2013

SCRI-MINDS – Year 4 Report

Precision Irrigation and Nutrient Management for Nursery, Greenhouse and Green Roof Systems:

Wireless Sensor Networks for Feedback and Feed-forward Control

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Executive Summary

Year four was a critical implementation and testing year for the SCRI-MINDS project. The engineering effort that we put into the development of the advanced monitoring and control (nR5) node and supporting software (Sensorweb) in years 2 and 3, was implemented in all of our research sites and commercial operations during 2013. Further development and testing of the hardware and software is continuing, on the path to commercializing the system at the end of year 5. We are now actively monitoring and controlling irrigation in 15 different locations, including nine commercial greenhouses and nurseries. Many of the exciting results reported by the scientific and economic teams this year are based on this implementation.

Significant results reported by the various teams in Year 4 include:

1. <u>Engineering Hardware and Software Development</u>:

- The engineering teams at Carnegie Mellon University and Decagon Devices, Inc. developed a commercialization and support plan for the advanced irrigation nodes and continued developing the system to improve scalability and add new features. Specifically, benchmarking efforts have focused on:
  - Robust base station hardware development
  - Virtual private network for remote troubleshooting
  - The wireless sensor network access point
  - An Irrigation controller interface
- A major focus has been to make the Sensorweb user interface more intuitive, easier to use, scalable, and to continue increasing the reliability of the system. In addition, new data sources have been added to Sensorweb both in the form of grower tools and integration of new sensors. The Sensorweb software is deployed and being field tested at more than 15 different sites

2. <u>Scientific Research and Development</u>:

- Our scientific research efforts in the last year have focused on quantifying irrigation and nutrient leaching with fertilizer rate and plant growth interactions, using gardenia and petunia as model species. Part if this research is to validate the performance of the GS3 and ES-2 electrical conductivity sensors, for use in soilless substrates. We have also started work in new areas, including the dynamics of oxygen concentrations in the root zone, as well as the hydraulic properties of soilless substrates. The use of deficit irrigation for height control, as a substitute for plant growth regulators is also being investigated.
- Comparative studies of grower-controlled irrigation versus substrate set-point control have continued in various commercial field (soil), container-nursery and greenhouse operations.
  - Experiments confirmed that sensor-based irrigation control can be safely implemented in greenhouse cut-flower production systems, with no significant reductions in yield. Current efforts are now focused on scaling up sensor-controlled irrigation to larger (commercial) production areas of the greenhouse.
  - A large control block was implemented in a pot-in-pot operation to scale and integrate set-point control decisions in this 200-acre operation. Sensor-controlled (set-point) irrigation of six different indicator species (of varying growth rates) were continued to provide irrigation volume, runoff and nutrient (EC) data, in comparison to grower-controlled irrigation.

- Experimentation was started to investigate the effects of set-point irrigation management on pathogen reduction (*Phytophthora cinnamomi*) using *Rhododendron* as a model species.

- Green roof monitoring and stormwater model predictions are helping to improve our understanding of the underlying mechanisms that are responsible for green roof rainfall retention efficiency. A three-year green roof study was completed in year 4. The resulting green roof water balance model and findings are being prepared for publication.

3. **Model Development:**

- In order to scale up irrigation to large acreages using model-based prediction of plant water use, we have focused in on two parameters that we identified to comprise the majority of transpiration prediction power. We now understand the power of one parameter (G_0 - night time conductance) and we are currently working on how to use G_0, along with generalized C_3 parameter sets, to scale up to large areas of plant production for precision irrigation control.

4. **Economic Research:**

- Three economic case-studies from grower operations have provided insightful data on resource input reductions, growth acceleration (reduced time to harvest), improved plant health, lower disease losses and enhanced appearance. Adoption of sensor networks is profitable whenever these benefits outweigh the costs of installing and running the network.

5. **Communication and Outreach:**

- During year 4, the SCRI-MINDS team published one book chapter, thirteen peer-reviewed journal and conference papers, six non-refereed conference and seven trade publications. In addition the team gave 12 invited national and international presentations, 4 webinars and 28 conference and other presentations.

Global Project Goals and Objectives

As a Coordinated Agricultural Specialty Crops Research Initiative Project, we are focused on delivering a commercial wireless sensor network (WSN) capable of supporting the intensive production system requirements of field nurseries, container nurseries, greenhouse operations and green roof systems. The global goals of this project are (1) to provide a more integrative and mechanistic understanding of plant water requirements, spanning from micro-scale (e.g. plant level) to macro-scale (e.g. whole production site) for irrigation and nutrient management and (2) to quantify private (farm) and public (societal) economic benefits of this technology. The project is integrated across various scales of production by using small and large commercial test sites that allows us to take a systems approach to identify micro- to macro-scale answers underlying nursery, greenhouse, and green roof irrigation management. An economic, environmental and social analysis will identify cost and benefits to the green industry and society as well as barriers to adoption of this new technology. The project structure allows us to engage green industry collaborators on a day-to-day basis to ensure satisfaction and quickly resolve problems, with new hardware and software products developed by our teams and our commercial partners.

Further details of the entire project, teams and management can be found on the SCRI-MINDS Project Website at http://www.smart-farms.net and the Knowledge Center at http://www.smart-farms.org

A. Engineering - Hardware and Software: Carnegie Mellon Robotics Institute and Decagon Devices

During year four the engineering teams at Carnegie Mellon University and Decagon Devices, Inc. developed a commercialization and support plan for the advanced irrigation nodes and continued developing the system to improve scalability and add new features. Some of the engineering accomplishments are listed below.

- ✓ Developed commercialization plan for this new system
- ✓ Developed support and training model for this new system
- ✓ Developed an irrigation controller interface to integrate nodes with existing irrigation controllers
- ✓ Improved scalability of the system
  - Developed wireless to ethernet bridge so base radio and base computer can be in separate locations
  - Irrigation zones can be configured for simplified irrigation management
  - Em50G cellular nodes distributed across the world can be incorporated into a single system
- ✓ Control node can now control multiple solenoids connected in series
- ✓ Prototyped farm management tool to fuse farm management with sensor data Added new Decagon sensors to Sensorweb for increased functionality of the nodes

1. Commercialization, Support & Training

Decagon developed a commercialization plan to allow growers to purchase this system starting in late summer, 2014. The commercialization plan consists of proving hardware and support solutions to customers. The commercialized product will include:

a) Wireless sensing and control nodes: This includes both the nR5 and nR5-DC nodes, which are AA battery powered, can measure up to five Decagon sensors, and can switch irrigation solenoid valves typically seen in horticulture. These nodes are configured through web-based software.
b) Decagon soil moisture and environmental sensors.
c) Web-based software. Software interface will allow configuration of the entire system, and will be the primary interface for setting control set-points. Web software designed for desktop and mobile device browsers.
d) Secure remote access for collaboration

We recognize that while the system is designed to be easy to use and plug-and-play, three principal points of challenge continue to exist. These include:

1. Setup of system and learning to use the software
2. System design to accomplish grower goals
3. Data management that allows a grower to make a decision

Decagon works with a trained consultant network to minimize of the above challenges. The consultants in this network will be "authorized" by Decagon, and will have the following training and business model. This model mimics the network used by Decagon in open-field commercial agriculture.

1. Decagon provides phone and e-mail support, annual training, virtual seminars, and customer visits to existing consultant network.
2. The consultant works with the grower to determine the best system design for their goals.

3. Decagon sells instrumentation to consultants, as opposed to direct the grower. The consultant then either sells or rents the instrumentation to the grower, depending on the specific consultant's business model and the goals of the grower.
4. Consultants include at least one of the following services in their business model:
   - Installation and maintenance of all instrumentation sold
   - Grower training on instrumentation
   - Irrigation recommendations at a frequency relevant to the crop being grown
   - Other crop consulting as is appropriate for the consultant's expertise.

Prior to the release of the product to the marketplace, we will hold a consultant training session to:

1. Introduce the new features of this system, and discuss how the new wireless network is different from our current wireless network (which is not web-based and has no control capabilities).
2. Discuss differences between the commercial ornamental market and the commercial horticulture market. Our hope is to have horticulture experts on hand to discuss these challenges
3. Train on installation, system set-up, and troubleshooting.

2. Hardware Development

During year 4, Decagon spent much of their efforts on technology development to ensure that the commercial system will be robust and supportable when deployed to non-partner growers. Specifically, benchmarking efforts have focused on the:

1. Robust base station hardware development
2. Virtual private network for remote troubleshooting
3. Wireless sensor network access point
4. Irrigation controller interface

2.1 Base Station Hardware

Decagon worked with industrial computing vendors to test appropriate platforms to build the base station appliance (See Fig. 1). The desired characteristics include:

- Reliable operation when powered on 24/7 for years
- Fanless cooling to remove the most common hardware failure point
- Solid-state drive (SSD) storage
- Long manufacturing commitment

In addition to the base computer hardware, Decagon developed a simple LCD display board that mounts into a custom bezel in the front of the base station. There are two main purposes of the LCD board when used on an appliance computer without a normal computer display.

1. It provides a minimal user interface to help the grower know the correct IP address to use with their web browser to access the full features of the web application. Further this simple interface also has a buttons and a menu system to restart or shutdown the computer, initiate the VPN feature, and reset the network settings.
2. The LCD also implements a so-called watchdog timer. If the system becomes unresponsive, the LCD board will automatically restart the system.

Fig. 1. Ruggedized base station hardware with LCD display.

Another common challenge with the current research system was enabling remote access to collected data by both the growers and the research partners. During Year 4, Decagon took preliminary steps in making remote access more turn-key. Decagon created an open VPN-based virtual private network (VPN) to test how support technicians might gain access to a grower's base station across the Internet. This VPN can be configured for always-on operation or only enabled on-demand. This type of VPN configuration doesn't require the grower to have special network configurations from their Internet service provider (ISP) or at their local router.

2.2 Wireless Sensor Access Point

Current Sensorweb systems deployed with partner growers have a radio receiver attached to the base station. This constrains the location where the base station can be deployed in order to have a successful radio network. Decagon anticipates there are grower sites where it won't be practical to install the radio receiver next to the base station and growing situations where multiple radio receivers will be needed. Decagon is testing wireless sensor access point hardware to fill these needs (Fig. 2).

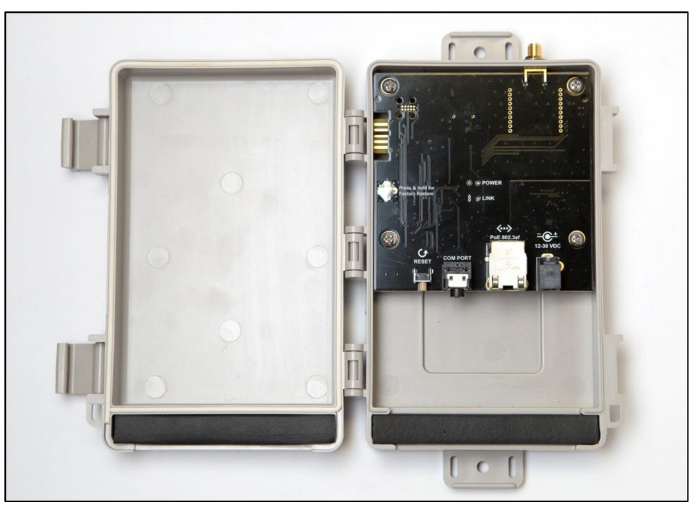


Fig. 2. Prototype wireless sensor access point in weatherproof enclosure.

This hardware acts as a gateway between the radio network and a local area network (LAN) where the base station and the grower's computer are connected. It contains the radio module coupled with an Ethernet-enabled microprocessor and is housed in a weatherproof enclosure. The gateway hardware uses Power over Ethernet technology (IEEE 802.3af) so that only one cable is needed for both communications and power. Alternatively, many of these controllers have a way to monitor the output of simple analog sensors. Decagon engineers are exploring the use this interface for "communicating" with the irrigation controllers.

2.3 Irrigation Controller Interface

Some commercial growers have invested in sophisticated irrigation controllers. Decagon believes these growers will be more likely to adopt the commercial monitoring and control system if there is a way to work with their existing controller rather than replace it with the simple control capabilities of the nR5 node. Decagon engineers spent time researching the kinds of irrigation controllers in the market today. Some may have a way to communicate with the Decagon commercial software; however, there are no standards governing these communications and their use may need formal licensing from the controller manufacturer. Trying to create software to digitally communicate with these controllers becomes a formidable task.

Decagon designed and is testing Irrigation Controller Analog Interface (ICAI) hardware to explore communicating with an irrigation controller via their analog inputs (Fig. 3). This prototype hardware has 4 analog outputs that could represent the average of different sensor values in a zone (e.g. average VWC, EC, and temperature).

Alternatively, these outputs could represent the average VWC in 4 irrigation zones. The ICAI also has one digital output (on or off) that can be used to trigger an irrigation event. This hardware communicates over Ethernet with the prototype base station. Decagon anticipates supporting multiple ICAIs for large growers with many irrigation zones.

Fig 3. Prototype irrigation controller analog interface hardware.

3. Software Development

This year a major focus has been to make the Sensorweb user interface more intuitive, easier to use, scalable, and to continue increasing the reliability of the system. Mouse over (or touch control with a smart-phone/tablet) gestures have been updated to show growers more of the data that they want to see. Touch feedback from mobile devices is now fully supported in the charts letting growers' access data from anywhere. Charts can now be organized so it is easier to find the chart you need (Fig. 4).

Irrigation nodes can now be assigned to a group; this allows growers to change the irrigation settings for the entire group instead of having to update each node individually. The beauty of groups is that while the grower can configure multiple nodes as a group each node continues to operate independently making its own irrigation decisions delivering the precision that distributed WSN nodes provides.

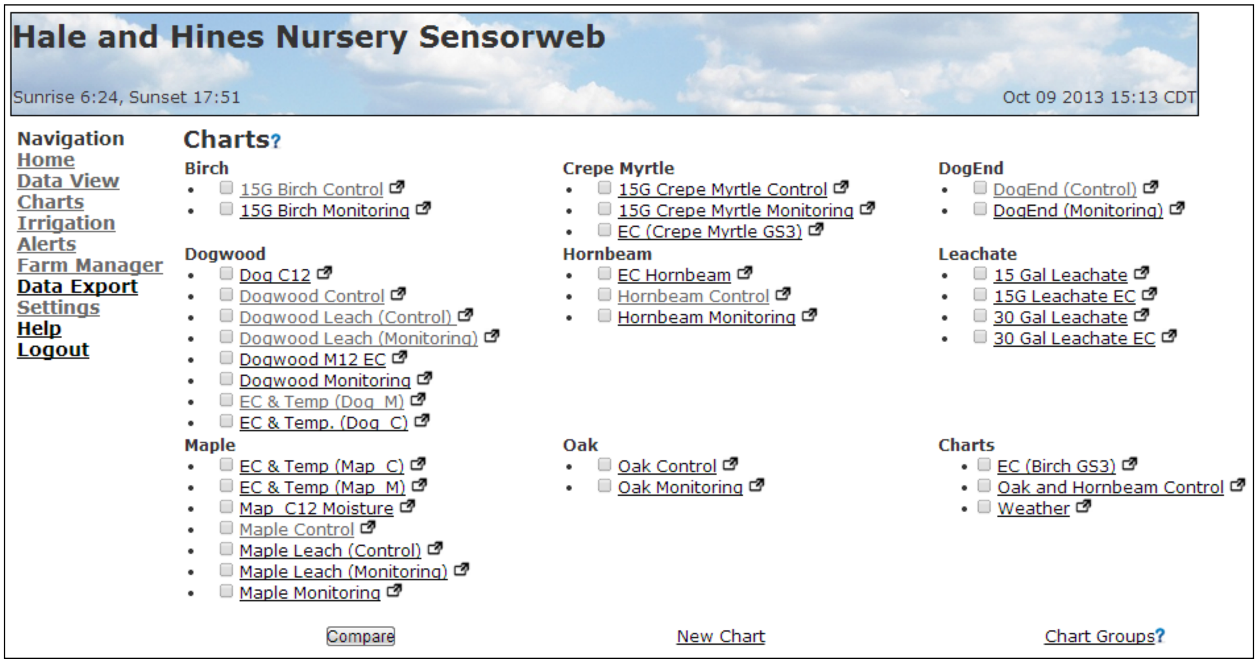


Fig. 4. Charts organized based on category to aid users. In this case each species has its own category.

Another new feature to improve the scalability of this system is the ability to read data from EM50G nodes. EM50G nodes transmit data over a cellular network making them easy to deploy throughout the world. Data from these nodes can be included within Sensorweb. This allows remote nodes to be viewed with existing nodes or to have a Sensorweb site that only contains remotely located nodes. One example of this is a new test site where the base station is in Maryland, USA while the nodes are in Ecuador.

New sources of data have been added to Sensorweb both in the form of grower tools and new sensors. The grower tool interface has been reworked to be more intuitive and new tools have been added for things such as computing evapotranspiration (Fig. 5) and water usage savings.

In addition, new sensors have been added:

- VP3 sensor which provides temperature, humidity, and vapor pressure deficit;
- Normalized Difference Vegetation Index (NDVI) sensor,
- Photochemical Reflective Index (PRI) sensor, and
- In-line EC (ES-2) sensor for monitoring irrigation tank/reservoir conditions.

These new sources of data are becoming important tools for crop monitoring and are being evaluated to simplify existing plant water use models.

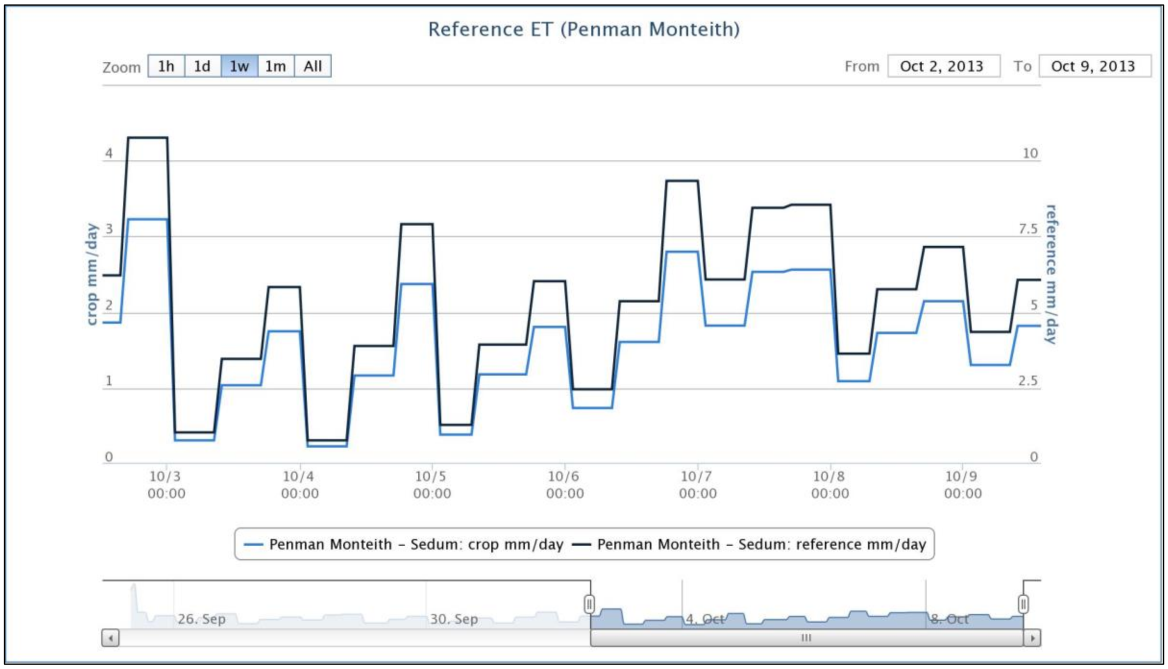


Fig. 5. Chart showing sample data with both reference evapotranspiration and crop specific evapotranspiration.

A farm manager tool was developed that allows growers to monitor inventory and track actions that are performed, and that need to be performed, for a selected crop. This tool is useful to let the growers track a crop as well as to compare different crops. Using this tool a grower can see the differences between a prior crop and the current crop to determine why one is growing better than the other.

