2011

SCRI-MINDS – YEAR 2 REPORT

PRECISION IRRIGATION AND NUTRIENT MANAGEMENT FOR NURSERY, GREENHOUSE AND GREEN ROOF SYSTEMS:

WIRELESS SENSOR NETWORKS FOR FEEDBACK AND FEED-FORWARD CONTROL

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Executive Summary

The SCRI-MINDS group has made significant progress during the second year, and almost all aspects of the project are on track or ahead of schedule. The following accomplishments are detailed in this report:

1. Engineering Hardware and Software Development:

Engineering developments have been the number one project priority during year 2, since further scientific discovery, implementation and model development in years 3-5 are entirely dependent upon this critical work. We achieved all our year two engineering goals, including:

- Development of a new sensor network base station with the intelligence to manage nodes with irrigation control capability.
- Development of a web-based graphical user interface (sensorweb) that can be used to view data and control nodes.
- Manufacture of two next-generation Decagon nodes, which both have built-in irrigation control capability.
- Evaluated a new water content, electrical conductivity and temperature sensor, which has been designed specifically to work in highly porous nursery and greenhouse (soilless) substrates.

2. Model Development:

The models developed by Antir software and various scientists are the key to minimizing water usage and having an optimal irrigation strategy. These models are being integrated directly into the sensorweb graphical user interface by the engineering team.

- The Petunia model and most of the MAESTRA model were integrated into sensorweb in year 2.
- The interactive effects between various environmental variables and their effect on transpiration with the MAESTRA model are being studied. This sensitivity analysis will have important implications for irrigation scheduling based on live, or forecast environmental data.
- A green roof stormwater model has been parametized and the model is currently being encoded.
- Additionally, work started in year 2 on parametizing the Snapdragon model, based on measuring plant growth, daily intercepted light integral and vapor pressure deficit.

3. Scientific Research and Development:

A large number of individual plant research studies are underway at the various Universities, looking at various aspects of plant water use, including plant growth and adaptation to drought stress, reduced nutrient use and reduced disease incidence. Many of the environmental data being measured by the various projects (both in research sites and on farms – see below) are being used to develop and test predictive plant water use models and quantify the economic and environmental benefits of using sensor networks.

- The amount of water needed to grow high quality petunia plants was surprisingly low. Only 400 ml (1/10 gallon) was needed to grow petunia plants from plug seedling to full bloom in 23 days, with no nutrient leaching. Only 0.6- 0.8 g /plant (< 0.03 oz) of fertilizer was needed to grow these plants.
- Sensor networks have the capability to monitor and control sub-irrigation systems, which further conserve water and reduce nutrient loss to virtually zero risk. In addition, it helps growers control plant growth and quality.
- Various plant experiments both in greenhouse and outdoor nursery environments have demonstrated that sensor-controlled irrigation can precisely manipulate plant growth, for height and canopy density control, enhancing plant quality and customer appeal.

- Plant water use is strongly correlated to daily light interception, vapor pressure deficit and plant size. All of these variables are easily measured by various sensors or manually input into models. Preliminary plant water use models developed thus far have shown that we can accurately predict water use, by using sensor networks at various scales.
- Based on measurements of spatial and temporal variation in substrate water contents, we are developing species-specific sensor instructions for sensor installation for large tree containers, and have a good idea of the number of sensors required to place within blocks of different tree species.
- Measurement of wind extinction coefficients in outdoor nurseries has shown that this is an important variable in predicting field (outdoor) plant water use, which should be carefully characterized by installing additional anemometers within tree rows.
- Recent work with CT scans at Cornell has been able to nondestructively image whole roots in soilless nursery substrates.

4. <u>On-Farm Research</u>:

- All growers in the project are actively using soil moisture and environmental data from their sensor networks for better decision-making, on a daily basis. New software “grower tools” that calculates based on integrated information, such as daily light integral (DLI), delta VWC (change in water content) and degree-days (for predictive insect and/pr plant development) are providing added-value information, in addition to typical weather station data such as air temperature, relative humidity, rainfall and wind speed, which are used daily for many cultural management decisions.
- We are monitoring and modeling daily water use of snapdragon within a production greenhouse environment. Preliminary results have shown that snapdragon water use can be modeled from measurement of intercepted light, vapor pressure deficit and plant age.
- Preliminary root density measurements from mature soil-grown red maples show that the prevalence of fine roots is strongly correlated to drip emitter placement and fine roots persist in this drip zone for up to two years, after no further irrigation.
- Most roots from a 2 and 4-year-old tree were confined to the top 30cm (12”) of the soil profile. These results have important implications for the precise placement of sensors for monitoring soil moisture and EC (nutrients) in the root zone.

5. <u>Economic Research:</u>

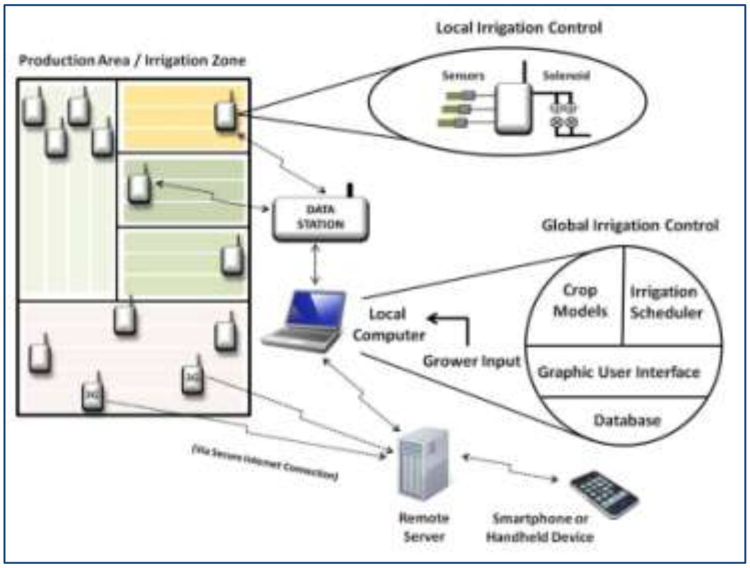
- By controlling irrigation using soil moisture sensors we minimized overwatering and reduced disease. In one on-farm study, the normal production time of a salable crop of gardenia was reduced by 43% and typical crop losses due to root disease were reduced from 30% to zero.
- The total increase in profits from reduced production time and elimination of shrinkage, which corresponded to $1.06 savings per ft^2 per production cycle. In this case, the $3,000 precision irrigation system installed in this study would have a payback period of less than 2 months.

6. <u>Communication and Outreach</u>:

- A new website and knowledge center (http://www.smart-farms.net) was completely redesigned and deployed to communicate our progress to our stakeholders and the general public.
- A project Impact statement (see below) was published in the American Society for Horticultural Science: Center for Horticultural Impact Statements at http://ashsmedia.org/?p=62
- During year 2, one book chapter, 9 peer-reviewed papers, 10 conference papers, 2 trade articles and 17 conference abstracts were published by the SCRI-MINDS group. In addition, members gave 9 international / national invited presentations and contributed 18 conference presentations.

2011 Project Impact Statement

More than 56.6 million acres of land were irrigated in the United States in 2007, of which 56% was irrigated by sprinkler and microirrigation systems.[1] We are developing advanced sensor technology to precisely monitor plant water use, to allow for better control of irrigation water applications and increase the efficiency of water and nutrient use in nursery and greenhouse operations. By using cost-effective networks of soil and environmental sensors, we are providing growers with real-time remote information about soil moisture and plant water use on their computers and smart phones.



Through collaborations between plant scientists, engineers, and economists at five universities and two commercial companies, we have developed new sensor technology and software to automatically control irrigation based on plants' needs in commercial nursery and greenhouse operations in MD, GA, TN and OH. Close cooperation among researchers and commercial growers is taking advantage of everyone's expertise, to ensure rapid progress towards implementation of the science into practice.

During the first two years of this project, commercially-available sensor technology was deployed on these farms, which growers are using to make daily irrigation decisions. We have already reduced water applications by more than 50%, by making smarter irrigation scheduling decisions. Improving water management not only reduces nutrient leaching but also improves plant quality and reduces losses from plant diseases. In the case of one nursery, improving their irrigation practices resulted in a $1 per square foot economic benefit for a specific crop. These savings from just one small area of this nursery operation would have paid for the sensor network in less than two months. Given that most nurseries have 10's to 100's of acres in production, the economic benefit for individual nurseries is likely to be many thousands of dollars each year. However, better irrigation not only benefits growers, it helps conserve the nation's water resources. By improving ornamental irrigation efficiency by 50%, we can save more than 42 gallons of water per person for each of the 310 million people in the US each year[2]. More detailed results from the project can be found at http://www.smart-farms.net

[1] *Kenny et al., 2009. Estimated use of water in the United States in 2005: U.S. Geological Survey Circ. 1344, 52 p.*

[2] *U.S. Dept. Agric, 2009. 2008 Farm and Ranch Irrigation Survey: Horticultural Operations Data. Nat. Agric. Stat. Serv., Washington, D.C.*

Global Project Goals and Objectives

As a Coordinated Agricultural Specialty Crops Research Initiative Project, we are focused on delivering a commercial wireless sensor network 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 and public economic benefits of this technology. The project is integrated across various scales of production by using small and large commercial test sites which allow us to take a systems approach to identify the 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 industry and society as well as barriers to adoption of this new technology. The project structure allows us to engage the industry collaborators on a day-to-day basis to ensure satisfaction with new hardware and software products developed by our teams and our commercial partners.

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

Engineering

During the second year, the engineering team from Carnegie Mellon and Decagon Devices, Inc. developed and released a new prototype sensor-control network system and began deploying it at test sites in collaboration with other project scientists. Briefly, the engineering accomplishments during the year were:

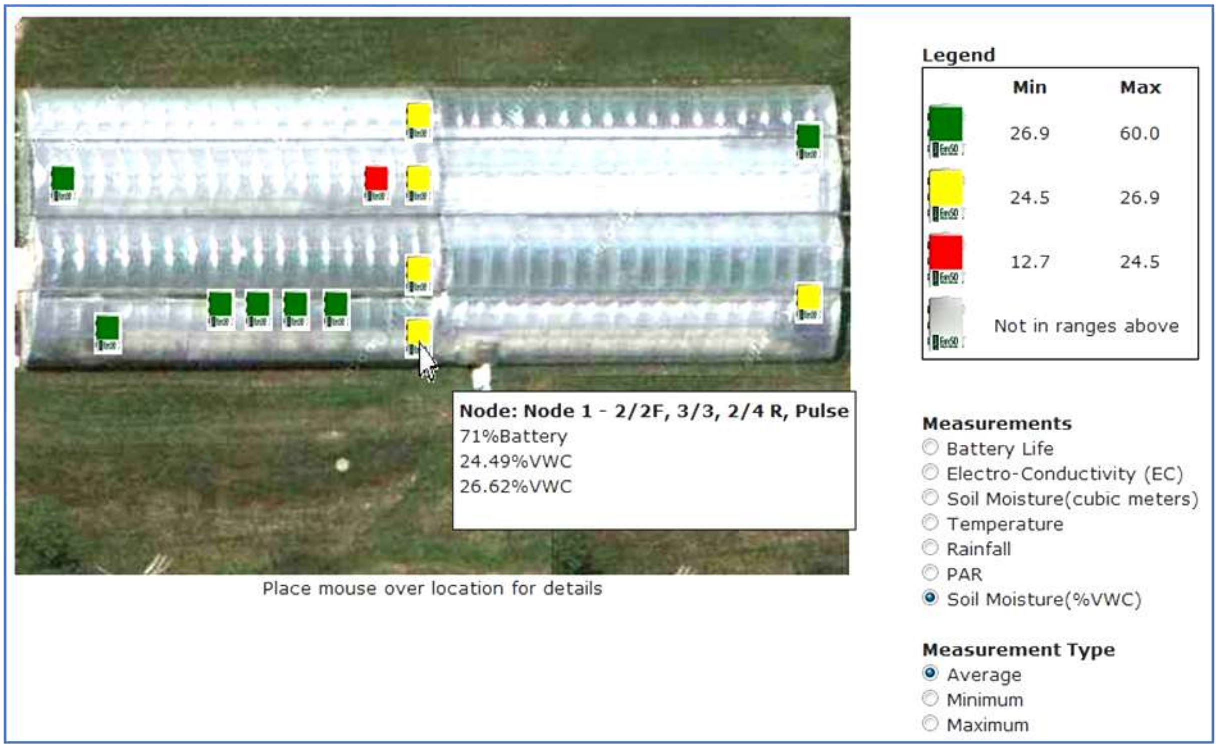
- Developed a new base station for sensor networks with the intelligence to manage nodes with irrigation control capability and the flexibility to work with all of the various sensors and nodes in use on the project.
- Developed a web-based graphical user interface that can be used to view data and control irrigation events by communicating with the sensor nodes in the field.
- Built two new generations of Decagon nodes, both of which have built-in control capability (one that uses 24 VAC solenoids powered from an external source, and one that uses DC latching solenoids powered by on-board batteries)
- Developed a communication protocol to allow the basestation to exchange sensor data and control commands with the new nodes.
- Deployed the new network (in some cases in hybrid networks that include older nodes) at several test sites to demonstrate both sensing and control capabilities.
- Although not a specific deliverable for this project, Decagon developed a new water content, electrical conductivity and temperature sensor which combines easy insertion, good accuracy, and durability with simple connectivity to measurement nodes, and which was designed specifically for use in porous nursery and greenhouse (soilless) substrates
- Integrated the Petunia model and most of the MAESTRA model with the new Sensorweb software.

