (Penman, 1948) and Priestly-Taylor (Priestly and Taylor, 1972), which calculate the amount of water a plant loses in a day based on environmental factors, plant size and age, and specific climate and season. However, these measurements are crop specific and must be calculated throughout the season to account for developmental differences and they assume a closed canopy making them unsuitable for nursery application. Beeson (2012) simplified the calculation by using canopy closure data to allow for one equation to calculate water use, regardless of season or plant size. However, separate crop coefficients must still be developed for each species and canopy closure measurements must be taken every few weeks to adjust the calculations.

Other research uses physiological data to determine irrigation rates and timing (Doltra et al., 2007; Fernández et al., 2008; and Green et al., 2006). Basing irrigation on physiological data is ideal because it measures the direct response of plants to water stress, indicating exactly when the stress occurs. A system based on physiological data would initiate irrigation only when the crop needed water, eliminating superfluous irrigation. However, it is often difficult to measure physiological responses and these systems are triggered only after a plant has experienced some level of stress. To optimize a production schedule, irrigation needs to be triggered before the plant is stressed enough to reduce growth. One indication of water stress is when a plant shuts down photosynthesis (Griffin et al., 2004). By developing an irrigation system based on the relationship between photosynthetic rate and VWC over a range of substrate moisture contents, Fulcher et al. (2012) found that photosynthetic rates in rose mallow (*Hibiscus rosa-sinensis* L. 'Cashmere Wind') follow a sigmoidal relationship; rates remained relatively constant above 0.25 $m^3 \cdot m^{-3}$ but drop precipitously if substrate VWC dried below that point. Fulcher and Geneve (2011) showed *Cornus florida* and *Cornus kousa* species exhibited a similar sigmoidal relationship between photosynthetic rate and substrate moisture. If the relationship between photosynthesis and VWC is not species-specific, photosynthesis decreases substantially at the same VWC, and if 100% container capacity values are similar, then an automated irrigation system could potentially be used for multiple species without the need for individual species calibrations, which would enhance industry adoption of this system as the basis for scheduling irrigation.

Therefore, the objectives of this research were to: 1) characterize the photosynthetic light response of four diverse woody species; 2) develop a model characterizing the relationship between photosynthesis and VWC for four diverse woody species; 3) determine if container capacity volumes differ between species; and 4) determine if the VWC that photosynthesis precipitously decreases is the same for species in this study, such that one value can be used as a conservative set point for multiple species on an automated irrigation system.

Materials and Methods

Species were chosen from a range of nursery crops based on providing a botanically diverse selection of woody plants and the importance of the genera to the nursery industry. Plants included in this study were as follows: rooted cuttings of eastern redbud (*Cercis chinensis* Bunge 'Don Egolf'), arrowwood viburnum (*Viburnum dentatum* L. 'Ralph Senior'), and oakleaf hydrangea (*Hydrangea quercifolia* Bartr. 'Alice') (Spring Meadows Nursery, Grand Haven, MI) and bare root liners of common mallow (*Hibiscus moscheutos* L. 'Pink Elephant' , Walters Gardens, Zeeland, MI). Common mallow was potted directly into 11.4 L plastic containers (C1200, Nursery Supplies Inc., Chambersburg, PA) because of the size of the existing root system. All other species were potted into 3.8 L containers (C400, Nursery Supplies Inc., Fairless Hill, PA) with an 85 pine bark : 15 sphagnum peat moss (by volume) substrate (Renewed Earth Inc., Kalamazoo, MI). The first planting occurred on 25 Feb. 2012. To ensure measurements taken during different seasons were not affected by the age of the plant, a second crop was planted on 6 Aug. 2012. To obtain rooted cuttings of the same age, eastern redbud and arrowwood viburnum rooted cuttings were purchased, whereas common mallow and oakleaf hydrangea were rooted on site. Softwood cuttings of oakleaf hydrangea were taken from stock plants on 8 June 2012, dipped in 5,000 mg kg^{-1} KIBA, stuck in perlite, and placed under mist. Softwood cuttings of common mallow were taken from stock plants on 18 June 2012, dipped in 3,000 mg kg^{-1} KIBA, stuck in 50:50 perlite to sphagnum moss (by volume), and placed under mist. All plants were drenched on either 13 March or 19 Aug. with Aquagro® L (Aquatrols, Paulsboro, NJ) at 600 mg/L to ensure even wetting because the substrate became hydrophobic during preliminary research. One week after transplanting, plants were top-dressed with 19N-1.75P-11.6K, 5-6 month controlled release fertilizer with micronutrients (Polyon®, Harrell's Inc., Lakeland, FL) at 12 g per container (medium label rate) and fertigated twice weekly with 300 mg/L of 20N-8.7P-16.6K (Peters Professional® General Purpose 20-20-20, Scotts Sierra Horticultural Products Co., Marysville, OH). Plants were grown in a controlled greenhouse environment at the University of Tennessee North Greenhouse in Knoxville, TN (35.946°N, -83.939°W).

EC-5 soil moisture capacitance sensors (Decagon Devices Inc., Pullman, WA) were connected to a multiplexer (AM 16/32, Campbell Scientific, Logan, UT) wired to a datalogger (CR1000, Campbell Scientific), and programmed to read and convert mV output from the EC-5 sensors to VWC based on a substrate-specific calibration for each sensor (Appendix I). Capacitance sensors were installed half way between the base of the plant and the container sidewall, one per container. Sensors were oriented vertically with the broad face to plant stem and inserted into the substrate so that the sensor overmold/wire junction was 2.5 cm below the surface of the substrate. Sensor readings were automatically measured every 15 sec and averages were recorded every 15 min.

Light response curves were measured between 10 AM and 2 PM using an infrared gas analyzer (Li-6400, LI-COR® Biosciences, Inc., Lincoln, NE) on sunny days between 14 June and 17 August 2012. Light response curves were measured on the second fully expanded, recently matured leaf of each plant. High and low light curves were conducted on separate days. For the high light curve, photosynthetic rates were measured at decreasing irradiance levels of 2000, 1800, 1600, 1400, 1200, 1000, 800, 600, 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Low light curves were measured at irradiance levels of 400, 300, 250, 200, 150, 100, 50, 25, 10, and 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. CO_2 levels were 390 ppm for all measurements. Dates of light curve measurements were as follows: common mallow 14, 19, 21, and 22 June, 20 and 25 July; oakleaf hydrangea 14, 19, 20, 21, and 25 June, 16, 17, and 21 Aug.; eastern redbud 19, 21, 22, and 26 June, 24 July, 18 Aug.; arrowwood viburnum 20, 21, 22, and 26 June, 26 July, and 1 Aug. Values from the high light curves were used to calculate the maximum predicted photosynthetic rate. A regression line was fit to the linear portion of the low light curves, 50, 25, and 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and apparent quantum efficiency was calculated from the slope of the regression line. Dark respiration rate was predicted from the regression line at the intersection with light intensity at 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Light compensation point was determined from the intersection of the regression line and the x-axis, when net photosynthetic rate was 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Light curve data was also collected for *Acer rubrum* L. 'Red Sunset' (red maple) and is presented in Appendix II.

Root proliferation was periodically monitored in a cohort of plants that were not included in the experiment to determine root establishment. Plants were hand watered until roots reached the container sidewall. Upon initiating experiments, the substrate was hand watered and containers placed in 2.5 cm of standing water for 30 min to ensure complete saturation of the substrate. Containers were left to drain to 100% container capacity, which took 1 h for 3.8 L and 2 h for 11.4 L containers (common mallow), and then water was withheld for the remainder of the experiment. Weight, soil moisture, and photosynthetic rate were measured once or twice daily between 10 am and 2 pm beginning at 100% container capacity and continuing as the containers dried. Gas exchange measurements were taken on the second fully expanded, recently matured leaf with an infrared gas analyzer with light intensity maintained at 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and CO_2 at 390 ppm. Models were developed from measurements taken as the plants dried down until the plants were wilting. Model development experiments were conducted three times for eastern redbud and four times for the other species throughout the 2012 growing season on the following dates: eastern redbud: 23-29 May, 26 June-9 July, and 30 Oct.-8 Nov.; common mallow: 11-20 May, 24-29 July, 7-24 Sept., and 25 Sept.-11 Oct.; oakleaf hydrangea: 30 Apr.-4 May, 26 June-9 July, 25 Sept.-11 Oct., and 30 Oct.-8 Nov.; arrowwood viburnum: 11-20 May, 26 June-9 July, 7-24 Sept., and 25 Sept.-11 Oct. Only three time periods were measured for eastern redbud because of the extended substrate drying time required for this species.

Regression analysis was used for the light response curves (SigmaPlot™, SPSS, Chicago, IL) to determine the relationship between photosynthetic rates and light intensity for each plant. Then, light response characteristics of each plant were individually determined. For the model development experiments, the relationship between photosynthetic rates and VWC was graphed for each plant. All curve options on SigmaPlot™ were evaluated for each plant to determine the best fit. Once the best fit curve was selected, VWC values were determined that corresponded to 90% of maximum predicted photosynthetic rate. Model development experiments were conducted three times for eastern redbud and four times for all other species. Light response characteristics and VWC values were analyzed using the PROC MIXED procedure in SAS® (v.9.3, SAS Institute Inc., Cary, NC) and means were separated using Tukey's HSD *t*-test (α=0.05). For all light response and model development experiments there were five replicate plants. All experiments were in a randomized block design with time period as the blocking factor.

Results

For each species, there was no difference between the maximum photosynthetic rate from light response curves and the predicted maximum photosynthetic rates from the model development experiments (data not shown, *P* value=0.0691). Therefore, photosynthetic rates from model development experiments are not presented. The maximum photosynthetic rate of common mallow was the highest at 24.8 µmol CO_2 m^{-2}·s^{-1}. Eastern redbud, 15.4 µmol CO_2 $m^{-2}s^{-1}$, was greater than oakleaf hydrangea, 10.3 µmol CO_2 m^{-2}·s^{-1}, but neither differed from arrowwood viburnum, 13.8 µmol CO_2 m^{-2}·s^{-1} (Table 2.1, see Appendix). Predicted light compensation points ranged from 14.3 to 23.4 µmol CO_2 m^{-2}·s^{-1} but were not different. Quantum light efficiency ranged from 0.060 to 0.065 and also was not different between species. Dark respiration rates of eastern redbud, -1.85 µmol CO_2 $m^{-2}s^{-1}$, and arrowwood viburnum, -1.80 µmol CO_2 $m^{-2}s^{-1}$, were lower than those of oakleaf hydrangea and common mallow, -1.22 and -1.04 µmol CO_2 $m^{-2}s^{-1}$, respectively (Table 2.1).

Based on r^2 values, a three parameter sigmoidal curve was the best fit to describe the relationship between VWC and photosynthetic rates for all species (Fig. 2.1). All species had average r^2 values equal to or greater than 0.86 (Table 2.2). For all species, 100% container capacity was between 0.51 and 0.53 m^3·m^{-3} and was not different (Table 2.2). The set point, or lower VWC threshold to automatically trigger irrigation, was calculated at 90% maximum predicted photosynthesis based on the hypothesis that drying to this point would conserve the most water without reducing plant growth. The VWC values calculated to maintain photosynthesis at 90% of maximum predicted rates ranged from 0.34 to 0.38 m^3·m^{-3} (Table 2.2) and were not different for the four species.

Discussion

These experiments attempted to characterize photosynthetic metrics and determine if the relationship between substrate moisture and photosynthetic rate were similar for a diverse group of woody plants. While values were different between species in this study, the overall characterization of light response was consistent with other woody plants. The maximum predicted photosynthetic rates between species differed from 10.3 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ at the lowest to 24.8 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ at the highest, a difference of 58% (Table 2.1). These rates are consistent with established measurements for woody ornamental plants, for example: linden (*Tilia spp.*) and maple (*Acer spp.*) range from 3.59 to 13.03 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ (Forrai et al., 2012), redbud (*Cercis spp.*) 10 to 25 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ (Griffin et al. 2004), and dogwood (*Cornus spp.*) 5.6 to 14.1 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ (Fulcher, 2010). Light compensation points ranged from 14.3 to 23.4 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ and were similar to those measured on other woody ornamental species under comparable conditions. Beckman et al. (1992) showed sour cherry (*Prunus cerasus* L.) light compensation points ranged from 12 to 20 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ and Baltzer and Thomas (2007) showed a range of 7.4-16.9 µmol CO_2 $m^{-2}{\cdot}s^{-1}$ for several woody ornamental species. Quantum yields calculated in this study, 0.060 to 0.065, (Table 2.1) are within the range of 0.027 to 0.082 documented in a review of quantum yield of herbaceous and perennial species (Singsaas et al., 2001). Dark respiration rates, -1.04 to -1.85 µmol CO_2 $m^{-2}{\cdot}s^{-1}$, were also similar to values measured on other woody species in other studies such as red maple and yellow poplar (*Liriodendron tulipifera* L.), -1.95 and -1.55 µmol CO_2 $m^{-2}{\cdot}s^{-1}$, respectively (Groninger et al., 1996). The species chosen in this study were a botanically diverse selection of woody plants, representing Malvaceae, Adoxaceae, Fabaceae, and Hydrangeaceae plant families. The species displayed a range of photosynthetic characteristics but the metrics were consistent with established values for other woody ornamental plants.

The r^2 values (>0.86) indicate that a three-parameter sigmoidal curve accurately describes the relationship between VWC and photosynthetic rates for all four species (Table 2.2). The precipitous decrease in photosynthetic rate as substrate VWC decreased was mirrored by stomatal conductance in plants tested (data not shown). The sigmoidal relationship between photosynthesis and VWC is consistent with that observed in other woody ornamentals such as rose mallow, flowering dogwood (*Cornus florida*), and kousa dogwood (*Cornus kousa*) (Fulcher et al. 2012; Fulcher and Geneve, 2011). Plants maintained maximum photosynthetic rates at VWC values below container capacity until the substrate dried past a certain point, 0.34-0.38 $m^3 \cdot m^{-3}$, when photosynthesis began to precipitously decrease.

To achieve precision irrigation, the amount of water used in evapotranspiration can be calculated relative to container capacity and irrigation applied to return to container capacity without excess, as in the method of Warsaw et al. (2009). However, using this or similar irrigation technology relies on consistent 100% container capacity values among plants within an irrigation zone. It was hypothesized that differential root proliferation among species and variation in substrate volume per container may lead to a range of container capacity values. However, these factors did not significantly affect container capacity. All species' averages were between 0.51 $m^3 \cdot m^{-3}$ and 0.53 $m^3 \cdot m^{-3}$ indicating that at this stage of production substrate moisture content at maximum holding capacity was consistent (Table 2.2). This also demonstrates that the plants were subjected to similar compaction during transplanting and subsequent care. Uniformity is important for precision irrigation to be feasible, and low variability such as documented here may decrease the number of sensors needed; therefore, decreasing costs for growers to adopt sensor-based automated irrigation systems.

One objective of these experiments was to determine the substrate moisture content at which near maximum photosynthetic rates could be achieved. The VWC corresponding to 90% of the maximum predicted photosynthesis was selected because as VWC decreased below that point, photosynthetic rates dramatically decreased (Fig. 2.1). Based on previous research, it was hypothesized that maintaining substrate moisture content so photosynthetic rates remained above 90% would maximize water conservation without impacting plant growth. While biomass is generally affected before photosynthesis (Taiz and Zigler, 2002), Fulcher et al. (2012) demonstrated that maintaining VWC just above the precipitous decrease in photosynthesis did not negatively impact plant growth. Therefore, this set point would be best suited as the set point to trigger irrigation within an automated irrigation system without decreasing biomass. The irrigation set points determined in this research, 0.34-0.38 $m^3 \cdot m^{-3}$, are similar to minimum substrate moisture levels required to maintain optimum growth found in other studies. Miralles-Crespo and van Iersel (2011) found that begonia plant size decreased when substrate moisture levels were maintained below 0.35 $m^3 \cdot m^{-3}$ in a peat-based substrate. Van Iersel et al. (2010) recorded a decrease in petunia plant mass after substrate moisture decreased below 0.25 $m^3 \cdot m^{-3}$ in a peat-based substrate. Fulcher et al. (2012) found that although plant height was not impacted until substrate moisture content dropped to 0.22 $m^3 \cdot m^{-3}$, plant biomass decreased when substrate moisture content dried to 0.30 $m^3 \cdot m^{-3}$ between irrigation events. The set points chosen in this study, i.e., the VWC corresponding to 90% of the maximum predicted photosynthetic rate, were not different for the four species tested. Therefore, using one VWC value as the lower set point for irrigation initiation for a wide range of species appears possible.

More species should be tested to confirm this hypothesis, as O'Meara (2012) found that the set point at which transpiration stopped differed between french hydrangea (*Hydrangea macrophylla* (Thunb.) Ser. 'Fasan') and common gardenia (*Gardenia jasminoides* Ellis 'Radicans'), 0.16 and 0.12 $m^3 \cdot m^{-3}$, respectively. The differences in the VWC value at which growth is inhibited between studies is likely due to differences in hydrological properties from the range of substrates used.