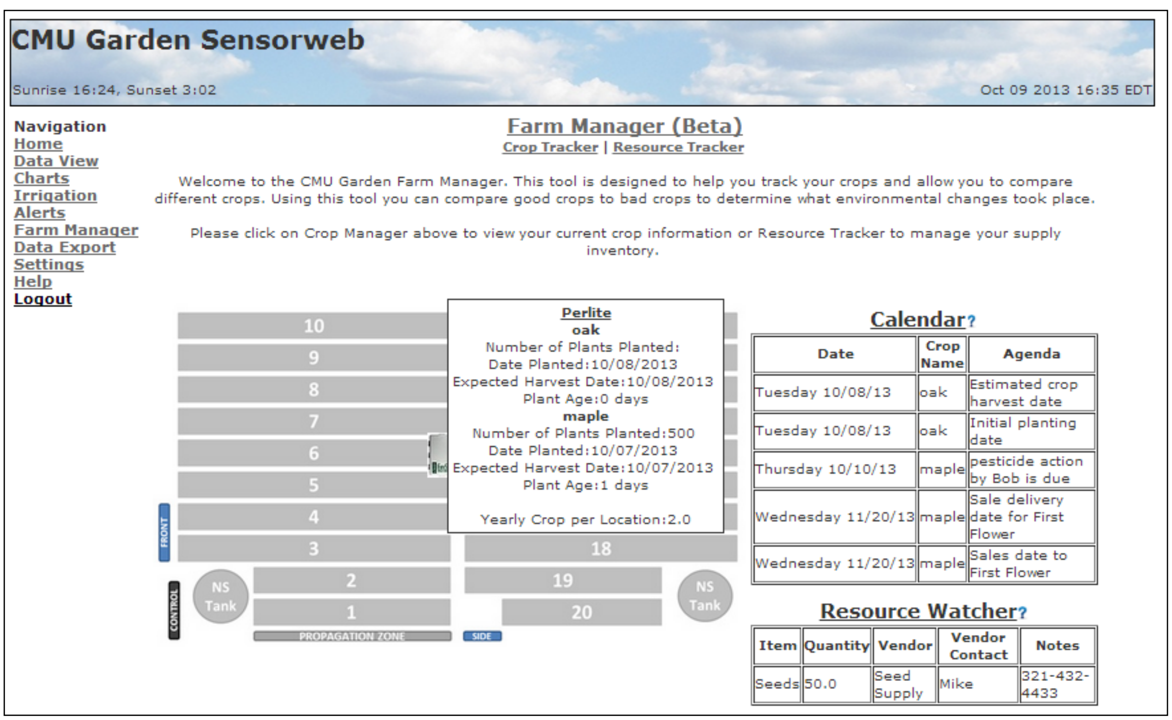


Fig. 6. Image of the farm manager tool.

The right side of the screen shows upcoming events and resources that are below a critical value and need to be replaced. Mousing over the image on the left (Fig. 6) allows for a detailed view of crops at that location as well as basic statistics. The crop tracker module allows the user to view statistics and see all the data for that specific crop and time period.

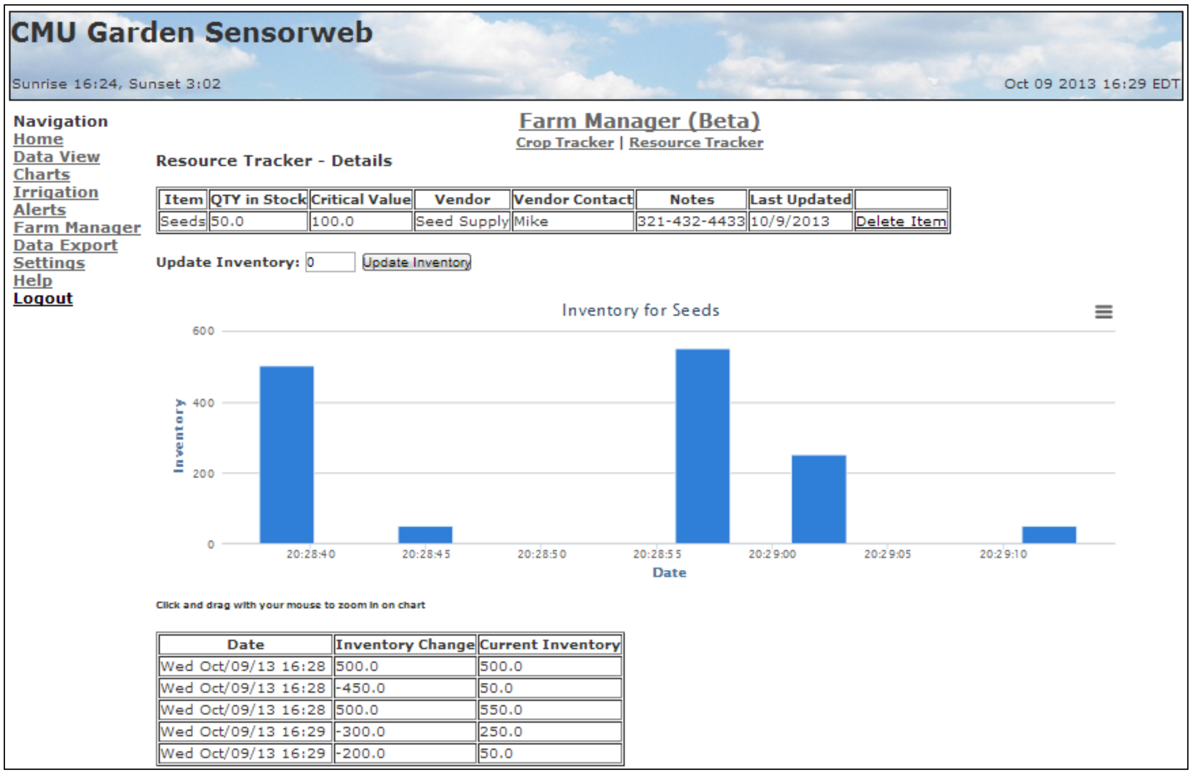


Fig. 7. Chart showing inventory of Seeds. This allows for tracking inventory usage.

4. Summary

This year significant effort and progress has been made to make this system ready to be used commercially. Adding new features while improving reliability makes for a more useful and appealing product. Further by developing a plan for commercializing and selling this system, while also creating a system for training and supporting the end user, this project is well on its way for creating a successful product.

5. Field Testing and Support

The Sensorweb system is deployed at more than 15 different sites; the sites accessed online from http://www.frc.ri.cmu.edu/sensorweb/sensorwebSites.html

B. Scientific Research and Development - Colorado State University

To scale to the entire horticulture operation (e.g. one to hundreds of acres) we have focused in on two parameters that we identified to comprise the majority of transpiration prediction power. We now understand the effect of one (night time conductance) and we are currently working on how to use the parameters, along with generalized C_3 parameter sets, to scale up to large areas of plant production. These results enable us to focus in on two physiology parameters and scale transpiration based on their measurement.

Barnard, D.M. and W.L. Bauerle. 2013. The implications of minimum stomatal conductance on modeling water flux in forest canopies. Journal of Geophysical Research: Biogeosciences, 118, doi: 10.1002/jgrg.20112 was published based on this research.

a) Carbon and water flux responses to physiology by environment interactions: A sensitivity analysis of climate impacts on biophysical model parameters

We have analyzed the contribution of temperature and photoperiod on the control of seasonal patterns of maximum carbon uptake and canopy-scale photosynthetic light response: The manuscript tests the leaf-level and global findings of Bauerle et al. (2012, PNAS 109: 8612-8617) at the canopy/ecosystem scale using nearly four hundred site-years of eddy covariance data from over eighty flux towers. We find that day length, in addition to temperature, helps explain the seasonal variability in canopy scale photosynthetic function.

Stoy, P.C. A.M. Trowbridge, A.M., W.L. Bauerle. 2013. Controls on seasonal patterns of maximum ecosystem carbon uptake and canopy-scale photosynthetic light response: contributions from both temperature and photoperiod. Photosynthesis Research DOI 10.1007/s11120-013-9799-0.

The analysis allows us to determine what transpiration parameters we need to focus on when we are operating under specific environmental conditions. We address the question of constant versus dynamic changes in physiology parameter input effects for models that scale photosynthesis and transpiration. We demonstrate that key input parameters used at a larger scale change in importance with climate gradients, such that environment by physiology interactions change the parameter input effect on photosynthesis and transpiration estimates. Testing the output sensitivity to our input parameter ranges in a three-dimensional model, founded on a sound micro-meteorological and biological vegetation-atmosphere scheme, illustrates the dynamic parameter effects of key physiological input parameters under a range of environmental conditions. Our results have broad implications toward the development of a biological parameter ranking system based on the changing parameter effects for estimates of water fluxes from horticulture systems.

b) The implications of minimum stomatal conductance on estimating water flux in containerized tree nurseries

Stomatal conductance (g_s) models are widely used at a variety of scales to predict fluxes of mass and energy between vegetation and the atmosphere. Several g_s models contain a parameter that specifies the minimum g_s estimate (g_0). Sensitivity analyses with a canopy flux model (MAESTRA) identified g_0 to have the greatest influence on transpiration estimates (seasonal mean of 40%). A spatial analysis revealed the influence of g_0 to vary (30-80%) with the amount of light absorbed by the foliage and to increase in importance as absorbed light decreased. The parameter g_0 is typically estimated by extrapolating the linear regression fit between observed g_s and net photosynthesis (A_n). However, our measurements demonstrate that the g_s-A_n relationship becomes nonlinear at low light levels and thus, extrapolating values from data collected in well-lit conditions resulted in an underestimation of g_0 in *Malus domestica* when compared to measured values (20.4 versus 49.7 mmol m^{-2} s^{-1} respectively). In addition, extrapolation resulted in negative g_0 values for three other woody species. We assert that g_0 can be measured directly with diffusion porometers (as g_s when $A_n \leq 0$), reducing both the time required to characterize g_0 and the potential error from statistical approximation. Incorporating measured g_0 into MAESTRA significantly improved transpiration predictions (6% overestimation versus 45% underestimation respectively), demonstrating the benefit in g_s models. Diffusion porometer measurements offer a viable means to quantify the g_0 parameter, circumventing errors associated with linear extrapolation of the g_s-A_n relationship.

Bauerle, W.L., A.B. Daniels, and D.M. Barnard. 2013. Carbon and water flux responses to physiology by environment interactions: A sensitivity analysis of variation in climate on photosynthetic and stomatal parameters. Climate Dynamics, doi:10.1007/s00382-013-1894-6.

This manuscript solidifies the importance of model parameters at larger scales (like a nursery) and starts to tease apart how they change in importance in response to environmental conditions. The findings will help guide our ability to scale water use estimates at the nursery scale.

c) A comparison of the potential for scaling up irrigation scheduling techniques: substrate moisture sensing versus predictive water use modeling

Evapotranspiration equations (e.g. Penman-Monteith) are widely used to estimate crop irrigation. However, crop coefficients that adjust potential evaporation to crop-specific transpiration are empirically derived, absent of physiological response descriptions. Although complex mechanistic models exist for predicting crop water use (e.g. MAESTRA), their application in commercial nurseries has, so far, only been conceptual. Alternatively, irrigation scheduling can take place by substrate moisture measurement, triggering irrigation based on predefined volumetric water contents (threshold method). In this study we grew trees in a containerized pot-in-pot production system and irrigated them with both scheduling methods. The threshold method maintained substrate volumetric water content between 35 and 42%.

The modeling method used MAESTRA to estimate transpiration on a 15-minutes time step, triggering periodic irrigation from crop water use estimates. Tree growth (stem caliper) and canopy development (m^2 of leaf area) were measured over the growing season. In addition, we monitored daily irrigation and leachate for water balance and irrigation application efficiency calculations. We tested the hypothesis that precise characterization of two physiology parameters [minimum stomatal conductance (g_0) and the marginal water cost per unit of carbon gain (g_1)] could yield accurate transpiration estimates (within 10%). Predictive water use modeling exceeded our 10% error window, but we were able to estimate irrigation within 20% of measured values. Overall, trees irrigated by the MAESTRA method developed more (up to 15%) stem caliper and accumulated up to an additional 25% of leaf area in one growing season. However, the modeling method applied more water (~20% across species). Despite the additional amount of water, we found the efficiency of applied irrigation (percent of water that did not leach) to be similar between the two methods (within 10%). We conclude that MAESTRA holds promise as an effective means for scheduling irrigation with generalized physiology parameter sets.

Currently, we are actively working on designing experimentation and procedures to test the validity of scaling plant physiological functional groups to entire nurseries. The proposed research and scale-up will focus on improving the minimum stomatal conductance and stomatal sensitivity to the marginal water cost of carbon gain parameters representing stomatal conductance and their response to environmental drivers in nursery scale water use models. Key woody species representing dominant physiological functional types will be used to identify the physiological variation in stomatal conductance parameter values. Complementary experiments will take place at Colorado State University and Willoway Nurseries Inc. A hierarchical physiological model (MAESTRA) will be used to understand the basis by which minimum stomatal conductance and stomatal sensitivity to the marginal water cost of carbon gain affect transpiration function.

Estimates of minimum stomatal conductance and stomatal sensitivity to the marginal water cost of carbon gain will be derived from gas exchange measurements made by varying light and VPD, using portable photosynthesis systems with light, humidity, VPD, and temperature controlled cuvettes. In response to the environment, our preliminary data suggest a mechanistic water stress response that decreases minimum stomatal conductance and stomatal sensitivity to the marginal water cost of carbon gain in response to increasing drought, as well as tracking the seasonal course of VPD. If true, we will construct climate-based scalars for minimum stomatal conductance and stomatal sensitivity to the marginal water cost of carbon gain to incorporate into nursery scale models, analogous to the development of a day length-based scalar to modify photosynthetic potential by Bauerle et al. (2012).

C. Scientific Research and Development - Cornell University

We compared root standing crop populations of four ornamental tree species including, *Acer rubrum* L.'Franksred' (*Acer*), *Carpinus betula* L. 'Columnaris' (*Carpinus*), *Gleditsia tricanthos* L. var. *inermis* 'Skycole' (*Gleditsia*), and *Quercus rubra* L.'Rubrum' (*Quercus*) grown in a nursery mix substrate within large 57-L containers using an X-ray computed tomography approach through time. Individual root identification was performed manually on 2D slices of CT scans. Our data show high variation in species total root number through time with *Carpinus* exhibiting the largest root population throughout the study period. However, species exhibited differences in root distribution patterns as exemplified by the shallow and horizontally more uniform rooting pattern of *Acer* in comparison to the highly plastic root distribution in space through time in *Gleditsia*. Root frequencies within 1 mm root diameter class distributions shifted by species, with the most drastic differences found between high frequencies of relatively small diameter roots in *Acer* versus pronounced shifts in dominate root diameter size class as found in Gleditsia and lesser so in *Carpinus* during a growing season. Our findings demonstrate differences in whole tree root systems space occupation non-destructively through time and highlight a disparity in how species fill a container volume during growth.

Three, two-year-old liner replicate trees, (n=3) were transplanted in April of 2010 into 57-L pots (44 cm wide by 38 cm deep) containing a mixture of 71% pine bark, 21% peat moss, 7% sterilized regrind potting soil, and 1% 12N-0P-34.9K slow-release fertilizer (Agrozz Inc., Wooster, OH). We used a medical CT scanner (Toshiba Aquilon, Tokyo, Japan) to acquire one full scan per tree replicate during each scanning session. Containers were placed horizontally on the scanning bench and aligned with pre-placed markings to ensure container positioning. The field of view was filled with sample to eliminate differences in beam intensity.

Three concentric rings resulting in four areas of 63.6 cm^2, 190.9 cm^2, 318.1 $cm^2$and 445.3 cm^2 were superimposed onto the projection images to provide user orientation (Photoshop v. CS6, Adobe systems Inc., San Jose, CA) (Fig. 8.1). Ring 1 refers to the innermost location within the container and ring 4 to the outermost location within the container. Every 25 image slices from the stack of CT scans (approximately 2.5 cm depth increments) were used to count total number of roots present and to measure root diameter (Image J, National Institutes of Health, Bethesda, MD, http://rsb.info.nih.gov/ji/) (Fig. 9).

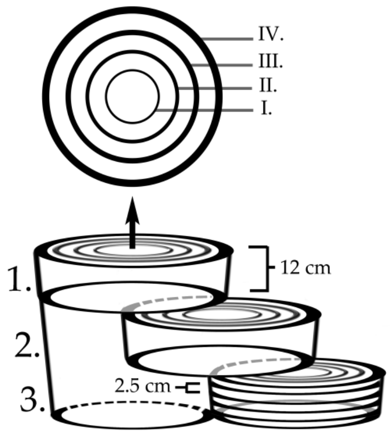


Fig. 8. Schematic diagram representing four concentric rings (1-4) and three depth intervals (1-3) used for root distribution assessment of CT scans. Root number and diameter were measured every 25 image slices, *ca.* 2.5 cm

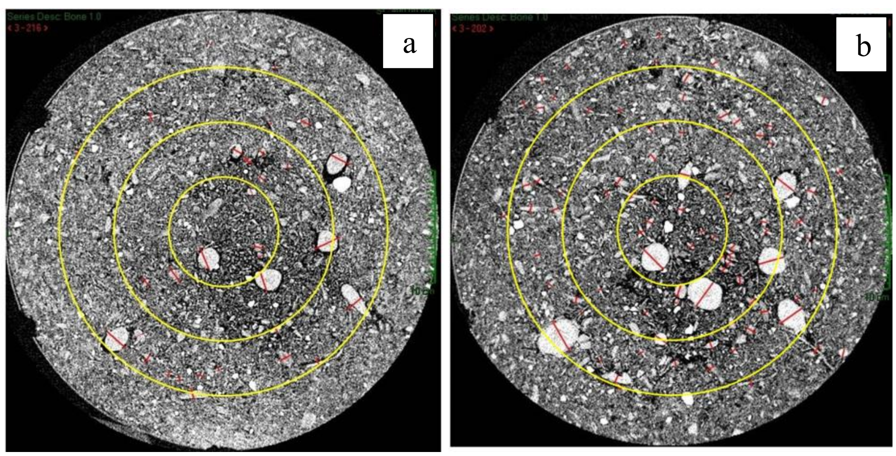


Fig. 9. Examples of identical cross slices through two dimensional Computed tomography scans in May (a) and September (b). Yellow concentric rings were used to mark distance from the center of the container.

The species *Acer* produced the largest proportion of roots less than 2 mm, but also the smallest total root standing crop throughout the study (Fig. 10).

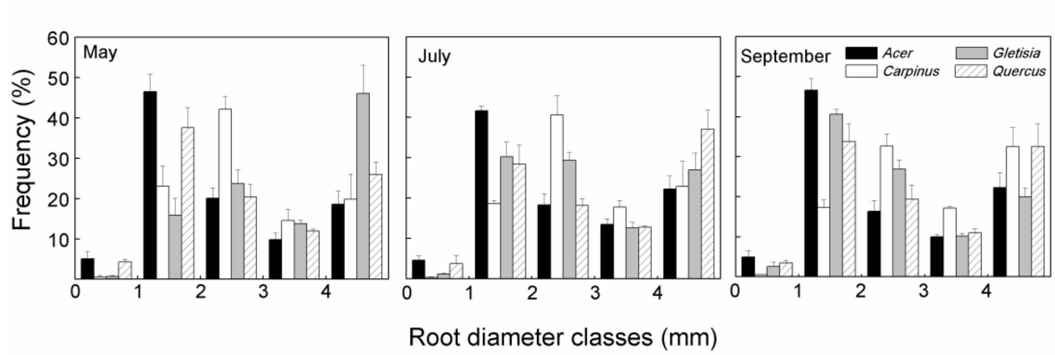


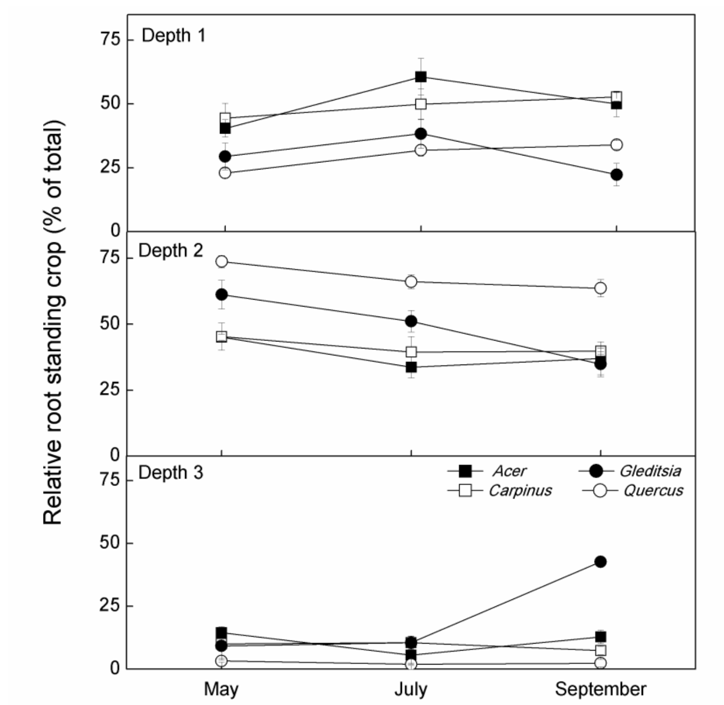
Fig. 10. Root diameter class structure of roots present in May, July, and September for four ornamental tree species (*Acer, Carpinus, Gleditsia,* and *Quercus*). Diameter classes are in 1 mm intervals (*i.e.*, diameter class one represents roots from 0-.99 mm) with the exception of diameter class five which represents all roots ≥ 4 mm.

Two factors that may have contributed to this disparity arise from the lack of roots produced in higher root diameter classes within the species and compared to other species, as well as the fraction of finer roots(≤1 mm in diameter) that were not accounted for as a result of CT resolution. In contrast, *Carpinus* and *Quercus,* tree species with generally "finer" roots (Pregitzer et al., 2002), produced a significantly larger root standing crops compared to *Acer* and *Gleditsia*, yet, notably with a large proportion of roots in higher diameter classes.

Our results emphasize the shallow root foraging of *Acer* and *Carpinus* versus the "deeper" root placement in *Quercus* and especially *Gleditsia* over time, suggesting possible differences in root foraging strategies between the species we examined. Our study supports the widespread agreement on the centrality of the coarse root fraction within the horizontal rooting profile (Millikin and Bledsoe, 1999; Ouimet et al., 2008). However, within the fine root fraction, species exhibited greater variation in root placement with *Carpinus* exhibiting a predominately centrally located fine root fraction compared to the more evenly dispersed root system of *Acer*. Interestingly, within a single species, with the exception of *Gleditsia*, root standing crop across the growing season was relatively stable across concentric rings suggesting either long root lifespans or relatively slow turnover of the root population.