A more detailed description of these accomplishments follows.

1. Base Station and User Interface:

The CMU sensorweb basestation has proven to be a very useful tool for growers as well as for researchers. The gateway for this interface is the home page that allows for an instant view of the entire operation. This instant view also provides a mouseover capability, which allows the viewing of detailed information from each sensor node, as simply and quickly as possible (Fig. 1). Irrigation scheduling is the primary objective of the graphic use interface, which allows growers to either manually control irrigation, manage a schedule-based controller (Fig. 2) or alternatively, manage local setpoint control (irrigating based on data collected from a particular node) all from a centralized website. A more advanced global control utilizing full plant models is being developed and will be ready for use shortly.

The irrigation tool also allows the user to set up complex irrigation patterns. For example growers can specify that at each irrigation cycle the water should pulse on and off, to allow for slower water infiltration and less nutrient leaching. Another useful time saving feature is that node configurations can be updated from any computer with internet access saving users from having to go to each node in the field and manually enter the configuration.



Node: Node 1 - 2/2F, 3/3, 2/4 R, Pulse
71%Battery
24.49%VWC
26.62%VWC

Place mouse over location for details

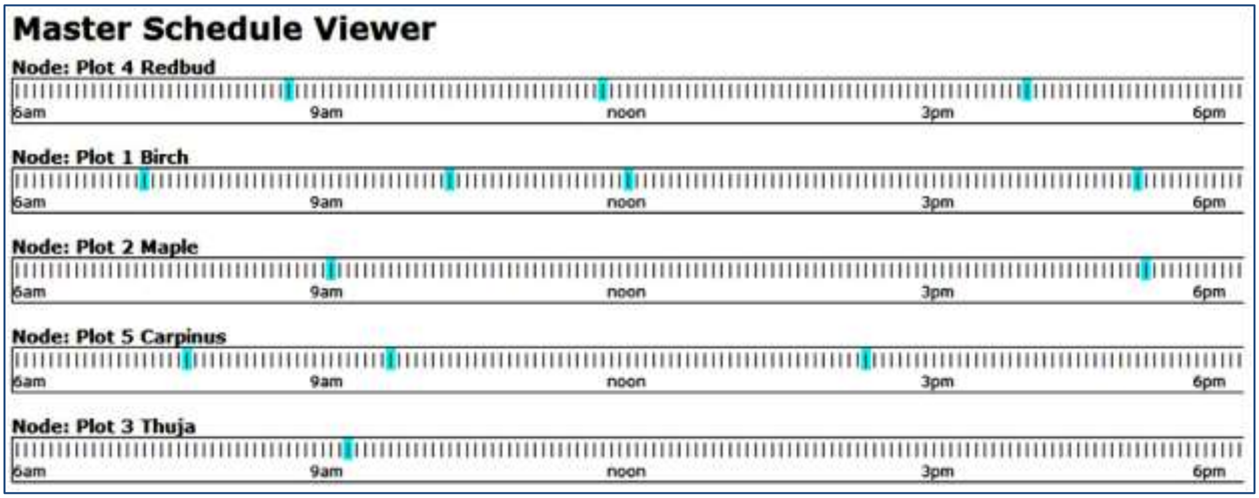
Legend

	Min	Max
🟩	26.9	60.0
🟨	24.5	26.9
🟥	12.7	24.5
⬜	Not in ranges above	

Measurements
○ Battery Life
○ Electro-Conductivity (EC)
○ Soil Moisture(cubic meters)
○ Temperature
○ Rainfall
○ PAR
● Soil Moisture(%VWC)

Measurement Type
● Average
○ Minimum
○ Maximum

Fig 1. This is the main graphic on the entry screen to the sensor network interface. It shows a snapshot that graphically summarizes the most recent set of sensor readings, with a “red, yellow, green” display that colors the nodes based on user-configurable thresholds.



Master Schedule Viewer

Node: Plot 4 Redbud
6am 9am noon 3pm 6pm

Node: Plot 1 Birch
6am 9am noon 3pm 6pm

Node: Plot 2 Maple
6am 9am noon 3pm 6pm

Node: Plot 5 Carpinus
6am 9am noon 3pm 6pm

Node: Plot 3 Thuja
6am 9am noon 3pm 6pm

Fig. 2. This shows the master irrigation scheduler, which allows a user to centrally configure irrigation schedules on all of the control nodes from a single point.

This system has the flexibility to modify calibrations and add new sensors on the fly. Tools such as real time charting (Figs. 3 and 4), a customizable data extraction tool and various data extraction formats give growers and researchers the power to work with the data and utilize it as they see fit. The interface is also remotely accessible via a webpage that requires user authentication.

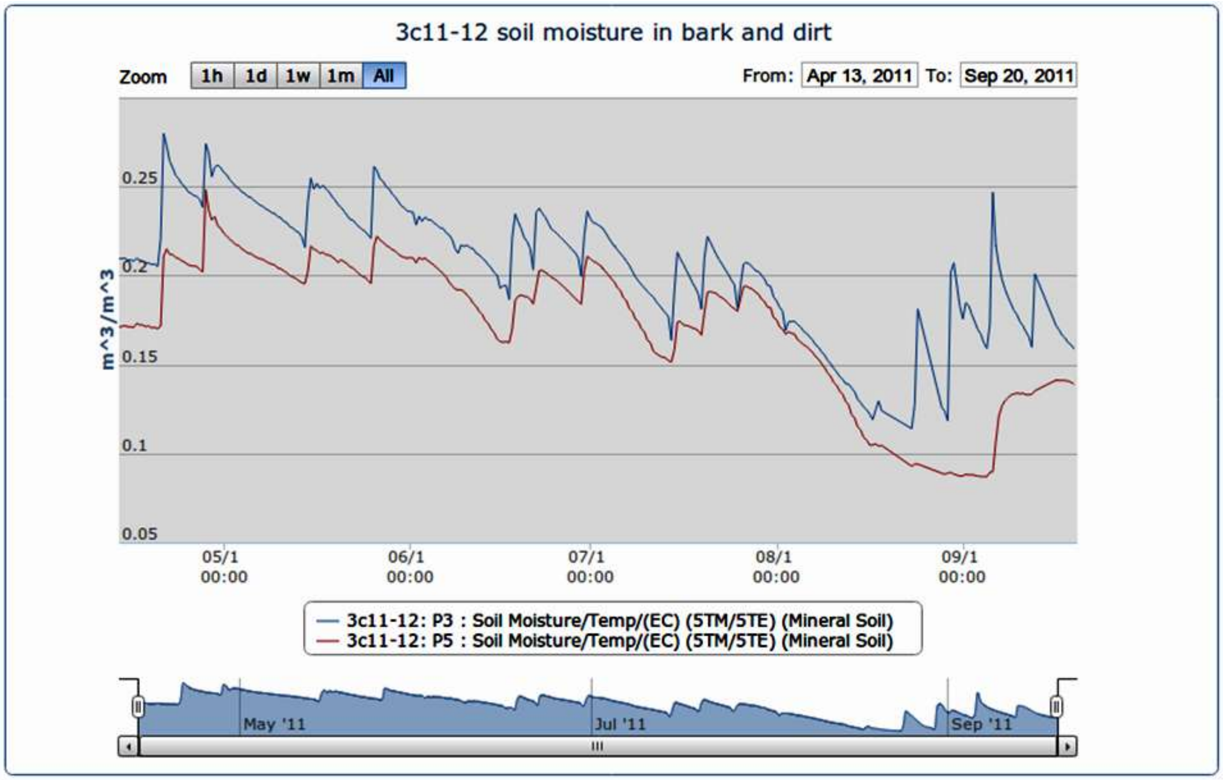


Fig. 3. This figure shows a typical plot generated using the charting function in the sensor network interface. This interactive plotting tool allows for easily configured views that can be zoomed in or out and shifted left or right with mouse actions.

The interface has various access control levels ranging from administrator with full control to a data view account that only allows viewing of data, but not modification of any setting that could affect crop production, such as irrigation parameters. While the interface is the visible part of the base station there is a lot of software working behind the scenes. In order to create a robust system that can handle irrigation commands wirelessly and without error, we developed and implemented a new protocol for exchanging data between nodes and the base station. This protocol, which resides on both the nodes and the base station, is responsible for sending the configuration from the interface to the nodes, reporting irrigation status from the nodes to the interface and for making sure this all happens in a safe and reliable manner.

On the base station, this software also handles placing the data into a sqlite3 database so that the interface can access and work with the data.

2. Sensing and Control Nodes: Decagon created monitoring and control nodes for use in a wireless irrigation control system. Like the older Em50R wireless data logger product Decagon currently sells, the

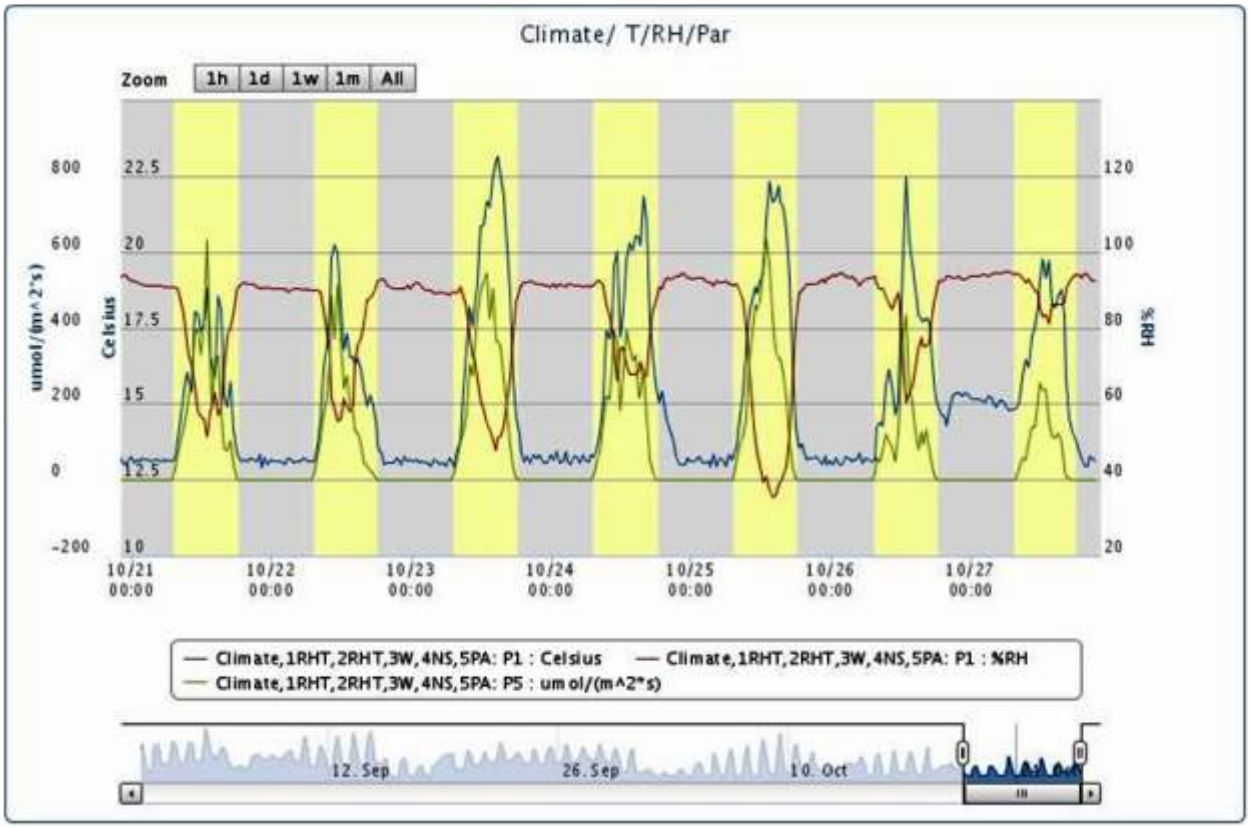


Fig. 4. Another example of a plot generated with the charting tool. This one displays sunrise and sunset times (the yellow and grey bars) along with the various sensor data.

new wireless nodes created for this project support monitoring up to 5 sensors that include soil/substrate moisture, electrical conductivity, temperature and other environmental measurements. The radio hardware is also similar to the Em50R that has proven to be a good choice for reliable, farm-wide radio networks. Including circuitry to control irrigation in the node is a large departure from the Em50R logger that is designed only for monitoring. The first measurement and control node Decagon developed, known as the nR5, includes a latching relay. The node uses a relay to switch power to an irrigation solenoid valve (typically 24VAC). Using a latching relay saves node battery power since this type of relay doesn't require energy from the node to hold the valve open. The node includes circuitry to monitor the presence of the 24VAC power necessary to control irrigation. This feature allows the team to remotely troubleshoot missed irrigation events that could happen when the 24VAC is missing. Team members successfully deployed these nodes in the last growing season. Decagon is now incorporating the feedback from their experiences.