Substrates' hydrological properties are dependent on the physical properties of the substrate and the container volume and height. VWC represents all of the water present in a volume of substrate at a given time, including gravitational, available, and unavailable water. The VWC can be identical in two different substrates but the water potential may be different, meaning that the water may be more available to the plants in one substrate than another. Thus, a plant that wilts at 0.25 $m^3 \cdot m^{-3}$ in one substrate will not necessarily wilt at 0.25 $m^3 \cdot m^{-3}$ in a different substrate. Therefore, the set points determined in this and other studies are substrate and container specific and may need to be determined individually for each substrate and container used, in spite of the relative consistency among results described above.

Based on these results, an irrigation system would only need one lower set point to initiate irrigation and one upper VWC value for 100% container capacity regardless of the species under irrigation. However, this does not imply that all species can be simultaneously grown under one irrigation system, just that set points would only need to be developed once per substrate-container combination. Plants may experience water stress at the same substrate water content, but the rate at which the plants use water and the time required for containers to dry past the set point are different. During one time period in this study, oakleaf hydrangea experienced water stress after 2 to 3 days, whereas eastern redbud began experiencing water stress after 7 to 8 days. This underscores the importance of grouping crops according to water needs. Results from this research and Fulcher and Geneve (2011) suggest that the same program could be used to irrigate different woody species without developing VWC set points for each species, but species would have to be grouped into irrigation zones so that they would dry at the same rate.

The inherent variation among individual plants and containers causes some plants to dry out more quickly than others, even when crops are grouped appropriately. This variation can reduce the precision that can be achieved by any irrigation system and may increase the number of substrate moisture sensors necessary to accurately measure the average VWC of a block of plants. For plants in 3.8 L containers, this research suggests that using less conservative values for the lower irrigation set point, 0.38 $m^3 \cdot m^{-3}$, and 100% container capacity set point, 0.53 $m^3 \cdot m^{-3}$, are advantageous for automated irrigation systems. Using the wettest set point estimates of 0.38 $m^3 \cdot m^{-3}$ and 0.53 $m^3 \cdot m^{-3}$ would compensate for uneven distribution of irrigation water and individual container variation; ensuring containers are irrigated before water stress occurs and all containers are fully irrigated to 100% container capacity. These less conservative set points reduce the potential water savings, but help prevent the plants from experiencing water stress. Choosing a lower set point to trigger irrigation would save more water, but would risk stressing plants that are drier than the crop average due to the inherent variation within a production block, such as plants on the edge of the block. One of the benefits of using this system is its dynamic nature. As the restrictions and cost for water increase, growers may decide it is more prudent to choose a lower set point that carries greater risk of water stress and reduced growth in exchange for maximizing water savings.

Fulcher et al. (2012) describe a successful irrigation model as having these traits: 1) do not increase production time compared to current irrigation scheduling; 2) the ability to be automated; 3) accurately estimate water use to prevent over and under irrigation and thus conserve water and minimize leaching; 4) simple; and 5) easily configured to a large number of crops. An irrigation system based on the relationship between VWC and photosynthetic rate presented here shows great potential for fulfilling these requirements. Once installed, sensor measurement, irrigation calculation, and application can be automated and controlled with one system. Container capacity and lower set points were not different between species allowing for both accurate estimates of water use and the application of one set point for irrigating a potentially large number of species with proper use of irrigation zones. This research demonstrated that the physiologically-based model presented here has the potential to be effectively implemented into an automated nursery irrigation system.

Acknowledgements: The authors wish to thank Renewed Earth Inc., Phil Flanagan, Lori Osborne, and Whitney Yeary for their contributions as well as support from Tennessee Agricultural Experiment Station.

Literature Cited

Ackerman, F. and E.A. Stanton. 2011. The last drop: climate change and the southwest water crisis. Stockholm Environment Institute-U.S. Center. Somerville, MA. January 25, 2013. <http://sei-us.org/Publications_PDF/SEI-WesternWater-0211.pdf>.

Baltzer, J.L. and S.C. Thomas. 2007. Physiological and morphological correlates of whole-plant light compensation point in temperate deciduous tree seedlings. Oecologia 153:209-223.

Beckman, T.G., R.L. Perry, and J.A. Flore. 1992. Short-term flooding affects gas exchange characteristics of containerized sour cherry trees. HortScience 27(12):1297-1301.

Beeson Jr., R.C. 2012. Development of a simple reference evapotranspiration model for irrigation of woody ornamentals. HortScience 47(2):264-268.

Beeson Jr., R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in ten year. J. Environ. Hort. 22(2):113-115.

Beeson Jr., R.C. and J. Brooks, 2008. Evaluation of a model based on reference crop evapotranspiration (ETo) for precision irrigation using overhead sprinklers during nursery production of *Ligustrum japonica*. Acta Hortic. 792, 85–90.

Beeson, R.C. and J. Haydu. 1995. Cyclic microirrigation in container-grown landscape plants improve plant growth and water conservation. J. Environ. Hort. 13:6-11.

Beeson Jr., R.C. and G.W. Knox 1991. Analysis of efficiency of overhead irrigation in container production. HortScience 26(7):848-850.

Beeson Jr., R.C. and T.H. Yeager. 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. HortScience 38(7):1373-1377.

Doltra, J., J.A. Oncins, J. Bonanay, and M. Cohen. 2007. Evaluation of plant-based water status indicators in mature apple trees under field conditions. Irr. Sci. 25:351–359.

Fare, D.C., C.H. Gilliam, and G.J. Keever. 1992. Monitoring irrigation at container nurseries. HortTechnology 2(1):75:78.

Fernández, J.E., S.R. Green, H.W. Caspari, A. Diaz-Espejo, and M.V. Cuevas. 2008. The use of sap flow measurements for scheduling irrigation in olive, apple and Asian pear trees and in grapevines. Plant and Soil 305:91–104.

Forrai, M., M. Sutorine Dioszegi, M. Ladanyi, P. Hofni, and K. Hrotko. 2012. Studies on estimation of leaf gas exchange of ornamental woody plant species. Appl. Ecol. and Environ. Res. 10(2):195-206.

Fulcher, A.F., 2010. Modeling water use in nursery crops. Univ. of Kent., Lexington PhD Diss. Abstr. 121.

Fulcher, A.F., J.W. Buxton, and R.L. Geneve. 2012. Developing a physiological-based, on-demand system for container production. Sciencia Hort. 138:221-226.

Fulcher, A.F. and R.L. Geneve. 2011. Relationship between photosynthesis and substrate moisture for container-grown *Hibiscus* and *Cornus.* Acta Hort. (ISHS) 922:183-186.

Grant, O.M., M.J. Davies, H. Longbottom, and C.J. Atkinson. 2009. Irrigation scheduling and irrigation systems: optimizing efficiency for container ornamental shrubs. Irr. Sci. 27:139-153.

Green, S.R., M.B. Kirkham, and B.E. Clothier. 2006. Root uptake and transpiration: from measurements and models to sustainable irrigation. Agr. Water Mgt. 86:165–176.

Griffin, J., T.G. Ranney, and D.M. Pharr. 2004. Heat and drought influence photosynthesis, water relations, and soluble carbohydrates of two ecotypes of redbud (*Cercis Canadensis*). J. Amer. Soc. Hort. Sci. 129(4):497-502.

Groninger, J.W., J.R. Seiler, J.A. Peterson, and R.E. Kreh. 1996. Growth and photosynthetic responses of four Virginia Piedmont tree species to shade. Tree Physiol. 16:773-778.

Houston, L.L., M. Watanabe, J.D. Kline, and R.J. Alig. 2003. Past and future water use in Pacific coast states. U.S. Dept. of Agr. Washington D.C.

LeBude, A.V. and T.E. Bilderback. 2007. Managing drought on nursery crops. North Carolina Cooperative Extension, Raleigh, NC. 19 Mar. 2013. <http://www.slideshare.net/Faizah68w/k1b460>.

Marella, R.L. and M.P. Berndt. 2005. Water withdrawals and trends from the Floridan [sic] aquifer system in the Southeastern United States. U.S. Geological Survey. Denver, CO.

Mathers, H.M., T.H. Yeager, and L.T. Case. 2005. Improving irrigation water use in container nurseries. *HortTechnology* 15(1):8-12.

Miralles-Crespo, J. and M.W. van Iersel. 2011. A calibrated time domain transmissometry soil moisture sensor can be used for precise automated irrigation of container-grown plants. HortScience 46(6):889-894.

O'meara, L.M. 2012. Dynamics of water use in *Hydrangea macrophylla* and *Gardenia jasminoides*. Univ. of Ga., Athens, MS Thesis.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Royal Soc. London. 193:120–145.

Priestley, C.H.B. and R.J. Taylor. 1972. On the assessment of the surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100: 81–92.

Singsaas, E.L., D.R. Ort, and E.H. DeLucia. 2001. Variation in measured values of photosynthetic quantum yield in ecophysiological studies. Ocecologia 128:15-23.

State of Oregon. Water Resources Department. Water protection and restrictions. Feb. 20, 2013. < http://www.oregon.gov/owrd/pages/pubs/aquabook_protections.aspx>

Taiz, L. and Zeiger, E., 2006. Plant Physiology, 4th ed. Sinauer, Massachusetts.

Turral, H., J. Burke, and J.M. Faurès. 2011. Climate change, water, and food security. Water Reports, No. 36. Food and Agriculture Organization of the United Nations, Rome. Jan. 23,2013. <http://www.fao.org/docrep/014/i2096e/i2096e.pdf >.

Van Iersel, M.W., S. Dove, J. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45(2):277-282.

Warren, S. and W. Bilderback. 2005. More plants per gallon: getting more out of water. HortTechnology. 15(1):14-18.

Warsaw, A.L., R.T. Fernandez, and B.M. Cregg. 2009. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. HortScience 44(5):1308-1318.

Zinati, G. 2005. Irrigation Management Options for Containerized-Grown Nursery Crops. Rutgers Coop. Res. and Ext., Rutgers University, New Brunswick, NJ.

Appendix

Table 2.1: Photosynthetic light response curve-derived values. Measurements taken on the second fully expanded mature leaf of four woody ornamental species.

Species	Maximum photosynthesis ($\mu mol\ CO_2\ m^{-2}\cdot s^{-1}$)	Light compensation point ($\mu mol\cdot m^{-2}\cdot s^{-1}$)[z]	Quantum light efficiency (Q_{app})[y]	Dark respiration ($\mu mol\ CO_2\ m^{-2}\cdot s^{-1}$)[x]
Cercis chinensis 'Don Egolf'	15.4±1.3b[w]	23.4±2.6	0.065±0.005	-1.85±0.15b
Hibiscus moscheutos 'Pink Elephant'	24.8±1.3a	14.3±2.6	0.061±0.005	-1.04±0.17a
Hydrangea quercifolia 'Alice'	10.3±1.2c	16.3±2.4	0.060±0.004	-1.22±0.14a
Viburnum dentatum 'Ralph Senior'	13.8±1.2bc	23.0±2.6	0.063±0.005	-1.80±0.15b
P value	<.0001	0.0826	0.4837	0.0052

[z]Determined from where the linear portion of the low light curves, i.e., 50, 25, and 10 $\mu mol\cdot m^{-2}\cdot s^{-1}$ values, and the x-axis intersect, when net photosynthetic rate was 0 $\mu mol\cdot m^{-2}\cdot s^{-1}$.

[y]Predicted from the intersection of the regression line for linear portions of low light curves, i.e., 50, 25, and 10 $\mu mol\cdot m^{-2}\cdot s^{-1}$ values, with light intensity levels of 0 $\mu mol\cdot m^{-2}\cdot s^{-1}$.

[x]Calculated from the slope of the regression line for linear portions of low light curves, i.e., 50, 25, and 10 $\mu mol\cdot m^{-2}\cdot s^{-1}$ values.

[w]Means followed by the same letter were not significantly different (Tukey's HSD α=0.05).

Table 2.2: r^2 of regression line, container capacity, and irrigation set point based on the relationship between photosynthesis and volumetric water content for four woody ornamental species.

Species	r^2 values[y]	Container capacity ($m^3 \cdot m^{-3}$)	90% of maximum predicted photosynthesis ($\mu mol\ CO_2\ m^{-2} \cdot s^{-1}$)	Irrigation set point ($m^3 \cdot m^{-3}$)[z]
Cercis chinensis 'Don Egolf'	0.91	0.53	14.6ab[x]	0.38
Hibiscus moscheutos 'Pink Elephant'	0.89	0.51	19.0a	0.34
Hydrangea quercifolia 'Alice'	0.92	0.53	8.5b	0.35
Viburnum dentatum 'Ralph Senior'	0.86	0.53	10.8b	0.35
P value	---	0.8707	0.0017	0.8152

[z]Relationship between photosynthetic rate and VWC were plotted and three parameter sigmoidal curves fit to the data for each of the five plants in each time period. Value representing the average r^2 values of those lines.

[y]Set point to initiate irrigation, driest calculated value that can maintain photosynthesis at 90% of the predicted maximum rate. Average of all the volumetric water content points corresponding to 90% of the maximum predicted photosynthetic rate for each plant. Points were derived from the equation of the sigmoidal curve best fitting the relationship between photosynthetic rate and volumetric water content.

[x]Means followed by the same letter were not significantly different (Tukey's HSD α=0.05).

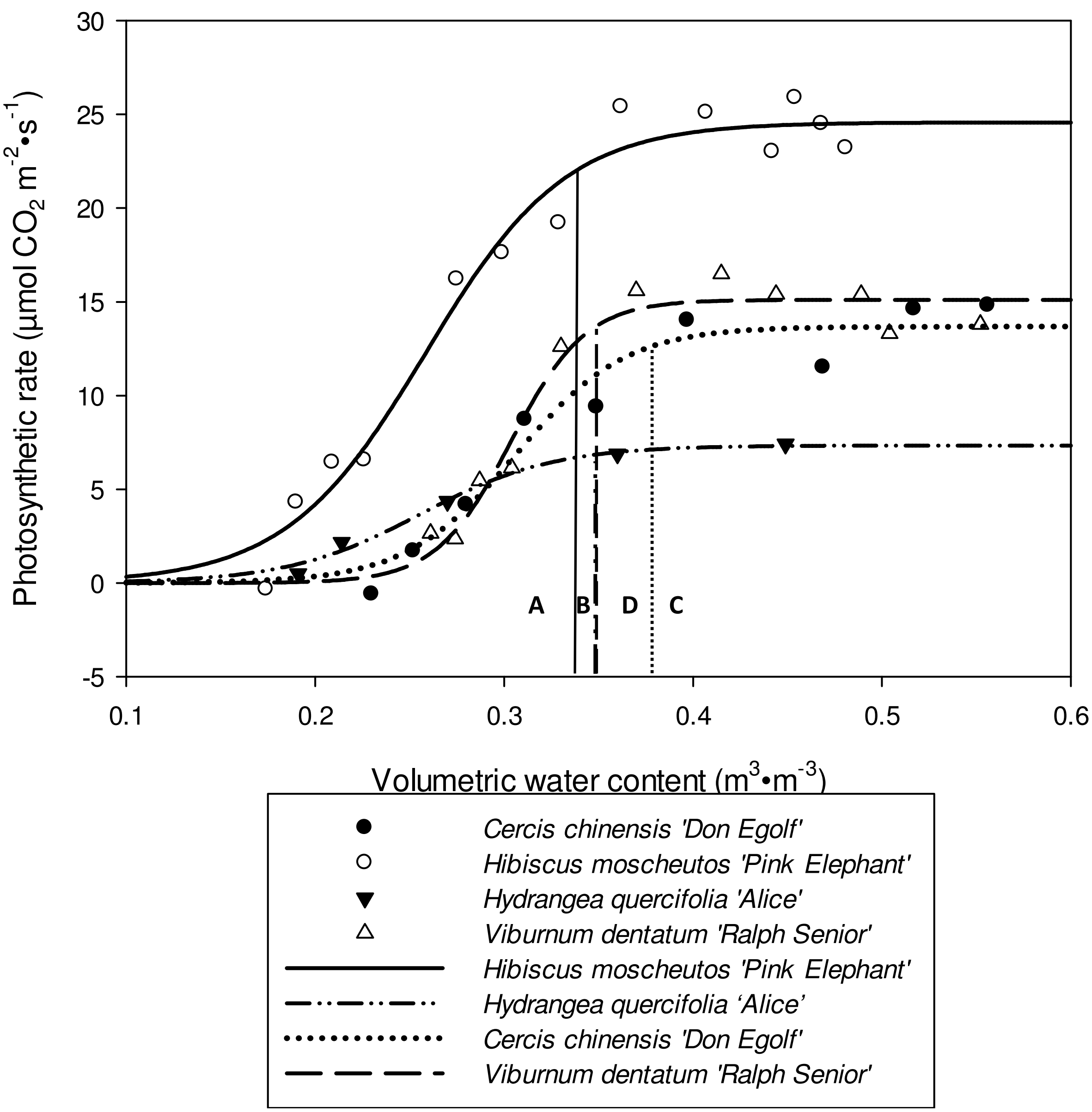

Figure 2.1: Representative examples of the relationship between photosynthetic rate and substrate moisture content for four woody ornamental species. Actual measurements shown as symbols; lines represent the predicted photosynthetic rate. The average set point determined from all samples for each species is shown as the corresponding grey line for comparison. Equations of the regression lines are included where y=photosynthetic rate and θ=volumetric water content: A- 0.34 $m^3 \cdot m^{-3}$ *Hibiscus moscheutos* 'Pink Elephant' {y=24.6/(1+e(-(θ -0.258)/0.037))}, B- 0.35 $m^3 \cdot m^{-3}$ *Hydrangea quercifolia* 'Alice' {y=7.34/(1+e(-(θ -0.256)/0.035))}, C- 0.38 $m^3 \cdot m^{-3}$ *Cercis chinensis* 'Don Egolf'{y=13.67/(1+e(-(θ - 0.306)/0.029))}, and D- 0.35 $m^3 \cdot m^{-3}$ *Viburnum dentatum* 'Ralph Senior'{y=15.1/(1+e(-(θ -0.304)/0.02))}.