Among four widely used ornamental species, we found *Gleditsia* to be the most plastic in its fine root growth and allocation within the container as emphasized by its decrease in root standing crop in the center depth of the container and subsequent increase in the deepest substrate depth interval (Fig. 11).

Fig. 11. Vertical distribution of the population of roots (standing crop) expressed as (% of root produced in each soil depth/ total root production for that species) (±1 SE) for *Acer* (black squares), *Carpinus* (white squares), *Gleditsia* (Black circles), and *Quercus* (white circles) tree species over three soil depths. Depth 1 (0-12cm), depth 2 (12-24 cm) and depth 3 (25-38 cm)



Likewise, *Gleditsia* also had the greatest reduction in root standing crop within the central portion of the container and greatest increase toward more peripheral concentric rings (Fig. 12).

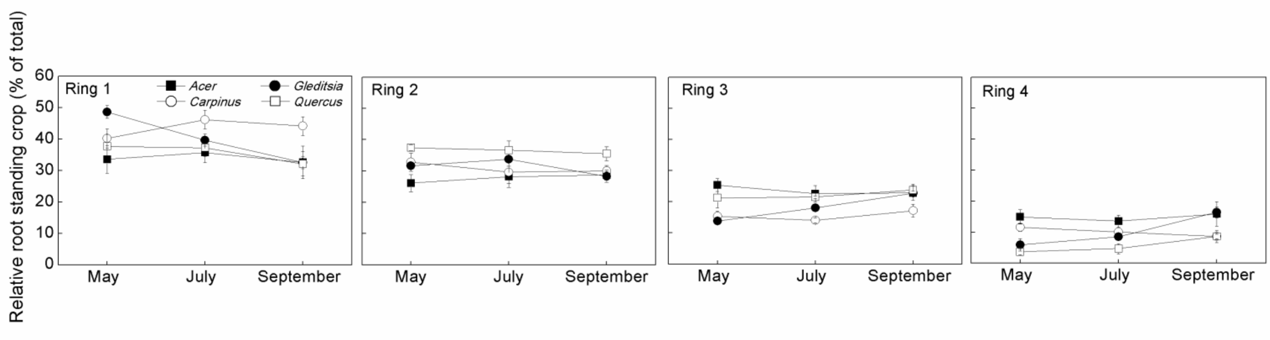


Fig. 12 Horizontal distribution of the population of roots (standing crop) expressed as (% of root produced in each concentric ring/ total root production for that species) (±1 SE) for *Acer* (black squares), *Carpinus* (white squares), *Gleditsia* (Black circles), and *Quercus* (white circles).

Experiment 2:

The aim of this study was to examine the relationship of substrate moisture sensor readings in six ornamental trees to their root distribution patterns within a container. Following root anatomical analysis, tree root systems were dissected by root order as a means to separate fine (uptake) roots and coarse (transport) roots. Substrate moisture variability was measured through the deployment of 12 substrate moisture sensors per container. Of the tree species studied, we found two patterns of root distribution a shallow, "conical-shaped", root system, with the broadest portion of the root system in the shallow soil layer, and a more evenly distributed "cylindrical-shaped" root system. Root system distribution type influenced substrate moisture reading variability. Conical root systems had lower substrate moisture variability and high fine root variability, while the opposite was true for cylindrical root systems - most likely due to the larger, coarse woody mass of roots. We were unable to find any correlations between fine root morphological features including root diameter, length, or surface area and substrate moisture variability. However, higher specific root length was associated with higher substrate moisture variability. Classifying a tree's root system by its growth and distribution within a container can account for variation in substrate moisture readings and help inform future decisions on sensor placement within containerized systems.

The following six nursery tree species with varying root growth strategies were selected for this study: red maple, (*Acer rubrum* L. 'Franksred'); honey locust, (*Gleditsia triacanthos* L. var. intermis 'Skycole'); red oak, (*Quercus rubra* L.'Rubrum'); hornbeam, (*Betula nigra* L. 'Cully'); redbud, (*Cercis canadensis* L.); and birch, (*Carpinus betulus* L. 'Columnaris'). Five replicates of 2-year-old liners per species were transplanted in Apr. 2010 into 15-gal pots (17.3 in wide X 15 in deep) containing a mixture of 64% pine bark, 21% peat moss, 7% sterilized reground potting soil, 7% Haydite Type "B" (DiGeronimo Aggregates LLC, Independence, OH), and 1% slow-release fertilizer 12N-0P-34.9K (Agrozz Inc., Wooster, OH).
To characterize within-layer variation in substrate moisture, we deployed an array of 12 capacitance/frequency-domain sensors (model 5TM; Decagon Devices, Pullman, WA) with a 1 L field of measurement in one container of each of the six species. Sensors were inserted 15 cm into the container through a hole drilled in the container wall. Holes were covered with duct tape to prevent preferential flow paths. The sensors were arranged in a matrix of three vertical layers (10, 20, and 30 cm below the substrate surface) with four sensors in each layer (one sensor in each of the four cardinal directions). Sensors were connected to wireless data loggers (model EM50R, Decagon Devices) that read sensor output once every minute from which a 5-min average was recorded. Raw sensor output (mV) was then averaged over the four sensors within each layer and converted to VWC via a calibration

equation developed specifically for this substrate-sensor combination. Variance measurements were calculated on a layer basis as the average of the four sensors per layer.

Three replicate trees of each species were randomly selected and destructively harvested in Jul. 2010. The stem was first separated from the root collar with a fine tooth saw and then we separated the container into three equal volumes by depth (about 10 cm thick), dividing each layer into nine equal sections for a total of 27 sections per container. Two random root segment samples, one from a quadrate located in the interior portion of the container and one from an exterior quadrate were carefully excavated from each soil layer and immediately wrapped in damp paper towels and refrigerated. The roots in the remaining sections were gently washed free of adhering soil and brought back to the lab for analysis. Three replicates of 10 cm long segments of each tree species were fixed in FAA (5ml formaldehyde, 5 ml acetic acid and 90 ml of 70% ethanol) solution and dissected by root order (Berntson, 1997; Fitter, 1982; Guo et al., 2008) following Strahler's stream ordering system (Pregitzer et al., 2002) such that, roots ending in a tip were classified as first order; two first order roots join a second order root; two second order roots join a third order root, and so on. This classification recognizes a shift in function from fine roots (roots with primary anatomical development that are responsible for water uptake) to coarse roots (roots responsible for transport and anchorage) that occur with increasing root order (Pregitzer et al., 2002). Root segments were fresh sectioned and imaged under light microscope (Axioskop II; Zeiss, Jena, Germany) at 20x magnification. Cross-sections were used to determine the anatomical development of root orders of each species with the presence or absence of a periderm and indications of secondary development. Based on these findings, subsequent root biomass in the harvested sections were separated by appropriate species specific root orders that represented fine roots of primary anatomical development (uptake) roots (red maple, orders 1-2; honey locust, order 1; birch, orders 1-2; redbud, orders 1-2; hornbeam, orders 1-3; red oak, orders 1-3) versus coarse (transport) development as a means of identifying root function (Table 1).

Table 1. Root morphological characteristics, including mean root diameter, root length, and root surface area of the first order roots for six ornamental tree species, red maple, honey locust, red oak, birch, redbud, and hornbeam (± 1 SE).

Species	Mean root diam (mm)	SE	Mean root length (cm)	SE	Mean root surface area (cm^2)	SE
red maple	0.371	0.035	0.310	0.028	0.088	0.035
birch	0.189	0.020	0.504	0.084	0.080	0.046
honey locust	0.194	0.008	0.164	0.028	0.115	0.044
red oak	0.321	0.015	0.456	0.023	0.095	0.052
hornbeam	0.189	0.020	0.114	0.011	0.090	0.047
redbud	0.182	0.033	0.079	0.007	0.096	0.048

D. Scientific Research and Development - University of Georgia

Our research efforts in the last year have had a focus on leaching, fertilizer rate, and plant growth interactions, using gardenia and petunia as model species. We have also started work in new areas, that were not part of the original plan of work, but whose importance became clear over the course of this project. These areas include the dynamics of oxygen concentrations in the root zone, as well as the hydraulic properties of soilless substrates.

1. Temporal Dynamics of Oxygen Concentrations in a Peat-Perlite Substrate

Anoxic conditions in soilless substrates have been implemented in disease development, reduced growth rates, and denitrification, but there is little quantitative information on oxygen concentrations in soilless substrates. We measured the partial pressure of oxygen (pO_2) in peat-perlite substrate planted with petunia (*Petunia × hybrida*). There are distinct diurnal fluctuations in substrate pO_2, and these can be largely explained by changes in substrate temperature, which increase the amount of water vapor in the air in the substrate, diluting oxygen and other gases.

Barometric pressure (p_{air}) and substrate volumetric water content (θ) also affected substrate pO_2. Substrate pO_2 decreased with decreasing p_{air} and with increasing θ (Fig. 13). Photosynthetic photon flux had a highly significant, but small effect on pO_2. Substrate density had no significant effect on pO_2. Overall, substrate pO_2 was between 19.1 and 20.6 kPa, even after watering the substrate to container capacity. Since such high levels of pO_2 are unlikely to induce any detrimental anoxic effects on plants, our data do not provide any supporting evidence for the idea that anoxia is an important potential problem in peat-perlite substrates.

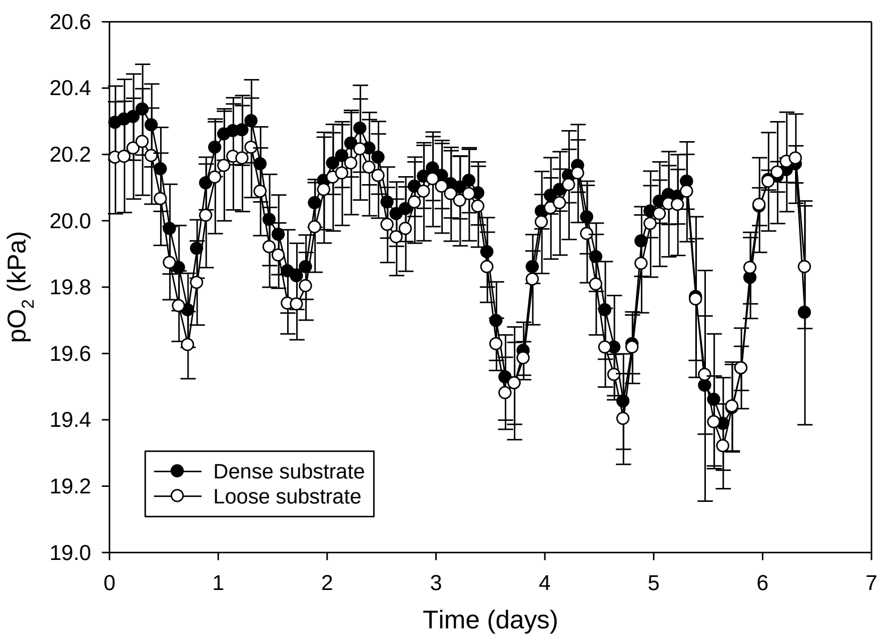


Fig. 13. Temporal dynamics of the partial pressure of O_2 (pO_2) in a peat-perlite substrate in a loosely and densely packed substrate. There was no significance effect of substrate density on the partial pressure of oxygen. Diurnal fluctuations in pO2 are closely correlated with substrate temperature.

2. Irrigation Volume and Fertilizer Concentration Effects on Leaching and Growth of Petunia

Excessive irrigation in greenhouse production causes leaching of water with dissolved nutrients. This leaching causes a direct economic loss to growers by removing fertilizer from the pots and potentially causes environmental pollution. Improving irrigation efficiency can reduce leaching, decrease the amount of fertilizer needed and improve both economic and environmental sustainability. Our objective was to quantify the interactive effect of fertilizer concentration and irrigation volume on leaching and growth of petunia (*Petunia × hybrida*) and determine whether growers can use less fertilizer if they irrigate more efficiently.

Petunia seedlings were grown to a salable size in 15-cm pots filled with peat:perlite (80:20) substrate using two concentrations of N (at 100 and 200 $mg{\cdot}L^{-1}$) of water soluble fertilizer (15N–2.2P–12.5K) injected into a drip irrigation system. Plants were irrigated when substrate moisture content (θ) dropped below 0.45 $m^3{\cdot}m^{-3}$, but with different amounts of water (control with efficient irrigation and low, medium, and high irrigation volumes), resulting in different leaching volumes over the course of the production cycle. Specifically, we used 384, 661, 982, and 2910 mL/pot in the control, low, medium, and high irrigation and 100 $mg{\cdot}L^{-1}$ N treatments and 1128, 1568, 2030, and 3064 mL/pot in the control, low, medium, and high irrigation and 200 $mg{\cdot}L^{-1}$ N treatments, respectively. Shoot dry mass more than doubled as fertilizer concentration increased from 100 to 200 $mg{\cdot}L^{-1}$ N, regardless of the irrigation volume. No difference in shoot dry mass was observed among the irrigation treatments (Fig. 15).

The 200 $mg{\cdot}L^{-1}$ N resulted in more leaching than the 100 $mg{\cdot}L^{-1}$ N, except at the high irrigation volume (Fig. 14). Because the plants grown with 200 $mg{\cdot}L^{-1}$ N were larger and needed more water to sustain their growth, they were irrigated more often, resulting in larger leaching volumes. Contrary to our hypothesis, this study provided no proof that fertilizer rates can be reduced when more efficient irrigation practices are used. However, even reducing just the amount of irrigation water applied, without decreasing the fertilizer concentration, will reduce the amount of fertilizer applied, thus reducing production costs and decreasing the risk of environmental pollution.

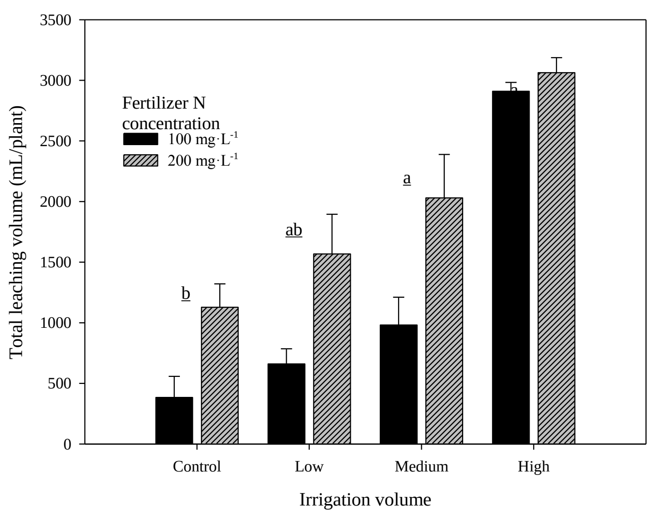


Fig. 14. Total leaching volume at different irrigation volumes (low, medium & high) and two fertilizer rates (100 and 200 $mg{\cdot}L^{-1}$ N). Bars (mean ±SD) with the same letters are not significantly different. The letters indicate significant difference among irrigation treatments. 200 $mg{\cdot}L^{-1}$ N fertilizer resulted in more leaching than 100 $mg{\cdot}L^{-1}$ N *(P=0.02)*.

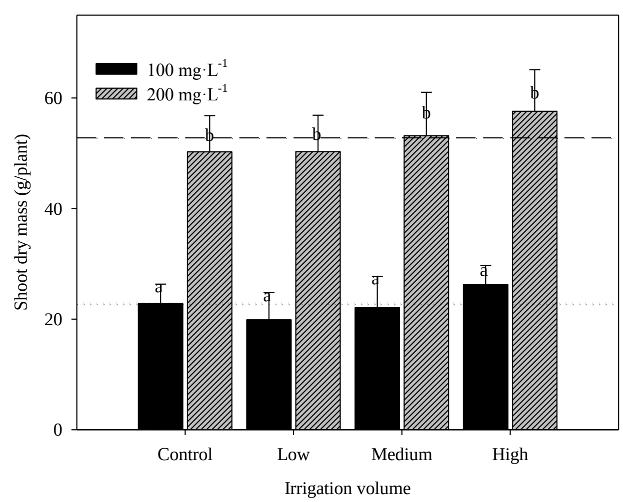


Fig. 15. Mean shoot dry mass of petunias fertigated with fertilizer solution containing 100 or 200 $mg{\cdot}L^{-1}$ N, and irrigated efficiently (control) or with different amounts of leaching (low, medium or high). Bars (mean ± SD) with the same letter are not significantly different.

3. Fertilizer rate and irrigation duration affect leachate volume, electrical conductivity, and growth of *Gardenia jasminoides*

An increasing number of laws and regulations regarding runoff and water use are necessitating container nursery growers to irrigate more efficiently. However, over-irrigation and intentional leaching are still common in the industry. Leaching of fertilizers often leads to the need for additional fertilizer applications, which are costly for the grower and the environment. By reducing fertilizer application rates and irrigating more efficiently we believe that salable plants can be produced with little or no irrigation-induced leaching. In this study, we related fertilizer application rate and irrigation duration to leachate volume, leachate electrical conductivity, and plant growth. A soil moisture sensor-controlled irrigation system was used to irrigate Gardenia jasminoides 'Madga I' (sold as Heaven Scent). Controlled release fertilizer was applied at 100, 50, and 25% of the label rate and irrigation durations were 2, 3, 4, or 5 minutes, applying 66, 100, 132, or 165 ml per irrigation.

All plants within an experimental block were irrigated when the volumetric water content of the control plants (2 minute irrigation duration, 100% fertilizer treatment) reached 35%. At that time, plants in all treatments were irrigated. This provided excessive irrigation to plants irrigated for 3, 4, or 5 min. Leachate was collected biweekly and included leachate caused by rainfall. Leachate volume was greatest for plants receiving the 5 minute irrigation for all fertilizer treatments. The cumulative leachate volume was 15, 12.5, 10.5, and 9 L/plant for the 5, 4, 3, and 2 min irrigation treatments respectively. Electrical conductivity (EC) of the leachate was highest with the 100% fertilizer rate and decreased with reduced fertilizer rate.

Fertilizer rate and the interaction of fertilizer rate with irrigation duration had a significant effect on shoot dry weight. Average shoot dry weight was 18.7, 25.3, and 27.3 g per plant for the 25%, 50%, and 100% fertilizer treatments respectively. Using 3-minute irrigation cycles, shoot dry mass of plants grown with 50% fertilizer was only 0.2 g lower than that of plants grown with 100% fertilizer, while with 4-minute irrigation cycles, this difference was only 1.1 g. This shows the potential for reduced fertilizer use with moderate irrigation applications. In this study, we have shown that reduced fertilizer application rates can be used along with moderate irrigation durations to reduce leaching of nutrients, without negatively impacting plant growth (Fig. 16).

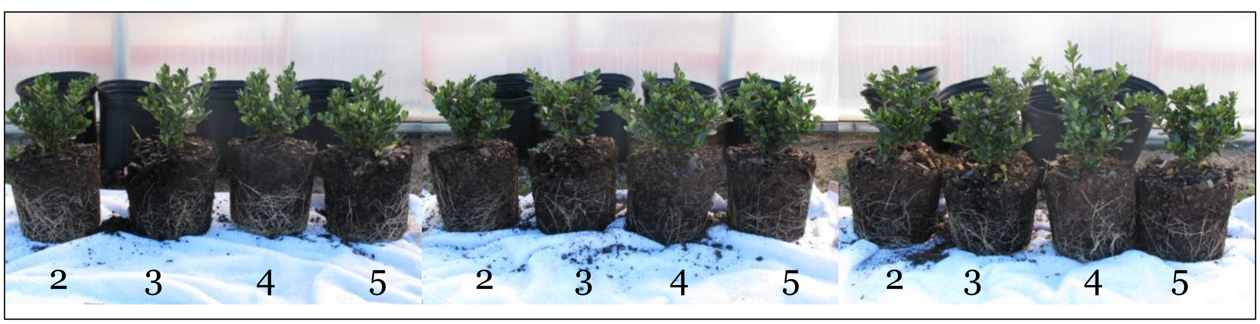


Fig. 16. Photos of plants showing all treatment combinations at the conclusion of the experiment. Treatments are 25% fertilizer rate to the left, 50% in the center, and 100% to the right and irrigation volumes are from 66-165 ml (2, 3, 4, and 5) moving left to right in all pictures.

4. Control of Poinsettia Stem Elongation: Height Limits Using Deficit Irrigation

Height regulation is crucial in poinsettia production for both aesthetics and transportation. Shorter plants are preferred by consumers and occupy less space during transport, allowing for more plants per truck. Controlled water deficit, reducing substrate water content in a controlled fashion when plants are too tall, offers an alternative to plant growth regulators (PGRs) for poinsettia height regulation. We have previously shown that a controlled water deficit can be used to regulate poinsettia stem elongation. However, it is not clear what the limits are for height control using deficit irrigation and how this affects aesthetic qualities, such as bract size.