After seeing the nR5, two of the nursery partner growers in the MINDS project pointed out they would rather not depend on powered 24VAC irrigation valves. They explained this kind of system was costly to install because of the 24VAC wiring between an irrigation controller and each valve. Also, the control function of the MINDS software is complicated by the need for an external source of power to switch the irrigation valve. From this feedback, Decagon started working on a control node that would not depend on 24VAC. The second node, the nR5-DC, is designed to control DC latching solenoid valves. This type of irrigation system is not dependent on 24VAC power wired to each valve. The node circuitry includes a charge pump and H-bridge that works directly with the DC valve to control irrigation flow. This means the node is capable of being a self-contained irrigation controller for one latching solenoid. This node hardware is currently in early testing.

3. **Communication Protocol:** The wireless network protocol used between the nodes and base station gained key irrigation control improvements. Most node settings can be configured from the base station software. Additional node metadata is also included in the wireless protocol so the growers can know the status of their network. The node supports four irrigation modes: manual commands, schedule based, local sensor thresholding, and global control from base station signals. These four modes allow growers and researchers full flexibility over crop irrigation choices. The new firmware for this node is more secure, uses strong checksums, and requires that all packets be confirmed in order to prevent incorrect irrigation events.

4. **Field Testing:** There are currently nine base stations being used, one not being used, and two more that are ready for use. The Willoway Nursery in Ohio has two separate networks one monitoring about 20 nodes and the other monitoring four nodes and using another five nodes to control irrigation. The Bauer's site in Maryland has 14 nodes for monitoring and another eight nodes for monitoring and control. The University of Georgia has five base stations and is actively testing with three of them. The University of Maryland greenroof platforms has 18 monitoring nodes. There is also a test network at Carnegie Mellon University used for monitoring experimental hydroponic systems and for climatic data acquisition. Photos from some of these sites are shown in Fig. 5.

5. **Field Support:** Significant engineering effort was spent in year two on field support of research sites. In addition to providing project scientists with the data they need, these activities provide a setting in which we can stress test more well-developed mature technologies and also try out new experimental ideas. Many field sites are in remote locations with unreliable internet connections making data access both slow and unreliable. To alleviate this problem, data can be mirrored onto a remote server that has a faster and more reliable connection.

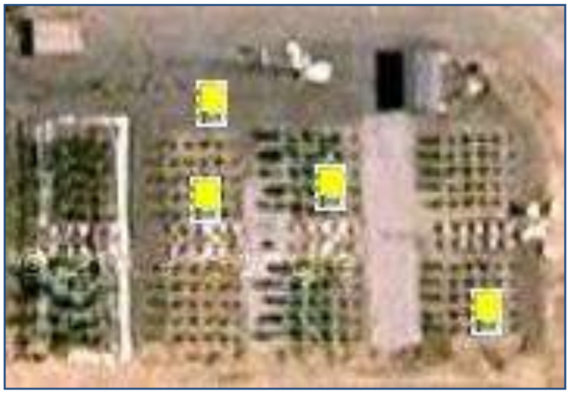


Fig. 5. Photos from some of the test sites used in Year 2. Previous Page: (at left) a CMU node deployed at the Bauer's Greenhouse site. At Right: Decagon sensing nodes deployed at the Willoway site.
This page at Left: The new Decagon sensing and control nodes (nR5) being used to control irrigation in a small testbed at CMU's Robot City site. At Right: An aerial image depicting of the deployment of Decagon nR5s at the Willoway nursery site.

We currently mirror data to the remote server every six hours. While this update time is adjustable we chose six hours since it is a good balance between the researchers accessing current data and not placing a large load on the low bandwidth site connections. The total bandwidth used between the field and the remote server is minimized by only transferring items that change in the database.

6. New Electrical Conductivity (EC) Sensor: Current soil moisture/EC/temperature sensors used in our tests are difficult to install in soilless media and lack adequate contact for accurate EC measurements.

Although not specifically a deliverable for this SCRI project, this new EC sensor (Fig. 6) was designed for more precise measurement of EC in porous soilless substrates. Stainless steel needles, instead of fiberglass prongs, allow the sensor to slide easily into soil and soilless media without compaction. They also provide a large surface area over which to make the EC measurement, instead of the two small stainless steel screw heads on the previous 5-TE sensor

A number of ongoing evaluations show a substantial improvement in precision over previous versions of this sensor.

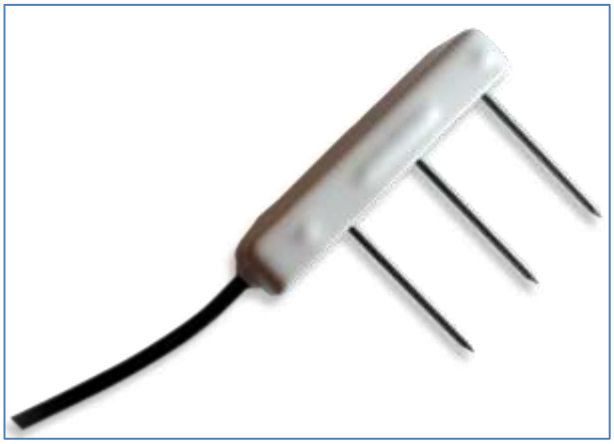


Fig. 6. The new GS3 Electrical conductivity (EC), soil moisture and soil temperature sensor

Model Development and Software Integration

The models developed by the Antir Software and various scientists are the key to minimizing water usage and having an optimal irrigation strategy. Carnegie Mellon is integrating these models into the sensorweb software, to provide a seamless tool for the end-user. At present, the Petunia model (University of Georgia), outlined in the year one report is fully implemented and the MAESTRA Red Maple model (Colorado State University) is 90% implemented. These models are currently being integrated into the sensorweb software, so that the models can be tested and validated with research blocks in Athens, GA and Willoway Nursery in Ohio. This means that we will use real-time estimates of plant water use, as well as soil moisture sensors for irrigation control. This integration has already started, but will be more fully implemented in year three.

1. UGA Petunia Model: In collaboration with Richard Bauer and David Kohanbash, the University of Georgia group has incorporated the first, simple version of the petunia model into the SensorWeb software. This model predicts petunia water use based on a plant's age and DLI. The next step is to test how well this software predicts actual plant water use and if the nR5 nodes are capable of successfully and efficiently irrigating plants based on this model approach. We have concluded in several studies, and with a variety of species, that plant age and light levels (DLI) are vitally important for determining plant water use (generally with a significant interaction between the two as well). We believe this indicates that water use is primarily driven by light and the water use of a particular plant depends on how much light that plant intercepts. Thus, as plant age increases (and plants get larger), the plant(s) will intercept more light and require more water. Likewise, plants will intercept more light on days with high light (DLI), increasing water use. The interaction between plant age and DLI indicates that DLI is more important as plants get larger (because there is more leaf area to intercept the incoming light).

Based on these findings, we want to test if we can determine plant water use directly from the amount of light intercepted by the plants. Light interception can be determined from two factors: the incoming light (DLI) and the fraction of light intercepted by the plants (as measured using a ceptometer). Ceptometer data only needs to be collected occasionally, and the fraction of the incoming light intercepted by the plants can then be determined using interpolation. We have collected a preliminary data set on impatiens to test this approach, but those data have not yet been analyzed.

2. CSU MAESTRA Model: Working with CMU, we have integrated and run the MAESTRA model with the sensorweb graphic user interface. We manually scheduled multiple daily irrigations at the Willoway nursery research site in Ohio from Colorado State University via the internet, in year 2. Although we expected to have a "live MAESTRA model" schedule the irrigation by the end of year 2, it seems like progress is on track to use live data in the model and automatically schedule irrigations using the model output in year 3.

Further research and development in support of the implementation of the MAESTRA mode (with ten different tree species) is described below under the Colorado State University and Willoway Nursery reports.

3. UMD Green Roof Stormwater Model:

A green roof stormwater model (University of Maryland) has been parametized and the model is currently being encoded. We expect to start validating the first version of this model with research datasets from the green roof research site at the University of Maryland in year 3.

Replicated soil moisture and stormwater runoff data from the green roof research site is already supporting off-line validation and testing of this model. Soil-moisture sensor measurements and runoff measurements are compared with estimates of soil moisture and stormwater runoff using the FAO Penman-Monteith model (Fig. 7).

A number of plant and substrate components (e.g. plant coverage, root density, organic matter content) are concurrently being integrated as part of the overall model development. See the University of Maryland research report (below) for further detail.

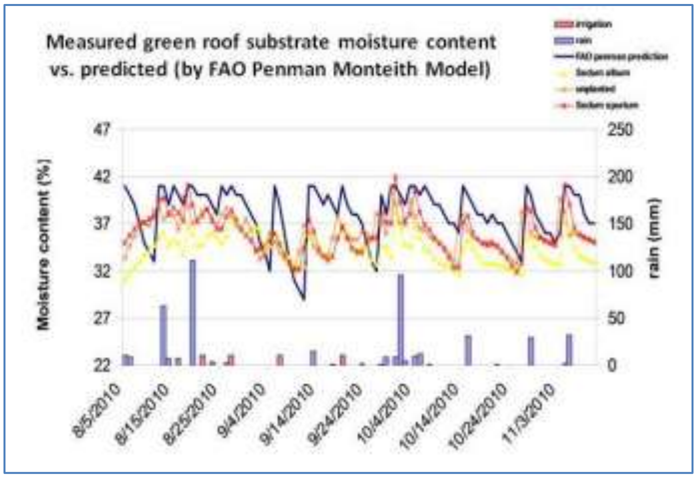


Fig. 7. Measured vs. predicted green roof soil moisture and runoff from green roof experimental platforms.

4. UMD Snapdragon Model:

Additionally, work started in year 2 on parametizing the Snapdragon model, based on measuring plant canopy light interception vapor pressure deficit over the development of the crop (Fig. 8).

This work is described in more detail in the University of Maryland research report and in the Bauers greenhouse report (below).

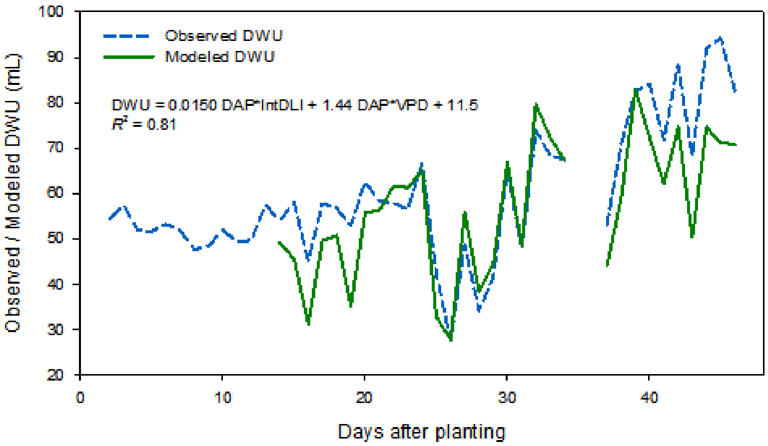


Fig 8. Predicted vs. measured daily water use of snapdragon, using daily light integral (DLI), vapor pressure deficit (VPD) with days after planting (DAP).

University Research and Development

A. University of Maryland

1. Green Roof Research

Small but significant ($P<0.01$) and potentially meaningful differences in stormwater runoff have been observed in planted platforms compared to non-planted ones and these differences are species dependent. For a 0.3 inch storm on October 1, platforms planted in *Sedum kamptschaticum* stored on average 2.84L more runoff than the unplanted ones, achieving a 33% reduction in total runoff (Fig 9). If these results could be scaled up linearly to a 1000 ft^2 roof, the effect of the plant treatment could be as great as 176L (44gallons).