Chapter 3

Determining Optimum Sensor Orientation and Depth within an 11.4 L Container to Estimate Whole Container Volumetric Water Content

Abstract

An experiment was conducted to determine which of the five sensor placements best estimates volumetric water content (VWC) in 11.4 L containers and the effect of low VWC on sensor reading variability. Five sensor placements were tested; three sensors were horizontally inserted into the sidewall at 5 cm, 10 cm, and 15 cm from the base of the container and the other two placements were inserted into the substrate surface either vertically or diagonally. All positions showed a strong linear relationship (r^2> 0.92) making them all appropriate models of container substrate moisture. Sensors placed 15 cm above the base had a y-intercept closer to zero than sensors at 5 cm from the base, vertical and diagonal, but the slope was less accurate than the other placements. Vertical placement had a more accurate slope than 15 cm from the base, but the y-intercept was significantly further from zero. The substrate was dried to 0.11 $m^3 \cdot m^{-3}$ during the experiments and became hydrophobic. This substantially decreased the amount of water that could be held at container capacity and increased sensor variability. No placement proved better than the others, but choosing a vertical placement is most practical for sensor calibration, installation, and removal.

Keywords: capacitance, irrigation, nursery, substrate water content

Introduction

Soil moisture sensors and other environmental sensors are now becoming affordable. Therefore, utilization of these technologies is no longer restricted to research applications. Recently, commercial agricultural producers have begun adopting sensors to guide management decisions (Rundel et al., 2009). These sensors have the potential to allow growers to utilize more precise irrigation practices that improve efficiency and reduce water use. The traditional use of static timers to apply irrigation is often extremely wasteful (Fare et al. 1992; Grant et al., 2009) and lacks the benefits of a dynamic, sensor-based system that adjusts for day-to-day changes in plant water requirements. Warsaw and Fernandez (2009) showed that using a soil moisture sensor to calculate daily water use and manually watering the plants to return them to container capacity reduced water use up to 70% as compared to conventional irrigation scheduling. Further, the method in Warsaw and Fernandez (2009) did not affect plant size. Using an automated system based on moisture sensor measurements to calculate and apply irrigation has shown to be a precise and effective method to maintain a consistent substrate moisture, thus preventing plants from experiencing drought stress while eliminating leachate from excess irrigation (Garland et al., 2012; Kim et al., 2011; Miralles-Crespo and van Iersel, 2011; van Iersel et al., 2010). Utilizing this type of automated control can result in water savings of 60-85% compared to conventional irrigation practices, without reducing plant growth as long as an appropriate VWC is maintained (van Iersel et al., 2009). Water savings increase as the substrate moisture content level at which irrigation is triggered is lowered, but a minimum threshold exists below which growth inhibition occurs (Fulcher et al., 2012; van Iersel et al., 2009; van Iersel et al., 2010).

The efficacy of sensor-based systems is entirely dependent on the accuracy of measurements; in this case, soil moisture capacitance readings. Capacitance sensors measure the dielectric constant of the substrate, or the ability of molecules in the surrounding substrate to hold a charge when an electric field is projected into the soil. Water particles readily store and transmit the projected electric charge, whereas almost all other substrate components carry the charge extremely weakly, so the dielectric constant is an effective basis to determine volumetric water content (VWC) (Decagon Devices Inc., 2010). However, the effective range of the electric field is limited; approximately a 2 cm radius from the sensor, so accuracy of the readings is susceptible to the inherent variability of water content found within nursery containers (Daniels et al., 2012).

Many types and sizes of both organic and inorganic substances are mixed to create substrates for the horticulture industry. Water status in a substrate is affected by amount of pore space, size of pores, and attraction between water and the substrate (Drzal et al., 1999). These properties not only vary between substrate mixes, but also vary within a container creating localized differences in water content and availability (Drzal et al., 1999). Within a container, a hydraulic gradient forms in the substrate because of the opposing forces of gravity and capillary action (Bilderback and Fonteno, 1987). This gradient results in a perched water table or saturated zone at the bottom of the container that occurs regardless of container size or how many drainage holes are made (Bilderback and Fonteno, 1987; Spomer, 1980). Often, few or no roots grow in this saturated part of the container until a plant has become well established or pot-bound and therefore, sensors placed entirely in this zone will give inaccurately high measurements that do not reflect the substrate moisture content the plant experiences. Any irrigation regime relying on such a placement would expose the plant to moisture stress long before the sensor indicated suboptimal moisture content. In contrast, artificially low moisture readings from sensors placed near large air pockets or dry areas can result in overwatering and decreased water savings. Uneven drying, hydrophobic pockets, settling, and large particles wedging between the sensors tines are additional concerns that could result in sensor readings that are not representative of the whole container substrate moisture content.

Sensor placement is an often overlooked variable, but the abovementioned factors make placement of substrate moisture sensors, both orientation to the surface and depth in substrate, crucial when trying to obtain accurate substrate moisture measurements. Often, sensor placement within a container is not mentioned (Nemali and van Iersel, 2006; van Iersel et al., 2009). When mentioned, sensor orientation varies: perpendicular (Fulcher et al., 2012; Fulcher and Geneve, 2011), 45° angle (van Iersel et al., 2010), and horizontal (Burnett and van Iersel, 2008) have all been used. Similarly, depth of sensor placement in the substrate profile is rarely discussed. Daniels et al. (2012) recommend a consistent sensor depth in all containers because of a strong linear gradient increasing from low to high VWC with increasing depth within the container. However, Daniels et al. (2012) did not investigate the best orientation for the sensors. This illustrates the need for research into the effects of sensor orientation and depth on the accuracy of substrate moisture readings. The objectives of this experiment were to: 1) determine the sensor placement that most accurately reflects the whole container water status for an 11.4 L container; and 2) document the variation that low substrate moisture levels may introduce into sensor-based systems.

Materials and Methods

Hibiscus moscheutos L. 'Pink Elephant' (common mallow) cuttings were taken from established stock plants on 19 Aug. and 2 Sept. 2012, dipped in 3000 mg kg^{-1} KIBA (Hormodin®2, E.C. Geiger Inc., Harleysville, PA), and stuck in a 1 perlite : 1 sphagnum moss substrate mix (by volume, Pro-Moss TBK, Premier Tech Horticulture, Rivière-du-Loup, Québec, Canada). Cuttings were placed under mist for 6 weeks until rooted. The cuttings were planted in 11.4 L plastic nursery containers (C1200, Nursery Supplies Inc., Chambersburg, PA) with 85% pine bark : 15% sphagnum peat moss substrate (by volume, Renewed Earth, Inc., Kalamazoo, MI) on 6 and 22 Oct. 2012. Substrate physical properties were as follows: 89.9% total porosity, 61.3% container capacity, 28.6% air space, and 0.16 g/cc bulk density. One week after transplanting, plants were top-dressed with 19N-1.75P-11.6K, a5-6 month controlled release fertilizer with micronutrients (Polyon®, Harrell's Inc., Lakeland, FL) at 53 g per container (medium label rate). Root proliferation was periodically monitored in a cohort of plants that were not included in the experiment to determine root establishment. Plants were hand watered until roots reached the container sidewall. At this point, EC-5 capacitance sensors (Decagon Devices Inc., Pullman, WA) were installed in each container and wired to a multiplexer (AM 16/32, Campbell Scientific, Logan, UT) that was connected to a datalogger (CR1000, Campbell Scientific). The datalogger was programmed to read mV output from the EC-5 sensors and convert that value to VWC based on a previously determined substrate-specific calibration for each sensor (Appendix I). Sensor measurements were made every 15 sec and averages were recorded every 15 min.

Five different sensor placements were tested (Fig. 3.1, see Appendix). Horizontal sensor placements in positions 1-3 were 5 cm, 10 cm, or 15 cm from the base of the container to the sensor overmold/wire junction. There were 5 cm between the highest sensor placement and the substrate surface. Small vertical slits were cut into the sides of the containers so sensors could be horizontally inserted 2.5 cm past the overmold with the narrow aspect facing up. Duct tape was placed around the slits to prevent water and air movement through the opening. The fourth placement was half the distance from the center of the container to the sidewall, vertically inserted with the wide aspect of the sensor parallel to the sidewall. The sensor was installed to a depth such that the overmold/wire junction was 2.5 cm below the substrate surface. The fifth placement was also inserted in the surface of the container, half the distance from the center to the sidewall also such that the overmold was 2.5 cm below the substrate surface. This placement differed by orienting the sensor at a 45° angle with the wide aspect perpendicular to the sidewall to prevent water pooling on the tine blades. The sensors' projected capacitance fields have an effective range of 2 cm radius (Decagon Devices Inc., 2009). Therefore, the minimum distance between any parts of two sensors exceeded 5 cm to ensure there was no interference between the sensors. The experiment was conducted from 29 Nov. 2012 to 13 Dec. 2012 and from 14 Dec. 2012 to 29 Dec. 2012 in a controlled greenhouse environment in Knoxville, TN at the University of Tennessee North Greenhouse (35.946°N, -83.939°W).

To initiate the experiment, containers were hand watered and allowed to drain to container capacity. Once drained, the containers were weighed and substrate surface level marked. Water was withheld and the weight of each container was then recorded daily until plants wilted. When wilting was apparent, final weights were recorded at an average VWC of 0.11±0.01 $m^3 \cdot m^{-3}$. To examine objective 2, plants were then hand watered and drained for 1 h to remove all gravitational water, returning containers to 100% container capacity before being weighed. Substrate was dried in an oven at 45°C until all moisture was removed as determined by periodic gravimetric measurements indicating no further weight change. Substrate volume was determined as the volume of water required to fill the container to the substrate level marked when fully hydrated. Actual substrate VWC for any given measurement during the experiment was calculated as the weight of water (difference between substrate weight and final dry mass) divided by the total substrate volume.

Five sensor placements were tested in eight replicate containers. The experiment was repeated using eight plants from the second cutting date to ensure both trials contained plants of the same age. Individual regression lines were fitted to the relationship between VWC estimated by sensors and VWC calculated gravimetrically for each sensor using PROC REG in SAS® Version 9.3 (SAS Institute Inc., Cary, NC). A MANOVA was conducted on the slope, y-intercept, and r-square values of the regression lines and means were separated using Tukey's HSD (*P* value=0.05). Data were analyzed as a randomized complete block, blocked by time period. Block effect was not significant so data were pooled. Placements were statistically analyzed against each other and evaluated based on the perfect relationship between measured and gravimetric VWC: a line with slope=1, *y*-intercept=0, and r^2= 1.0.

Results

A linear relationship was observed for all sensor placements; r^2 values exceeded 0.92 and were not different for all placements (Table 3.1; Fig. 3.2). Sensor placement did affect the relationship between sensor-estimated and gravimetrically determined VWC; slopes and y-intercepts of the regression lines were different among sensor placements (Table 3.1). A slope of 1.0 was considered ideal for the model. Sensors placed 15 cm from the container base had a slope of 0.739, which differed from that of sensors placed vertically and 10 cm from the base at 0.904 and 0.888, respectively, but not from the diagonal or 5 cm from the base placements, 0.809 and 0.836, respectively. An ideal y-intercept for the relationship between sensor-estimated and gravimetrically determined VWC is zero. The y-intercept for sensors placed 15 cm from the base differed from vertical, diagonal, and 5 cm from the base, 0.042 compared to 0.117, 0.122, and 0.101 $m^3 \cdot m^{-3}$, respectively (Table 3.1)

Two placements' initial sensor readings differed from the gravimetrically determined VWC at 100% container capacity, 0.49 $m^3 \cdot m^{-3}$ (Table 3.2). VWC for sensors in the vertical placement, 0.55 $m^3 \cdot m^{-3}$, was greater than that for the gravimetric determination and VWC for sensors 15 cm from the base was lower, 0.43 $m^3 \cdot m^{-3}$. All other positions were not different from the actual VWC. Plants reached an average gravimetric VWC of 0.11 $m^3 \cdot m^{-3}$ at their driest, before rehydration. At the driest point during the experiment sensor placements 5 cm from the base, vertical, and diagonal, 0.18, 0.20, and 0.20 $m^3 \cdot m^{-3}$, respectively, measured greater VWC than the actual, 0.11 $m^3 \cdot m^{-3}$ (Table 3.2). Sensors at 10 and 15 cm from the base were not different from gravimetric readings. The differences between initial and terminal 100% container capacity readings were significant for all placements. A reduction in container capacity sensor readings of 27-44% was observed after the substrate dried and was rehydrated to 100% container capacity. This corresponded with a decrease in actual container capacity of 51%, from 0.49 to 0.24 $m^3 \cdot m^{-3}$, as determined gravimetrically (Table 3.2). Following rehydration, sensor readings were greater than the gravimetric VWC of 0.24 $m^3 \cdot m^{-3}$ for all positions except 10 and 15 cm from the base, which were not different at 0.32 and 0.24 $m^3 \cdot m^{-3}$, respectively (Table 3.2).

Sensor variation was also assessed. The average difference of individual sensor VWC readings from the actual, gravimetrically-determined VWC at initial container capacity were not different among placements and fell within the range of 0.04-0.07 $m^3 \cdot m^{-3}$ (Table 3.3). Following rehydration, the two placements nearest the substrate surface, vertical and diagonal placements, had greater differences in sensor readings, 0.15 and 0.14 $m^3 \cdot m^{-3}$, than sensors 15 cm from the base, 0.07 $m^3 \cdot m^{-3}$ (Table 3.3).

Placements 5 and 10 cm from the base did not differ from other placements. Comparing container capacity readings at the initiation of the experiment to those measured following rehydration showed an increase in variation from the gravimetric determination in all placements except 15 cm from the base (Table 3.3).

Discussion

Our goal was to identify the sensor placement within a container that most accurately measured VWC. Practically speaking, all positions showed a strong linear relationship ($r^2 > 0.92$) making them all appropriate models of container substrate moisture (Table 3.1). Calibration adjustments could be made for any of the positions and programmed into a system to account for the differences in both slope and intercept. Sensors placed 15 cm above the base had a y-intercept closer to zero than sensors at 5 cm from the base, vertical and diagonal, but the slope was less accurate than two other placements (Table 3.1). Vertical placement had a more accurate slope than 15 cm from the base, but the y-intercept was significantly further from zero (Table 3.1). However, vertical placement appears to be the best choice because it closely follows the rate at which container moisture changes, as shown by its slope, and would be the simplest position for sensor calibration, installation, and removal when plants are sold. Sensors in the vertical placement would estimate a VWC consistently higher than the actual VWC, but by programming the datalogger-based irrigation system to subtract the y-intercept value determined in this experiment from all measurements, accurate VWC values can be obtained throughout the range experienced by plants.

Efforts are made to prevent substrate drying to the point of wilting, but it is not uncommon for plants to wilt at least once during production due to human error, equipment malfunction, or extreme conditions. Pine bark-based substrates have a tendency to become hydrophobic if allowed to dry (Beardall and Nichols, 1982; Lamack and Niemiera, 1993; Warsaw et al., 2009) and present a problem for conservative irrigation regimes. Substrates that are hydrophobic are less able to retain water, shedding rather than absorbing it, which can increase irrigation requirements. Water channeling within hydrophobic bark increases run off and decreases irrigation efficiency (Beeson and Haydu, 1995; Warsaw et al., 2009; Warren and Bilderback, 2005). While plants can tolerate a VWC below container capacity without experiencing water stress, the substrate's physical properties are less robust and the drier they become the more likely hydrophobicity will develop and reduce the amount of water the substrate can hold. The substrate used in this experiment was hydrophobic when dried to 0.11 $m^3 \cdot m^{-3}$, reducing the amount of water the substrate held by 51% when irrigated again back to container capacity (Table 3.2). The containers held an average of 2.25 kg less water at container capacity after drying, a 36% decrease in total weight from 6.23 to 3.98 kg. These results underscore the dramatic effect that even a single drying event can have on the ability of a substrate to serve as a water reservoir and the impact on the effectiveness of sensor-based automated programs.

The presence of hydrophobic pockets in the substrate could have also contributed to the increase in sensor variation after the substrate was allowed to dry and subsequently rehydrated, observed in four out of five positions (Table 3.3). The only position that sensor variation did not increase was 15 cm from the base, but was highest for vertical and diagonal placements. Reducing sensor accuracy increases the chance that plants experience water stress from irrigation errors, decreasing crop quality and extending the production time. Operating deficit-based irrigation would increase the probability of stress occurring from error because by definition it is operating closer to the wilting point and likely does not allow as much time for growers to recognize and correct an error as conventional irrigation. Some placements also indicated the substrate was wetter than the gravimetrically determined 100% container capacity measured at the initiation and termination of the experiment, following rehydration. Using overestimated values for an automated system that determined irrigation timing based on VWC would delay irrigation, allow the substrate to dry beyond the point at which plants experience stress, and increase the risk of hydrophobicity. While hydrophobicity can help explain the increase in variability, it does not explain the variation in container capacity values observed at the initiation of the experiment. There does not appear to be any clear pattern in the differences of the five placements' VWC readings from the actual gravimetrically-determined VWC at initial 100% container capacity compared to the differences observed after drying and rehydration. Whether this is due to heterogeneous water distribution and/or plant water uptake, these data seem to indicate variability in sensor-container systems limit the level of precision that can be obtained with sensor-reliant irrigation scheduling.