Our objectives were to determine how much shoot elongation can be inhibited using controlled water deficits and to investigate possible adverse effects of on shoot morphology. Rooted cuttings of poinsettia (*Euphorbia pulcherrima* 'Classic Red') were transplanted into 6 inch pots filled with peat:perlite (80:20) substrate. The plants were fertigated through drip irrigation system with 200 $mg{\cdot}L^{-1}$ N of water soluble fertilizer (15N–2.2P–12.5K). Three target heights (43.2, 39.4 and 35.6 cm) were set at pinching and growth tracking curves were used to monitor plant height throughout the production cycle. Substrate water content (θ) was maintained at 0.40 $m^3{\cdot}m^{-3}$ (approximately -5 kPa) during normal growth and reduced to 0.20 $m^3{\cdot}m^{-3}$ (approximately -75 kPa) when plants were too tall, based on the tracking curves. When plant height was once again within the appropriate range, θ was increased again to 0.40 $m^3{\cdot}m^{-3}$.

Control plants were maintained at a θ of 0.40 $m^3{\cdot}m^{-3}$ throughout the study. The θ levels were maintained using a soil moisture sensor-based automated irrigation system. Plant height in the 35.6 cm target height treatment remained above the upper limits of the tracking curve, despite being kept at a θ of 0.20 $m^3{\cdot}m^{-3}$) for 70 days after pinching and the final plant height of these plants was 39.8 cm. However, we were able to achieve the target heights of 39.4 and 43.2 cm (Fig. 17.). Relative to control plants, bract area was reduced by 53, 47 and 31% in the 35.6, 39.4 and 43.2 cm target height treatments respectively. Our results indicate that the minimum height that can be achieved using deficit irrigation is approximately 39-40 cm, but that water deficit may also decrease bract size (Fig. 18).

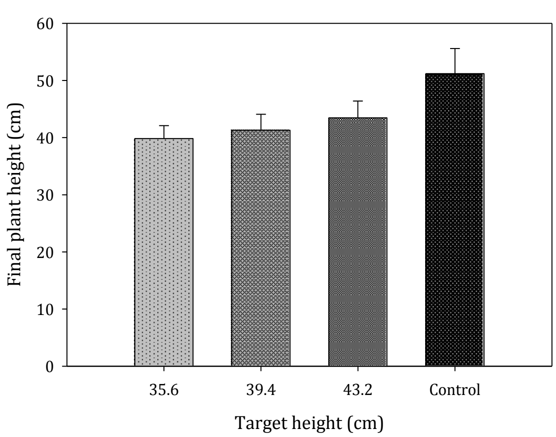


Fig. 17. Final plant height in the different treatments. Controlled drought stress was an effective method of growth control, although a target height of 35.6 cm could not be achieved.

Fig. 18. Visual appearance of plants from the different treatments at the end of the study (left to right; target heights of 35.6, 39.4, and 43.2 cm, and a control plant). Note that we were not able to achieve a target height of 35.6 cm

5. Hydraulic properties of peat-based substrates: The importance of hydraulic conductance

The availability of water to plants grown in soilless substrates is typically evaluated with substrate moisture release curves, which describe the relationship between substrate water content and substrate matric potential. Past studies have generally concluded that there is little or no plant available water left at substrate matric potentials (Ψ_m) of -30 kPa. However, plant water potential is typically much lower than -30 kPa and the substrate-to-plant water potential gradient should allow for continued water uptake. This suggests that plant water uptake may not be limited by substrate matric potential. We hypothesize that hydraulic conductivity may limit water movement in soilless substrates. To test this, we measured substrate water content, matric potential, and evapotranspiration from a peat-perlite substrate (80:20, v:v) simultaneously. These results were then used to determine substrate moisture release curves and hydraulic conductivity. The substrate moisture release curves showed a typical trend, with the pF declining from -0.8 (Ψ_m = 0.6 kPa) at a substrate water content of about 75% (by volume) to -2.9 (Ψ_m = -74 kPa) at a substrate water content of 21% (Fig. 19).

The hydraulic conductivity was approximately 3,000 higher at a substrate water content of 36% (0.098 cm/d) than at 21% (0.00004 cm/d). This dramatic decrease in hydraulic conductivity as the substrates dries out is consistent with our hypothesis that hydraulic conductivity may limit plant water uptake. As plants are transpiring and take up water from the substrate, they create a depletion zone around the roots. The low hydraulic conductivity of dry substrates may limit water flow into this depletion zone, and thus inhibit plant water uptake.

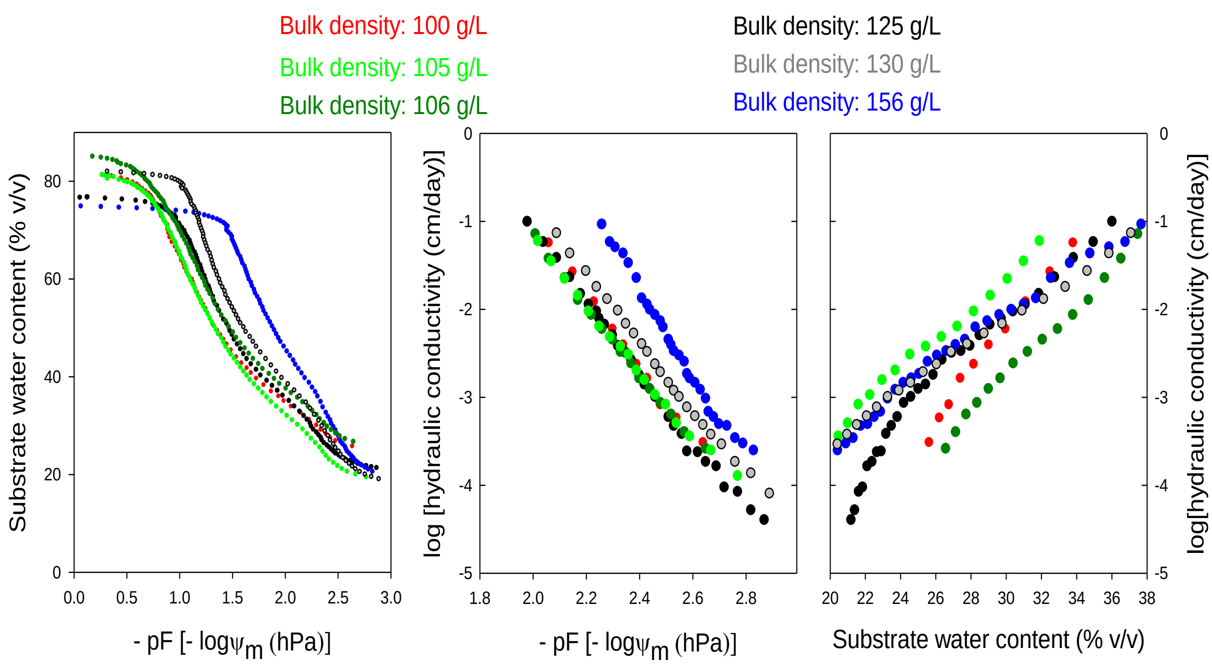


Fig. 19. The effect of substrate density on the hydraulic properties of a peat-perlite substrate. pF is the log of the substrate matric potential in hPa (or bar). A density of 100 g/L is very loosely packed, while 156 g/L is extremely dense. Note that the hydraulic conductivity decrease over 1000x in response to a relatively small change in pF. Very high bulk density results in a higher hydraulic conductivity at the same matric potential (middle graph)

Collaborating Georgia Growers

1. McCorkle Nurseries

The wireless sensor network at McCorkle Nurseries has been expanded to one include one additional greenhouse. The first greenhouse that was fully automated used 54 valves to irrigate a 2-acre area, making it necessary to control up to 14 valves with a single node. Installation of nodes in the 2nd greenhouse was much simpler. This 4-acre greenhouse has only two, large, valves. Initially two nR5 nodes were installed in this greenhouse. To be able to automate irrigation using Sensorweb, these nodes needed to be close to the valves, which raised logistical issues, since that part of the greenhouses does no always have plants in it. Initially McCorkle Nurseries simply placed a few plants close to the nodes so that substrate moisture content in those nodes could be monitored. However, those plants were not representative of other crops in that same irrigation zone. This issue was addressed by adding two additional nodes. Those nodes are mounted on a movable post and can thus be easily placed wherever the main crop is. Irrigation decision are now made based on the substrate water content as measured by EC-5 sensors attached to this movable node, using the ‘global control’ option in Sensorweb. So far, the global control has worked well.

Fig. 20. An nR5 irrigation control node in the 4-acre greenhouse at McCorkle Nurseries (left) controls water flow through a 4” water line (right), using a standard 24 VAC solenoid. Note the lack of plants in the area around the irrigation control node. Irrigation decisions are made using data collected by an EM50R node that is placed in the crop in the background. Sensorweb’s ‘global control’ allows the nR5 node to irrigate based on sensor readings from another node in the wireless sensor network.

The 2-acre greenhouse uses 10HS sensors, rather than EC-5 sensors. We had many sensor failures in this greenhouse, apparently related to a batch of 10HS sensors with an unusually high failure rate. We have replaced all these 10HS sensors with new sensors, and that appears to have resolved this issue. Uniformity testing done in 2012 showed that the uniformity of the irrigation system in this 2-acre greenhouse was poor. This irrigation system has since been replaced, and we plan to test the uniformity of the new irrigation system in cooler weather.

At the Center for Applied Nursery Research, located at McCorkle Nurseries, we are currently conducting a study to determine how irrigation practices affect disease development in *Gardenia* (Fig. 21). We have three irrigation treatments, very wet, dry and alternating between wet and dry, with half the plants in each treatment inoculated with *Phytophthora*. We will determine in fall '13 how these different treatments affect disease severity.

Fig. 21. Overview of the study looking at the effect of irrigation practices and inoculation with *Phytophthora* on disease severity in *Gardenia*.

2. Evergreen Nursery.

The wireless sensor network at Evergreen now consists of a total of 15 nodes, including two weather stations, four EM50R nodes for monitoring purposes, and nine nR5 nodes for monitoring and control. The expansion of the network during the past year has been in a newly developed production area. Evergreen has added approximately 2 acres of shade houses for the production of hellebores and other shade crops. We have installed one weather station, one EM50R monitoring node and four nR5 monitoring and control nodes in this area. All four nR5 nodes have been configured to automatically irrigate, but we have little information on how well the system is performing: due to excessive rain through much of the summer, the plants in this area have required practically no irrigation. However, overall the sensor network at Evergreen has performed well. The main problem has been lightning damage. A lightning strike at the nursery has damaged several nodes, which have been replaced. This appears to be a drawback to regular nR5 nodes, since that are connected to the entire 24 VAC electrical network in the nursery. Lightning damage seems much less likely when using nR5-DC nodes.

3. Garden Design Nursery – Danielsville, GA

Garden Design Nursery is a new addition to the project. Garden Design Nursery is a relatively small nursery, specializing in Japanese maples. A five node network was installed here in May - June 2013, consisting of one weather station and four nR5-DC nodes for monitoring and control. The head grower, Dave Freed, had heard enough about the system already to be fully convinced of its potential. As a result, he wanted to implement monitoring and control from the very start, rather than starting with monitoring only to become familiar with the setup.

The nursery was already using DIG latching solenoid valves, which were easy to use with the nR5-DC nodes. The main challenge during the installation of this network was that there was great overlap between some of the different irrigation zones. Part of the irrigation system needed to be reconfigured to minimize this overlap. Once this was done, installation of the nR5-DC nodes was simple. Port forwarding from the base computer was configured with help from David Kohanbash, but web-based access to the site still appears to be spotty. This may be related to the internet setup at the nursery, rather than a problem with Sensorweb hardware or software.

People involved

In addition to four faculty members at UGA (Drs. Marc van Iersel, Matthew Chappell, John Ruter, and Paul Thomas), one technician has assisted with this research (Sue Dove). There currently are three PhD students (Mandy Bayer, Alem Peter, and Shuyang Zhen) and one MS student (Alex Litvin) working on this project. Mandy, Alem, and Alex are supported directly by the grant, while Shuyang Zhen is a new PhD student, supported by UGA's Department of Horticulture.

As of August 1, 2013, Dr. Kang Jong Goo, a visiting scientist from South Korea has joined Dr. van Iersel's lab and he will spend part of his 2-year visit working on the MINDS project. Dr. Rhuanito Soranz Ferrarezi, who recently received his PhD in agricultural engineering from UniCamp in Brazil, joined Dr. van Iersel's lab as a post-doc in early September and will also spend part of his time on the MINDS project. Drs. Kang and Ferrarezi will both be at UGA for two years.

Off-shoot research projects

The MINDS project has resulted in several collaborative projects in related areas:

Rhuanito Soranz Ferrarezi, a PhD student at UniCamp in Campinas, Brazil (and former visiting scientist at UGA) used our irrigation approach in his research on automating subirrigation of citrus rootstock in Brazil. He recently completed his PhD and has returned to the University of Georgia as a post-doc to continue to work on this project.

Francesco Montesano, a researcher at the University of Bari, Italy (and former visiting scientist at UGA) is using our irrigation approach in his research on automating greenhouse irrigation. He is part of a European research group that recently received a large grant for work on efficient irrigation. Dr. van Iersel is expected to serve as a consultant on this project and this European group may adopt the technology developed by the MINDS project.

Matthew Chappell, Paul Thomas, Jean Williams-Woodward, and Marc van Iersel have received a Specialty Crop Block Grant from the Georgia Department of Agriculture to look at the use of sensor networks to improve pathogen management and crop production.

E. Scientific Research and Development - University of Maryland

We have studied the application of set-point irrigation control using nR5 nodes and Sensorweb functionality in field and container nurseries during year three. The results (which have been reported during year three) were savings in the amount of water applied, which translated into nutrient savings by reducing leaching, labor and energy savings and overall improvement in plant health.

Summary of Results from Commercial Nursery and Greenhouse Operations

1. Bauers Greenhouse (Jarrettsville, MD)

- We have finished two studies aimed at observing the utility of nR5 control nodes in snapdragon production in a greenhouse environment. In both studies, comparison was made between snapdragon flowers that were produced by the nR5 nodes (from start to finish) and flowers produced by the greenhouse grower following normal irrigation practice. Differences in terms of plant characteristics and flower quality for the two irrigation systems were not significantly different. The nR5 nodes controlled irrigation system produced snapdragon flowers that were on par with flowers produced by the grower, but utilized fewer resources (water and nutrients).
- We have started a study with the objective of characterizing and understanding the variability that exists in the tray system snapdragon production that Charles Bauer has recently adopted. The system constitutes 4 independently controlled irrigation zones. Irrigation decision in each zone is being made by nR5 nodes based on average substrate volumetric readings of 8 EC-5 sensors. The variability in substrate volumetric contents as well as plant characteristics and flower quality will be analyzed at the end of the experiment.

2. Raemelton Farm (Adamstown, MD)

- We have installed two separate blocks in which various species of trees are under nR5 controlled irrigation. The goal is to examine whether the growth rate of these trees can be increased.
- We have continued and obtained an additional year data for studies that started last year with the aim of comparing the efficiency and utility of the nR5 control nodes in a field nursery with that of the standard irrigation practice followed in the nursery by the grower. Analyses of data collected (growth, irrigation applications etc.) will be made after the end of the growing season.

3. Waverley Farm (Adamstown, MD)

- We have started a new study comparing two irrigation systems in two tree species – dogwood (*Cornus florida*) and lilac (*Syringa prestoniae*). One row of trees from both species is being irrigated by nR5 nodes based on volumetric soil moisture readings from four 10HS sensors inserted into the root ball of four individual trees. A second row of trees from each species is being irrigated by the grower following the normal irrigation practice followed in the nursery.
- The amount of water used to irrigate each row of trees is measured with flow meters. In addition, regular growth measurements are being made on 10 trees in each row in order to see growth differences arising due to the irrigation systems.

4. Moon Nursery (Chesapeake City, MD)

- A study was started early this year with the objective of understanding how irrigation management can effect pathogen survival in two Rhodendron species (*R. catawbiense* and *R. chenoides*) grown in 2-gal containers. The experiment is laid out in a split plot design and has three irrigation treatments: a wet irrigation treatment, nR5 controlled irrigation treatment where irrigation decisions are based on substrate moisture set-points, and a wet and dry alternating cycle treatment. Data is being collected for irrigation water application using flow meters.

- In addition, half of the plants of each species were inoculated with a *Phytophtora cinnamomi*.. In addition, regular growth measurements are being taken. Destructive harvests have also been made to characterize difference in plant growth parameters. The root balls are being analyzed to see the pathogen development in the root system of each species.

5. Hale and Hines Nursery (McMinnville, TN)

- The comparative experiments on irrigation methods (nR5 set-point control and grower practice) that were started last year have been continued and an additional year data have been collected. Data from two years will be compiled and analyzed to see differences between the irrigation treatments.
- We installed a new control block at the beginning of 2103. This fully sensed block will enable us to conduct various studies on four plant species in year 4, comparing grower-scheduled vs. nR5-setpoint controlled irrigation. Results can then be translated and applied to the rest of the nursery. The experimental block allows for independent control of two species in 15-gal, and two species in 30-gal containers, with ten replicate trees per row.

6. Green Roof Experimentation

- Green roof systems are being installed worldwide for various environmental benefits, primarily to reduce stormwater runoff associated with impervious roofs in dense urban environments. There are many questions regarding how green roof design elements influence the performance and efficiency of green roof systems to mitigate stormwater runoff.
- Variability in performance may arise due to differences in construction (media and plant species used), plant growth and site-specific variables related to climate and rainfall intensity. For these reasons, a wide range of measured efficiencies in green roof performance have been reported.
- To effectively quantify the stormwater retention and efficiency of green roofs at any scale, we need to be able to resolve two important issues: (1) Monitoring of green roofs is both resource-intensive and expensive; (2) Green roofs have both physical and biotic components, both of which change over time.
- To achieve these objectives, we have installed and tested a commercially-available sensor network system (Decagon Devices, Inc.) that resolves the issue of being able to cost-effectively measure the performance of green roofs over time. This sensor network was deployed in 16 experimental greenroof platforms at the University of Maryland with four replicate platforms planted with three *Sedum* species (*S. album*, *S. kamtschaticum*, and *S. sexangulare*) or left unplanted.
- Two years of real-time microclimatic data were collected from a suite of environmental sensors, in addition to replicated soil moisture and temperature sensor data (Echo-TM, Decagon Devices) from each of the platforms (n=4 sensors per platform). These data were used to parameterize a greenroof water balance model, which is focused on predicting rates of evapotranspiration (E_T), the major influence on antecedent green roof soil moisture conditions, and hence the system capacity for mitigating stormwater runoff at any specific time.
- During 2011, 985mm of rain fell on the replicated platforms. Average annual runoff totals were 736(±11), 656(±48), 695(±24) and 772(±21) liters for *S. album*, *S. kampschaticum*, *S. sexangulare* and unplanted platforms, respectively. Modeled E_T rates were highly correlated (R^2=0.68; P <0.001) to rates of E_T measured from the experimental greenroof platforms. Further data from 2012 are being used to conduct sensitivity analyses to refine and improve the various model parameters.

- These monitoring capabilities and model predictions will help improve our understanding of the underlying mechanisms that are responsible for green roof stormwater retention efficiency. Only with a clear understanding of how much stormwater green roof systems can retain in different climatic scenarios, will we be able to consider or refine policies regarding permitting and incentives for this type of roof construction.

Experimental Details

1. Bauers Greenhouse (Jarrettsville, MD)

During year four, two experiments aimed at observing the utility the set-point control irrigation system in snapdragon production in a greenhouse environment were completed. In both studies, comparison was made between snapdragon flowers that were produced by the nR5 nodes and flowers produced by the greenhouse grower following normal irrigation practice.

The objectives of these comparative studies were to:

- Compare nR5 set-point control and time schedules irrigation in snapdragon production
- Compare plant quality parameters such as leaf area, plant height, dry biomass, spike length, opened and total number of florets
- Compare the economic benefits (water and nutrients savings, labor savings, energy savings) of the nR5 set-point control irrigation over the time-based irrigation scheduling

The Snapdragon (*Antirrhinum majus* L.) cultivar Potomac Early White, which is a group III spring crop, was utilized for the first experiment from February 10 till May 21, 2013. Two production benches (6.25' wide and 100' long) were retrofitted in such a way that plants on one production bench were irrigated using set-point control and plants on the second bench were irrigated using time-scheduled irrigation. Each bench was divided into two irrigation zones and irrigation water was provided on two sides (from the top as well as the bottom of the bench) in order to rectify pressure differences inherent to the irrigation system (Fig. 22). Badger flow meters (Badger Meters, Inc., Milwaukee, WI) were utilized to measure irrigation volumes to each of the 4 irrigation zones.