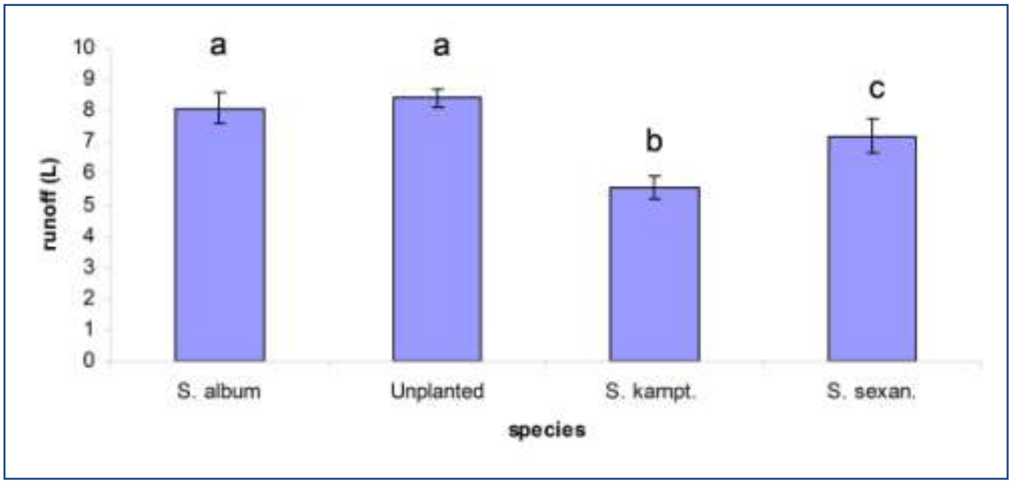


Fig. 9: Runoff from Oct. 1, 2011 and light 0.3" storm

Though the previous graph is fairly typical of what we have seen most of the year, these findings have not been consistent for all storms. For hurricane Irene, we saw no treatment effect (fig 10). Obviously greenroof plants are not as effective for retaining water from storms of this size or intensity, compared with smaller storms. Future analysis will investigate the effects of storm size and intensity on stormwater retention by greenroofs for different seasons.

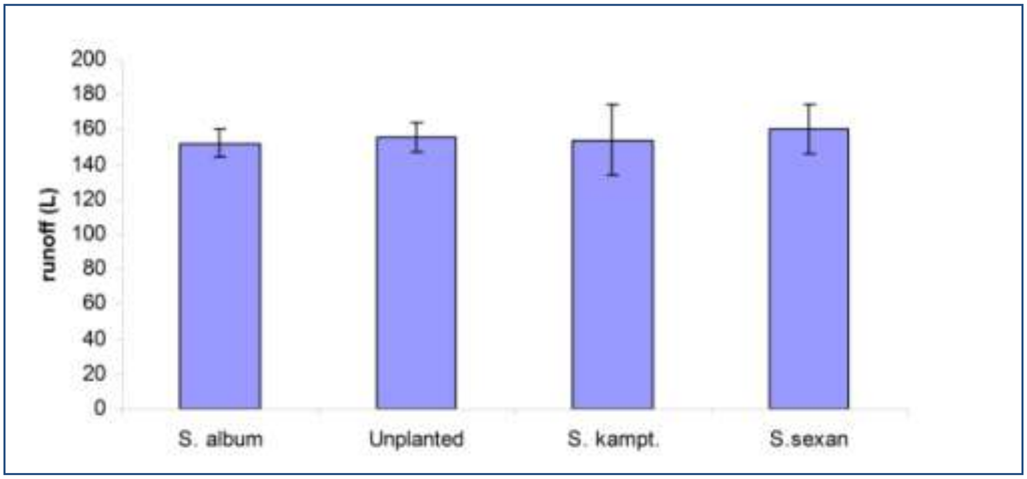


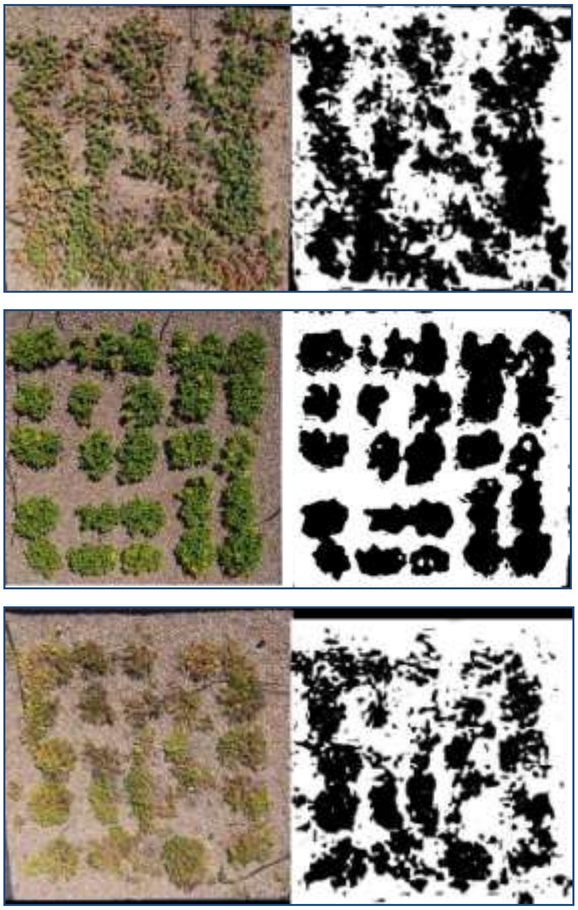
Fig. 10: Runoff from 27th August, 2011 after hurricane Irene (6" event).

We are collecting data about plant aboveground coverage. These images are representative of each of our study species at the end of Aug 2011.

Figs. 11a, b and c (at right) show how we estimated 50, 53, and 38% coverage using digital analysis, for replicate platforms planted with *S. album*, *S. kamptschaticum*, and *S. sexangulare* respectively.

This analysis is being done at three times a year, together with root density sampling and dry weight analysis (Fig 12). In order to more clearly interpret our stormwater retention results, we are collecting additional information about root dry weight from the platforms.

Though having more root biomass would help the greenroof capture more stormwater, having less root biomass might allow the roof to dry down more quickly in between storms, providing enhanced potential for stormwater storage through different means.



Figs. 11 a, b and c. Plant coverage in late May, 2011 for *S. album*, *S. kamptschaticum*, and *S. sexangulare* respectively.

During spring 2011, *S. kamptschaticum* had less root biomass than *S. sexangulare* ($p<0.05$), but this difference was not significant by August when no significant difference between species was observed.

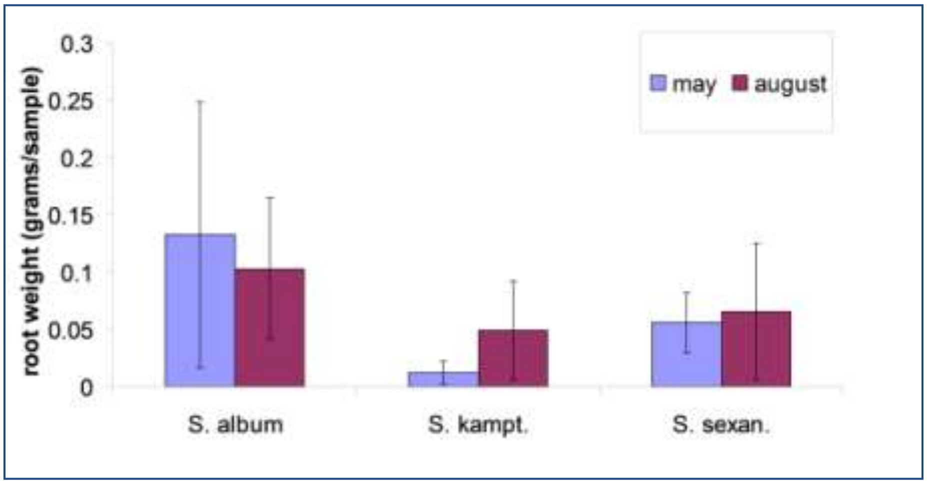


Fig. 12. Average root dry weights sampled May 20, 2011

We are constantly trying to improve our methods for data collection. New large volume rain gauges were installed in early 2011, the data from which is logged by a multiplexed Campbell CR10X. We installed splashguards to prevent water loss from our experimental set-up, where the smaller ECRN-50 rain gauges are nested in the larger rain gauges (Fig 13). The regression below reveals that the old and new gauges are reporting similar results for small storms.

Fig. 13. Nested rain gauges measuring runoff from each green roof platform

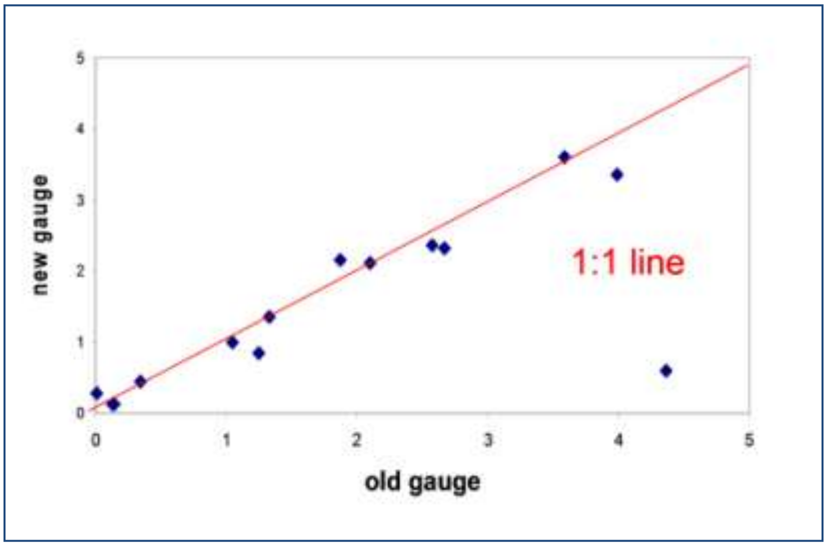


Fig 14. Regression of stormwater runoff predictions from the older ECRN-50 (small capacity rain gauges vs. the new large capacity rain gauges.

Results of our study on how to predict greenroof media content using the Penman Monteith equation and a very basic model of the greenroof water cycle were presented at the ASABE Annual Meetings (Fig 15; [Starry et al., 2011](#)).

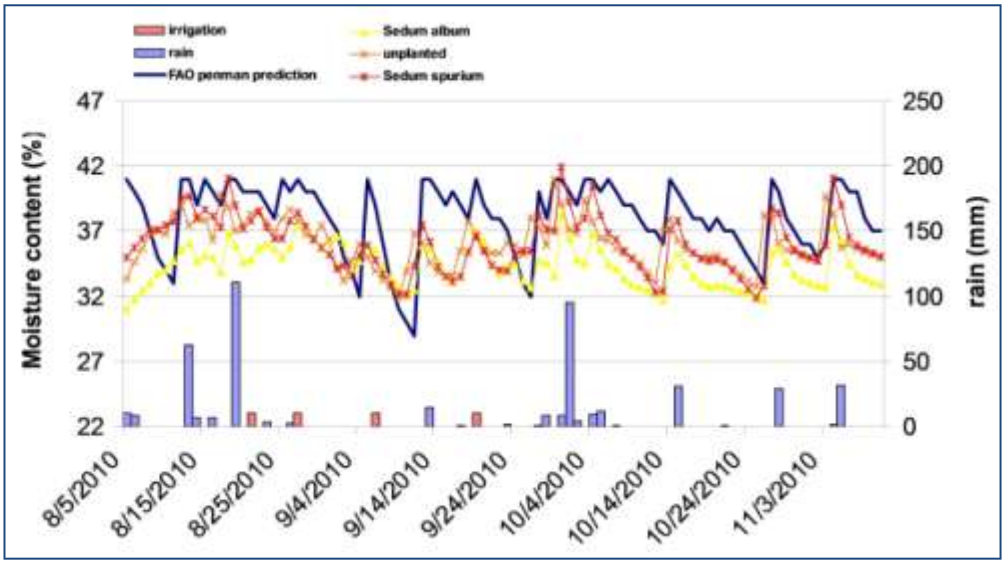


Fig. 15. Predicted vs. actual Echo-TM soil moisture data, with rainfall and irrigation events (From Starry et al., 2011)

2. Snapdragon Research

The snapdragon research site described in the 2010 report was disassembled and moved to the Bauers greenhouse in Jarrettsville, MD, as it was determined that the temperature and incident radiation conditions in the UMD research glasshouse were radically different from most commercial environments. Since temperature and light are tightly integrated with plant water use and the model development, we chose to take advantage of this opportunity to work directly with Charles Bauer. This research and model development is described below in the on-farm sensor network section.

B. University of Georgia

1. Petunia – Substrate Moisture and Fertilization Interactions

We conducted a study in fall 2010 to look specifically at fertilizer and substrate water content interactions on petunia growth and quality.

The objective of this study was to quantify the optimal fertilizer rates for petunia, when the plants are grown at different substrate volumetric water contents.