Bilderback and Fonteno (1987) state that the combination of substrate and container effects determine the hydrologic properties and should always be considered as a unit and not as individual factors. Both the unique physical characteristics of each substrate and the effects of container size and shape on hydraulic properties must be taken into consideration when utilizing sensors to measure substrate moisture content. The bottom of a container acts similar to an impervious layer in soil and creates a perched water table, or zone of saturation, on the bottom of the container (Bilderback and Fonteno, 1987). A hydraulic gradient forms above the water table with the substrate surface drier than deeper regions of the container profile (Bilderback and Fonteno, 1987; Daniels et al., 2012). The height of the water table and subsequent gradient is highly variable and dependent on both the physical properties of the substrate and the container size and height. As a result, the optimal height of sensor placement determined for this container/substrate combination is most likely not optimal in containers of different heights or different substrates in the same size container. Therefore, further research is needed on the effects of substrate physical properties and container size and shape on accuracy of sensor position.

All sensor positions proved to be accurate models of substrate moisture, but the vertical position is also the most practical placement for calibrating, installing, and removing at harvest. While all placements were effective for this substrate and container dimensions, it may be different for other substrate-container combinations. More research is needed to confirm if the vertical placement will consistently have the same relationship between sensor-measured and actual VWC in different containers and substrates. Attention should also be paid to the effect of irrigation programs on substrate physical properties. Using an irrigation system that allows substrates to dry excessively can decrease the water-holding capacity of the substrate, as well as decrease accuracy of sensor measurements. Both reduced water-holding capacity and measurement accuracy can have drastic impacts on the effectiveness of conservative automated irrigation systems relying on consistent container capacity values and sensor measurements to schedule irrigation.

Acknowledgements: The authors wish to thank Wesley Wright, Phil Flanagan, Lori Osborne, and Whitney Yeary, Harrell's Inc., Walters Gardens, and Renewed Earth Inc., for their contributions as well as funding from Tennessee Agricultural Experiment Station.

Literature Cited

Beeson, R.C. and J. Haydu. 1995. Cyclic microirrigation in container-grown landscape plants improve plant growth and water conservation. J. Environ. Hort. 13:6-11.

Beardall, D.V. and D.G. Nichols. 1982. Wetting properties of dried out nursery container media. Sci. Hort. 17:49-59.

Bilderback, T.E. and W.C. Fonteno. 1987. Effects of container geometry and media physical properties on air and water volumes in containers. J. Environ. Hort. 5:180–182.

Burnett, S.E. and M.W. van Iersel. 2008. Morphology and irrigation efficiency of *Gaura lindheimeri* grown with capacitance sensor-controlled irrigation. HortScience 43:1555–1560.

Daniels, A.B., D.M. Bernard, P.L. Chapman, and W.L. Baurle. 2012. Optimizing substrate moisture measurements in containerized nurseries. HortScience 47(1):98-104.

Decagon Devices Inc. 2009. EC-5 Volume of Sensitivity. 23 Apr., 2013. <http://www.decagon.com/assets/Uploads/EC-5-Volume-of-Sensitivity.pdf>.

Decagon Devices Inc. 2010. Virtual seminar: Why does my soil moisture sensor read negative? How accuracy of dielectric soil moisture sensors can change your data. Feb., 2013. <http://www.decagon.com/education/virtual-seminar-why-does-my-soil-moisture-sensor-read-negative-how-accuracy-of-dielectric-soil-moisture-sensors-can-change-your-data-set/>.

Drzal, M.S., W.C. Fonteno., and K.D. Casse 1999. Pore fraction analysis: A new tool for substrate testing. Acta Hort. 481.

Fare, D.C., C.H. Gilliam, and G.J. Keever. 1992. Monitoring irrigation at container nurseries. HortTechnology 2(1):75:78.

Fulcher, A.F., J.W. Buxton, and R.L. Geneve. 2012. Developing a physiological-based, on-demand system for container production. Sciencia Hort. 138:221-226.

Fulcher, A.F. and R.L. Geneve. 2011. Relationship between photosynthesis and substrate moisture for container-grown *Hibiscus* and *Cornus.* Acta Hort. (ISHS) 922:183-186.

Garland, K.F., S.E. Burnett, M.E. Day, and M.W. van Iersel. 2012. Influence of substrate water content and daily light integral on photosynthesis, water use efficiency, and morphology of *Heuchera americana.* J. Amer. Soc. Hort. Sci. 137(1):57-67.

Grant, O.M., M.J. Davies, H. Longbottom, and C.J. Atkinson. 2009. Irrigation scheduling and irrigation systems: optimizing efficiency for container ornamental shrubs. Irr. Sci. 27:139-153.

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin. 2009. Estimated use of water in the United States in 2005. U.S. Geological Survey, Reston, VA. Circular 1344:52.

Kim, J., M.W. van Iersel, and S.E. Burnett. 2011. Estimating daily water use of two petunia cultivars based on plant and environmental factors. HortScience 46(9):1287-1293.

Lamack, W.F. and A.X. Niemiera. 1993. Application method affects water application efficiency of spray stake-irrigated containers. HortScience 28(6):625-627.

Miralles-Crespo, J. and M.W. van Iersel. 2011. A calibrated time domain transmissometry soil moisture sensor can be used for precise automated irrigation of container-grown plants. HortScience 46(6):889-894.

Nemali, K.S. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. Scientia Hort. 110:292–297.

Rundel, P.W., E.A. Graham, M.F. Allen, J.C. Fisher, and T.C. Harmon. 2009. Environmental sensor networks in ecological research. New Phytologist 182:589-607.

Spomer, L.A. 1980. Container soil water relations: production maintenance, and transplanting. J. of Arboriculture 6(12):315-320.

Van Iersel, M.W., S. Dove, J. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45(2):277-282.

Van Iersel, M., Seymour, R.M., Chappell, M., Watson, F. and Dove, S. 2009. Soil moisture sensor-based irrigation reduces water use and nutrient leaching in a commercial nursery. Proc. Southern Nursery Assoc. Res. Conf. 54:17-21.

Warren, S. and W. Bilderback. 2005. More plants per gallon: getting more out of water. HortTechnology. 15(1):14-18.

Warsaw, A.L., R.T. Fernandez, and B.M. Cregg. 2009. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. HortScience 44(5):1308-1318.

Appendix

Table 3.1: Analysis of five sensor placements in an 11.4 L container. The 5 cm, 10 cm and 15 cm from the base were inserted horizontally through a cut in the side; vertical and diagonal were inserted into the substrate surface. Regression lines were calculated for the relationship between each sensor's volumetric water content measurement and the gravimetrically calculated volumetric water content of the container. Slope, y-intercept, and r^2 values shown are the mean values for each sensor placement. n=40. $VWC_{grav} = m \cdot VWC_{sensor} - b$.

Sensor position	r^2	Slope	y-Intercept
Horizontal 5 cm from base	0.986	0.836ab[z]	0.101b
Horizontal 10 cm from base	0.981	0.888b	0.084ab
Horizontal 15 cm from base	0.923	0.739a	0.042a
Vertical	0.986	0.904b	0.117b
Diagonal	0.980	0.809ab	0.122b
P value	0.3612	0.0148	0.0012

[z]Means followed by the same letter were not significantly different (Tukey's HSD α=0.05).

Table 3.2: Comparing actual, gravimetric VWC to sensor VWC readings for five sensor placements. Plants were watered to container capacity, allowed to dry to wilting, 0.11 $m^3 \cdot m^{-3}$, and then rehydrated back to container capacity. VWC was recorded for 100% container capacity at initiation, at the driest point when plants were wilting, and for 100% container capacity at termination of the experiment. *n*=40.

	Stage of experiment				
Sensor position	Initiation of experiment ($m^3 \cdot m^{-3}$)	Wilting point ($m^3 \cdot m^{-3}$)	Termination of experiment ($m^3 \cdot m^{-3}$)	Decrease in container capacity[z] (%)	*P* value
Actual gravimetric VWC	0.49bA[yx]	0.11cC	0.24bB	51	<.0001
5 cm from base	0.50bA	0.18abC	0.34aB	32	<.0001
10 cm from base	0.51abA	0.16abcC	0.32abB	37	<.0001
15 cm from base	0.43cA	0.12bcC	0.24bB	44	<.0001
vertical	0.55aA	0.20aC	0.39aB	29	<.0001
diagonal	0.52abA	0.20aC	0.38aB	27	<.0001
P value	<.0001	<.0001	<.0001	---	---

[z]Percent reduction in 100% container capacity values between initiation and termination of experiment. The substrate was dried to 0.11 $m^3 \cdot m^{-3}$ during the experiment before rehydration at experiment termination.

[y]Means in the same column followed by the same lowercase letter were not significantly different (Tukey's HSD α=0.05).

[x]Means in the same row followed by the same uppercase letter were not significantly different (Tukey's HSD α=0.05).

Table 3.3: Variation in sensor VWC readings calculated as the average difference between sensor readings and gravimetric VWC at 100% container capacity. Five sensor placements were evaluated both at the initiation of the experiment and at termination following rehydration. Containers were watered to container capacity, allowed to dry to an average of 0.11 $m^3 \cdot m^{-3}$, and then rehydrated to container capacity. *n*=40.

Sensor position	Beginning of experiment ($m^3 \cdot m^{-3}$)	Termination after rewetting ($m^3 \cdot m^{-3}$)	*P* value
5 cm from base	0.06B[z]	0.11abA[x]	0.0292
10 cm from base	0.04B	0.09abA	0.0008
15 cm from base	0.07A	0.07bA	0.9111
vertical	0.07B	0.15aA	0.0008
Diagonal	0.05B	0.14aA	<.0001
P value	0.1066	0.0067	

[z]Means in the same row followed by the same uppercase letter were not significantly different (Tukey’s HSD α=0.05).

[x]Means in the same column followed by the same lowercase letter were not significantly different (Tukey’s HSD α=0.05)

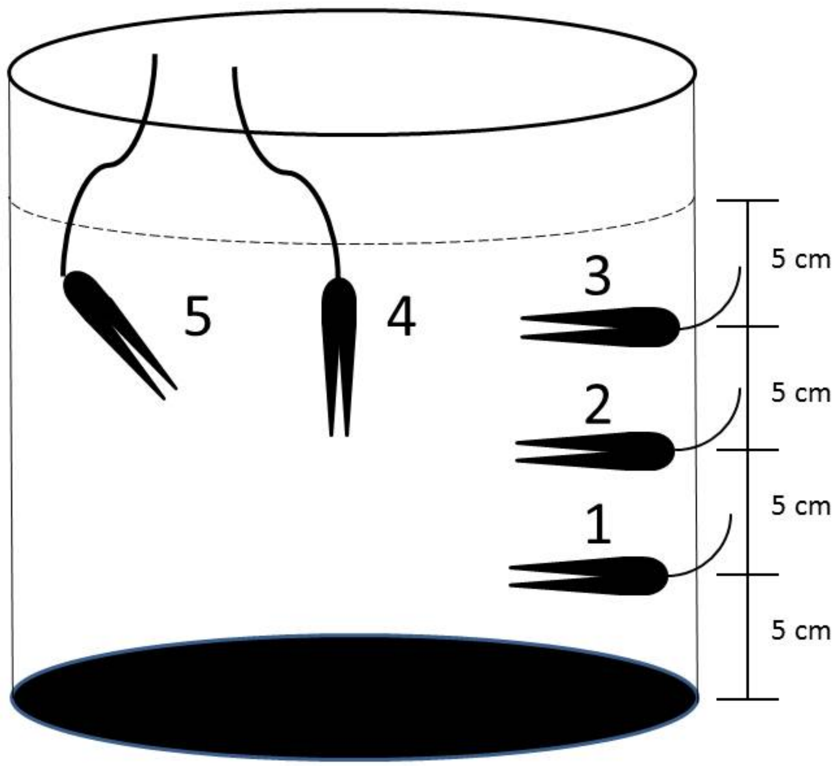

Figure 3.1: The positions and orientations of the five sensor placements: 1) 5 cm from base 2) 10 cm from base 3) 15 cm from base 4) vertical at the surface 5) 45° diagonal at the surface.

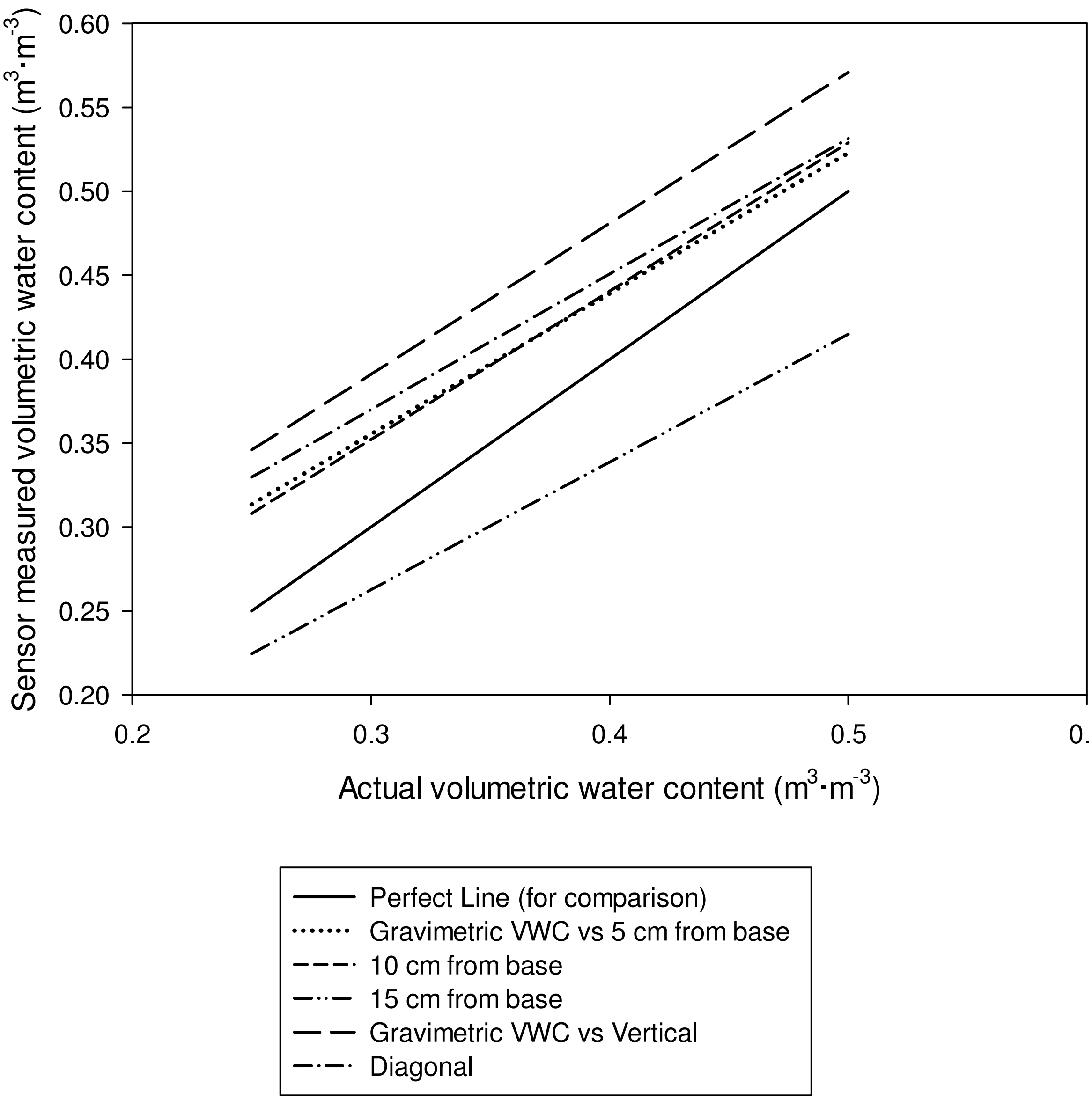

Figure 3.2: Regression lines representing the relationship between capacitance sensor measurement and actual volumetric water content for five sensor placements. Actual volumetric water content was determined gravimetrically. Placements tested were measured 5 cm, 10 cm and 15 cm from the base of the container and inserted horizontally through a cut in the side as well as vertical and diagonal insertions into the surface of the substrate. Equations of the lines are as follows where y=sensor-measured VWC (θ) and x=gravimetrically determined VWC: 5 cm from base y=0.836x-0.101, 10 cm from base y=0.888x-0.084, 15 cm from base y=0.739x-0.042, vertical y=0.904x-0.117, and diagonal y=0.98x-0.122. For comparison, the perfect relationship is shown as a solid line: slope=1, y-intercept=0, and r^2=1.