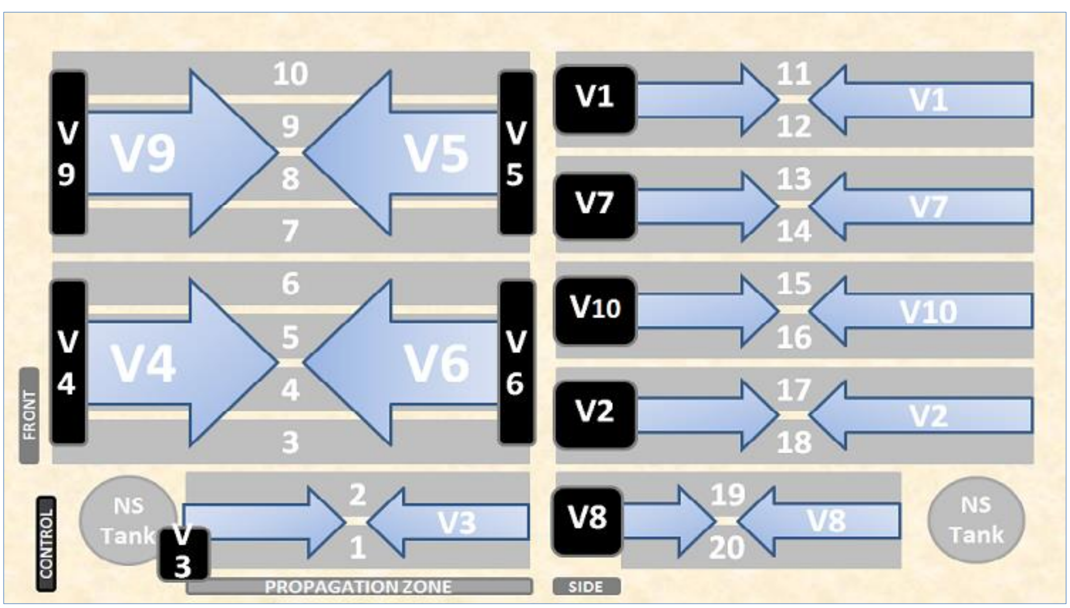


Fig. 22. Irrigation map of Bauers Greenhouse. The experiment was conducted on Bench 1 and 2.

Each production bench had 6 rows that are made up of 15 plastic bags each (Fig. 23). The cylindrical plastic bags that are 6 ft in length and approximately 10 inches in diameter are filled with perlite, the growing medium at the Bauers Greenhouse. Plants from the middle 11 bags were selected for this experiment, i.e. the total number of plants was 1782 per bench/irrigation treatment.

EC-5 soil moisture sensors (Decagon Devices, Inc., Pullman, WA) were inserted in 3 randomly selected rows at four locations (bottom-bottom, bottom-top, top-bottom and top-top) across the length of the bench to capture the variation that arises in volumetric water contents (VWC) due to the 3% slope the benches had (Fig. 23). A custom calibration curve that was performed for the EC-5 sensors and perlite before the experiment was utilized to convert sensors raw readings into meaningful VWC values.

Set-point irrigation control was started five weeks after transplanting, based on the average percent VWC reading of 3 EC-5 sensors that were positioned in the wetter part of each irrigation zone. A set-point of 29% was found to be optimum and was utilized for this purpose. Sensors from the wetter part of each irrigation zone were selected to minimize any risk of under watering. Plants in the time-scheduled irrigation system continued to be watered based on the schedule set by the grower.

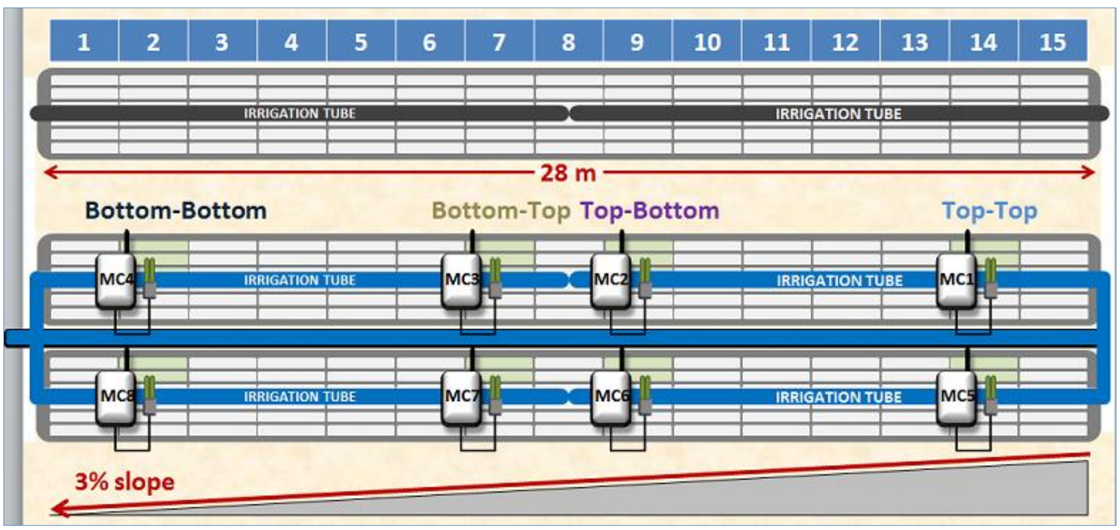


Fig. 23. The experimental layout on the two benches.

Two plants were selected randomly from each row of the four locations on the two benches to compare the two irrigation treatments. Plant height was measured biweekly to compare the growth rate of the snapdragon plants. During harvest, the following parameters were measured/obtained:

- Shoot: Number of leaves, leaf area, leaf fresh weight
- Plant height (stem length and spike length), total dry biomass
- Number of opened and total florets; Numbers of stems and grade

A split plot analysis of all data was conducted using SAS (SAS Institutes, Cary, NC) version 9.2. Significant differences were determined using Tukey's.

Irrigation Applied

The nR5 set-point control irrigation system applied slightly less water compared to the time-scheduled irrigation system (2637 gal and 2847 gal, respectively). The water savings at 7.4% is only minor, but can translate into a significant saving for the whole greenhouse. Any savings in water is also a saving in nutrients (cost of fertilizer) and energy costs (pumping cost). The nR5 set-point control irrigation at a set-point of 29% was very efficient and reactive to plant demands and the environment (Fig. 24).

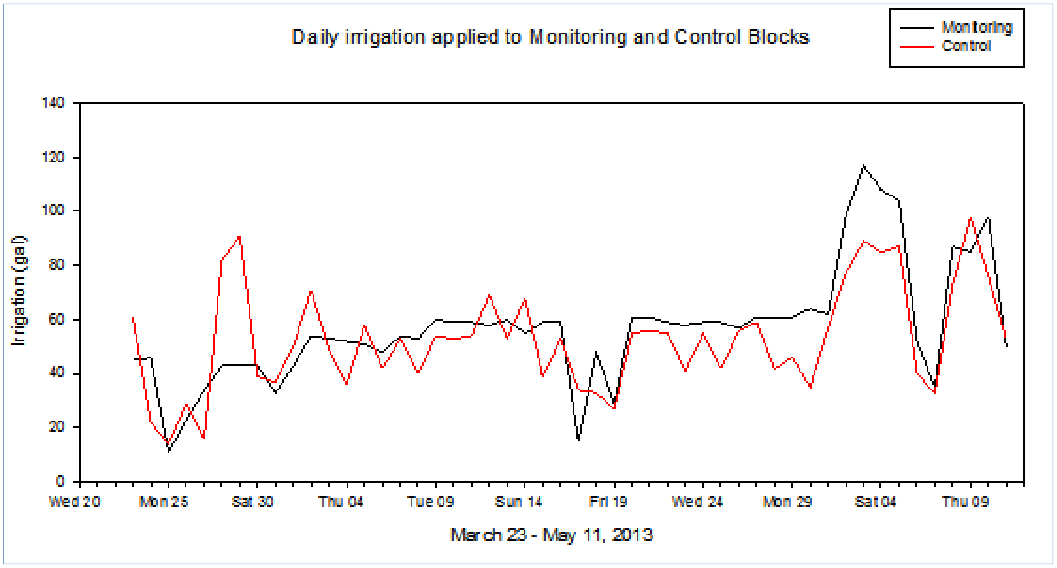


Fig. 24. Set-point (control) and time-based (monitoring) irrigation applications.

Summary of Results:

- There were no significant differences in number of leaves, leaf area and leaf fresh weight between the grower-(time-based) and sensor (set-point) based irrigation treatments.
- Differences in plant height and total dry biomass were not significant between treatments and locations although there was an overall tendency for total biomass to be higher on the wetter parts of the bench. Both stem length and spike length (cm) were not significantly different between treatments.
- There were no significant differences for opened and total number of florets between the two irrigation treatments and the four locations.
- During harvest, all plants were graded according to the criteria used by Bauers Greenhouse. Different grade flowers have differing prices on the market, with Grade 1 getting the highest price. Roughly 60% of the snapdragons harvested from the set-point control treatment were Grade 1 as compared to about 55% from the time-scheduled irrigation bench. The percentage of Grade 2 flowers was slightly higher for the monitored plants and the two treatments had equal percentage of Grade 3s (Table 2). The total yield for the monitoring bench (at 82%) was slightly higher than the set-point control bench (75%).

Table 2. Snapdragon yield and flower grade.

	nR5 Set-Point Control			**Grower-Scehduled (Monitoring)**		
	Grade			Grade		
	1	2	3	1	2	3
# of Plants	775	539	26	796	637	31
Grade %	58%	40%	2%	54%	44%	2%
Harvest %	75.3%			82.2%		

Overall Conclusions:

- The nR5 nodes controlled irrigation system produced snapdragon flowers that were on par with flowers produced by the grower, but utilized slightly fewer resources (water and nutrients).
- Analyses of data obtained from a similar experiment conducted during summer 2013 showed results were similar to the above.
- These experiments confirmed that sensor-based irrigation control can be safely implemented in advanced greenhouse production systems, with no significant reductions in yield.
- Considering the set-points used in these experiments were precautionary, we are confident that further experimentation will allow for refinement of set-points that will optimize fertigation timing and duration, especially as a new tray system (wjth reduced substrate volumes / plant) has been adopted by Flowers by Bauers (see below)

Scaling Up With New Tray Production:

- We initiated a new study in year 4, with the aim of characterizing and understanding the variability that exists in the tray system snapdragon production that Flowers by Bauers has recently adopted (Fig. 25).
- Trays that are 1'x2' in size and 4" deep have replaced the plastic bag /perlite system that they have used since 1999. A total of 32 plants – 8 plants in 4 rows – are transplanted per tray on either side of two irrigation tubes that run on top of each tray.

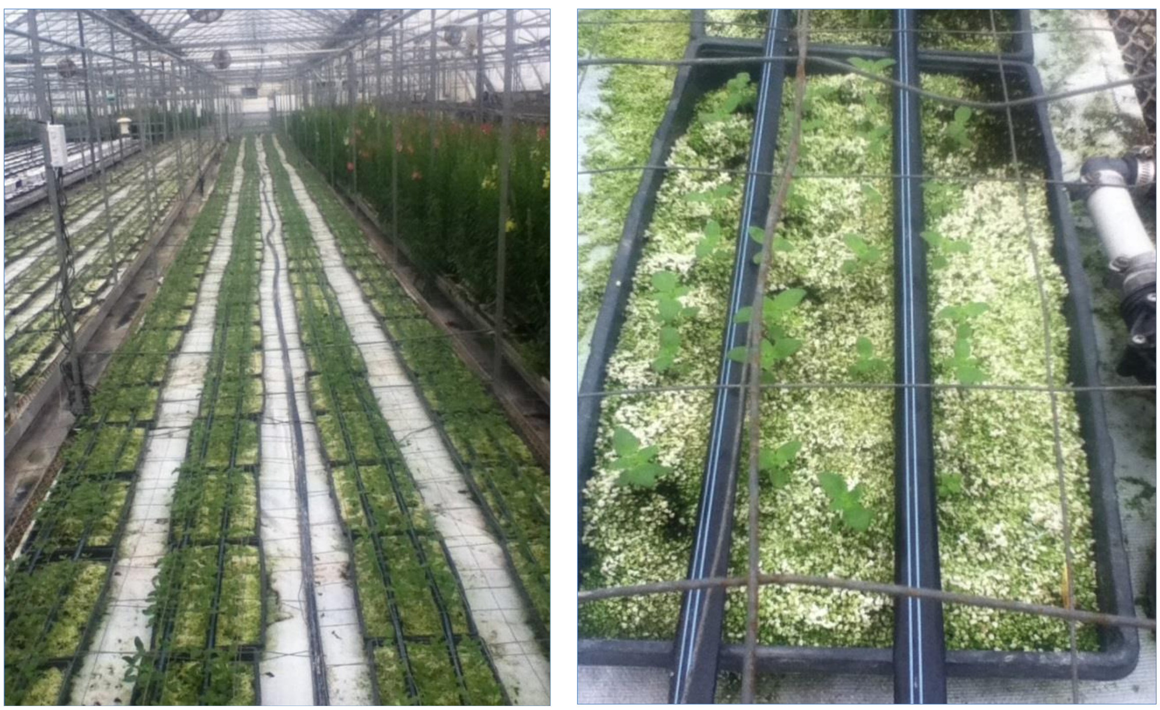


Fig. 25. The new tray production system at Bauers Greenhouse.

- The scaled up set-point experiment is laid out on two benches and in four sensor-controlled irrigation zones. Independent irrigation decision are made in each zone using one nR5-DC and one EM50R node, based on average substrate volumetric readings of eight EC-5 sensors using the global control function of Sensorweb.
- Substrate VWC readings were taken every minute and averaged over a 15-minute period for irrigation control decisions.

The objectives of this scaling-up experiment are to:

- To understand how the irrigation systems, in combination with the reduced substrate volume in the trays, affects irrigation frequency and timing as the crop grew
- To determine the optimal positioning of sensors on the bench and within the individual trays
- To quantify any differences between cultivars grown in the four zones

Data on plant growth rates, floral quality, harvest percentage and grades will be collected and compared for the irrigation zones. The variability in substrate volumetric contents as well as plant growth rate and flower quality will be analyzed for each irrigation zone at the end of the experiment.

2. Moon Nursery (Chesapeake City, MD)

Precise irrigation management is not only important in saving water and other resources but also has an overall positive impact on plant health. In container production systems, where the rooting volume is limited, supplying the plants with the right amount of water is critical. Growers and irrigation managers almost always err on the side of caution and prefer to apply excess water when irrigating container plants. This excess water is lost immediately, leaching nutrients with it, and the container dries out depending how fast water is consumed by the plant and the evaporation rate. In addition to the losses of water and nutrients, the rapid wetting and drying cycles can stress plants and may create a favorable condition for plant pathogens. Decision-based irrigation systems (nR5 set-point control) can supply exact amounts of irrigation water only when plants require it, thereby mitigate many of the problems associated with over watering.

The study at Moon Nursery, MD was started in February 2013 and tested the applicability of the nR5 nodes and Sensorweb for precision irrigation in a pathogen management study.

The specific objectives of the experiment are to:

- To test three different irrigation treatments and their impact on pathogen development and survival in two Rhodendron species,
- To determine the effect of the irrigation treatments on plant growth and development.

Treatments

The two Rhododendron species used in the experiment were *Rhododendron catawbiense* and *Rhododendron chenoides*, grown in 2-gal containers. A 60% pine bark: 40% peat moss substrate mixed with starting fertilizer was used for the experiment. Irrigation for all the three treatments was scheduled through nR5 nodes and Sensorweb. A custom calibration was performed for the substrate and 10HS sensors (Decagon Devices, Inc., Pullman, WA) used in the study. These calibration coefficients were entered into Sensorweb to convert raw reading of the 10HS sensors into volumetric water contents.

The three irrigation treatments are:

- A continuously wet irrigation treatment where irrigation is scheduled a number of times every day to provide plants with ample readily available water,
- nR5 set-point controlled irrigation treatment where irrigation decisions are made based on a given set-point and average volumetric water content (VWC) readings of soil moisture sensors,
- A wet and dry alternating cycle treatment where two/three days of ample water supply is followed by a dry period during which no water is supplied through irrigation.

Food waste substrate treatment

In order to compare side by side the effect of a food waste that the nursery uses as a soil amendment, a fourth additional treatment was added to this experiment. Plants in this treatment are grown in a substrate that is composed of 25% food waste and 75% of the pine bark-peat moss mix used for the other three treatments. Irrigation of plants in this treatment was also scheduled using nR5 nodes and Sensorweb based on the average volumetric water content readings of sensors and a given set-point that was determined after conducting custom made calibration for the 10HS sensor and the substrate-food waste amendment mix.

Pathogen Inoculation

Half of all plants used in the experiment were inoculated with the plant pathogen (*Phytophtora cinnamomi*). The inoculation was done by introducing rice beans that are colonized by the pathogen into the root ball of the plants (Fig. 26). All plants that received inoculums were watered well for three days to create a wet environment that is favorable for the pathogen development.

Fig. 26. Inoculation of *Phytophthora cinnamomi* into the root ball of plants with rice granules

Experimental Layout

The experiment is laid out in a split plot design with irrigation treatments as the main factor and inoculation as the sub factor. There are a total of 40 experimental units that are 8 ft in length and 4 ft in width. A schematic diagram of the experimental layout is given in Fig. 27.

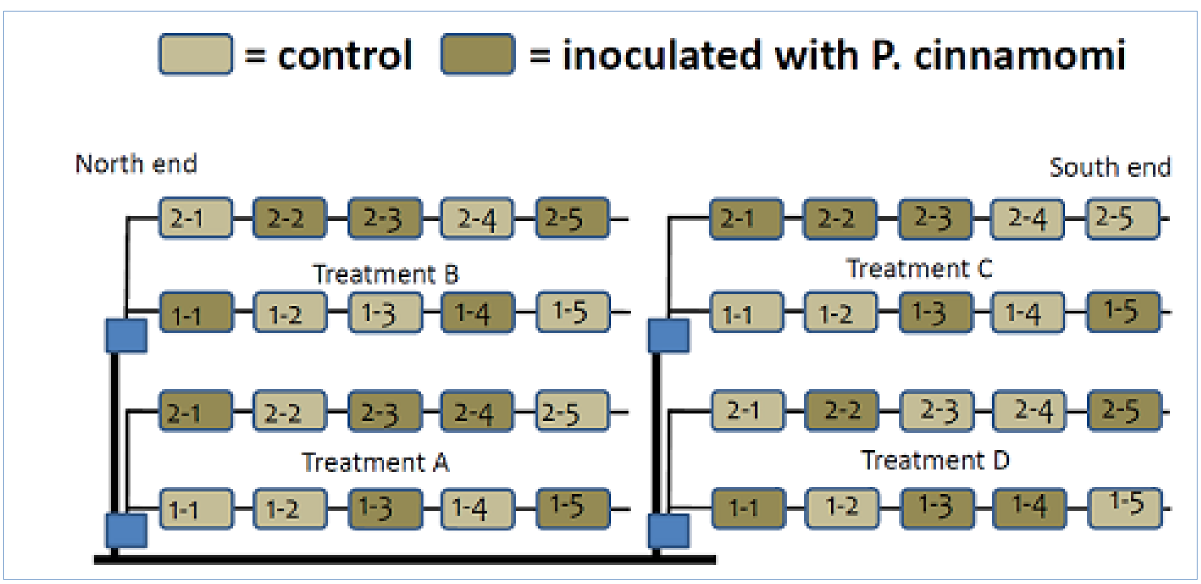


Fig. 27. The experimental layout showing the four major treatments (A = Substrate 1 and wet treatment, B = Substrate 1 and set-point control, C=Substrate 2 and set-point control, and D = Substrate 1 and alternating wet and dry cycles).

There are a total of 24 plants on each experimental unit, 12 plants from each of the *R. catawbiense* and *R. chenoides,* that are placed side by side on pallets. Irrigation to each plant is supplied by Netafim yellow spray stakes (Netafim USA, Fresno, CA) at a rate of 0.04 gal/min (Fig. 8).

A distance of 6ft is maintained between the experimental units on all sides, to avoid cross-contamination between inoculated and non-inoculated experimental units. In addition, all plants were placed on 4 ft x 4 ft wooden pallets to raise them above ground to avoid cross contamination from running water during irrigation. (Fig. 28).

Substrate volumetric water content (10HS sensor) and flow data (Badger flow meter) are being collected for each irrigation treatment. In addition, regular monthly growth measurements are being taken on plants that are randomly selected from each treatment.

Fig. 28. An experimental unit in the study with 12 *R. catawbiense* and 12 *R. chenoides* plants placed on two pallets.

These randomly selected plants will be harvested destructively at different stages of growth in order to characterize differences in plant growth parameters between the irrigation treatments. The root balls will be analyzed to see the pathogen development in the root system of each species.

3. Hale and Hines Nursery (McMinnville, TN)

Located in McMinnville, TN Hale and Hines Nursery consists of 200 acres of pot-in-pot ornamental tree production. We previously reported in Year 3 for a grower-controlled (monitoring) vs. nR5 controlled experiment with Dogwood and Maple that the average daily irrigation water applied by the grower (Terry Hines) totaled 0.92 gals/tree, compared to 0.34 gals/tree applied by the sensor-controlled irrigation for Dogwood (Table 3). For Red maple, this difference was less (1.72 vs. 1.33 gals/tree); nevertheless nR5-controlled irrigation still used about 34% less water than an expert irrigation manager.

As importantly, there were no significant differences in Dogwood or Maple trunk diameter between treatments (Fig. 29). The sensor controlled irrigation therefore resulted in nearly a three-fold increase used to irrigate Dogwood trees and a 1.5 times increase in efficiency of water used to irrigate Dogwood and Red maple, respectively , without reducing growth or quality of the trees.

Also of interest is at what season the greatest water savings were achieved (Figs. 30 A, B). For Dogwood, these savings were achieved across the whole year (Fig. 30A) but were greater during summer, when the trees were using a lot less water than was judged by the grower. For Maple, the greatest water savings were achieved during spring, when the trees used much less water than thought

(Fig 30B). This is important since fertilizer applications done in spring can easily be leached from the container, before the tree has had adequate time for nutrient uptake.

Table 3. Total and average water applications for dogwood and red maple trees for the period from 1 Apr. 2012 to 15 Nov. 2012.