Petunia plants (*Petunia × hybrid* 'Dreams White') were grown at four substrate water contents (0.1, 0.2, 0.3, and 0.4 $m^3 \cdot m^{-3}$) and with 8 fertilizer rates (0 - 2.5 g/plant; Osmocote 14-14-14). Plant growth increased with increasing substrate water content (Figs. 16 and 17).

Plant growth also increased as fertilizer rate increased from 0 to about 1.5 g/plant, with little effect of higher fertilizer rates. However, higher fertilizer rates reduced flowering and resulted in excessive vegetative growth (Fig. 16).

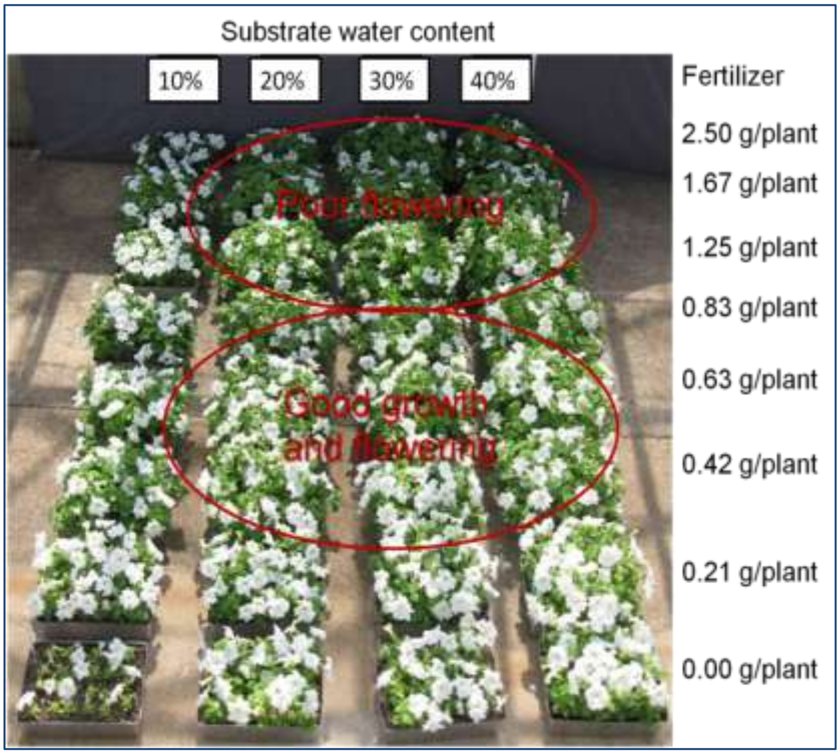


Fig. 16. Visual appearance of petunias grown with different amounts of fertilizer and different substrate water content

Conclusions: The amount of water needed to grow high quality plants was surprisingly low. With no leaching, approximately 0.4 liters of water per plant was needed to grow petunias from plug seedling to full bloom in 23 days at a VWC of 0.4 $m^3 \cdot m^{-3}$. Growers should be able to reduce fertilizer rates with efficient irrigation methods that minimize leaching.

A large percentage of fertilizer applied to plants can be lost through leaching if irrigation is excessive. Soil moisture sensor-controlled irrigation can significantly reduce or even eliminate leaching. If leaching is reduced, growers might be able to use lower fertilizer rates to grow their crops, which can result in significant financial savings.

With no leaching, we grew high quality petunias with only 0.6 to 0.8 g of fertilizer per plant (5 - 7 lbs/yd^3 of substrate). Although the fertilizer label does not specify rates for bedding plants, the recommendation for nursery stock is 12 lbs/yd^3, twice the amount that resulted in optimal quality.

Substrate water content and fertilizer rate also affected leaf size; the size of leaves doubled as the VWC set point increased from 0.10 to 0.40 m^3·m^{-3} and increased by 16 – 34% as the fertilizer rate increased from 0 to 2.5 g/plant (Fig. 17).

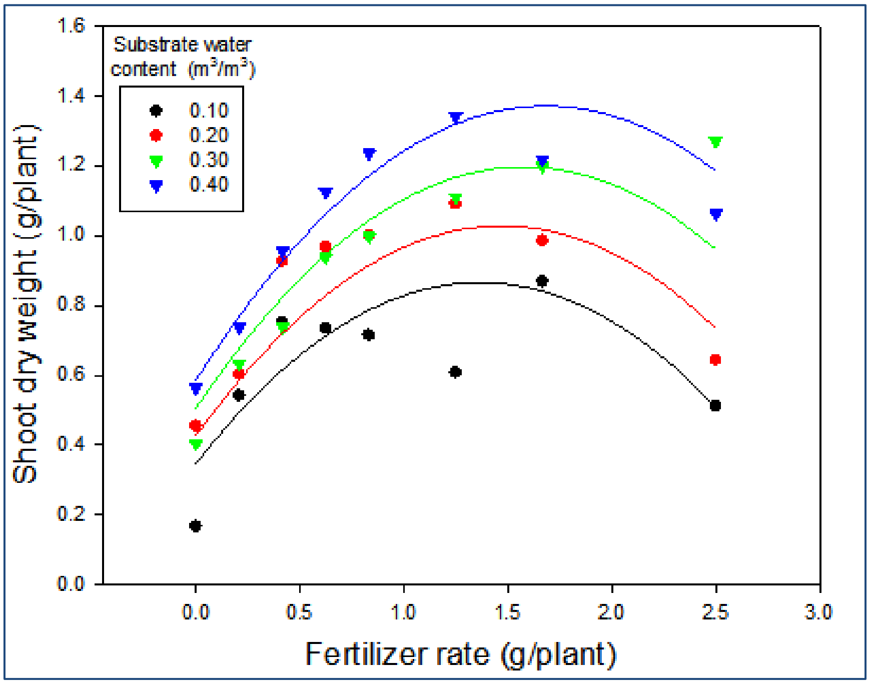


Fig. 17. The effect of fertilizer rate and substrate water content on shoot dry weight of petunia.

2. Poinsettia – Controlled Drought and Height Control

We decided to use poinsettia as a model crop for height control using controlled drought, since poinsettia height control is crucial for plant quality and shipping, but can be difficult to achieve. There are also objective standards for poinsettia height and established methods for tracking height over the course of a production cycle. This allows for objective decisions on the need for height control.

A drawback of using poinsettia is that it can only be grown in fall, and we have just initiated the first study specifically aimed at height control (Fig. 18). In this study, we are comparing controlled drought stress (reducing substrate water content to 0.20 m^3·m^{-3} as needed) with spray and drench applications of plant growth retardants.

Fig. 18. An overview of the poinsettia height control study using regulated drought stress.

3. Subirrigation Control: A case study with Hibiscus acetosella

Subirrigation can be used to reduce water loss and nutrient leaching in nurseries and greenhouses, because it is a closed system in which the nutrient solution is recirculated (Fig 19). However, the irrigation normally is controlled by timers, without monitoring and controlling substrate moisture content. Thus, irrigation is not based on the actual plant water requirements or the substrate water content required for optimal plant growth.

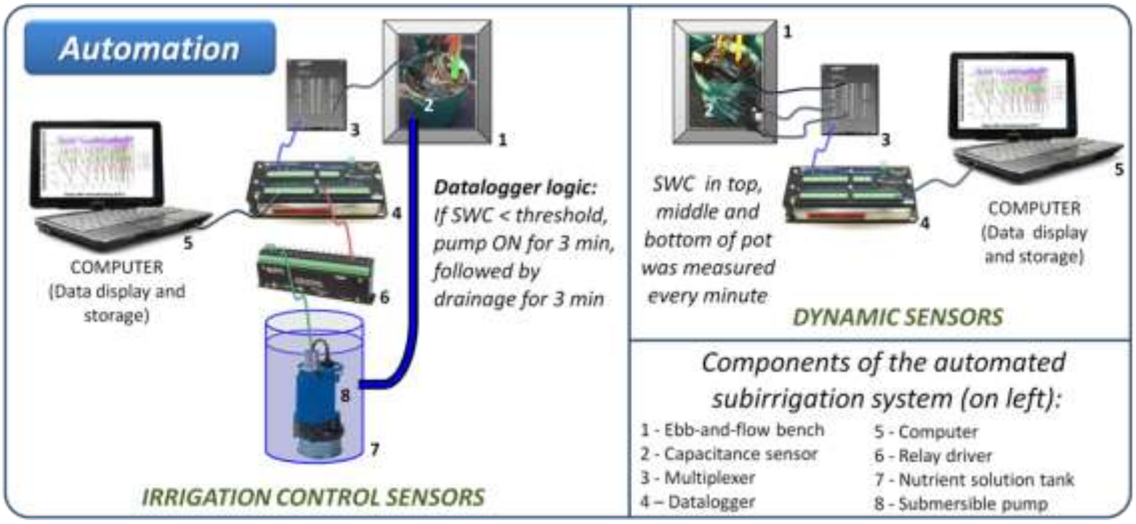


Fig. 19. An overview of the experimental setup to control subirrigation using soil moisture sensors, by applying water as needed and optimizing plant production for subirrigation systems .

A second set of sensors was used to look at dynamic changes in substrate water content, monitoring substrate water content to control irrigation (Fig. 20).

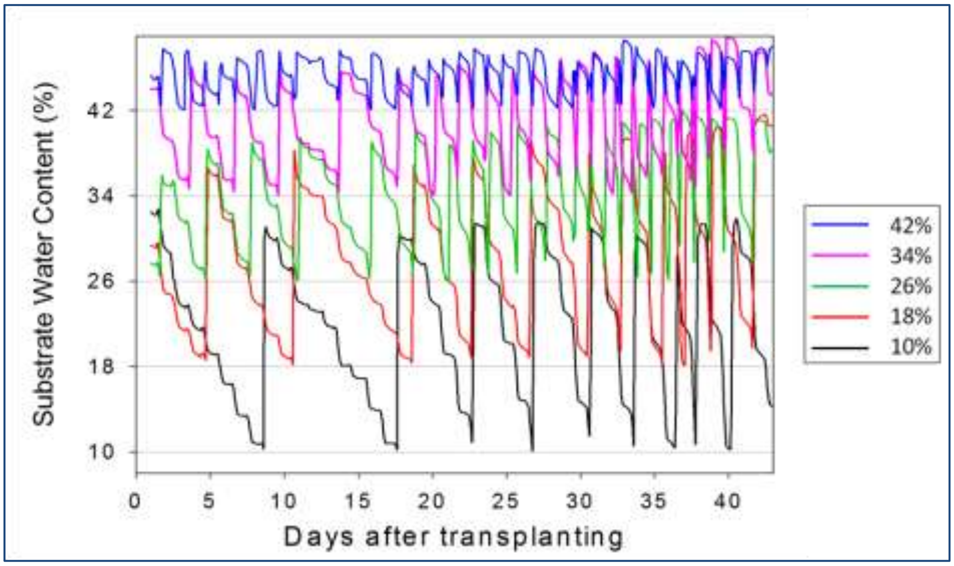


Fig. 20. Substrate water content of subirrigated hibiscus during a 45 day study. Plants were subirrigated when substrate water content dropped below a particular threshold (dashed vertical lines).

Our results show that sensor-controlled subirrigation is indeed feasible. We subirrigated *Hibiscus acetosella* 'Panama Red' (pp #20,121) when the substrate water content dropped below 0.10, 0.18, 0.26, 0.34 or 0.42 $m^3 \cdot m^{-3}$. Plants that were irrigated when the substrate water content dropped below 0.42 $m^3 \cdot m^{-3}$ were watered often, sometimes, multiple times per day (Fig. 20).

Irrigation only increased substrate water content of these plants slightly, to about 0.46 $m^3 \cdot m^{-3}$. If the substrate was allowed to dry out to a substrate water content of 0.10 $m^3 \cdot m^{-3}$, irrigation increased substrate water content by about 0.20 $m^3 \cdot m^{-3}$ to about 0.30 $m^3 \cdot m^{-3}$.

If the substrate was allowed to dry out more before irrigation, the substrate water content immediately after irrigation was lower than that of plants that got irrigated at higher substrate water content, *i.e.* irrigation did not bring the substrate back to container capacity (Fig.20).

Lower thresholds for irrigation resulted in less frequent irrigation and reduced both plant height and shoot dry weight (Fig. 21). This indicates that soil moisture sensors cannot only be used to control irrigation, but to manipulate plant growth as well.