Chapter 4

Comparing Substrate Moisture-Based Daily Water Use and On-Demand Irrigation Regimes for Oakleaf Hydrangea Grown in Two Container Sizes

Abstract

Independently controlled irrigation plots were designed to test two container nursery irrigation regimes on oakleaf hydrangea (*Hydrangea quercifolia* 'Alice') in both nursery and controlled greenhouse environments. The experiments were conducted in both 3.8 and 11.4 L containers. Plants were automatically irrigated by one of two soil moisture sensor-based regimes: 1) a daily water use (DWU) system that delivered the exact amount of water that had been lost in the previous 24 h and 2) an On-Demand (OD) irrigation system based on a specific substrate moisture content derived from the relationship between substrate moisture and photosynthetic rate. In this system, irrigation was applied when the substrate moisture level fell below 33% container capacity, which corresponded to 90% maximum predicted photosynthetic rate. Both treatments delivered the volume of water required to return the containers to container capacity by overhead irrigation except that the DWU system was static, irrigating once per day, while OD was dynamic and irrigated whenever the substrate moisture reached the 33% threshold level. Gas exchange was measured at the driest point prior to the next irrigation event. Periodical growth index, water use, and final dry weight were recorded. OD generally used less water than DWU and had either no or a positive impact on biomass in all but one trial. For 3.8 L plants, photosynthesis and gas exchange were consistently greater when irrigated by the OD program. Both treatments used significantly less water than the industry standard of 2.5 cm per day. This research demonstrated that both DWU and OD are a dramatic improvement over conventional irrigation scheduling and could be adopted as conservative irrigation systems for nursery production.

Keywords: water deficit, capacitance sensors, conservative irrigation, nursery crops, photosynthesis

Introduction

Water scarcity is a growing concern across the globe and is projected to become more severe due to increases in population growth, urbanization, and per capita consumption as well as changing water availability due to climate change (Food and Agricultural Organization of the United Nations, 2007). Irrigation withdrawals account for over 70% of all freshwater used (Food and Agricultural Organization of the United Nations, 2007) and produce over 40% of the world's food supply (Turral et al., 2011). This shows the vulnerability of agriculture to water scarcity, but it also highlights how improvements in irrigation could have a large impact on reducing overall agricultural water use and preventing water scarcity. Nursery irrigation is particularly inefficient and modifying irrigation practice is necessary as legislation continues to tighten restrictions on water use. Florida, California, Texas, and Oregon are just a few examples of major nursery states that now face irrigation restrictions (Ackerman and Stanton, 2011; Beeson, et al. 2004; Beeson and Brooks, 2008; Houston et al., 2003; Marella and Burndt, 2005; State of Oregon, 2013).

The most common form of irrigation found in nursery production is overhead sprinklers controlled by timers. Overhead irrigation is extremely inefficient with over 20% of applied irrigation missing the substrate surface under ideal conditions with no wind (Beeson and Knox, 1991). Using static timers for control does not account for day-to-day changes in plant water requirements, often over-irrigating and reducing water use efficiency compared to calculating and returning the substrate to container capacity (Warsaw et al., 2009). Water lost from excessive leachate and from increasing plant spacing further reduces overhead efficiency, with realistic efficiencies typically between 15 to 30% (Beeson and Knox, 1991; Weatherspoon and Harrell, 1980). Most of the excess water is lost as nutrient and pesticide laden runoff that pollutes waterways (Bilderback, 2002; Keese et al., 1994). There are many production benefits that can be obtained from refining irrigation scheduling, which encompasses both volume applied and timing. Refined irrigation systems minimize water and nutrient loss in runoff, which decreases production costs and reduces environmental impact of commercial nurseries (Lea-Cox et al., 2011). Over-irrigation can harm a crop, however, production time and crop losses from disease can be reduced with accurate irrigation. Chappell et al. (2012) showed that the production cycle of common gardenia (*Gardenia jasminoides* Ellis) was reduced by 6 months and typical crop losses of 20-30% were reduced to zero using precision irrigation. Warsaw et al. (2009) calculated and applied the water lost the previous day resulting in a 27-70% decrease in water use without impacting plant growth on a range of taxa. A commercially acceptable irrigation system that would take advantage of these benefits would need to be developed using the following guidelines. It must be: 1) be simple; 2) easily configured to a large number of crops; 3) accurately estimate water use to prevent over and under irrigation (thus conserving water and minimizing leaching); 4) not increase production time compared to current irrigation scheduling; and 5) have the ability to be automated (Fulcher et al., 2012).

There are a number of strategies to refine irrigation such as grouping plants according to water needs, using cyclic irrigation, and decreasing plant spacing (Beeson and Knox, 1991; Grant et al., 2009; Warren and Bilderback, 2005). While these systems reduce water use, they are rudimentary strategies to correct egregious over-application and fall short of expectations for a truly efficient system. Basing irrigation systems on physiological responses shows great potential for meeting the guidelines stated above while maximizing efficiency by adjusting to the daily changes in evapotranspirational demand. It is difficult to use physiological responses, such as wilting, to determine irrigation scheduling because responses often occur only after plant growth is affected (Jones, 2004; Slatyer, 1967). Irrigation must be triggered before the plants are stressed for the system to be effective. An alternative is equation-based irrigation that relies on physiological responses to predict the correct irrigation time and volume, as opposed to programs that are controlled and respond directly to real-time physiological measurements. Automated irrigation systems have been developed for orchards and vineyards using equations based on sap flow (Green et al., 2006; Fernández et al., 2008a; Fernández et al., 2008b) and stem diameter

(Doltra et al., 2007; Velez et al., 2007). However, these physiological measures work effectively on plants with a single trunk and no low branches, but they are ill-suited for many nursery species with multi-stemmed or prostrate stem architecture. Other physiologically-based irrigation systems have shown promise in determining when plants need irrigation based on infrared thermometry or thermal imagery (Diaz-Espejo and Verhoef, 2002; Jones, 1999, 2004; Martin et al., 1994), but these lack the ability to determine the volume to apply and are not readily adapted for crops without a closed canopy. The system developed by Fulcher et al. (2012) and examined in this experiment would be the first physiologically based system for container nursery crops that automates both aspects of precision irrigation scheduling: timing of irrigation and volume of water needed. The objective of this experiment was to compare a physiologically-based, on-demand irrigation regime with a daily water use replacement regime: Irrigating plants when they reach a certain dryness threshold based on the relationship between photosynthesis and substrate moisture content regardless of time of day (On-Demand), and replacing water lost in the previous 24 h at a specified time (daily water use).

Materials and Methods

This research consisted of a series of experiments testing physiologically-based and daily water use irrigation systems, as described below, in both outdoor nursery and controlled environment settings. All trials tested these irrigation systems on Alice oakleaf hydrangea (*Hydrangea quercifolia* Bartr. 'Alice'). Two container sizes (3.8 L and 11.4 L) were used in Lexington, Kentucky (38.105°N, -84.486°W) and Knoxville, Tennessee (35.946°N, -83.939°W), respectively. Trials were conducted in both nursery and greenhouse production settings in both locations.

Irrigation systems

Root proliferation was periodically monitored in a cohort of plants that were not included in the experiment to determine root establishment. Plants were hand watered until roots reached the container sidewall. Once the roots reached the sidewall, irrigation was controlled by an automated system. Substrate moisture levels were measured and controlled using dielectric capacitance sensors (ECHO-5, Decagon Devices Inc., Pullman, WA) connected to a datalogger (CR1000, Campbell Scientific Inc., Logan, UT) with a multiplexer (AM16/32, Campbell Scientific Inc.) and a 16-channel relay controller (SDM-CD16AC, Campbell Scientific Inc.) to operate solenoid valves. Volumetric water content (VWC) values were calculated from mV output and sensor-specific calibration equations in the program (Appendix I). One capacitance sensor per container was installed halfway between the base of the plant and the container sidewall. Sensors were oriented vertically with the broad side of the sensor facing the plant stem and inserted into the substrate so that the sensor overmold/wire junction was 2.5 cm below the surface of the substrate. The VWC of each irrigation zone was calculated by averaging values from three sensors per zone. The datalogger measured VWC every minute and recorded 15-min averages. Water use over the course of the experiment was calculated for each zone based on the amount of time each solenoid remained open and the flow rate, calculated by measuring the volume of water captured in pans during timed trials. A rain gauge was wired to the datalogger for local precipitation data.

The two irrigation systems developed for this experiment were On-Demand (OD), a system with a physiological basis, and daily water use (DWU). Both programs calculated the difference between the instantaneous VWC and container capacity and applied the exact water volume required to return the substrate to 100% container capacity. The main difference between the two systems was the static timing for initiation of irrigation in DWU versus dynamic irrigation scheduling for OD. In OD plots, irrigation was triggered instantaneously when the average sensor reading fell below 0.33 $m^3{\cdot}m^{-3}$ volumetric water content. This value was chosen based on a preliminary experiment that recorded repeated measurements of photosynthetic rate in plants as the substrate became drier (Fulcher et al., 2012) (Appendix III). A sigmoidal curve best described the relationship between photosynthetic rate and VWC. The selected irrigation set point, 0.33 $m^3{\cdot}m^{-3}$, corresponded to the substrate moisture level that supported photosynthesis at 90% of maximum predicted photosynthetic rates (Fig. 4.1, see Appendix). Our hypothesis was that maintaining photosynthetic rate at 90% or greater of maximum rates, growth would not be reduced but substantial water savings could be achieved. Triggering irrigation only when the substrate reached this set point allowed for flexibility in irrigation timing; plants were automatically watered as many times as necessary on high water use days (high evapotranspirational demand), and irrigation was withheld on days of low water use. DWU was irrigated on a static 24-h cycle. Daily water use during the previous 24-h cycle was calculated as the difference between 100% container capacity and the instantaneous VWC measured immediately prior to irrigation. The program multiplied the VWC difference by the container volume and divided by the irrigation flow rate to calculate irrigation time. Examples of irrigation scheduling for each program can be seen in Figure 4.2. Container capacity was determined in preliminary experiments to be 0.53 $m^3 \cdot m^{-3}$ for the Kentucky greenhouse study and 0.50 $m^3 \cdot m^{-3}$ for all other studies. For DWU, an afternoon irrigation time of 1 PM was chosen to allow photosynthetic measurements during the time of day with maximum light intensity. Irrigating in the afternoon ensured that photosynthesis could be measured before irrigation, at the DWU treatment plants' driest point, as it was for OD plants.

For the outdoor experiments, irrigation zones consisted of twelve independently controlled, square irrigation plots of 3.05 m^2, constructed from 1.9 cm PVC pipe (standard ¾") allowing for 0.76 m between each zone. Irrigation was applied with four overlapping sprinklers (Toro® 570 Shrub Spray, The Toro Co., Riverside, CA) per irrigation plot. Emitters were mounted on 1.3 cm diameter risers at a height of 66 cm. There were three replicate irrigation zones and treatment combination for a total of six zones. Controlled environment irrigation systems were different and described for each location below.

Outdoor Experiment

Tennessee

Oakleaf hydrangea rooted cuttings (10.2 cm Spring Meadows Nursery, Grand Haven, MI) were potted into 11.4 L plastic containers on 17 Mar. 2011 and 8 Mar. 2012 (C1200, Nursery Supplies Inc., Fairless Hill, PA) with a 85 pine bark : 15 peat moss (by volume) substrate mix (Renewed Earth, Inc., Kalamazoo, MI). One week after transplanting, plants were top-dressed with 19N-1.75P-11.6K, 5-6 month controlled release fertilizer with micronutrients (Polyon®, Harrell's Inc., Lakeland, FL) at 53 g per container (medium label rate). A wetting agent (Aquagro® L, Aquatrols, Paulsboro, NJ) was applied as a drench of 600 mg/L the second year two weeks after planting to ensure even wetting of the substrate. Eight plants (subsamples) were placed in the center of each irrigation zone in staggered rows of 3-2-3 with 15.25 cm between container sidewalls. Border plants of the same species were spaced around the perimeter of the containers in the experiment to mitigate edge effects.

Leachate was captured with 25.4 cm drip pans (Curtis Wagner Plastics Corp., Houston, TX) on two plants per irrigation zone. The leachate pans were shielded from the overhead irrigation by an inverted 11.4 L plastic container with the bottom removed. EC and pH measurements were recorded every other week. Gas exchange and leaf water potential measurements were taken during the following time periods for 2011: 23-30 Aug., 31 Aug.-6 Sept., 13-20 Sept., and 27 Sept-4 Oct. Time periods for 2012 were as follows: 15-21 July, 22-24 July, 25-29 July, 19-25 Aug., 1-20 Sept., and 25 Sept.-11 Oct. Experiments were conducted from 18 Aug.-3 Oct. 2011 and 27 June-16 Oct. 2012.

Kentucky

On 15 May 2011, rooted cuttings of oakleaf hydrangea were potted into 3.8 L plastic containers (C400, Nursery Supplies Inc.) using the same substrate described for Tennessee. One week after transplanting, plants were top-dressed with 19.0N–2.2P–7.5K controlled release fertilizer with micronutrients (HFI Topdress Special, Harrell's Inc.) at 11 g per container (medium label rate). Fifteen plants were placed in the center of each zone. Border plants of the same species were spaced around the perimeter of the containers in the experiment to mitigate edge effects. EC and pH measurements were recorded biweekly. Gas exchange and leaf water potential measurements were taken during the following time periods for 2011: 29 Aug., 31 Aug., and 12 Sept. The Kentucky nursery trial was conducted from 6 Sept.-7 Oct. 2011.

Controlled Environment Experiment

Tennessee

Oakleaf hydrangea rooted cuttings were potted as previously described into standard 11.4 L containers (C1200, Nursery Supplies Inc.) on 20 Jan. 2012 and 25 Oct. 2012 then grown in a controlled greenhouse environment. Supplemental 1000W HID lights were used to maintain light intensity at 1000-1400 PAR for 12 h per day. They were grown as previously described until their roots reached the side walls of the container.

Independent irrigation lines were constructed in a greenhouse using solenoids (D2 Model 75-2-T-E, Dorot® Control Valves, Fresno, CA) and polyethylene tubing. Each plant was irrigated with individual dribble rings (10" dribble rings, Dramm Corp., Manictowoc, WI). One ring was placed in each container equidistant from the container sidewall. Each time all OD plots were irrigated, all plants were hand fertilized with 500 mL of 400 mg/L of 20N-8.7P-16.6K (Peters Professional® General Purpose 20-20-

20, Scotts Sierra Horticultural Products Co., Marysville, OH) and 100 mg/L wetting agent (Aquagro® L, Aquatrols). The fertilizer treatment was applied after all OD plots had been triggered at least once, ensuring that all zones received fertilizer at the same frequency.

Leachate traps were built from 25.4 cm plastic drip pans and 3/8” aquarium tubing that drained into 2 L plastic soft drink bottles under the greenhouse benches. Sections of 10.1 cm diameter PVC cut 7.5 cm long (standard 4”) were placed in the drip pans to prevent the containers from sitting in leachate. Leachate was captured and measured daily for all plants. Gas exchange and leaf water potential measurements were taken during the following time periods when the experiment was initially conducted: 6-11 May, 20-24 May, 27 May-1 June, and 2-4 June, 2012 and during the following periods when it was repeated; 13-17 Dec., 18-23 Dec., 24-27 Dec., and 28 Dec. 2012-4 Jan. 2013. EC and pH measurements were recorded at the termination of the experiments. There were three replicate irrigation zones per treatment and each zone contained a single row of six plants (subsamples). Greenhouse trials were conducted from 19 Apr. to 4 June 2012 and 21 Dec. 2012 to 9 Jan. 2013.

Kentucky

Oakleaf hydrangea were potted in 3.8 L containers (C1200, Nursery Supplies Inc.), top-dressed with 19.0N–2.2P–7.5K controlled release fertilizer with micronutrients (HFI Topdress Special, Harrell’s, Inc.) at 11 g per container (medium label rate), and were placed in a controlled environment greenhouse under 400 W HPS lights (P.L. Lightsystems, Beamsville, ON, Canada) on a 12 h photoperiod. The experiment was conducted from 8 Nov. 2011 to 2 Jan. 2012. There was one irrigation line per treatment with ten plants per treatment; individual plants were treated as replicates. The containers were irrigated by angle drip stakes via pressure compensating emitters (MOD 4, Netafim, Fresno, CA). Gas exchange was measured on five plants per zone as opposed to the three described for the othertrials; otherwise, data collection methods were similar. Gas exchange and leaf water potential measurements were taken on 4, 7, 9, 10, 11, 15, 16, and 17 of December. EC and pH measurements were recorded weekly.

Data Collection

Photosynthesis, leaf temperature, stomatal conductance, transpiration, and vapor pressure deficit were recorded during the trials using an infrared gas analyzer (LI-6400, LI-COR, Lincoln, NE) at 390 ppm CO_2 and light intensity at 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on the second fully expanded, most recently matured leaf of the three plants (subsamples) within each irrigation zone that contained capacitance sensors. These measurements were only taken when the VWC of the OD treatments was within 5% VWC of the lower irrigation set point, and when it was between 10 AM and 2 PM to ensure light conditions supported maximum photosynthetic rates. Petiole water potential of the second fully expanded, most recently matured leaf was measured immediately following photosynthetic measurements on three plants (subsamples) per plot using a pressurized chamber (Soil Moisture Equipment Corp., Santa Barbara, CA). Because the process required destructive harvesting, plants chosen for water potential measurements were rotated to limit the defoliation to which each individual plant was subjected. Electrical conductivity (EC) and pH measurements of the Tennessee 2012 greenhouse experiment were recorded immediately following an irrigation event using a paste extract method (U.S. Salinity Laboratory Staff, 1954) with a portable meter (HI 9811-5, Hanna Instruments, Smithfield, RI). Measurements in all other experiments followed the pour through method described by Wright (1986).