Irrigation Method	Total Water Applied (gal/row)	Average Water Application (gal/tree/day [z])	Average Efficiency (Timed vs. Control)	Water Savings (Control vs. Timed)
Dogwood: Timed, Cyclic	29,005	0.92	0.**37**	2.69
Dogwood: Sensor-controlled	10,770	0.34		
Red maple: Timed, Cyclic	24,184	1.72	0.66	1.51
Red maple: Sensor-controlled	15,465	1.13		

[z] Tree counts/row: dogwood grower-controlled = 133, dogwood sensor-controlled = 133, red maple grower-controlled = 60, and red maple sensor-controlled = 59.

Control Block Establishment (March 2013)

To help gain further insight into the varying water use of their diverse inventory of tree species, a sensor control block was installed at Hale and Hines nursery in March 2013 (Fig. 31). This control block consists of 4 rows of 15-gal containers and four rows of 30-gal containers, each with 10 trees per row (80 trees in total). Species being studied during year 4 include *Betula nigra* (River Birch) and *Lagerstroemia indica* (Crepe Myrtle) in 15-gal containers; *Quercus rubra* (Red Oak) and *Carpinus caroliniana* (Hornbeam). These species were specifically chosen by Terry Hines, as indicator species within different Irrigation Functional Groups (IFG's)

The drainage lines under each row were hard plumbed with PVC, so that leachate from each tree is captured and measured using an ECRN-100 rain gauge at the bottom of each row (Fig. 31). In addition, an in-line electrical conductivity (EC; EC-2 sensor) is installed in a well at the end of each row, allowing for continuous monitoring of leachate EC, and for direct comparison of substrate EC measurements using GS3 sensors installed in two trees per row. Five trees per row are additionally instrumented with five 10-HS sensors to measure substrate VWC. All rows have flow meters to measure irrigation water applied. Thus, complete water balances can be calculated for all species comparing grower-scheduled irrigations with sensor-controlled irrigation events, based on a substrate VWC threshold value.

This fully sensed block is enabling us to study differences between grower-scheduled irrigation and sensor-controlled nR5-setpoint irrigation. Through the use of the 10-HS sensors and Sensorweb™, automated irrigation takes place when the average substrate VWC in five trees reaches a determined "set point" for each species. By monitoring these parameters, we also have a complete dataset to study water and nutrient use and loss dynamics in an open (rain and irrigated) environment.

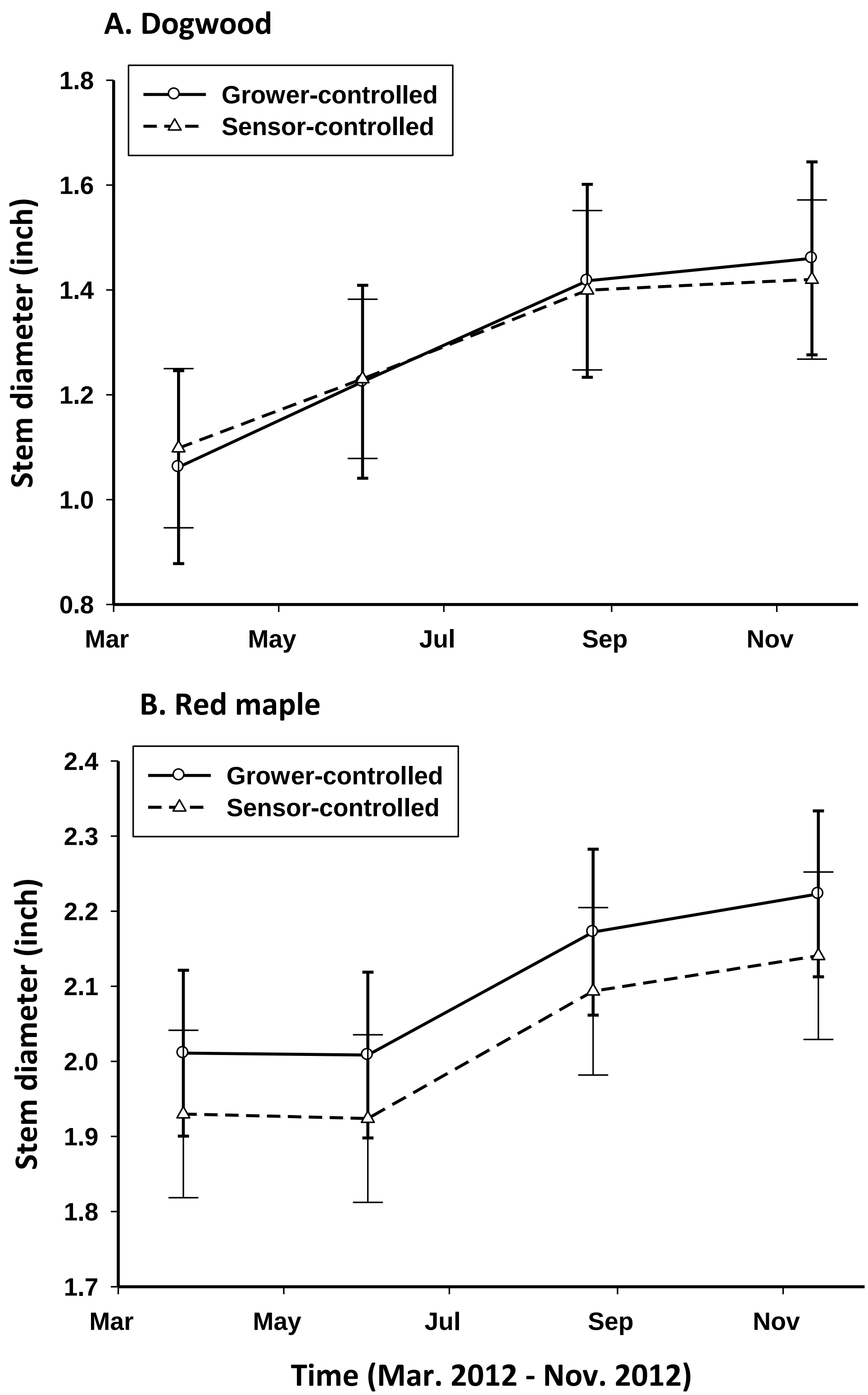
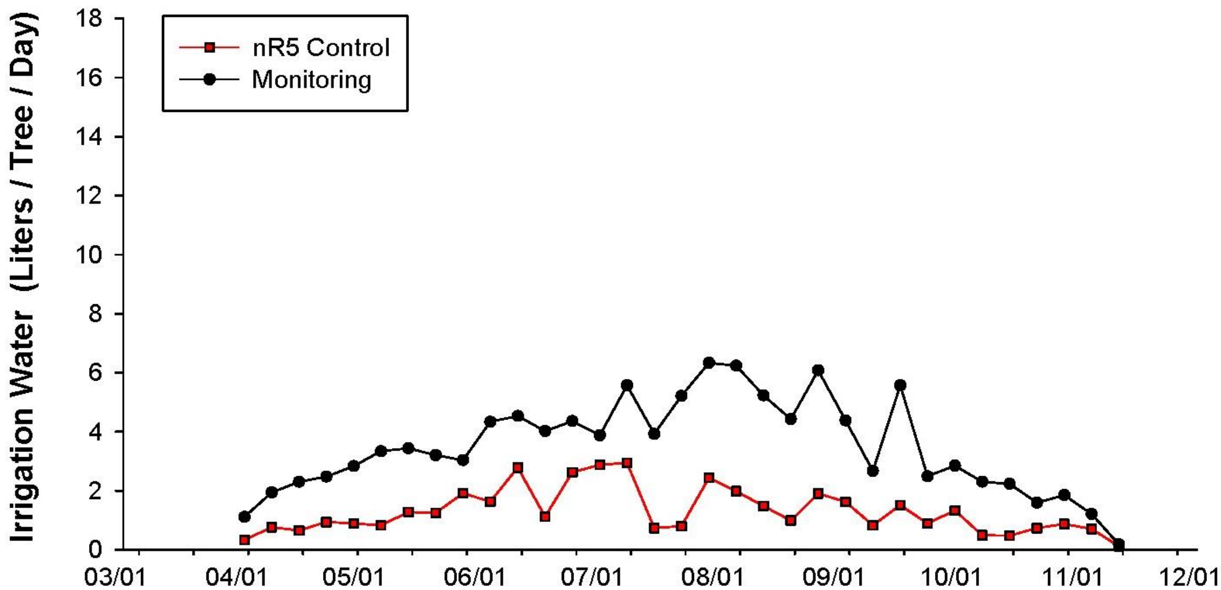


Fig. 29. Average increase in tree trunk diameter (inches) measured at 6-inch height for (A) dogwood and (B) red maple trees. Error bars (thick lines with narrow cap for grower-controlled trees and thin lines with wide cap for sensor-controlled trees) represent standard deviations about the mean.

A. Dogwood



B. Red Maple

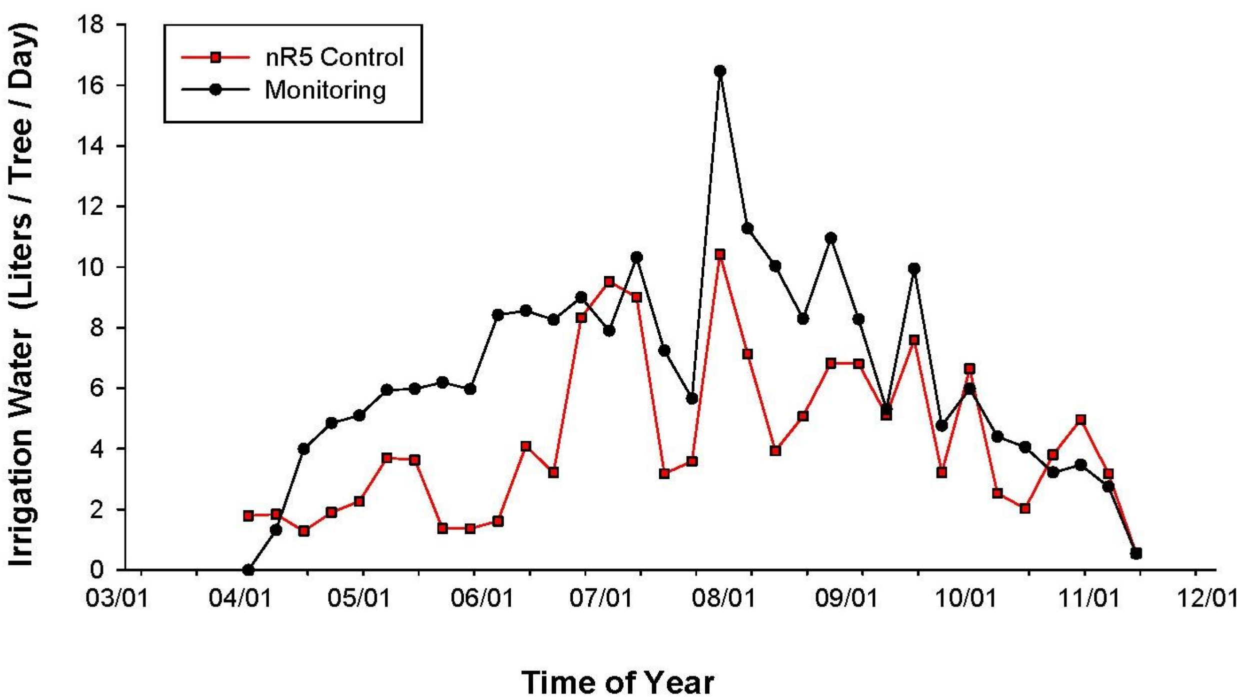


Fig. 30. Average irrigation water applications (liters/tree/day) for (A) Dogwood (*Cornus florida*) and (B) Red maple (*Acer rubrum*) trees from 1 Apr. 2012 through 15 Nov. 2012.

Fig. 31. Installing the sensor network control block at Hale and Hines Nursery. Here, ECRN-100 rain gauges are being integrated into the drainage line, to quantify leachate from the ten trees in each row. Inset pictures at left show in-line EC (ES2) sensor in cross-section and from the top, where the drainage line enters the rain gauge.

People involved at University of Maryland

In addition to four faculty members at UMD (Drs. Lea-Cox, Ristvey, Cohan and Lichtenberg), we have been ably assisted by Mr. Bruk Belayneh (Research Technician) and Ms. Ruth Miller (Administrative / Financial Assistant). Drs. Cohan, Ristvey and Lea-Cox are the leads on the green roof research with Mr. Patrick Beach (IT guru in the Plant Science Department) has provided continuous support on Connect webconferencing, Traction and server maintenance for the project.

There is currently one Postdoctoral Research Associate (Dr. John Majsztrik), two PhD students (Olyssa Starry and Whitney Gaches) and two MS students (Clark de Long and Elizabeth Barton) being supported by this project. John Majsztrik has led the national survey effort and the economic analysis of Flowers by Bauers and Hale and Hines data with the Economic team of Drs. Erik Lichtenburg and Dennis King.

Additionally, three undergraduate students (James Zazanis, Zach Beichler and Ian Reichardt) are student research interns working on the project. Dr. Lea-Cox and Bruk Belayneh support all research at Bauers greenhouse, Hale and Hines nursery, Raemelton and Waverly farms together with assistance from James Zazanis and Zach Beichler. Ian Reichardt is working on a web-based interface with Sensorweb for green roof applications.

Other Supported Collaborations

The MINDS project has resulted in several collaborative sensor network research and educational projects:

- ✓ Clark de Long (MS student, PSLA Department) is studying the tolerance of native plant species to drought in green roof substrates, and is using a sensor network to quantify water use from each species.
- ✓ Whitney Gaches (PhD student, PSLA Department) is studying alternative (low-carbon footprint) substrates for use in green roofs. She is quantifying plant water use, root density and water-holding characteristics using a Decagon network and working to add those components to the UM green roof stormwater model.
- ✓ Elizabeth Barton (MS student, PSLA Department) is studying the fate of organic matter in green roof substrates, again using a sensor network to quantify changing water-holding characteristics over time

We are supporting the Taproots Environmental Education program founded by Anthony Dimeglio and Jennifer Himmelstein at the University of Maryland

- ✓ TapRoots is an environmental educational program supported by the Chesapeake Education Art Research Society (CHEARS), Prince George's County 4-H, University of Maryland Extension, and the United States Department of Agriculture.
- ✓ TapRoots's mission is to "tap" into university resources to stimulate the growth of community "roots" and propagate ecological stewardship in youth ages 12-18.
- ✓ TapRoots enhances Prince George's County Science Technology Engineering and Mathematics (STEM) initiatives by integrating agricultural education programs focused on topics of ecological stewardship, soil health, nutrition, and food safety.

F. Economic and Environmental Benefits - University of Maryland

The overall goal of the SCRI-MINDS project economic team is to quantify the private and public benefits of wireless sensor networks in field, container, and greenhouse ornamental production, and monitoring of green roof systems. Information from sensor networks is valuable when (1) it allows growers to make better decisions and (2) the increase in value from better decisions exceeds the cost of acquiring and processing the information. During year 4 of the project, the economics team was able to demonstrate and quantify the potential profitability, environmental benefits, and adoption rates of wireless sensor networks in a variety of contexts.

1. Profitability Analysis of Wireless Sensor Networks

In year three of the project, the economic team developed conceptual models of profit-maximizing investment in precision equipment like sensor networks. Those models identified several ways in which the use of sensor networks might increase profitability. Potential benefits included input reductions, growth acceleration (reduced time to harvest), improved plant health, lower disease losses and enhanced appearance. Adoption of sensor networks is profitable whenever these benefits outweigh the costs of installing and running the network.

During year 4 of the project, these conceptual models were applied in three case studies that combined experimental data with operational information from growers involved in the project.

1. ***Gardenia production in Georgia*.** Data on production practices and costs with and without a sensor network were obtained from experiments conducted at McCorkle Nurseries. The use of sensors increased profit substantially, mainly due to reduction in the time from planting to sale. Reductions in disease mortality and disease treatment costs were also substantial sources of increased profitability. Results of this analysis were presented at the annual meeting of the American Society for Horticultural Science (Thomas et al. 2013). A manuscript reporting them has been accepted for publication in HortTechnology (Lichtenberg et al. 2013).
2. ***Tree production in Tennessee*.** Data on water use and irrigation management costs with and without a sensor network were used to estimate profitability in the Hale and Hines pot-in-pot container tree nursery. The sensor network reduced both irrigation water application and irrigation management time by at least half. Even though water costs consist only of the cost of pumping water from a nearby river, investment in the wireless sensor network yielded a high rate of return. Sensitivity analysis indicated that sensor networks would be even more profitable in areas where water is scarce and costly (e.g., California). A manuscript reporting these results have been accepted for publication in HortTechnology (Belayneh et al. 2013).
3. ***Snapdragon production in Maryland*.** Analysis of production records from our greenhouse snapdragon partner showed that wireless sensor networks accelerated production time and increased yields. One additional crop was harvested annually, while yields increased from 5% to 80%, depending on cultivar, resulting in a high rate of return on investment. This analysis was presented at the annual meeting of the Agricultural and Applied Economics Association (Lichtenberg 2013) and a manuscript is in preparation.

2. Adoption Prospects of Wireless Sensor Networks

The economic team developed a national ornamental grower survey to better understand current perceptions of sensor-based irrigation technology. Data were collected from January 2012 to March 2013. A total of 252 useable responses were analyzed. These data have been used in two studies:

1. ***Grower perceptions of wireless sensor technology***. Growers were asked about their positive and negative perceptions of these systems, to assess current receptivity of this technology. Grower perceptions were overwhelmingly positive, with the majority of respondents agreeing that wireless sensor systems would provide a number of benefits including; increased irrigation efficiency, reduced product loss, reduced irrigation management costs, reduce disease prevalence, and reduce monitoring costs. System cost and reliability were major concerns. Grower perceptions of irrigation sensor networks varied across size and type of operation as well as geographically and by the type of water source used. Results of these analyses were presented at the annual meeting of the American Society for Horticultural Science (Majsztrik et al. 2013), and are in press in HortTechnology (Majsztrik et al. 2013b).

2. ***Grower willingness to pay for wireless sensor technology***. Growers were asked about their willingness to purchase (a) a base system and (b) additional nodes in order to assess likely initial adoption, potential speed of diffusion, and likely ceiling adoption of wireless sensor networks. A standard dichotomous choice format was used: They were asked whether they would purchase a base system at price X. Then they were asked how many additional nodes they would purchase at price Y assuming they had already purchased a base system. Close to 20% of growers would purchase a base system at the expected initial market price, while roughly 30% would not purchase a base system at any price. Growers who purchased a base system were estimated to be willing to purchase an additional 3 nodes at the expected initial market price. Sensitivity analysis was used to estimate the response of initial adoption to changes in base system cost, perceptions about wireless sensor system advantages and disadvantages, and prices of additional nodes. A manuscript reporting these results is in preparation.

3. Calculating Public Benefits

Using data collected from the national grower survey and additional sources, public benefits of widespread adoption of sensor networks were estimated based on various assumed adoption rates. The higher return on investment and short payback periods the project has demonstrated suggest that the adoption rate of this type of technology is likely to increase over time. Environmental benefits were projected under a variety of scenarios for ornamental growers. For example, a conservative estimate of 50% industry adoption, with a 50% water savings would have the following impacts: enough water for 400,000 households a year, reduced energy usage equivalent to removing 7,500 cars annually, and savings of 282,000 kg of nitrogen and 182,000 kg of phosphorus from entering the environment. This research is currently in press. Additional research is aimed at determining the feasibility of using this technology in other areas of agriculture, as well as in applications outside of the U.S. where water limitations are a significant barrier to sustainable food production.

G. Outreach – Website and Knowledge Center Development

Website: The SCRI-MINDS website was established at the outset of the project in September, 2009 with input from all team members. The domain name "Smart-Farm" was chosen for the project and the 'dot net' domain and 'dot org' names were purchased. The website can be viewed at http://www.smart-farms.net

The website was redeveloped in Drupal during year three (Fig. 32) to include all the new project information and allow for a gateway to the knowledge center at http://www.smart-farms.org which has been developed in Canvas (see Knowledge Center Development, below).