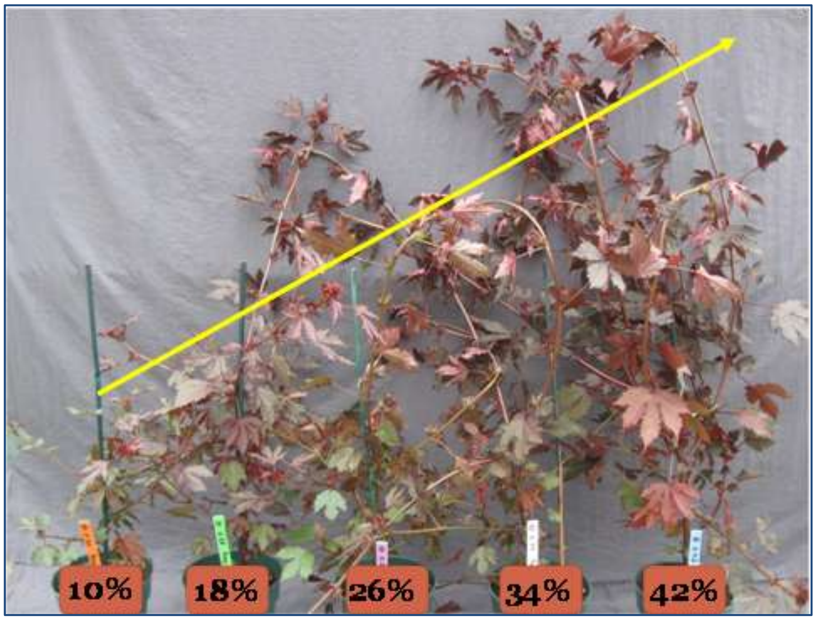


Fig. 21. The effect of different substrate water content threshold for irrigation on growth and appearance of hibiscus 'Panama Red'. Note the drastic increase in height of plants that were grown with higher substrate water content.

4. Nursery Research on *Hibiscus*

We conducted a study using *Hibiscus acetosella* 'Panama Red' grown at two different research station locations (Tifton and Watkinsville) during summer and fall 2010. This study looked at the effects of different substrate water contents on plant growth, morphology, and water use.

Plant dry weight, height, and water use increased with increasing substrate water content thresholds. Good quality plants were grown by maintaining the substrate water content at or above 0.35 $m^3 \cdot m^{-3}$ (Fig. 23). Growing plants at a substrate water content of 0.35 $m^3 \cdot m^{-3}$ reduced plant height and total water use as compared to a substrate water content of 0.45 $m^3 \cdot m^{-3}$ (Fig. 23).

Plants were watered with 60 mL of water when the substrate water content dropped below thresholds of 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, or 0.45 $m^3 \cdot m^{-3}$ (Fig. 22).

Due the frequent rain early on (see graph at right for data from Watkinsville), it took several weeks before the drier treatments reached the substrate water content threshold (Fig. 22).

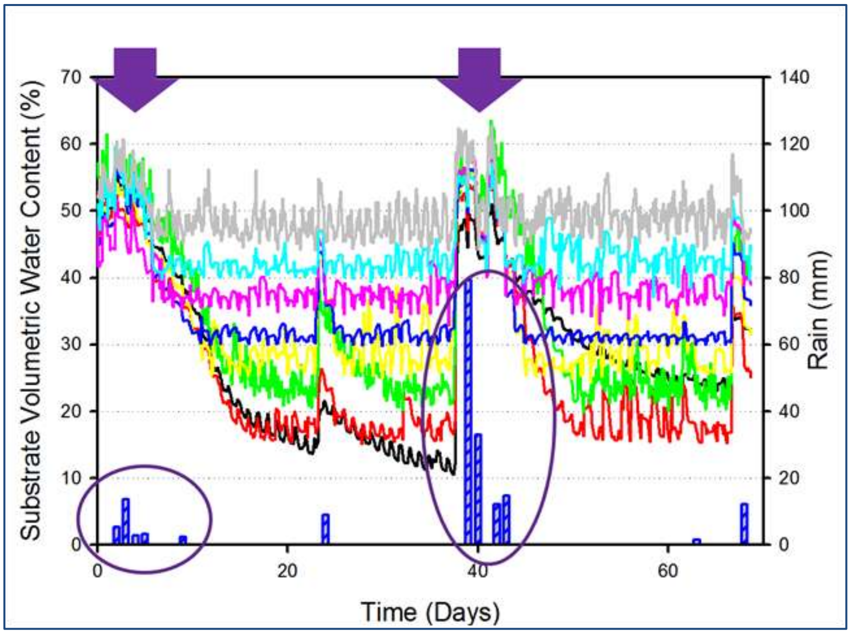


Fig. 22. Substrate water content of the course of the growing period in the Watkinsville study. Plants got irrigated when substrate water content dropped below a specific threshold (indicated by the dashed vertical lines).

We also noticed that compactness (calculated as shoot dry weight/plant height, a measure of 'density') decreased as the substrate water content threshold increased (Fig. 23).

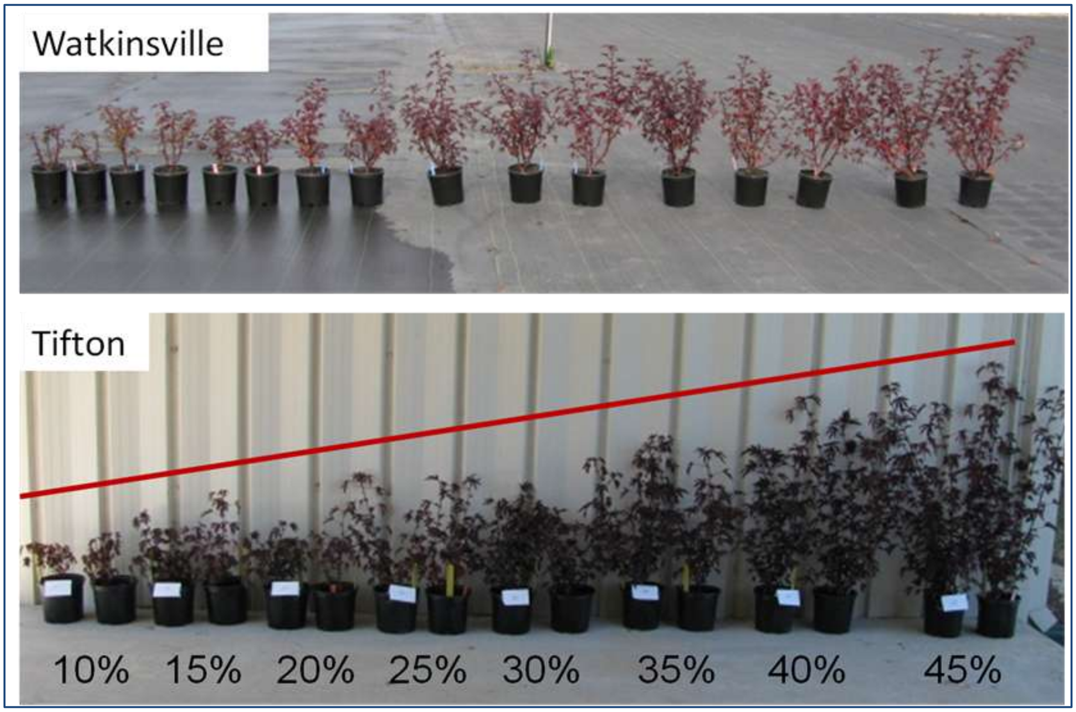


Fig. 23. Visual appearance of the plant grown at different substrate water contents in Tifton and Watkinsville. Note that plant height increases with increasing substrate water content threshold.

This suggests that keeping the substrate drier increases compactness and thus may help improve plant quality. The total amount of water required to maintain the substrate water content at or above 0.35 $m^3 \cdot m^{-3}$ was 15.4 L/plant in Watkinsville and 12.6 L/plant in Tifton. Water use was higher in Watkinsville, because these plants were grown for about 10 more days and grew better than those in Tifton. In addition, more rain and slightly cooler weather occurred in Watkinsville.

5. Nursery Research on *Gardenia*

We are currently conducting a similar study using two species of gardenia. Gardenia was selected for this study because of its diseases susceptibility and high subsequent mortality in commercial production environments. We were interested in understanding if improved irrigation control can reduce disease occurrence. To facilitate disease development, we inoculated a sub-set ofplants with *Phytophtora*, a common and often lethal pathogen. Unfortunately, we have not witnessed disease symptoms yet. We are also looking at physiological responses of the plants to substrate water content (leaf water relations and gas exchange) as well as quantifying the effects on substrate water content on flower drop and flowering.

6. Nursery Research on *Hydrangea*

In 2010, we conducted a study at the Center for Applied Nursery Research (located at McCorkle Nurseries, Inc. in Dearing, GA) to determine the impact of environmental factors on the daily water use of *Hydrangea macrophylla* ‘Pia’ and ‘Fasan’. Plants were automatically irrigated daily at 10 pm, weighed at midnight and weighed again at 10 pm the next evening (Figs. 24, 25), just before the following irrigation. The decrease in weight from midnight to 10 pm was used as a measure of plant water use during that day.

Fig. 24. An overview of the study to determine daily water use of hydrangeas. This picture was taken at the start of the study.

Fig.25. A close up of a pot mounted on a load cell. Load cells allowed us to weigh the plants automatically twice a day. Those weights were then used to calculate daily water use.

Differences between the two cultivars were small, and water use of both cultivars was greatly affected by plant size and environmental conditions (Fig. 26). Daily light integral (DLI) was by far the most important measured environmental factor. Although vapor pressure deficit (a measure related to relative humidity) and temperature had a statistically significant effect on daily water use, these effects were of little practical importance. Our results suggest that water use of the plants depends largely on two factors: plant size and light levels. We hope to be able to predict water use of hydrangea in the future simply based on the amount of canopy light interception.

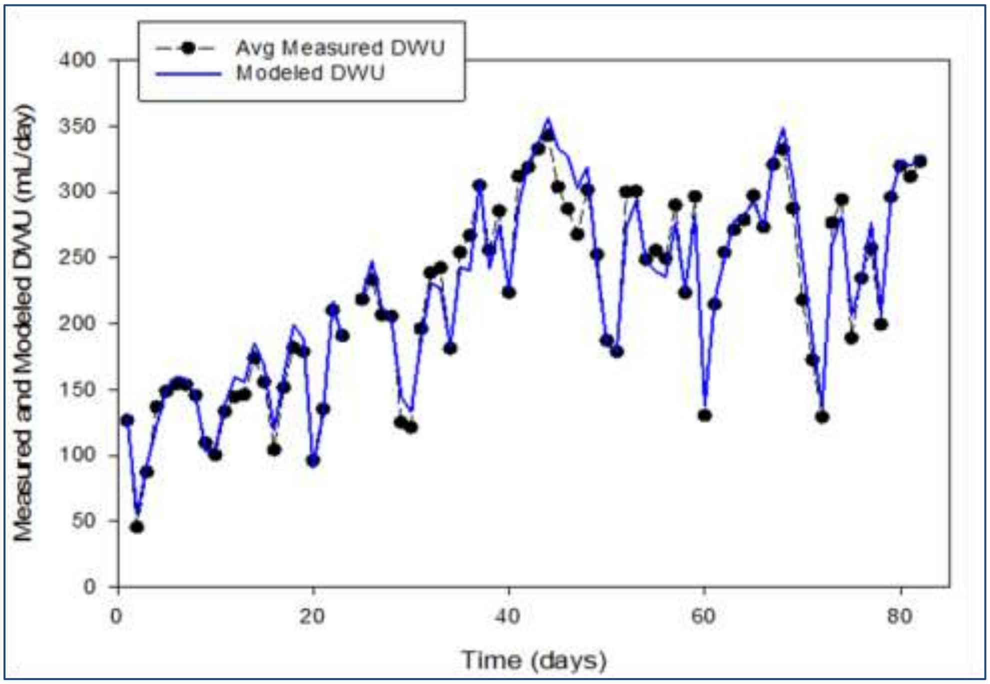


Fig. 26. Measured and modeled daily water use of hydrangea over an 80-day growing period. Water used was determined based on the decrease in pot weight during a day, while water use was modeled based on environmental conditions (light, temperature, vapor pressure deficit) and plant size.

We are continuously collecting environmental data at all of our research sites, which include the UGA research greenhouses, the UGA horticulture farms in Tifton and Watkinsville, and at our grower collaborators (Evergreen Nurseries and McCorkle Nurseries, Inc.). These environmental data can later be used to develop and test predictive plant water use models.

7. Comparative daily water use of hydrangea and gardenia

We are currently conducting a follow up to the 2010 study at the Center for Applied Nursery Research, comparing water use of two species: hydrangea and gardenia. Hydrangeas have not grown adequately due to extreme heat much of the summer and are therefore using much less water than the gardenias. Nonetheless, the two crops seem to have very similar responses to changes in weather conditions, with DLI once again appearing to be the most important factor. This study is ongoing and the data have not yet been analyzed.

8. People involved

In addition to four faculty members at UGA (Drs. Marc van Iersel, Matthew Chappell, John Ruter, and Paul Thomas), three technicians have assisted with this research (Sue Dove, Nancy Hand, and Bruce Tucker). There currently are three graduate students working on this project (Mandy Bayer, Alem Peter, and Lucas O'Meara).