Growth index was determined at the termination of the experiment using the formula [(plant width A + plant width perpendicular to plant width A + plant height)/3]. Plant height was measured from the base of the plant at the substrate surface to the most distal growth without altering the natural arch of the branches. Plant width was measured at the widest plant span and a second measurement was taken perpendicular to that line, without altering the natural branch architecture. Leaf width was measured on the largest leaf of each plant at the widest point perpendicular to the midrib. Plant foliar quality ratings were assigned on a scale of 1-4. Leaves from the experiment were selected to develop the leaf rating scale where 1=yellowing leaves, blade below 10 cm in length, 2= yellow-green leaves with length between 10-15 cm, 3=green leaves with length between 15-20 cm, and 4=dark green leaves above 20 cm in length. Plant architecture was rated on a scale of 1-5 as: 1= architecture not symmetrical, no upright growth, sparse foliage, 2= not symmetrical, some upright growth, somewhat dense foliage with large gaps in the canopy, sparse, 3= slightly symmetrical, some upright branches, moderately dense foliage with some gaps in the canopy, and 4= mostly symmetrical and upright growth, canopy at least 85% full (gaps in foliage <15%), 5= symmetrical, upright form, foliage uniformly full and dense. For dry weight measurements, the above ground portion of each plant was harvested at ground level and roots were gently hand-washed of substrate. Roots and shoots were dried separately in an oven at 55°C until there was no change in mass (approximately three days). To estimate water use efficiency (WUE) per plant, the total dry weight was divided by total water volume applied, including precipitation.

One of two irrigation regimes was assigned to each zone in a completely randomized design for all experiments. Data were analyzed separately for each season, environment, and location. All data were subjected to an analysis of variance and mean separation (Tukey's HSD α=0.05) using the PROC MIXED procedure in SAS® version 9.3 (SAS Institute Inc., Cary, NC). Individual plants were treated as subsamples and irrigation zones as replicates. Gas exchange, nutrient, and pH data were analyzed as repeated measures.

Results

In 2011, photosynthesis and stomatal conductance of OD were greater than DWU in 3.8 L plants both outside and in controlled environment experiments (Tables 4.1 and 4.2). Photosynthesis of OD and DWU were 10.6 compared to 8.5 µmol CO_2 $m^{-2}\cdot s^{-1}$ outdoors and 10.7 µmol CO_2 $m^{-2}\cdot s^{-1}$ compared to 8.2 µmol CO_2 $m^{-2}\cdot s^{-1}$ in the controlled environment. Stomatal conductance of OD and DWU were 0.108 compared to 0.092 mol H_20 $m^{-2}\cdot s^{-1}$ outside and 0.142 compared to 0.107 mol H_20 $m^{-2}\cdot s^{-1}$ in the controlled environment. For 11.4 L containers, photosynthesis and stomatal conductance were not different in any experiments (Tables 4.1 and 4.2), and neither was leaf water potential or vapor pressure deficit. Leaf petiole water potential, transpiration, and vapor pressure deficit did not differ for either container size in either location.

In 2011, outdoor OD dry weight of 3.8 L containers, 24.0 g, was greater than DWU, 22.9 g, but growth index was not different (Tables 4.3 and 4.4). In the controlled environment, OD had greater biomass and growth index than DWU for 3.8 L plants, 35.3 g versus 29.8 g and 62.8 cm versus 52.1 cm, respectively. In 2011 outside 11.4 L containers, dry weight and growth index of OD, 121 g and 60.6 cm, were less than DWU, 161 g and 70.9 cm respectively, but were not different in 2012 or controlled environment 11.4 L experiments (Tables 4.3 and 4.4). Electrical conductivity and pH were not different in all trials, with the exception of 11.4 L DWU plants having a greater pH in controlled environment experiments in 2012 (Tables 4.3 and 4.4). Foliage quality, plant architecture, and leaf diameter were not measured for 3.8 L trials. Foliage quality in outside trials was not different between OD and DWU; 2.8 and 3.4 in 2011 (*P* value=0.0941) and 2.6 and 3.1 in 2012 (*P* value=0.3046). Plant architecture ratings in outside trials was also not different, 3.5 and 2.8 for OD and DWU in 2012 (*P* value=0.1479). All plants in greenhouse trials received a 4 rating for foliage quality and 5 for plant architecture during both years. Leaf diameter also did not differ between OD and DWU; 14.4 versus 16.3 cm in the 2011 outside trial, 27.5 versus 27.4 cm for 2012 controlled environment, and 24.4 versus 25.6 cm for 2012-2013 controlled environment (*P* values =0.1779, 0.9031, and 0.6936, respectively).

WUE and total water use were affected by irrigation treatment. In the outdoor environment, OD irrigation reduced water consumption and increased WUE for both container sizes with the exception of 11.4 L plants in 2012, when WUE was not different (Table 4.5). Total water use of OD zones in 11.4 L containers was less than DWU outside in both 2011, 20.5 compared to 43.9, and 2012, 5.0 compared to 37.6 L (Table 4.5). Water use of OD in outside 3.8 L containers was also less than DWU, 4.7 and 8.1 L respectively. WUE was greater for OD in 11.4 L containers, 5.9 g/L, than DWU, 3.8 g/L, in 2011 but was not different in 2012. WUE for OD was also higher than DWU in outside 3.8 L containers; 7.4 g/L compared to 3.7 g/L. Greenhouse results were inconclusive; irrigation treatment didn't affect water consumption or WUE in 2012 for 11.4 L plants, but in 2012-13 OD treatment increased water consumption 74% and reduced WUE 81% (Table 4.6). Conversely, for 3.8 L containers in the controlled environment, WUE of OD was greater than DWU, 2.8 compared to 1.7 g/L (Table 4.6). Total leachate volume was not different for any experiment in which it was measured. Leachate per irrigation event was only different for 3.8 L containers in the outdoor environment in 2011 (Table 4.5) in which OD increased leachate compared to DWU, 346 ml and 290 ml, respectively. Precipitation days were defined as days when at least 7 mm of precipitation was recorded. Rainfall was recorded by weather stations located on site at each of the research facilities. In Tennessee, precipitation occurred on 5 of 46 days (11%) in 2011 and 20 of 112 days (18%) in 2012 amounting to a total of 202 and 520 mm, respectively. In Kentucky, precipitation occurred on 13 of 32 days (41%) for a total of 151 mm.

Discussion

There were distinct differences in how the irrigation systems performed in different production environments and container sizes. In 3.8 L containers, OD performed better than DWU with higher gas exchange rates and biomass while simultaneously reducing water use and increasing efficiency in both outdoor and controlled environments. In 11.4 L containers the results were not conclusive. Total water use of OD was less than DWU in outdoor experiments, but growth index and biomass of DWU was greater. In controlled environment trials, there was greater water use for OD or no difference was observed (Tables 4.5 and 4.6). Foliage quality, leaf diameter, and plant architecture were not impacted in 11.4 L containers and were not evaluated in 3.8 L containers. While plants are likely to grow to a smaller size in a smaller container and larger in a larger container, smaller containers hold less water and dry out quicker, especially for a hydrophilic plant such as oakleaf hydrangea. The 11.4 L containers hold more water and appear better able to serve as reservoirs, even though plants are generally much larger. This resulted in more frequent irrigation for the OD treatment in 3.8 L containers than in 11.4 L, which may explain the differences in OD performance between the two sizes. For 11.4 L plants, DWU was not different (outside 2012 and greenhouse both years) or had higher (outside in 2011) biomass compared to OD (Tables 4.3 and 4.4). DWU had 104% greater mass in 2012 but was not significant (SE=13.2), likely due to hail damage in July causing high variability compared to 2011 (SE=9.4). However, greater biomass did not correspond to higher photosynthetic rates in 11.4 L plants (Table 4.1). Taiz and Zigler (2002) describe how photosynthesis is less sensitive to moisture deficit than growth because it isn't turgor dependent, unlike cell growth and expansion, which may explain the difference in results.

The greatest difference observed between treatments was in water consumption. In outside experiments, DWU used 72 to 751% more water and decreased WUE by 36 to 65% in both container sizes (Table 4.5). Leachate per event was affected by the irrigation treatment in one experiment, but leachate volume was not different in the six other experiments conducted in this study. The benefit of using the OD irrigation system outside may be due to a combination of OD generally irrigating less frequently than DWU and the delivery method of the irrigation. OD treatments were irrigated 35% less frequently than DWU treatments when looking at both environments and container sizes. Typical examples of the two treatments showing the irrigation frequency are shown in Fig. 4.2. Because overhead irrigation has inherent application inefficiency, a large amount of water is lost due to non-uniform distribution and evaporation during application. Every irrigation event is wasteful, so more frequent irrigation events associated with DWU treatments would lead to greater water losses (Beeson, 2006). Fulcher et al. (2012) used a similar OD irrigation system that returned plants to container capacity after reaching a physiologically-based lower irrigation set point and found water use was reduced more when plants were irrigated less frequently with a greater volume than more frequently with a lesser volume. Total water use and WUE results in the controlled environment experiments were less definitive with no effects observed in 11.4 L plants during 2012, OD increased consumption 74% and decreased WUE 81% compared to DWU in 2012-13 11.4 L containers, and in 3.8 L, DWU had 65% greater WUE than OD. A possible factor that explains the differences observed between outdoor and indoor experiments was irrigation method. Outside trials used overhead irrigation whereas greenhouse trials used drip irrigation. As percent container capacity decreases, WUE of plants has been shown to increase with use of overhead irrigation (Karam and Niemiera, 1994) but decrease under micro-irrigation (Lamack and Niemiera, 1993). Drip irrigation applies water to the substrate surface, which minimizes losses due to poor application uniformity and may negate the benefits of using the OD system observed with overhead irrigation.

Differences in water use may also be explained by the hydraulic properties of the substrate. The substrate appeared to become hydrophobic on the surface over the course of the 11.4 L greenhouse experiments, not allowing the OD containers to reach 100% container capacity when irrigated. The hydrophobic tendencies of pine bark substrates have previously been described by Beardall and Nichols (1982), Lamack and Niemiera (1993), and others. Hydrophobicity was not observed in outdoor experiments, likely due to frequent rainfall and irrigation application method. Neither was it observed in 3.8 L containers grown in a controlled environment, most likely because they depleted the water reserve more quickly, triggering irrigation on average every 1.3 days compared to 2.1 days for 11.4 L containers. Because the OD 11.4 L containers were irrigated less frequently, especially during the beginning of the experiment, the increased time between events caused the substrate to become hydrophobic and increased channeling. Ring emitters were used in an attempt to mitigate this effect, but the substrate still became hydrophobic. This highlights the importance of selecting an appropriate irrigation set point for each substrate. The plants may be able to tolerate lower substrate moisture levels, but if the substrate cannot fully rehydrate, a higher set point is needed to maximize WUE and prevent the substrate from becoming hydrophobic. Despite the hydrophobicity that developed in some experiments, OD demonstrated the ability to attenuate irrigation to plant water requirements. The OD program was able to withhold irrigation on days when substrate moisture was acceptable, and irrigate multiple times on days of high evapotranspirational demand. Although multiple irrigation events in one day were only required a few times late in the season, this potentially prevented decrease of turgor pressure below the point at which growth ceases, or yield threshold (⍰), and the ensuing reduction in final biomass.

Large differences in water use and crop size were observed between 2011 and 2012 in 11.4 L nursery trials. It is hypothesized that the smaller size of plants, reduced water use, and high level of variability in the results of 2012 were the consequences of hail damage in July. Many of the damaged plants were stunted to varying degrees, likely reducing water use. OD plants recovered more poorly than DWU, as evidenced by the biomass and growth index. As expected, plants grown in all other 11.4 L trials were larger than 3.8 L plants, whereas the OD treatment in the 2012 nursery experiment produced plants whose size were comparable to those in 3.8 L trials. Water use of 3.8 L plants was also noticeably lower in 2011 compared with other trials, but this was likely due to a shorter experimental period and timely precipitation. Frequent rainfall can enhance a conservative irrigation regime’s ability to reduce water use. Precipitation provided a significant portion of water to nursery plants so total irrigation applied in between controlled environment and the 2012 nursery experiment was similar, despite these nursery trials lasting for approximately twice as long. Precipitation was so frequent that substrate moisture only fell below the set point once each for two of three 2012 OD zones in 11.4 L containers.

The differences between 3.8 and 11.4 L experiments and the differences between greenhouse and outdoor settings indicate that in general, there is no clear advantage to biomass, quality, or growth from using either irrigation system. However, it appears that utilizing the OD system with a lower VWC set point based on 90% maximum predicted photosynthesis is a generally conservative irrigation regime, especially outdoors. Assuming 1” per day is applied using traditional static irrigation timing at similar flow rates to Tennessee experiments, plants would receive 1197 mL and 463 mL of water per day for 11.4 L and 3.8 L containers, respectively. Both systems showed an improvement over traditional irrigation timing with average water use of OD and DWU lower than the estimated water use of conventional irrigation by 63 and 56%, respectively, in 11.4 L containers (433 and 521 mL per day), and 57 and 36% in 3.8 L containers (241 and 350 mL per day).

Conclusion

Future research should examine how to best adapt conservative irrigation regimes developed through research to actual production nurseries. An automated irrigation system that irrigates precisely when plants require water and applies the exact amount needed can reduce water use, crop losses, and time to marketability, especially for sensitive crops (Chappell et al., 2012). In these studies, neither treatment performed consistently superior in all trials. The lack of consistent results across different environments and container sizes indicate that the best irrigation program may be different for different environments, container sizes, or types of irrigation application systems, and effectiveness can be limited by substrate physical properties such as hydrophobicity. The results of these experiments indicate that plant growth may be negatively affected at the VWC chosen as the set point for OD in this experiment, but other research suggests using a slightly greater VWC set point to trigger irrigation could eliminate these negative consequences while preserving most of the water savings (Fulcher et al., 2012; Nemali and van Iersel, 2006; van Iersel et al., 2010). Overall, a physiologically-based OD system predicated on the relationship between photosynthesis and VWC shows great potential for outdoor nurseries. However, both DWU and OD are a dramatic improvement over the industry standard of 1” per day, and could be adopted as conservative irrigation systems. This research has shown that automated irrigation systems have the potential to precisely estimate daily water use and irrigate without over or under applying or extending the production time.

Acknowledgements: The authors wish to thank Harrell’s LLC, Renewed Earth Inc., Sharon Kester, Wesley Wright, Phil Flanagan, Lori Osborne, Tyler Campbell, Evan Wilson and Whitney Yeary for their contributions as well as funding support from Tennessee Agricultural Experiment Station.

Literature Cited

Ackerman, F. and E.A. Stanton. 2011. The last drop: climate change and the southwest water crisis. Stockholm Environment Institute-U.S. Center. Somerville, MA. January 25, 2013. <http://sei-us.org/Publications_PDF/SEI-WesternWater-0211.pdf>.

Beeson Jr., R.C. 2006. Relationship of plant growth and actual evapotranspiration to irrigation frequency based on management allowed deficits for container nursery stock. J. Amer. Soc. Hort. Sci. 131(1):140-148.

Beeson Jr., R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in ten year. J. Environ. Hort. 22(2):113-115.

Beeson Jr., R.C. and J. Brooks, 2008. Evaluation of a model based on reference crop evapotranspiration (ETo) for precision irrigation using overhead sprinklers during nursery production of *Ligustrum japonica*. Acta Hortic. 792, 85–90.

Beeson Jr., R.C. and G.W. Knox 1991. Analysis of efficiency of overhead irrigation in container production. HortScience 26(7):848-850.

Beardall, D.V. and D.G. Nichols. 1982. Wetting properties of dried out nursery container media. Sci. Hort. 17:49-59.

Bilderback, T.E. 2002. Water management is key in reducing nutrient runoff from container nurseries. HortTechnology 12:541-544.

Chappell, M., M. van Iersel, E. Lichtenberg, J. Majsztrik, P. Thomas, J. Ruter and S. Wells. 2012. Benefits of precision irrigation of *Gardenia augusta* 'Heaven Scent'™: reducing shrinkage, shortening the cropping cycle, and economic impact. SNA Research Conference Vol. 57:321-323.

Diaz-Espejo, A. and A. Verhoef 2002. Use of IR thermography for assessing the canopy exchange processes in sunflowers. Proc. of European Soc. of Agron. Congr. 7:265–266.

Doltra, J., J.A. Oncins, J. Bonanay, and M. Cohen. 2007. Evaluation of plant-based water status indicators in mature apple trees under field conditions. Irr. Sci. 25:351–359.

Fernández, J.E., S.R. Green, H.W. Caspari, A. Diaz-Espejo, and M.V. Cuevas. 2008a. The use of sap flow measurements for scheduling irrigation in olive, apple and Asian pear trees and in grapevines. Plant and Soil 305:91–104.