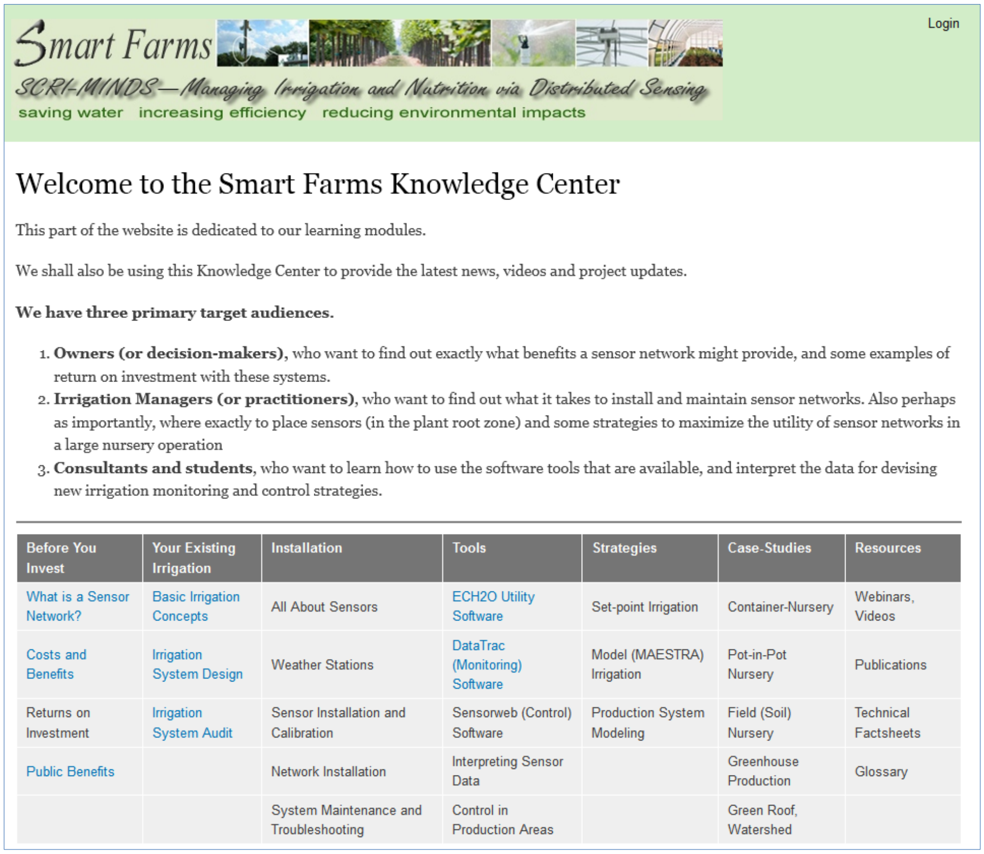
Fig. 32. The SCRI-MINDS Website and Knowledge Center

The website has been publicized through various project press releases and trade articles during the past four years.

Knowledge Center Development

Extension and outreach goals during Year 4 focused on planning and starting to develop a number of learning modules, which can be found by clicking the "Knowledge Center" tab at the top of the smart-farms website. This takes you to the http://smart-farms.org website. The links on this website (Fig. 33) take users directly into a series of secure learning modules, developed with the Canvas Content Management System (Fig. 34).

A total of 28 learning modules were outlined, under seven main themes. These include (1) Before you Invest; (2) Your Existing Irrigation System; (3) Installation; (4) Tools; (5) Strategies; (6) Case-Studies and (7) Resources (Fig. 33). Within each of these themes, a number of discrete learning modules serve as self-guided tutorials on a wide range of topics related to system design, troubleshooting, economics, maintenance, etc. Modules are designed to target specific audiences including business owners and decision makers, commercial growers, and researchers/students. The specific case studies will highlight implementation of precision irrigation monitoring and control systems at partner grower locations.



Smart Farms
SCRI-MINDS—Managing Irrigation and Nutrition via Distributed Sensing
saving water increasing efficiency reducing environmental impacts

Login

Welcome to the Smart Farms Knowledge Center

This part of the website is dedicated to our learning modules.

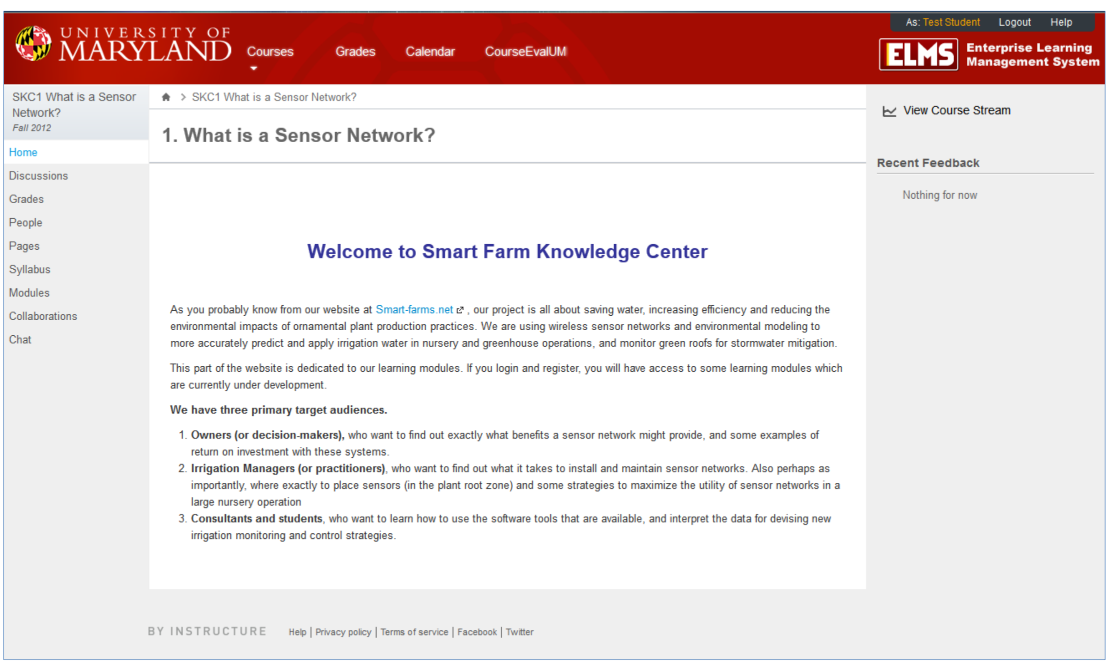
We shall also be using this Knowledge Center to provide the latest news, videos and project updates.

We have three primary target audiences.

1. **Owners (or decision-makers),** who want to find out exactly what benefits a sensor network might provide, and some examples of return on investment with these systems.
2. **Irrigation Managers (or practitioners),** who want to find out what it takes to install and maintain sensor networks. Also perhaps as importantly, where exactly to place sensors (in the plant root zone) and some strategies to maximize the utility of sensor networks in a large nursery operation
3. **Consultants and students,** who want to learn how to use the software tools that are available, and interpret the data for devising new irrigation monitoring and control strategies.

Before You Invest	Your Existing Irrigation	Installation	Tools	Strategies	Case-Studies	Resources
What is a Sensor Network?	Basic Irrigation Concepts	All About Sensors	ECH2O Utility Software	Set-point Irrigation	Container-Nursery	Webinars, Videos
Costs and Benefits	Irrigation System Design	Weather Stations	DataTrac (Monitoring) Software	Model (MAESTRA) Irrigation	Pot-in-Pot Nursery	Publications
Returns on Investment	Irrigation System Audit	Sensor Installation and Calibration	Sensorweb (Control) Software	Production System Modeling	Field (Soil) Nursery	Technical Factsheets
Public Benefits		Network Installation	Interpreting Sensor Data		Greenhouse Production	Glossary
		System Maintenance and Troubleshooting	Control in Production Areas		Green Roof, Watershed	

Fig. 33. The Smart-farms Knowledge Center Homepage at http://smart-farms.org



UNIVERSITY OF MARYLAND Courses Grades Calendar CourseEvalUM

As: Test Student Logout Help

ELMS Enterprise Learning Management System

SKC1 What is a Sensor Network?
Fall 2012

Home
Discussions
Grades
People
Pages
Syllabus
Modules
Collaborations
Chat

SKC1 What is a Sensor Network?

1. What is a Sensor Network?

View Course Stream

Recent Feedback

Nothing for now

Welcome to Smart Farm Knowledge Center

As you probably know from our website at Smart-farms.net, our project is all about saving water, increasing efficiency and reducing the environmental impacts of ornamental plant production practices. We are using wireless sensor networks and environmental modeling to more accurately predict and apply irrigation water in nursery and greenhouse operations, and monitor green roofs for stormwater mitigation.

This part of the website is dedicated to our learning modules. If you login and register, you will have access to some learning modules which are currently under development.

We have three primary target audiences.

1. **Owners (or decision-makers),** who want to find out exactly what benefits a sensor network might provide, and some examples of return on investment with these systems.
2. **Irrigation Managers (or practitioners),** who want to find out what it takes to install and maintain sensor networks. Also perhaps as importantly, where exactly to place sensors (in the plant root zone) and some strategies to maximize the utility of sensor networks in a large nursery operation
3. **Consultants and students,** who want to learn how to use the software tools that are available, and interpret the data for devising new irrigation monitoring and control strategies.

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Fig. 34. One of the Knowledge Center Learning Module homepages within Canvas, hosted by the University of Maryland

H. Project Management, Coordination and Communication - University of Maryland

Fiscal Accounting and Matching Documentation

Advanced systems for tracking and monitoring SCRI expenditures are now in place. This allows us to monitor SCRI spending in accordance with the grant requirements and monitor subcontract's cost sharing activities to ensure that they are fulfilling their obligations as matching partners.

All subcontracts report invoices and matching totals on a quarterly basis, which ensures timely payments and monitoring of expenditures. Total spending during Years 1 through 4 totaled $3,341,318 whereas total match amounted to $4,532,766. As of the end of Year 4, the cumulative match exceeded the projected matching totals by $1,191,448. All subcontracting leads and business offices do an excellent job, and we are grateful for their assistance to ensure accurate accounting and transparency for the project. The Year 4 Federal Financial report is attached as Appendix A.

Internal Communication

The Internal and team communication methods established using year one (refer to the 2010 report) are working well. The traction virtual workspace provides a mechanism to track notable project interactions and progress updates, and allows for more efficient tracking of documentation for the entire team than email. It also automatically sends out an automatic weekly digest to all project participants, including Advisory panel members and USDA project managers.

In addition to the traction workspace, bi-monthly SCRI webconferences are held to ensure communication and knowledge-sharing amongst project participants. Every second webconference includes advisory panel member and program manager involvement, if they are available. These webconferences are recorded and the archived link placed on Traction, so that people who could not make the teleconference can access the information at a convenient time.

Fourth Annual Project Meeting

The third annual project meeting was held from 19 – 21 June, 2012 in Athens, GA. In addition to the engineering and research faculty from the five Universities and companies, we were joined by seven of our advisory panel members, two postdoctoral researchers and five graduate students involved in various aspects of the project (Fig. 35).

During the first (reporting) day, we shared progress by the various working groups, starting with graduate student presentations. Additional posters were displayed during breaks on many of the studies. The second morning was devoted to in-depth discussions on monitoring and control, the new Sensorweb software development, integrating new sensors and model development and integration. The last afternoon was devoted to defining economic information requirements, the user survey and quantifying the value of information. Lastly we revisited year 3 goals and objectives (see Appendix B), in anticipation of tighter integration of the engineering and scientific objectives during the fourth year.

Fig. 35. The SCRI-MINDS team participants at the 4th Annual project meeting, held in Athens, GA.

I. Publications, Presentations and Outreach

Book chapters

1. Chappell, M., J. Owen, S. White and J. Lea-Cox. 2013. Irrigation Management Practices. IN T. Yeager, T. Bilderback, D. Fare, C. Gilliam, J. Lea-Cox, A. Niemiera, J. Ruter, K. Tilt, S. Warren, T. Whitwell and R. Wright (eds.) Best Management Practices: Guide for Producing Nursery Crops. 3rd edition Southern Nursery Association, Atlanta, GA (http://contents.sna.org/bmpv30.html).

Peer reviewed articles

1. Barnard, D.M. and W.L. Bauerle. 2013. The implications of minimum stomatal conductance on modeling water flux in forest canopies. *Journal of Geophysical Research: Biogeosciences*, 118, doi: 10.1002/jgrg.20112.
2. **Bauerle, W.L.**, A.B. Daniels, and D.M. Barnard. 2013. Carbon and water flux responses to physiology by environment interactions: A sensitivity analysis of variation in climate on photosynthetic and stomatal parameters. *Climate Dynamics*, doi:10.1007/s00382-013-1894-6.
3. Bayer, A., I. Mahbub, M. Chappell, J. Ruter, and M.W. van Iersel. 2013. Water use and growth of *Hibiscus acetosella* 'Panama Red' grown with a soil moisture sensor controlled irrigation system. *HortScience* 48:980-987.
4. Kim, J., A. Malladi, and M.W. van Iersel. 2012. Physiological and molecular responses to drought in Petunia: the importance of stress severity. *Journal of Experimental Botany* 63:6335-6345.
5. Majsztrik, J. and J.D. Lea-Cox. 2013. Water quality regulations in the Chesapeake Bay: Working to more precisely estimate nutrient loading rates and incentivize best management practices in the nursery and greenhouse industry. HortScience 48:1097-1102.
6. O'Meara, L., M.W. van Iersel, and M.R. Chappell. 2013. Daily water use of *Hydrangea macrophylla* and *Gardenia jasminoides* as affected by growth stage and environmental conditions. *HortScience* 48:1040-1046.
7. Stoy, P.C. A.M. Trowbridge, A.M., W.L. Bauerle. 2013. Controls on seasonal patterns of maximum ecosystem carbon uptake and canopy-scale photosynthetic light response: contributions from both temperature and photoperiod. Photosynthesis Research DOI 10.1007/s11120-013-9799-0.

Refereed conference proceedings

1. Alem, P.O., P.A. Thomas, and M.W. van Iersel. 201x. Irrigation volume and fertilizer concentration effects on leaching and growth of petunia. Acta Hort. (In press).
2. Bayer, A., K. Whitaker, M. Chappell, J. Ruter, and M. van Iersel. 201x. Effect of irrigation duration and fertilizer rate on plant growth, substrate solution EC, and leaching volume. Acta Hort. (In press).
3. Belayneh, B.E. and J.D. Lea-Cox. 201x. Implementation of Sensor-controlled Decision Irrigation Scheduling in Pot-in-Pot Nursery Production. Acta Hort. (In press).
4. Kim, J., J.D. Lea-Cox, M. Chappell, and M.W. van Iersel. 201x. Wireless sensors networks for optimization of irrigation, production, and profit in ornamental production. Acta Hort. In press.
5. Starry, O., J.D. Lea-Cox, A.G. Ristvey and S. Cohan. 201x. Monitoring and Modeling Green Roof Performance Using Sensor Networks. Acta Hort. (In press).
6. van Iersel, M.W. and S.K. Dove. 201x. Temporal dynamics of oxygen concentrations in a peat-perlite substrate. Acta Hort. (In press).

Non-refereed conference proceedings

1. Chappell, M. and M. van Iersel. 2012. Sensor network deployment and implementation in commercial nurseries and greenhouses. *Technical Proceedings: 2012 Irrigation Tradeshow and Education Conference.* Irrigation Assoc. Falls Church, VA. 10 p.
2. Kantor, G.F. and D. Kohanbash. 2012. Next-Generation Monitoring and Control Hardware Development. *Technical Proceedings: 2012 Irrigation Tradeshow and Education Conference.* Irrigation Assoc. Falls Church, VA. 7p.
3. Kim, J. 2012. Developing and integrating plant models for predictive irrigation. *Technical Proceedings: 2012 Irrigation Tradeshow and Education Conference.* Irrigation Assoc. Falls Church, VA. 6p.
4. Lea-Cox, J. D. and B. E. Belayneh. 2012. Irrigation Complexities - Using Sensor Networks for Real-time Scheduling in Commercial Horticultural Operations. *Technical Proceedings: 2012 Irrigation Tradeshow and Education Conference.* Irrigation Assoc. Falls Church, VA. 9p.
5. Majsztrik, J. M., E. Lichtenberg and J. D. Lea-Cox. 2012. A National Perspective on Irrigation Trends and Sensor Network Adoption in Ornamental Nursery and Greenhouse Operations. *Technical Proceedings: 2012 Irrigation Tradeshow and Education Conference.* Irrigation Assoc. Falls Church, VA. 7p.
6. van Iersel, M.W. 2012. Integrating soil moisture and other sensors for precision irrigation. *Technical Proceedings: 2012 Irrigation Tradeshow and Education Conference.* Irrigation Assoc. Falls Church, VA. 15 p.

Trade Publications

1. Kuack, D. 2013. Making sense of greenhouse irrigation. Greenhouse Product News 22(June) 22-29.
2. Majsztrik, J.C., S.A. White, J.S. Owen and J.D. Lea-Cox. 2013. The State of Water in the Green Industry Part I: Water Resource Availability. *Nursery Management.* June. 29(6): 28, 30-32.
3. Majsztrik, J.C., J.S. Owen, S.A. White and J.D. Lea-Cox. 2013. The state of water in the green industry Part II: Water Use Efficiency. *Nursery Management.* July. 29(7): 24, 26, 28.
4. White, S.A., J.S. Owen, J.C. Majsztrik and J.D. Lea-Cox. 2013. The state of water in the green industry Part III: Water Quality. *Nursery Management.* August. 29(8): 20-21,23-25.
5. Majsztrik, J.C., S.A. White, J.S. Owen and J.D. Lea-Cox. 2013. Water Smarts. The State of Water I. *Greenhouse Management.* August. 33(8): 24-26.
6. Majsztrik, J.C., J.S. Owen, S.A. White and J.D. Lea-Cox. 2013. Efficient Irrigation: The State of Water II. *Greenhouse Management.* September. 33(9): 22-25.
7. White, S.A., J.S. Owen, J.C. Majsztrik and J.D. Lea-Cox. 2013. Water Quality: Salts, Pests, and Pesticides - The State of Water Part III. *Greenhouse Management.* October. 33(10): 40, 42-46.

Invited presentations

1. Chappell, M. 2012. Irrigation sensor networks: from the source to the plant. UGA Rainwater Harvesting Symposium. Athens, GA.
2. Chappell, M. 2012. Irrigation: Fundamentals and Cost of Irrigation Efficiency and Uniformity. Tennessee Master Nursery Program. McMinnville, TN.
3. Chappell, M., G.F. Kantor and J.D. Lea-Cox. 2013. Decision Irrigation: How it Benefits Your Crop Health, Crop Quality and Your Wallet. Chesapeake Green Conference. 15 Feb, 2013. Baltimore, MD.
4. Lea-Cox, J. D. 2012. Some Observations on Interdisciplinary Project Planning and Management. In: Collaborative Research Projects Highlight the Economic Benefits of Agricultural Research. Webinar organized by the Tri-Societies (ASA/CSSA/SSSA) and Council on Food, Agriculture and Resource Economics (C-FARE) for USDA-NIFA Program Leaders. 15 Oct, 2012.

5. Lea-Cox, J. D., O. Starry, A. G. Ristvey and S. Cohan. 2012. Progress in Developing a Mechanistic Water Balance Model to Predict Green Roof Performance and Efficiency. In: Quantification of Green Roof's Contributions to Building and Community Performance. NASA-ESA International Workshop on Environment and Alternative Energy. 4 – 7 Dec, 2012. NASA-Goddard Space Center, Greenbelt MD.
6. Lea-Cox, J.D., S. Burnett and M. van Iersel. 2013. Irrigation Automation Session 2. Ohio Florist Association Short Course. Columbus, OH. 15 July, 2013.
7. van Iersel, M., S. Burnett and J.D. Lea-Cox. 2013. Irrigation Automation Session 1. Ohio Florist Association Short Course. Columbus, OH. 15 July, 2013
8. van Iersel, M.W. 2012. The plant propagation industry in the United States. International seminar on "Propagation Technologies and Certification of Nursery Plants". Rancagua, Chile.
9. van Iersel, M.W. 2012. Efficient water use during plant propagation. International seminar on "Propagation Technologies and Certification of Nursery Plants". Rancagua, Chile.
10. van Iersel, M.W. 2012. Automating irrigation: the evolution of an intelligent design. Department of Horticulture, University of Georgia. Athens, GA.
11. van Iersel, M. and M. Chappell. 2013. Sensor controlled irrigation: A case study with gardenia. WinterGreen 2013. CANR open house. Duluth, GA.
12. Thomas, P.A. 2013. Wireless Sensor Networks For Automated Irrigation Control in Container Nurseries. Georgia Farm Bureau Convention. Jeckyll Island, GA. December, 2013.

Abstracts, Conference Presentations

1. Alem, P.O, P.A. Thomas, and M.W. van Iersel. 2013. Irrigation volume and fertilizer concentration effects on leaching and growth of petunia. GroSci 2013. The International Symposium on Growing Media and Soilless Cultivation. p. 38.
2. Alem, P.O., P.A. Thomas, and M.W. van Iersel. 2013. Control of poinsettia stem elongation: height limits using deficit irrigation. *HortScience* 48:S141-142
3. Barnard, D.M. and W.L. Bauerle. 2013. The implications of minimum stomatal conductance on estimating water flux in containerized tree nurseries. *HortScience* 48:S180.
4. Barnard, D.M. and W.L. Bauerle. 2013. A comparison of the potential for scaling up irrigation scheduling techniques: substrate moisture sensing versus predictive water use modeling. *HortScience* 48:S180-181.
5. Bauerle, T.L. 2013. New methods to quantify root responses to variable water or nutrient supply. *HortScience* 48:S94.
6. Bauerle W.L., D.M. Barnard, G.S. Lloyd, A.B. Daniels, D. Banks, G. Reuning, and B. Miles. 2013. The implications of differences in stomatal conductance model parameters on estimates of ecosystem-atmosphere energy exchange. CESM land model and biogeochemistry working group meetings. February 20-22, Boulder, CO.
7. Bauerle, W.L., A.B. Daniels, and D.M. Barnard. 2013. Carbon and water flux responses to physiology by environment interactions: A sensitivity analysis of climate impacts on model parameters. Western Crop Science Society Annual Meeting, June 6-7, Pendleton, OR
8. Bauerle, W.L., A.B. Daniels, and D.M. Barnard. 2013. Carbon and water flux responses to physiology by environment interactions: A sensitivity analysis of climate impacts on biophysical model parameters *HortScience* 48:S143-144.
9. Bayer, A., J.M. Ruter, and M. van Iersel. 2013. Fertilizer rate and irrigation duration affect leachate volume, electrical conductivity, and growth of *Gardenia jasminoides*. *HortScience* 48:S182.
10. Bayer, A., and M. van Iersel. 2013. Using different teaching methods to enhance student learning of climate change. *HortScience* 48:S203.