C. Colorado State University

Much of the work described here is performed at various research installations at Willoway Nursery in Ohio. A summary of the research is presented here. A description of the research site was given in the first year report, available from the SCRI-MINDS website at http://www.smart-farms.net, under Impacts.

1. Substrate Moisture Research

We have analyzed the first year of substrate moisture data from the Willoway site. We examined spatial and temporal variation in volumetric water content (VWC, $m^3 \bullet m^{-3}$) among containers in ten commonly cultivated tree species over four months of the growing season.

Based on the observed spatial and temporal variation in substrate VWC, we recommend species specific soil moisture sensor deployment but the amount of sensors per species is variable and changes over time. This research has just been accepted for publication in HortScience.

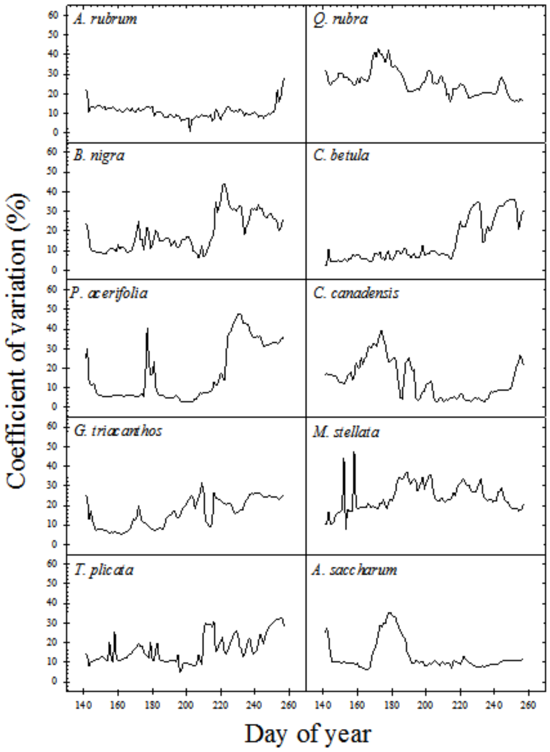


Fig. 27. Variation in substrate moisture content in 10 tree species during 2010.

To supplement the above work, we have collected a second year of data on a subset of these species in 2011, by adding 10HS sensors directly across from the Echo-5TM sensor, so that we can compare the two sensor outputs. The 10HS sensor has a much larger volume of soil measurement compared to the Echo-5TM.

We also placed 12 sensors per container in five species to characterize the water flow patterns within the container.

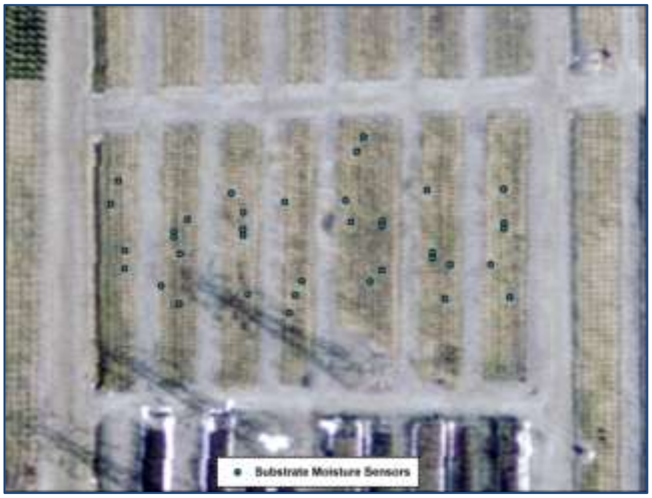


Fig 28. Position of trees with sensors at Willoway research site in Avon, OH.

2. Windspeed Extinction

We examined the canopy wind speed extinction coefficient (α) along a canopy depth profile in the ten Willoway tree species from year 1. By investigating the average α value over periods ranging from a single day to an entire growing season, we found a marked change in canopy α's as a result of leaf area development and canopy structure dynamics.

We used this variation in canopy α estimates, from different time scales and filtering methods, to parameterize a three dimensional mechanistic canopy transpiration model (MAESTRA) and assess the impact of different α values on canopy transpiration estimates.

Modeled estimates of canopy transpiration varied by as much as 30% over the measured error range (mean ± standard deviation), underscoring the importance of carefully characterizing the canopy wind speed extinction profile when above canopy wind speeds are greater than 1 m s^{-1} (Fig. 29).

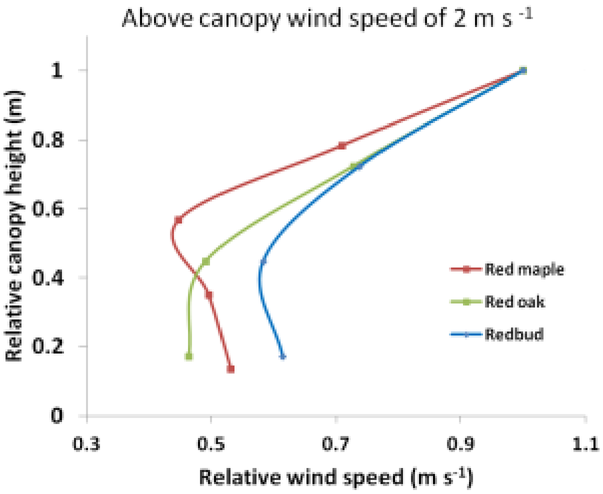


Fig 29. Wind speed attenuation for three tree species with height, at a wind speed of 2m s^{-1}.

We have supplemented the first year's data set with a second year using a wind tower outfitted with twice as many anemometers as the first year. We are in the process of incorporating the new data into a manuscript to communicate the findings of wind profile influences on canopy transpiration.

3. Transpiration Parameter Analysis – MAESTRA Model Sensitivity

Based on a completed leaf level *in silico* sensitivity analysis over a range of genotype parameters and under different climate forcing conditions (e.g. wind, light, humidity, and air temperature), we have focused on fine tuning the seven parameters that analysis identified as important for accurate transpiration predictions, and example of which is shown in Fig 30.

The manuscript based on this analysis is published in the August 2011 edition of the Journal of Experimental Botany.

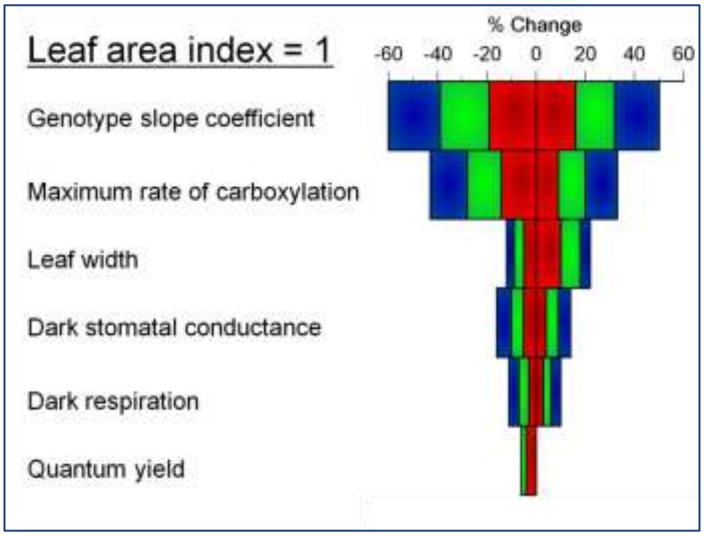


Fig 30. Tornado sensitivity analysis for various MAESTRA model water use parameters at a LAI = 1.

After parameterizing MAESTRA using first year data from Willoway, we have started an analysis on interaction effects between environmental variables and their effect on transpiration. This analysis could have important implications for irrigation scheduling based on live, or forecast environmental data.

From the physiology and morphology data collected across the season in year 1, we derived a complete set of physiological and morphological parameters for all ten species i.e. we parameterized the MAESTRA model with the species specific values.

Fig. 31. SCRI-MINDS Research Site at Willoway Nursery in Avon, OH

In 2011, we set up a validation experiment, to look at real-time water use and leaching. The research site (Figs. 32 and 33) deploys tipping bucket rain gauges to measure leachate from five containers simultaneously via a pot-in-pot system plumbed to a french drain that funnels the leachate to the tipping bucket. In addition, the pressure compensated irrigation system allows us to accurately measure the amount of water applied.

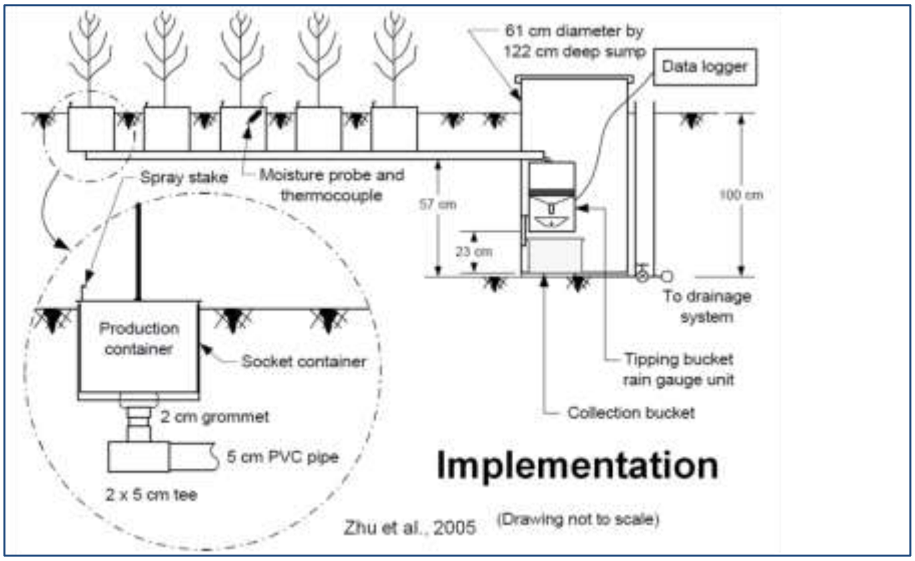


Fig. 32. Graphic of the USDA experimental research site at Willoway, to enable direct validation of MAESTRA water use predictions by measuring irrigation water applications and leaching.

This experimental set-up is on loan to us from the USDA and allows us to accurately validate and calibrate the model per species and in addition, allow for comparisons among irrigation application scenario's and make adjustments in real time.

4. Water Movement in Containers – HYDRUS Model

Simulations of soil moisture spatial patterns are being developed using the HYDRUS variably saturated subsurface flow model applied to the containers described in the last section (Figs. 32 and 33).

Simulations of soil moisture with this model require accurate data for input and output of water. Therefore, we have processed data from the measurement site to test for accuracy of each component of the water budget. For those sites and time periods with good water budget data, we are developing simulations that show how soil moisture in the pots responds to irrigation and transpiration.

Fig. 33. Picture of the USDA experimental research site at Willoway Nursery with trees installed.

These simulations will be used to (1) evaluate which measurement locations in the plot give the most representative value of soil moisture, and (2) explore how MAESTRA simulations of transpiration compare with transpiration values required for water balance in the study pots.

5. Root Distribution Effects

We are currently beginning the analysis phase of the second year's data set so that we can plan our research for the third season. For example, from the additional soil moisture data collected in year two, we are now trying to figure out how to join the root distribution and density change measurement at the microscale with soil moisture changes, how to parameterize the hydrology model correctly, how to run the model in the CMU sensorweb software.

D. Cornell University

1. Understanding Root Development Patterns:

The geometry and topology of plant root systems tells us a lot about their function. The standard technique to examine roots is to destructively harvest and scan them. Recent work with CT scans has been able to image roots whole and nondestructively in artificial mediums. This work uses CT scans of trees growing in a potting soil to examine the root structure and growth patterns in a more natural system. Two major hurdles are segmentation of root from soil and measurement of root geometry from the segmented image.

Cornell University's year two objectives were to build on our investigation of ten containerized ornamental tree and shrub species for root development patterns in standardized soil media. Completion of our non-destructive computerized tomography technique to monitor temporal tree root systems including horizontal and vertical roots leads us to our current task, reconstruct a 3D model of root system development over time. We have been working with several software packages that have primarily been designed for medical purposes as a means to decipher root placement through space and time in a standardized soil media common to nursery growers.