Fernández, J.E., R. Romero, A. Díaz-Espejo, J.L. Muriel, M.V. Cuevas, J.C. Montaño. 2008b. Design and testing of an automatic irrigation controller for fruit tree orchards based on sap flow measurements. Australian J. of Agr. Res. 59:589–598

Food and Agricultural Organization of the United Nations. 2007. Coping with water scarcity. Feb. 26, 2013. <http://www.fao.org/nr/water/docs/escarcity.pdf>.

Fulcher, A.F., J.W. Buxton, and R.L. Geneve. 2012. Developing a physiological-based, on-demand system for container production. Sciencia Hort. 138:221-226.

Grant, O.M., M.J. Davies, H. Longbottom, and C.J. Atkinson. 2009. Irrigation scheduling and irrigation systems: optimizing efficiency for container ornamental shrubs. Irr. Sci. 27:139-153.

Green, S.R., M.B. Kirkham, and B.E. Clothier. 2006. Root uptake and transpiration: from measurements and models to sustainable irrigation. Agr. Water Mgt. 86:165–176.

Houston, L.L., M. Watanabe, J.D. Kline, and R.J. Alig. 2003. Past and future water use in Pacific coast states. U.S. Dept. of Agr. Washington D.C.

Jones, H.G. 1999. Use of infrared thermometry for estimation of stomatal conductance in irrigation scheduling. Agr. and Forest Meteorol. 95:135–149.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. J. of Expt. Bot. 55(407):2427-2436.

Jones, H.G and F. Tardieu. 1997. Modelling (sic) water relations of horticultural crops: a review. Sciencia Hort. 74:21-46.

Karam, N.S. and A.X. Niemiera. 1994. Cyclic sprinkler irrigation and pre-irrigation substrate water content affect water and N leaching from containers. J. Environ. Hort. 12:198-202.

Keese, R.J., N.D. Camper, T. Whitwell, M.B. Riley, and P.C. Wilson. 1994. Herbicide runoff from ornamental container nurseries. 1. Environ. Qual. 23:320-324.

Lamack, W.F. and A.X. Niemiera. 1993. Application method affects water application efficiency of spray stake-irrigated containers. HortScience 28(6):625-627.

Lea-Cox, J., G. Kantor, W. Baurle, M. van Iersel, T. Baurle, E. Lichtenberg, D. King, R. Bauer, C. Campbell, L. Bissey, T. Martin. 2011. SCRI-MINDS Year 2 report precision irrigation and nutrient management for nursery, greenhouse and green roof systems: wireless sensor networks for feedback and feed-forward control. Feb. 27, 2013. <http://smart-farms.net/sites/default/files/SCRI-MINDS%20Year%202%20Report.pdf>.

Marella, R.L. and M.P. Berndt. 2005. Water withdrawals and trends from the Floridan [sic] aquifer system in the Southeastern United States. U.S. Geological Survey. Denver, CO.

Martin D.L., D.J. Wehner, and C.S. Throssell. 1994. Models for predicting the lower limit of the canopy-air temperature difference of two cool season grasses. Crop Sci. 34:192–198.

Nemali, K.S. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. Scientia Hort. 110:292–297.

Slatyer, R.O. 1967. Plant water relationships. London and New York: Academic Press.

State of Oregon. Water Resources Department. Water protection and restrictions. Feb. 20, 2013. < http://www.oregon.gov/owrd/pages/pubs/aquabook_protections.aspx>

Taiz, L. and Zeiger, E., 2006. Plant Physiology, 4th ed. Sinauer, Massachusetts.

Turral, H., J. Burke, and J.M. Faurès. 2011. Climate change, water, and food security. Water Reports, No. 36. Food and Agriculture Organization of the United Nations, Rome. Jan. 23, 2013.<http://www.fao.org/docrep/014/i2096e/i2096e.pdf >.

U.S. Salinity Laboratory Staff. 1954. Diagnosis and Improvement of Saline and Alkali Soils. USDA Agric. Hand. No. 60, U.S. Government Printing Office, Washington, D.C.

Van Iersel, M.W., S. Dove, J. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45(2):277-282.

Velez, J.E., D.S. Intrigliolo, and J.R. Castel. 2007. Scheduling deficit irrigation of citrus trees with maximum daily trunk shrinkage. Agr. Water Mgt. 90:197–204.

Warren, S. and W. Bilderback. 2005. More plants per gallon: getting more out of water. HortTechnology. 15(1):14-18.

Warsaw, A.L., R.T. Fernandez, and B.M. Cregg. 2009. Water conservation, growth, and water use efficiency of container-grown woody ornamentals irrigated based on daily water use. HortScience 44(5):1308-1318.

Weatherspoon, D.M. and C.C. Harrell. 1980. Evaluation of drip irrigation for container production of woody landscape plants. HortScience 15:488-489.

Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227-22.

Appendix

Table 4.1: Photosynthesis and gas exchange measurements for ‘Alice’ oakleaf hydrangea grown in an outdoor nursery in 3.8 and 11.4 L containers in Kentucky and Tennessee respectively, to compare two different irrigation systems, daily water use (DWU) and On-Demand (OD). *n*=12.

Year	Container size (L)	Photosynthetic rates (μmol CO_2 $m^{-2}\cdot s^{-1}$)	Transpiration (mmol H_2O $m^{-2}\cdot s^{-1}$)	Stomatal conductance (mol H_20 $m^{-2}\cdot s^{-1}$)	Leaf petiole water potential (MPa)	Vapor pressure deficit (kPa)
2011	11.4					
	Daily Water Use	11.4[z]	2.98	0.13	-0.54	2.21
	On-Demand	9.6	2.3	0.105	-0.64	2.46
	P value	0.44	0.428	0.665	0.237	0.1073
2012	11.4					
	Daily Water Use	8.6	2.37	0.161	---[y]	3.59
	On-Demand	7.4	2.51	0.106	---	2.59
	P value	0.2879	0.5739	0.0821		0.2458
2011	3.8					
	Daily Water Use	8.5b	2.83	0.092b	-0.67	2.43
	On-Demand	10.6a	2.87	0.108a	-0.63	2.53
	P value	<0.0001	0.2911	0.0001	0.251	0.5113

[z]Means followed by the same letter were not significantly different (Tukey’s HSD α=0.05).

[y]Data were not collected.

Tennessee trials were conducted 18 Aug.-3 Oct. 2011 and 27 June-16 Oct. 2012; the Kentucky trial was conducted 6 Sept.-7 Oct. 2011.

Table 4.2: Photosynthesis and gas exchange measurements for ‘Alice’ oakleaf hydrangea grown in an controlled greenhouse environment in 3.8 and 11.4 L containers in Kentucky and Tennessee respectively, to compare two different irrigation systems, daily water use (DWU) and On-Demand (OD). *n*=12.

Year	Container size (L)	Photosynthetic rates (µmol CO_2 $m^{-2} \cdot s^{-1}$)	Transpiration (mmol H_2O $m^{-2} \cdot s^{-1}$)	Stomatal conductance (mol H_20 $m^{-2} \cdot s^{-1}$)	Leaf petiole water potential (MPa)	Vapor pressure deficit (kPa)
2012	11.4					
	Daily Water Use	15.5[z]	5.58	0.335	-0.162	1.89
	On-Demand	14.7	5.3	0.316	-0.181	1.93
	P value	0.2274	0.6281	0.7519	0.3992	0.822
2012-13	11.4					
	Daily Water Use	5.3	2.01	0.066	-0.353	3
	On-Demand	5.1	1.88	0.065	-0.339	2.89
	P value	0.7626	0.7424	0.921	0.6874	0.54
2011-12	3.8					
	Daily Water Use	8.2b	2.32	0.107b	-0.4	2.64
	On-Demand	10.7a	2.96	0.142a	-0.45	2.72
	P value	<0.0001	0.0598	0.0184	0.4732	0.576

[z]Means followed by the same letter were not significantly different (Tukey’s HSD α=0.05).

Tennessee trials were conducted 19 Apr.-4 June 2012 and 21 Dec.-9 Jan. 2012-13; the Kentucky trial was conducted 8 Nov.-2 Jan. 2011-12.

Table 4.3: Biomass, quality, container soluble salts, and pH data for 'Alice' oakleaf hydrangea grown in an outdoor nursery in 3.8 and 11.4 L containers in Kentucky and Tennessee, respectively to compare two different irrigation systems, daily water use (DWU) and On-Demand (OD). *n*=12.

Year	Container size (L)	Shoot dry weight (g)	Root dry weight (g)	Total dry weight (g)	Growth index (cm)	Electrical conductivity (µS/cm)	pH
2011	11.4						
	Daily Water Use	137a[z]	25	161a	70.9a	451	6.5
	On-Demand	100b	21	121b	60.6b	458	6.5
	P value	0.0245	0.3271	0.0393	0.0149	0.9098	0.873
2012	11.4						
	Daily Water Use	48.7	10.0	58.7	50.2	658	6.9
	On-Demand	22.8	5.9	28.7	41.1	785	7.0
	P value	0.3998	0.8022	0.1845	0.2176	0.1087	0.6342
2011	3.8						
	Daily Water Use	---	---	22.9b	36.6	656	6.8
	On-Demand	---	---	24.0a	35.9	754	6.8
	P value			0.047	0.308	0.1972	0.6681

[z]Means followed by the same letter were not significantly different (Tukey's HSD α=0.05).

Tennessee trials were conducted 18 Aug.-3 Oct. 2011 and 27 June-16 Oct. 2012; the Kentucky trial was conducted 6 Sept.-7 Oct. 2011.

Table 4.4: Biomass, quality, container soluble salts, and pH data for 'Alice' oakleaf hydrangea grown in an controlled greenhouse environment in 3.8 and 11.4 L containers in Kentucky and Tennessee respectively, to compare two different irrigation systems, daily water use (DWU) and On-Demand (OD). *n*=12.

Year	Container size (L)	Shoot dry weight (g)	Root dry weight (g)	Total dry weight (g)	Growth index (cm)	Electrical conductivity (µS/cm)	pH
2012	11.4						
	Daily Water Use	72.3[z]	13.6	85.9	81.5	613	6.2a
	On-Demand	79.5	16.4	95.9	78.3	671	5.9b
	P value	0.5101	0.1669	0.405	0.0889	0.7703	0.0312
2012-13	11.4						
	Daily Water Use	45.1	7.2	52.3	73.2	449	7.4
	On-Demand	43	7.9	50.9	72.9	508	7.4
	P value	0.6976	0.6931	0.8476	0.928	0.689	0.4175
2011-12	3.8						
	Daily Water Use	---	---	29.8b	52.1b	653	6.8
	On-Demand			35.3a	62.8a	689	6.8
	P value			0.0414	0.0021	0.6356	0.8895

[z]Means followed by the same letter were not significantly different (Tukey's HSD α=0.05).

Tennessee trials were conducted 19 Apr.-4 June 2012 and 21 Dec.-9 Jan. 2012-13; the Kentucky trial was conducted 8 Nov.-2 Jan. 2011-12.

Table 4.5: Water use, water use efficiency, and leachate data for ‘Alice’ oakleaf hydrangea grown in an outdoor nursery in 3.8 and 11.4 L containers in Kentucky and Tennessee, respectively to compare two different irrigation systems, daily water use (DWU) and On-Demand (OD). *n*=12.

Year	Container size (L)	Total water use per container (L)	Water use efficiency (g/L)	Total leachate (L)	Leachate per irrigation event (mL)
2011	11.4				
	Daily Water Use	43.9a[z]	3.8b	7.5	551
	On-Demand	20.5b	5.9a	12.2	488
	P value	0.0004	0.0044	0.2305	0.695
2012	11.4				
	Daily Water Use	37.6a	1.5	9.4	136
	On-Demand	5.0b	4.2	1.6	321
	P value	0.0209	0.1465	0.0765	0.187
2011	3.8				
	Daily Water Use	8.1a	3.7b	---	290b
	On-Demand	4.7b	7.4a	---	346a
	P value	0.0001	0.0001		<.0001

[z]Means followed by the same letter were not significantly different (Tukey’s HSD α=0.05).

Tennessee trials were conducted 18 Aug.-3 Oct. 2011 and 27 June-16 Oct. 2012; the Kentucky trial was conducted 6 Sept.-7 Oct. 2011.

Table 4.6: Water use, water use efficiency, and leachate data for 'Alice' oakleaf hydrangea grown in an controlled greenhouse environment in 3.8 and 11.4 L containers in Kentucky and Tennessee, respectively to compare two different irrigation systems, daily water use (DWU) and On-Demand (OD). *n*=12.

Year	Container size (L)	Total water use per container (L)	Water use efficiency (g/L)	Total leachate (L)	Leachate per irrigation event (mL)
2012	11.4				
	Daily Water Use	26.5[z]	3.4	5.3	113
	On-Demand	24.8	4	0.8	65
	P value	0.7774	0.4557	0.1791	0.4613
2012-13	11.4				
	Daily Water Use	14.5b	3.8a	4.2	239
	On-Demand	25.3a	2.1b	2.5	318
	P value	0.0491	0.0356	0.089	0.5859
2011-12	3.8				
	Daily Water Use	17.2	1.7b	---	263
	On-Demand	12.7	2.8a	---	273
	P value	---[x]	0.0002		0.4059

[z]Means followed by the same letter were not significantly different (Tukey's HSD α=0.05).

[x]ANOVA was not run because there was only one solenoid valve for the OD and DWU treatments.

Tennessee trials were conducted 19 Apr.-4 June 2012 and 21 Dec.-9 Jan. 2012-13; the Kentucky trial was conducted 8 Nov.-2 Jan. 2011-12.

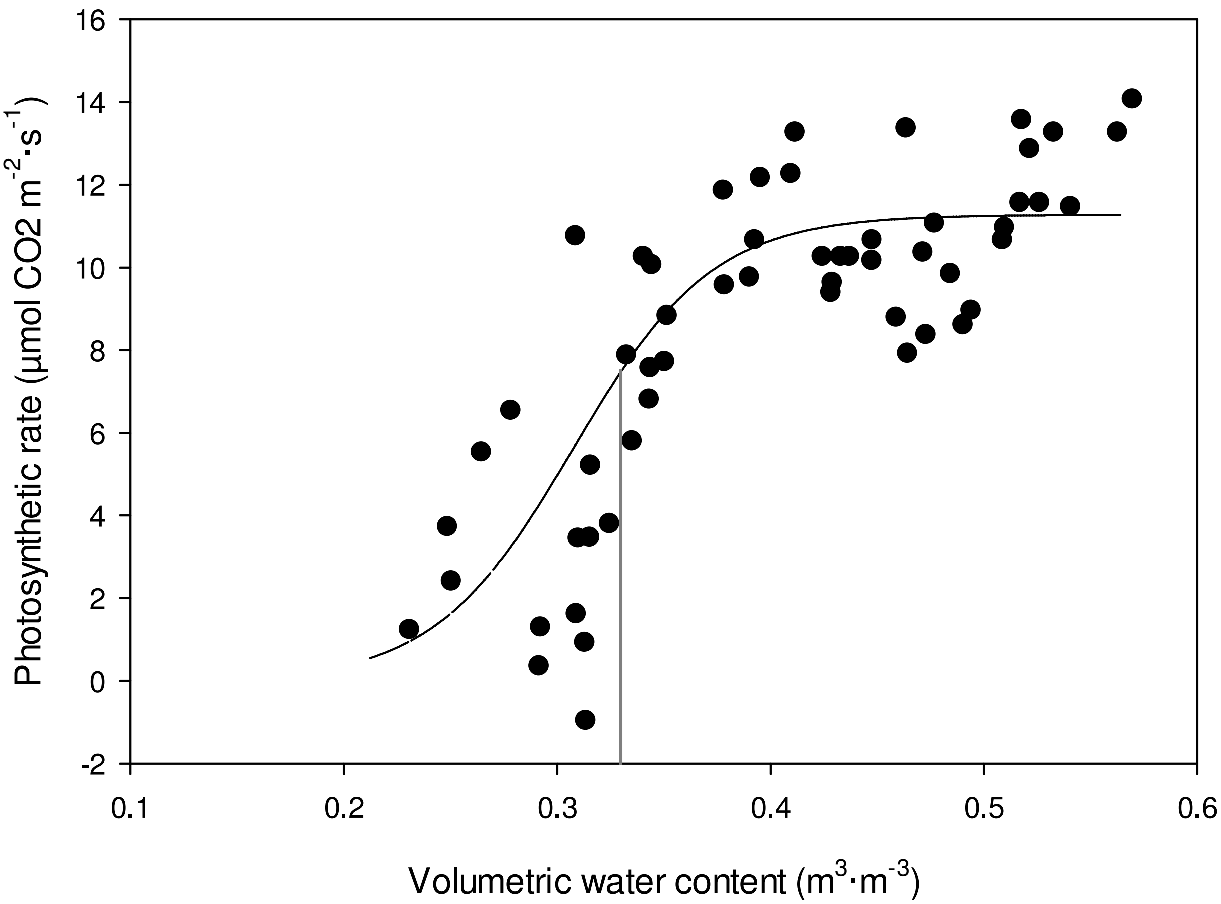

Figure 4.1: The relationship between photosynthetic rate and volumetric water content of 'Alice' oakleaf hydrangea plants. The irrigation threshold chosen at 90% maximum predicted photosynthetic rate is shown by the grey vertical line. n=5.