11. Bayer, A., K. Whitaker, M. Chappell, J. Ruter, and M.W. van Iersel. 2013. Effect of irrigation duration and fertilizer rate on plant growth, substrate EC, and leaching volume. GroSci 2013. The International Symposium on Growing Media and Soilless Cultivation. p. 74.
12. Belayneh, B.E. and J.D. Lea-Cox. 201x. Implementation of Sensor-controlled Decision Irrigation Scheduling in Pot-in-Pot Nursery Production. GroSci 2013. The International Symposium on Growing Media and Soilless Cultivation. p. ??
13. Crawford, L., J.D. Lea-Cox, J. Majsztrik, W. Bauerle, M. van Iersel, T. Martin, and D. Kohanbash. 2013. Behind the curtain: The support component of wireless soil moisture networks. *HortScience* 48: S181-182.
14. Ferrarezi, R.S., M.D. Ribeiro, M.W van Iersel, and R. Testezlaf. 2013. Subirrigation controlled by capacitance sensors for citrus rootstock production. *HortScience* 48:S142.
15. Lea-Cox, J. D., B. E. Belayneh and A.G. Ristvey. 2013. Daily and seasonal changes in the water quality of irrigation containment ponds. In: Workshop - The challenges of using alternative and recycled water sources for horticultural use. *HortScience* 48:S106.
16. Majsztrik, J., E. Lichtenberg, and M. Saavoss. 2013. Costs and benefits of sensor networks for greenhouse cut flower production. *HortScience* 48:S144-145.
17. Majsztrik, J., E. Lichtenberg, and M. Saavoss. 2013. Water, irrigation costs, and the benefits of sensor networks: Results from a national survey. *HortScience* 48:S181.
18. Rivera, L.D., L. Crawford, M. van Iersel and S. Dove. 2013. Comparing hydraulic properties of soilless substrates with natural soils: a more detailed look at hydraulic properties and their impact on plant water availability. *HortScience* 48:S426-427.
19. Starry, O., J. Kim, S. Dove, M. van Iersel, and J.D. Lea-Cox. 2013. Effects of water availability and temperature on CAM expression and water use efficiency by *Sedum album* and *Sedum kamtschaticum*. *HortScience* 48:S143.
20. Thomas, P.T., M. Chappell, J.M. Ruter, E. Lichtenberg, and M.W. van Iersel. 2013. Wireless sensor networks for automated irrigation control in container nurseries: implementation and economic impact. *HortScience* 48:S179.
21. van Iersel, M.W. and S. K. Dove. 2013. Temporal and spatial oxygen dynamics in soilless substrate as affected by environmental conditions. GroSci 2013. The International Symposium on Growing Media and Soilless Cultivation. p. 58.
22. White, S.A., J.S Owen, J.C. Majsztrik, R.T. Fernandez, P.R. Fisher, C.R, Hall, T.A Irani, J.D. Lea-Cox, J. Newman ad L.R. Oki. 2013. Containment, remediation, and recycling of irrigation water for sustainable ornamental crop production: Results of a SCRI planning grant. *HortScience* 48:S427-428.

Webinars

1. Chappell, M. 2012. Exciting New Irrigation Research (in Horticulture). UGA Center for Urban Agriculture Webinar Series. Griffin, GA. http://vimeo.com/63678588.
2. Lea-Cox, J.D. 2013. Using Sensor Networks to Monitor and Control Irrigation Events in Nursery and Greenhouse Operations. Decagon Virtual Seminar Series. http://tinyurl.com/mnnsaxq
3. Kim, J. and O. Starry. 2013. Beyond Saving Water: Using Moisture Sensors in Horticulture Research. Decagon Virtual Seminar Series. http://tinyurl.com/m6fuh28
4. van Iersel, M.W. 2013. Using soil moisture sensors for irrigation control: reducing nursery water use and increasing profits. Decagon virtual seminar series. http://tinyurl.com/l9rhghp

Other presentations

1. Bauerle, T. L., M. Centinari and J.D. Lea-Cox. 2013. Incorporating precision irrigation into water management strategies for nurseries. Long Island Agricultural Forum, Riverhead, NY (30 participants).

2. King, D., J. Majsztrik, E. Price, P. Hagan. 2013. SCRI-MINDS Analysis of wireless sensor networks public benefits. SCRI-MINDS Annual Conference. Athens, GA. June 3-6 2013.
3. Lichtenberg, E. 2013. Optimal investment in precision irrigation systems: a dynamic intraseasonal approach. Selected paper presented at the annual meeting of the Agricultural and Applied Economics Association. Washington, DC. August 4-6, 2013.
4. Lichtenberg, E. 2013. Profitability of a wireless sensor network for gardenia production. SCRI-MINDS Annual Conference. Athens, GA. June 3-6 2013.
5. Lichtenberg, E. 2013. Profitability of monitoring and control at Hale and Hines. SCRI-MINDS Annual Conference. Athens, GA. June 3-6, 2013.
6. Lichtenberg, E. 2013. Statistical and economic analysis of snapdragon production. SCRI-MINDS Annual Conference. Athens, GA. June 3-6, 2013.
7. Majsztrik, J., E. Lichtenberg, and M. Saavoss. 2013. Insights into grower perceptions of sensor networks. SCRI-MINDS Annual Conference. Athens, GA. June 3-6, 2013.
8. Saavoss, M., E. Lichtenberg, and J. Majsztrik 2013. Grower willingness to pay for wireless sensor networks. SCRI-MINDS Annual Conference. Athens, GA. June 3-6, 2013.

Appendix A:

FEDERAL FINANCIAL REPORT

(Follow form instructions)

1. Federal Agency and Organizational Element to Which Report is Submitted **USDA NIFA**	2. Federal Grant or Other Identifying Number Assigned by Federal Agency (To report multiple grants, use FFR Attachment) **Award #20095118105768**	Page 1 of 1 pages

3. Recipient Organization (Name and complete address including Zip code)

UNIVERSITY OF MARYLAND, OFFICE OF THE COMPTROLLER, CONTRACT AND GRANT ACCOUNTING
ROOM 4101, CHESAPEAKE BUILDING, COLLEGE PARK, MD 20742-3141

4a. DUNS Number	4b. EIN	5. Recipient Account Number or Identifying Number (To report multiple grants, use FFR Attachment)	6. Report Type	7. Basis of Accounting
790934285	**526002033**	**525317/525336**	☐ Quarterly ☐ Semi- Annual ☒ Annual ☐ Final	☒ **CASH** ☐ **ACCRUAL**

8. Project/Grant Period From: (Month, Day, Year)	To: (Month, Day, Year)	9. Reporting Period End Date (Month, Day, Year)
9/1/2009	8/31/2014	8/31/2013

10. **Transactions**	Cumulative
(Use lines a-c for single or multiple grant reporting)	
Federal Cash (To report multiple grants, also use FFR Attachment):	
a. Cash Receipts	$3,145,921.44
b. Cash Disbursements	$3,341,317.97
c. Cash on Hand (line a minus b)	($195,396.53)
(Use lines d-o for single grant reporting)	
Federal Expenditures and Unobligated Balance:	
d. Total Federal funds authorized	$5,161,495.00
e. Federal share of expenditures	$3,341,317.97
f. Federal share of unliquidated obligations	
g. Total Federal share (sum of lines e and f)	$3,341,317.97
h. Unobligated balance of Federal funds (line d minus g)	$1,820,177.03
Recipient Share:	
i. Total recipient share required	$5,161,495.00
j. Recipient share of expenditures	$4,532,765.86
k. Remaining recipient share to be provided (line i minus j)	$628,729.14
Program Income:	
l. Total Federal program income earned	
m. Program income expended in accordance with the deduction alternative	
n. Program income expended in accordance with the addition alternative	
o. Unexpended program income (line l minus line m or line n)	

11. Indirect Expense	a. Type	b. Rate	c. Period From	Period To	d. Base	e. Amount Charged	f. Federal Share
	Predetermined	50.00%	9/1/2009	8/31/2013	1,723,827.15	861,863.63	539,576.23
				g. Totals:	1,723,827.15	861,863.63	539,576.23

12. *Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation:*

13. **Certification: By signing this report, I certify that it is true, complete, and accurate to the best of my knowledge. I am aware that any false, fictitious, or fraudulent information may subject me to criminal, civil, or administrative penalties. (U.S. Code, Title 18, Section 1001)**

a. Typed or Printed Name and Title of Authorized Certifying Official **Diane Wechsler, Accountant**	c. Telephone (Area code, number and extension) 301-405-6662 d. Email address dwechsle@umd.edu
b. Signature of Authorized Certifying Official Diane Wechsler	e. Date Report Submitted (Month, Day, Year) 11/12/2013
	14. Agency use only:

Standard Form 425
OMB Approval Number: 0348-0061
Expiration Date: 10/31/2011

Paperwork Burden Statement
According to the Paperwork Reduction Act, as amended, no persons are required to respond to a collection of information unless it displays a valid OMB Control Number. The valid OMB control number for this information collection is 0348-0061. Public reporting burden for this collection of information is estimated to average 1.5 hours per response, including time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding the burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Office of Management and Budget, Paperwork Reduction Project (0348-0060), Washington, DC 20503.

Appendix B. Project Research and Development Objectives, by Working Group and Year

ID	PROJECT OBJECTIVES AND GOALS	WORKING GROUP	PROJECT ACTIVITIES BY QUARTER																			
			YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
			9-2009	12-2009	3-2010	06-2010	9-2010	12-2010	3-2011	06-2011	9-2011	12-2011	3-2012	06-2012	9-2012	12-2012	3-2013	06-2013	9-2013	12-2013	3-2014	06-2014
	University of Maryland Greenhouse Research																					
1.6.1	On-campus research			Begin plant physiological studies (water use) and varify sensor calibrations. Begin Model development.					Integrate sensor physiological research to next iteration of node networks. Continue physiological greenhouse studies and validate Model design						Finalize Model development and receive input from industry				Resolve any industry issues and concerns with Model use			
1.6.2	On-farm research			Deploy present generation node networks at commercial farm with commercial greenhouse partners. Begin initial monitoring.					Deploy next interation of node networks at commercial greenhouse. Begin to validate Model. Test monitoring and irrigation control capabilties						Contiue research with node networks with commercial greenhouse partners. Resolve issues with Model and irrigation control capabilies				Finalize Model and monitoring and irrigation control issues for commericalization.			
1.6.3	Technology implementation			Continue monitoring and begin irrigation control. Apply research data for Model development. Employ GUI.					Refine GUI and Model. Continue monitoring and control research and develop baselines. Determine spatial and temporal probe requirements.							Beta testing model/GUI software.				Release of commercial product		
1.6.4	Outreach				Preliminary findings presented at local extension programs and national conferences.				Write peer reviewed and trade journal manuscripts.			Previous seasons findings presented at local extension programs and national conferences.					Write peer reviewed and trade journal manuscripts.			National conferences and extension programming.		
1.6.5	Synergistic activities		Share monitoring and control data with CMU,UG, Cornell, UC and Decagon to develop model crop software and GUI.																			
1.6.6	Software and Modeling		Begin initial modeling research and develop baselines for Model GUI software development.				Begin model validation. Varify GUI utility.					Comntinue model validation and GUI utility.				Beta testing model/GUI software.				Release of commercial product.		
	In-Ground/Out of Ground Nursery Research																					
1.6.1	Field station research		Deploy present generation node networks at Field Research Station. Varify probe calibrations. Begin initial monitoring and irrigation control.			Deploy next interation of node networks at Field Station. Conitnue testing monitoring and irrigation control capabilties.				Continue node network research at Field Station. Conitnue testing monitoring and irrigation control capabilties. Determine spatial and temporal variations for Model.				Finalize node network research at Field Station. Wrap up monitoring and irigation control.				Finalize Model development and receive input from industry.			Resolve any industry issues and concerns with Model use.	
1.6.2	Commerical farm Research		Deploy present generation node networks at Commercial Farm. Begin initial monitoring.			Conitnue research on node networks at Commercial Farm. Begin monitoring and initial irrigation control. Employ GUI.				Deploy present generation node networks at Field Research Station. Begin initial monitoring and irrigation control.				Deploy present generation node networks at Field Research Station. Begin initial monitoring and irrigation control. Employ GUI.				Finalize Model development and receive input from industry.			Resolve any industry issues and concerns with Model use.	
1.6.3	Technology implementation		Employ GUI at Reaserch Farm			Validate GUI effectiveness and improve				Determine GUI usefulness and improve				Determine GUI usefulness and improve based on industry needs				Release of commercial product				
1.6.4	Outreach				Preliminary findings presented at local extension programs and national conferences.				Write peer reviewed and trade journal manuscripts.			Previous seasons findings presented at local extension programs and national conferences.					Write peer reviewed and trade journal manuscripts.			National conferences and extension programming		
1.6.5	Synergistic activities		Share monitoring and control data with CMU,UG, Cornell, UC and Decagon to develop model crop software and GUI.																			
	Software and Modeling		Begin initial modeling research (Buaerle) and develop baselines for model/ GUI software development.				Varify GUI utility.					Begin model validation and GUI utility.				Beta testing model/GUI software.				Release of commercial product		

ID	PROJECT OBJECTIVES AND GOALS	WORKING GROUP	PROJECT ACTIVITIES BY QUARTER																			
			YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
			9-2009	12-2009	3-2010	06-2010	9-2010	12-2010	3-2011	06-2011	9-2011	12-2011	3-2012	06-2012	9-2012	12-2012	3-2013	06-2013	9-2013	12-2013	3-2014	06-2014
	Green Roof Systems Research																					
1.6.1	On-campus/Field station research		Begin probe calibrations to green roof media and use node system in macroscale research				Resolve issues with calibrations to green roof media															
1.6.2	On-location research						Deploy node network on greenroof system				Conintue research on node network on greenroof system				Conintue research on node network on greenroof system							
1.6.3	Technology implementation						Employ GUI and begin water budget modeling.				Continue water budget modeling. Validate GUI.				Continue water budget modeling. Validate GUI.							
1.6.4	Outreach				Preliminary findings presented at local extension programs and national conferences.				Write peer reviewed and trade journal manuscripts.			Previous seasons findings presented at local extension programs and national conferences.					Write peer reviewed and trade journal manuscripts.			National conferences and extension programming.		
1.6.5	Synergistic activities		Share monitoring and control data with CMU,UG, Cornell, UC and Decagon to develop model crop software and GUI.																			
1.6.6	Software and Modeling						Begin initial modeling research and develop baselines for Model GUI software development.		Varify GUI utility.			Begin model validation and GUI utility.				Beta testing model/GUI software.				Release of commercial product.		

ID	PROJECT OBJECTIVES AND GOALS	WORKING GROUP	PROJECT ACTIVITIES BY QUARTER																			
			YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
			9-2009	12-2009	3-2010	06-2010	9-2010	12-2010	3-2011	06-2011	9-2011	12-2011	3-2012	06-2012	9-2012	12-2012	3-2013	06-2013	9-2013	12-2013	3-2014	06-2014
	Carnegie Mellon University																					
	Hardware Development																					
	Design	Decagon, CMU	team tech review	new node design			iterate design				iterate design					iterate design						
	Manufacture	Decagon				engineering prototype		build 50 field prototypes					build preproduction prototypes				produce/market sensor network system					
	Evaluate Deployments	Decagon, CMU				test/evaluate prototypes			collect engineering data from test sites						ollect engineering data from preproduction test site				collect engineering data on production units			
		Decagon, CMU	existing system to Bauers, UMD Greenhouse, Wye (others?)						field prototypes to test sites						preproduction prototypes to test sites				production units to test sites			
	GUI Development																					
	Development	CMU, Decagon, Antir	team tech review	rough GUI	dabase	design GUI, refine database			final GUI design/development, develop supporting documentation				refine GUI									
	Evaluate Deployments	CMU, Decagon, Antir				evaluate database and GUI			collect user feedback, evaluate				collect user feedback, evaluate				collect user feedback, evaluate					
		CMU, Decagon			rough GUI to existing field sites				GUI prototype to field sites (alpha test)				GUI beta test				market GUI as part of sensor network system					
	Crop-Specific Plug-Ins																					
	Petunia	CMU, Georgia, Antir	implement				evaluate at U. Georgia				beta test						market					
	Red Maple	CMU, CSU, Antir					implement				evaluate at CSU				beta test				market			
	Green Roof	CMU, UMD, Antir													implement				evaluate at green root test site			
	Snapdragon	Antir, UMD, CMU									implement				evaluate at Bauers Greenhouse				beta test			

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			9-2009	12-2009	3-2010	06-2010	9-2010	12-2010	3-2011	06-2011	9-2011	12-2011	3-2012	06-2012	9-2012	12-2012	3-2013	06-2013	9-2013	12-2013	3-2014	06-2014
	University of Georgia																					
	Greenhouse/nursery research																					
1.6.1	On-campus research		Determine effects of substrate water content on physiology, growth, and quality of different greenhouse crops, quantify water needs, start model development				Determine whether soil moisture sensor-controlled irrigation can be used to control stem elongation and improve plant quality, effects of substrate water content on physiology, growth, and quality of different nursery crops, continue model development				Validate petunia water use model, incoprorate model into software, determine how optimal fertilization practices should be altered with soil moisture sensor-controlled irrigation, continue work on stem elongation and plant quality.				Wrap up greenhouse research, address isues raised by industry partners, continue nursery research on plant morphology and quality				Wrap up nursery research, address unresolved issues raised by industry partners			
1.6.2	On-farm research			Quantify water use and plant water needs					Implement soil moisture sensor based irrigation, quantify water savings, effects on plant quality				Implement altered fertilization practices, quantify reductions in fertilizer use and nutrient leaching									
1.6.3	Technology implementation			Maintain and provide support for wireless network at EverGreen (already in place) and install wireless network at McCorkle					Upgrade on-farm wireless networks to incorporate control capability										Upgrade wirelees networks with latest GUI			
1.6.4	Outreach			Present preliminary findings at trade shows, present data at scientifi meeting					Publish first manuscript, write trade magazine articles			Publish manuscripts, write trade magazine articles			Publish manuscripts; Organize field day at industry partners for county faculty and growers; Develop outreach materials Web-based, PowerPoints, extension publications, trade magazine articles				Publish manuscripts; Organize field day at industry partners for county faculty and growers; Develop outreach materials Web-based, PowerPoints, extension publications, trade magazine articles			
1.6.5	Synergistic activities		Share water use and environmental data with UM, CSU, and Cornell; collaborate with UM on model development; Collect data needed for social and economic analyses				Share water use and environmental data with UM, CSU, and Cornell; collaborate with UM on model development; Collect data needed for social and economic analyses				Collaborate with UM/Antir on incirporating water use model into software; Collect data needed for social and economic analyses				Collect data needed for social and economic analyses							

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			9-2009	12-2009	3-2010	06-2010	9-2010	12-2010	3-2011	06-2011	9-2011	12-2011	3-2012	06-2012	9-2012	12-2012	3-2013	06-2013	9-2013	12-2013	3-2014	06-2014
	Colorado State University																					
	Nursery research																					
1.6.1	On-campus research		Deploy CMU node network with sensors at ARDEC, continue model parameterization and validation (from prior research), deploy lidar, and determine species specific water use and needs				Determine initial optimization of a macro-scale distributed environmental sensing network, scale species estimates from whole trees to stand and compare to measured values, continue model development				Detailed spatial analysis and validatation of nursery water use model, deploy lidar, begin incoprotatation of model into software, schedule irrigation treatments for prescribed irrigation evaluation				Wrap up ARDEC site research but yet address any unresolved issues				Address any unresolved issues			
1.6.2	On-farm research			Deploy CMU node network with sensors at Willoway, quantify water use and plant water needs, deploy lidar, quantify physiological variables and calculate model parameters					Determine initial optimization of macro-scale distributed environmental sensing network, deploy lidar, scale species estimates from whole trees to nursery beds and sections and compare to different nursery crop measured values, continue model development				Deploy lidar, determine spatial node and sensor placement and derive optimal system component placement and quantity per unit area, continue physiological measures, model development and scaling validation.				Wrap upWilloway site research but address any unresolved issues and demonstrate system to national audience					
1.6.3	Technology implementation			Install wireless network at ARDEC and Willoway					Upgrade on-farm wireless networks to incorporate control capability				Incorporate latest GUI						Continue upgrade wirelees networks with latest GUI			
1.6.4	Outreach			Present preliminary findings to Willoway employees, present data at scientific meeting					Submit first manuscript, write trade magazine articles			Present initial findings to national industry audience at Willoway site, publish manuscripts, write trade magazine articles			Publish manuscripts; hold field day at ARDEC; Develop outreach materials - Web-based, PowerPoints, extension publications, trade magazine articles				Hold national association short course to present to industry at Willoway site and Publish manuscripts			
1.6.5	Synergistic activities		Share water use and environmental data with UM, UG, and Cornell; collaborate with UM on model development; Collect data needed for social and economic analyses				Share water use and environmental data with UM, UG, and Cornell; collaborate with UM, UG, and Cornell on model development; Collect data needed for social and economic analyses				Collaborate with UM/Antir on incirporating water use model into software; Collect data needed for social and economic analyses				Collect data needed for social and economic analyses							