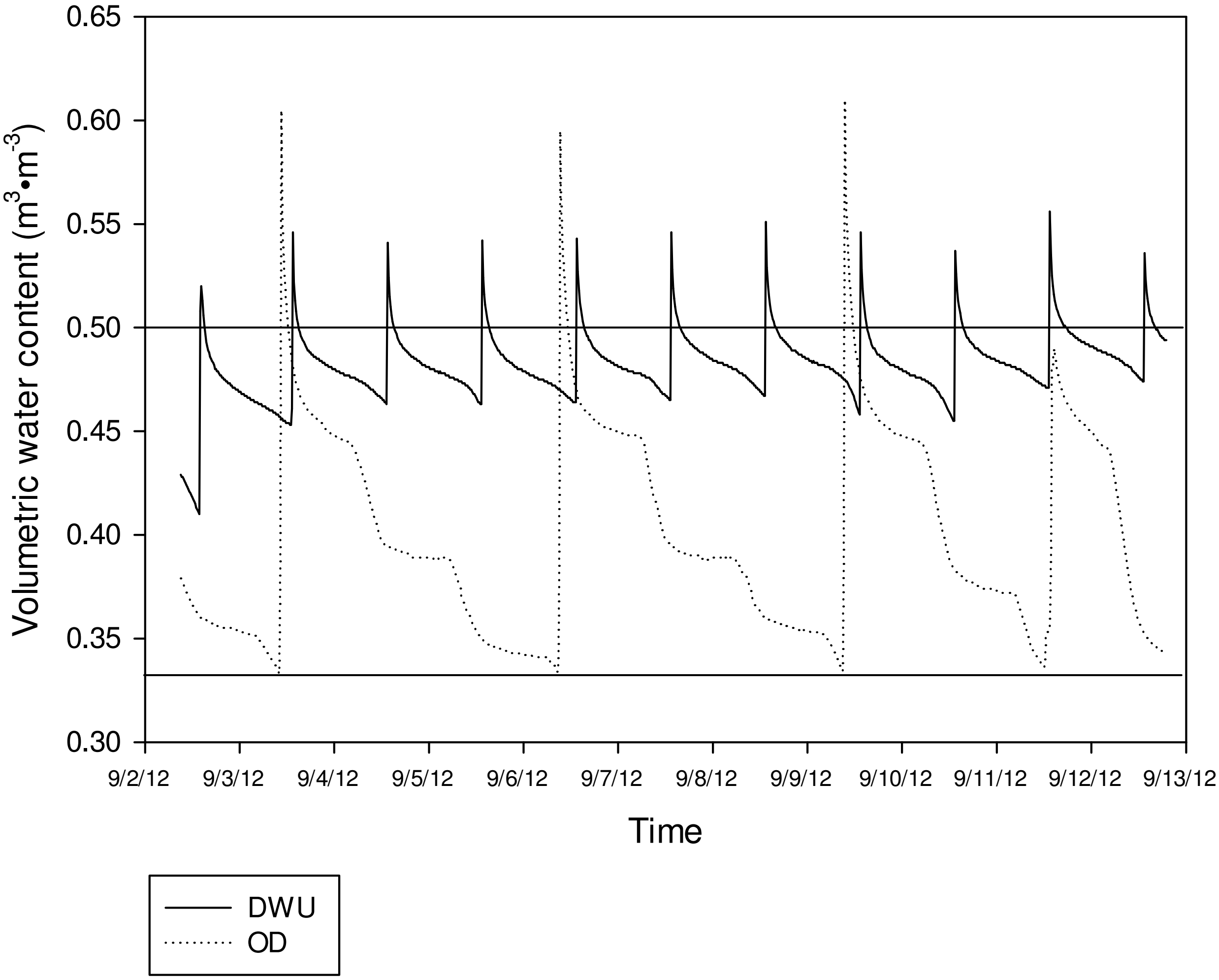

Figure 4.2: Examples of typical volumetric water content measurements from two irrigation schedules: On-Demand (OD) and Daily Water Use (DWU). Time elapsed between two DWU peaks is 24 h. Peaks are indicative of irrigation events. Horizontal lines indicate upper and lower irrigation set points.

Appendices

Appendix I
Sensor Calibration

EC-5 sensors were wired to the datalogger in a lab setting. Substrate used in the study was air dried until most moisture was gone and large particles removed. 250 g of substrate was weighed out and placed in six plastic bags. Water was added to the substrate in amounts of 50, 100, 150, 200, and 250 mL and mixed. No water was added to one container. Each bag was packed into a plastic container at approximately the bulk density of a nursery container, covered, and weighed. The level of substrate was marked for volume calculation. Each sensor was one-by-one inserted into each batch of substrate until sensor overmold/wire junction was completely covered and allowed to adjust. When readings were stable, the mV/mV output was recorded. Substrates were dried in an oven at 45°C until their weight remained unchanged in 24 h to obtain dry mass. Volumetric water content was determined by gravimetrically calculating the amount of water in each substrate sample and dividing by the volume. A regression line was created for each sensor that plotted the calculated gravimetric water content with the mV/mV output. The coefficients of the inverse lines of the regression lines were the calibration figures entered for the data collection and irrigation programs.

Appendix II

Photosynthetic response characteristics of *Acer rubrum* L. 'Franksred' Red Sunset™

Introduction

World population growth has increased demand and competition for natural resources as resource availability decreases (Turral et al., 2011). Over 40% of the world's food is produced on irrigation-dependent land making water one of the most crucial resources to conserve (Turral et al., 2011). Extreme weather conditions, practices such as unsustainable levels of groundwater extraction, and competition among industry, municipalities, and agriculture have resulted in irrigation restrictions. Major nursery crop production states such as Florida, California, Texas, and Oregon now face irrigation restrictions (Ackerman and Stanton, 2011; Beeson, et al. 2004; Beeson and Brooks, 2008; Houston et al., 2003; Marella and Burndt, 2005; State of Oregon, 2013). These restrictions hit container nurseries especially hard because of their high water use per acre. Assuming a nursery will irrigate with a standard amount of 2.5 cm per day, 27,000 gallons of water will be used per acre per day (LeBude and Bilderback, 2007).

Container nurseries are often extremely inefficient with 60% to 90% of applied irrigation being lost due to lack of application uniformity, excess volume applied, deflection of the canopy, and container spacing (Beeson and Yeager, 2003; Fare et al., 1992). Increasing irrigation application efficiency, i.e. increasing the proportion of water that is intercepted and retained by containers, can drastically reduce water consumption by nurseries. A number of strategies have been proposed to increase application efficiency in nursery irrigation, such as increasing distribution uniformity by optimizing container spacing to increase interception (Beeson and Knox, 1991). Irrigation timing also has an impact on irrigation efficiency, and watering crops at night or early morning reduces the amount of evaporative loss from overhead irrigation systems, (Mathers et al., 2005) although this may not be the best time for crop growth (Warren and Bilderback, 2005). Cyclic irrigation, or dividing a daily irrigation event into multiple shorter irrigation events, also has shown to reduce water use (Beeson and Haydu, 1995). Other strategies that have been proven to increase efficiency include grouping plants according to water use, using a more appropriate irrigation system design, and cleaning and replacing nozzles (Grant, 2009; Warsaw et al., 2009; Zinati, 2005). However, most of these commonly used strategies are passive attempts to address gross application inefficiencies and do not account for continually changing plant and environment-specific need for water.

To more fully maximize water conservation, an irrigation system would be dynamic and thus calibrate irrigation application volume and timing to plant and environmental demand, applying only the exact amount of water needed each day and only when needed. A number of methods were developed to determine the optimum irrigation volume to apply on a daily basis. Researchers have successfully developed crop coefficients for use in crop models such as Penman-Monteith (Penman, 1948) and Priestly-Taylor (Priestly and Taylor, 1972) that calculate the amount of water a plant loses in a day based on environmental factors, the plant's size and age, and the specific climate and season of the site. However, these measurements are crop specific and must be calculated throughout the season to account for age differences, and assume a closed canopy making them difficult for nursery application. Beeson (2012) simplified the calculation by using canopy closure data to allow for one equation to calculate water use, regardless of season or plant size. However, separate crop coefficients must still be developed for each species and canopy closure measurements taken every few weeks to adjust the calculations.

Other research uses physiological data to determine irrigation rates and timing (Doltra et al., 2007; Fernández et al., 2008a; and Green et al., 2006). Basing irrigation on physiological data is ideal because it measures the direct response of plants to water stress indicating exactly when the stress occurs. A system based on physiological data would initiate irrigation only when the crop needed water, eliminating superfluous irrigation. However, it is often difficult to measure physiological responses and they are triggered only after a plant has experienced some level of stress. To optimize production schedules, irrigation needs to be triggered before the plant is stressed enough to reduce growth. One indication of water stress is when a plant shuts down photosynthesis (Griffin et al., 2004). By developing an irrigation system based on the relationship between photosynthetic rate and volumetric water content over a range of substrate moisture contents, Fulcher et al. (2012) found that photosynthetic rates in *Hibiscus rosa-sinensis* L. 'Cashmere Wind' follow a sigmoidal relationship; they remain relatively constant above 0.25 $m^3 \cdot m^{-3}$ but drop precipitously if dried below that point. Fulcher and Geneve (2011) showed two *Cornus* species also exhibited a similar sigmoidal relationship between photosynthetic rate and substrate moisture. If the relationship between photosynthesis and VWC is not species specific and photosynthesis decreases substantially at the same VWC, then an automated irrigation system could potentially be used for multiple species without the need for individual species calibrations, which would enhance the ability of the industry to utilize this as a basis for irrigation.

Therefore, the objectives of this research were to 1) characterize the photosynthetic response of several woody species to light, 2) develop a model characterizing the relationship between photosynthesis and VWC, 3) determine if the previously described sigmoidal relationship adequately characterizes that relationship for other common woody ornamental plants, and 4) determine if the VWC at which photosynthesis precipitously drops is the same for all species in this study such that one value can be used as a conservative set point for any species on an automated irrigation system.

Materials and Methods

Bare root liners of *Acer rubrum* L. 'Franksred' Red Sunset™ (red maple) were obtained from Bottoms Brothers Nursery (McMinnville, TN) and potted into 3.8 L containers (C400, Nursery Supplies Inc., Fairless Hill, PA) with an 85:15 pine bark to peat moss substrate (Renewed Earth Inc., Kalamazoo, MI) on 25 Feb. 2012. Aquagro® L (Aquatrols, Paulsboro, NJ) was applied once to the substrate at 600 mg/L to ensure even wetting because the substrate began to display hydrophobic tendencies and had difficulty rewetting in preliminary research. One week after transplanting, plants were top-dressed with 19-1.75-11.6, 5-6 month controlled release fertilizer with micronutrients (Polyon®, Harrell's Inc., Lakeland, FL) at 12 g per container (medium label rate) and fertigated twice weekly with 300 mg/L 20-8.7-16.6 (Peters Professional® General Purpose 20-20-20, Scotts Sierra Horticultural Products Co., Marysville, OH).

EC-5 soil moisture capacitance sensors (Decagon Devices Inc., Pullman, WA) were connected to a multiplexer (AM 16/32, Campbell Scientific, Logan, UT) wired to a datalogger (CR1000, Campbell Scientific) and programmed to read and convert mV output from the EC-5 sensors to VWC based on a substrate-specific calibration for each sensor. Capacitance sensors were installed half way between the base of the plant and the container sidewall, one per container. Sensors were oriented vertically with the broad face to plant stem and inserted into the substrate so that the sensor overmold/wire junction was 2.5 cm below the surface of the substrate. Sensor readings were automatically measured every 15 sec and 15 min averages recorded.

Between 14 June and 17 Aug. 2012, light response curves were measured between 10 AM to 2 PM using an infrared gas analyzer (Li-6400, LI-COR® Biosciences, Inc., Lincoln, NE). Light curves were measured on the second fully expanded, recently matured leaf of each plant at 390 ppm CO_2. High and low light curves were conducted on separate days. For the high light curve, photosynthetic rates were measured at decreasing irradiance levels of 2000, 1800, 1600, 1400, 1200, 1000, 800, 600, 400 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Low light curves were measured at irradiance levels of 400, 300, 250, 200, 150, 100, 50, 25, 10, and 0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Data was collected on 21, 22, 25, and 26 of June, and 15 and 18 of Aug. Data for each plant was graphed using SigmaPlot™ (SPSS, Chicago, IL). Values from the high light curves were used to calculate the maximum predicted photosynthetic rate. A regression line was fit to the linear portion of the low light curves, the 50, 25, and 10 µmol $\cdot m^{-2} \cdot s^{-1}$ values, and was used to calculate apparent quantum efficiency. Dark respiration rate was predicted from the regression line at the intersection with 0 µmol $\cdot m^{-2} \cdot s^{-1}$. Light compensation point was determined from the intersection of the regression line and the x-axis, when net photosynthetic rate was 0 µmol $\cdot m^{-2} \cdot s^{-1}$.

There were five replicate for both high and low light curves. The results were analyzed using PROC MIXED procedure in SAS® version 9.3 (SAS Institute Inc., Cary, NC ($P < 0.05$). Means were separated using Tukey's *t*-test.

Results

The maximum predicted photosynthetic rate of red maple was 16.5 µmol CO_2 $m^{-2} \cdot s^{-1}$. The light compensation point was 20.1 µmol CO_2 $m^{-2} \cdot s^{-1}$ and quantum light efficiency was 0.071. The dark respiration rate of Red Sunset was -1.498 µmol CO_2 $m^{-2}s^{-1}$.

Table A.1: Photosynthetic light response curve derived values measured on the second fully expanded, mature leaf of *Acer rubrum* L. 'Franksred' Red Sunset™.

Species	Maximum predicted photosynthesis (µmol CO_2 $m^{-2}\cdot s^{-1}$)	Predicted light compensation point (µmol·$m^{-2}\cdot s^{-1}$)	Quantum light efficiency (Q_{app})	Predicted dark respiration (µmol CO_2 $m^{-2}\cdot s^{-1}$)
Acer rubrum 'Franksred'	16.5±1.3	20.1±2.6	0.071±0.005	-1.50±0.15

Appendix III
Model Development of Oakleaf Hydrangea

Rooted cuttings of *Hydrangea quercifolia* Bartr. 'Alice' were obtained from Spring Meadows Nursery (Grand Haven, MI) and transplanted on 17 Mar. 2011 into 3.8 L containers (C400, Nursery Supplies Inc., Fairless Hill, PA) with an 85:15 pine bark to peat moss substrate (Renewed Earth Inc., Kalamazoo, MI). One week after transplanting, plants were top-dressed with 19-1.75-11.6, 5-6 month controlled release fertilizer with micronutrients (Polyon®, Harrell's Inc., Lakeland, FL) at 12 g per container (medium label rate) and fertigated twice weekly with 300 mg/L 20-8.7-16.6 (Peters Professional® General Purpose 20-20-20, Scotts Sierra Horticultural Products Co., Marysville, OH). EC-5 soil moisture capacitance sensors (Decagon Devices Inc., Pullman, WA) were installed half way between the base of the plant and the container sidewall, one per container. Sensors were oriented vertically with the broad face to plant stem and inserted into the substrate so that the sensor overmold/wire junction was 2.5 cm below the surface of the substrate. Plants were grown in a controlled greenhouse environment in Knoxville, TN at the University of Tennessee North Greenhouse (35.946°N, -83.939°W).

Root proliferation was periodically monitored in a cohort of plants that were not included in the experiment to determine root establishment. Plants were hand watered until roots reached the container sidewall. Upon initiating experiments, the substrate was hand watered and containers placed in 2.5 cm of standing water for 30 min to ensure complete saturation of the substrate. Containers were then left to drain to container capacity, which took 2 h, and then water was withheld. Initial gravimetric measurements and soil moisture readings were recorded as the container capacity. Weight, soil moisture and photosynthetic rate were measured twice daily between 10 AM and 2 PM. Gas exchange measurements were measured on the second fully expanded, recently matured leaf with an infrared gas analyzer (Li-6400, LI-COR® Biosciences, Inc., Lincoln, NE) and capacitance sensor soil moisture readings recorded using a handheld sensor reading device (ProCheck, Decagon Devices Inc., Pullman, WA).

Models were developed from measurements taken as the plants dried down until the plants were wilting. All data fit curve options on SigmaPlot™ (SPSS, Chicago, IL) were evaluated for each individual plant. Once the best fit curve was determined as a 3-parameter sigmoidal curve, VWC values were determined for 90% of maximum predicted photosynthetic rate based on the hypothesis that allowing drying to this point would conserve the most water without impacting plant growth. The average VWC of the five replicate plants at 90% photosynthetic rate was used as the lower set point to trigger irrigation for OD treatments.

Vita

Ethan Hagen was born in Defiance, OH to the parents of Paul and Fay Hagen. He is the middle of three brothers; Noah and Collin. He attended Holgate High School in Holgate, Ohio. After graduation, he headed south to Ohio University to pursue his passion in Botany. He obtained a Bachelor of Science from Ohio University in June 2011 in Plant Biology. He accepted a graduate research assistantship at the University of Tennessee, Knoxville in the Plant Biology Program. Ethan is graduating with a Master of Science degree in Plant Biology in August 2013. He is moving to San Diego to pursue his career in the plant sciences field.