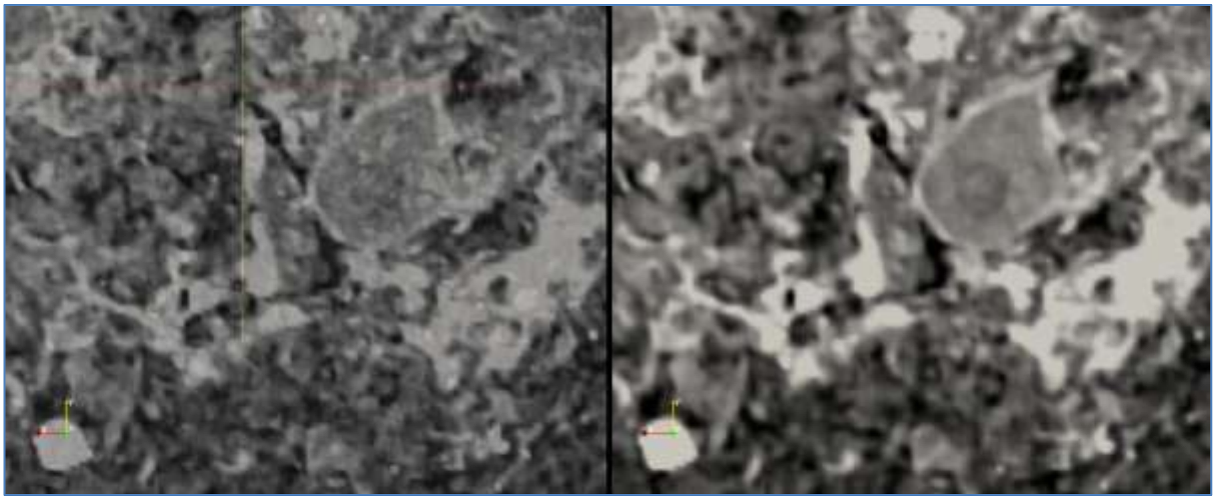


Fig. 34. Close up of slice from x-ray computed tomography scan. Original on the left and a liberal use of anisotropic smoothing filter on the right.

We have been firstly working on segmenting the model in order to measure root parameters. Simply speaking, there are two kinds of roots, coarse and fine. Coarse roots, as shown in the egg-yolk-like structure above (Fig. 34), have an inner core (the dark circle of less density) of dead cells used to transport water and nutrients.

Woody roots are more uniform in density then fine roots due to their woody composition. Fine roots, while individually small, can comprise a large percentage of total root mass. Given the 0.5 mm resolution of these scans, it could be possible to find fine roots as small as 1 mm. Tracking coarse roots does not seem as problematic as fine root tracking largely because of the density issue. The goal of this project however, is to incorporate coarse and fine roots into a single model, i.e., track the path from coarse root into fine root and to understand soil exploration by a tree root system.

There are a total of about 100 GB of data files from five time points for each of 10 tree species. So far, we have translated the DICOM to VTK format and processed the images with two types of edge-preserving diffusion filter and several simple segmentation algorithms available in ITK. We can find connected structures, but they include a lot of cruft, as shown in Fig. 35. We have not tried level set segmentation.

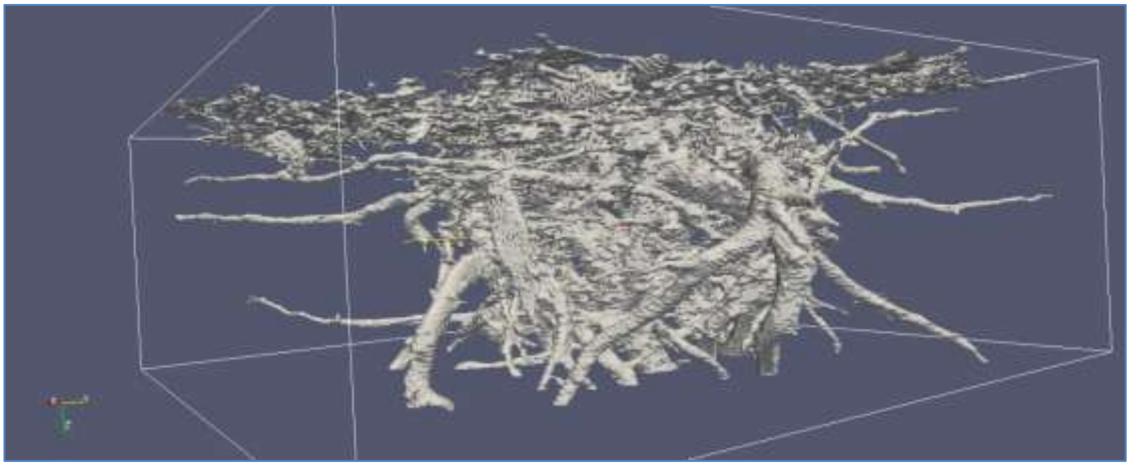


Fig. 35. Example of root system skeletonization using edge preserving diffusion filters and segmentation algorithms

The end goal is to obtain detailed measures of root growth, from simple convex hull bounds to fractal dimension. Almost all of these measures need a skeletonization of the root system. Many will work with an incomplete skeleton, which means we can get some, not all, of the scientific results if the segmentation algorithm yields a topologically disconnected structure.

Taryn Bauerle has set up a new collaboration with Dr. Anthony Reeves in the Department of Electrical and Computer Engineering at Cornell University. Dr. Reeves specializes in methods for analyzing digital images and digital image measurements. Together with Dr. Reeves lab group the Bauerle lab is in the process of “truthing” digital CT images using harvested tree root systems (Fig. 36).

Artificial scaffolding has allowed us to maintain root positions when the soil medium is removed. Rescanning of the final root system allows for a much finer scan resolution “in air” as opposed to “in medium”. Using analysis programs intended for use in medical radiology we are able to superimpose the “in air” scan over the “in medium” scan to help define training and test sets of images for preliminary studies.

Fig. 36. Example of a tree root system that had been CT scanned over a growing season. Soil was removed using an air spading technique. The roots were held in original locations using artificial scaffolding.

2. Root Spatial Distribution and HYDRUS model integration:

We have collaborated with Dr. William Bauerle at Colorado State to harvest a subset of seven tree species. Tree root systems were divided into three soil layers (Fig. 37a), made up of nine quadrates (Fig. 37b).

(a)

(b)

Fig. 37. Representation of 3 soil layer sampling scheme (a) and 9 quadrate division of each soil layer (b).

The Bauerle lab has also been working towards integrating the root systems' response to soil moisture and spatial distribution in containerized systems at different growth stages with hydrologic models to provide us with direct tools to model plant water use. Model parameters such as percentage of root biomass per container "layer", number of fine root tips, and the ability of the root system to transport water may vastly adjust how we currently model plant water use. The application of irrigation water can then be optimized depending on the growth stage of the tree, to conserve water and maximize yield.

On-Farm Research

A. Maryland

1. Bauers Greenhouse – Jarrettsville, MD

Bauers brothers established the Flowers by Bauers company in Jarrettsville, MD in 1975, and rapidly gained an reputation for producing high quality cut-flower snapdragons (*Antirrhinum* spp.) in the NE United States. They have remained competitive against South American cut-flower imports because of their attention to detail, and an in-depth knowledge of the physiological requirements to produce snapdragons in a greenhouse environment. This, combined with their knowledge of the retail industry has made them a leader in the cut-flower industry.

Objectives of Research
The objectives of the research at Bauer's greenhouse is to quantify and model the water use of snapdragons and monitor and control irrigation scheduling based on real-time environmental and substrate moisture sensor data. The greenhouse is a closed hydroponic system, so they have the ability to fertigate as frequently as necessary, without compromising efficiency. The ultimate goal of the project is to optimize plant growth, reduce plant stress and increase the percentage of #1 (highest quality) cut-flower snapdragon.

Bauers Sensor Network Description: The Bauer's greenhouse network consists of seven nodes of Carnegie Mellon wireless sensor network (CMU), seven Decagon EM50R nodes, and eight Decagon NR5 nodes. Bauers have used CMU nodes with Decagon EC-5 sensors for monitoring water status of the perlite bags since 2009, and they developed their own "GOOD RANGE" of sensor reading from their empirical practices. These values are very informative to Mr. Bauer for daily irrigation scheduling decisions, but translating these values into VWC content data would be more useful for a general audience. His "good" range of substrate water contents is from 0.25-0.27 $m^3 \cdot m^{-3}$.

The SNAP1-6 experimental site (Fig. 38, top left) is used for the experiment estimating daily water use of snapdragon (see below)

Six Em50R nodes were installed for daily water use experiment, and one EM50R is used for a weather station with light and temperature/relative humidity sensors. At the same time, this node measures electrical conductivity of nutrition tank (in/out) with Decagon GS3 sensors.

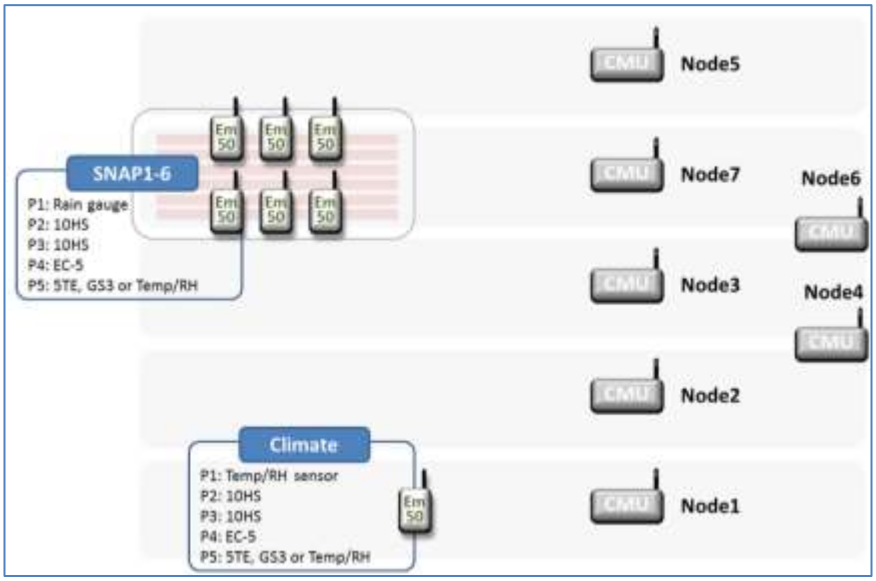


Fig. 38. A graphic of the wireless sensor network at Bauers greenhouse.

All CMU, Em50R, and NR5 nodes transmit data to the CMU basestation in the Bauer's greenhouse office. This data is transmitted to the CMU-GUI server and is available through the "Bauer's Sensor Network" website on sensorweb at http://sensorweb.frc.ri.cmu.edu:3101.

Daily Water Use Experiment Description: We monitored the daily water use of summer snapdragon 'Opus Fresh White' from July to August 2011. Six Decagon dataloggers (Em50R) have been installed to monitor substrate water contents and quantify daily water use (per bag) in a replicated study (Fig. 39. below). To investigate the effect of environmental factors on daily water use, we measured temperature, relative humidity, light intensity, and light intercepted by the plant canopy.

The objective of this extremely dense network is to monitor and model daily water use for snapdragon within the production environment (Fig. 39, at right)

We are using twelve load cells, eighteen soil moisture sensors, one flow meter, six rain gauges, two temperature/relative humidity sensors, four PAR sensors, and twelve custum line quantum sensors to monitor the daily evapotranspiration and environmental factors for six replicate perlite bags, with 64 plants per bag. The daily water balance from irrigation and leaching is measured using a flow meter and ECRN-50 rain gauges.

Fig. 39. Overview of the Snapdragon (Node 1-6) setup.

At the same time, we installed 12 load cells (ESP-35; Transducer Techniques, Temecula, CA), which were connected to a datalogger (CR10X; Campbell Scientific, Logan, UT).

Each bag was placed on two load cells (Fig. 40); the Campbell datalogger measured the bag weight every 5 seconds, and recorded the average every 5 min. From these instantaneous changes in bag weight, we calculated daily water use (evapotranspiration) by the plants.

Fig. 40. Load cells supporting each replicate perlite bag.

A load-cell based evapotranspiration monitoring system worked better than the "flow meter-rain gauge" water balance monitoring method, mostly due to lack of precision in flow meter (± 1 gallon) and the occasional clogging of rain gauges (requiring maintenance).

To measure the light interception of the plants, light levels above and below the canopy were measured with PAR sensor (SQ-110; Apogee Instrument, Logan, UT) and custom line quantum sensors (SQ-319; Apogee Instrument), (Fig. 41).

Custom line quantum sensors were sets of two 50cm bars, which measure six light levels with 15 cm distance between PAR sensors. Three independent PAR sensors were placed at the canopy level of the plants, and the six line quantum sensor sets were placed with leveled frame at the surface level of the perlite bags.

Fig 41. Custom made line quantum sensor with level frame.

Preliminary Results: From the snapdragon daily water use study, we found that water use of snapdragon was affected by plant age and light environment (Fig. 42), similar to other greenhouse crops being modeled (e.g. petunia).

Plant age (days after planting) was the most highly correlated variable with DWU (*P* < 0.001, *R* = 0.63). Between the light environmental factors, intercepted DLI had significant correlation with daily evapotranspiration (*P* < 0.01), while DLI did not show any significant correlation.

Intercepted DLI became very close to DLI at canopy closure (with plant height).

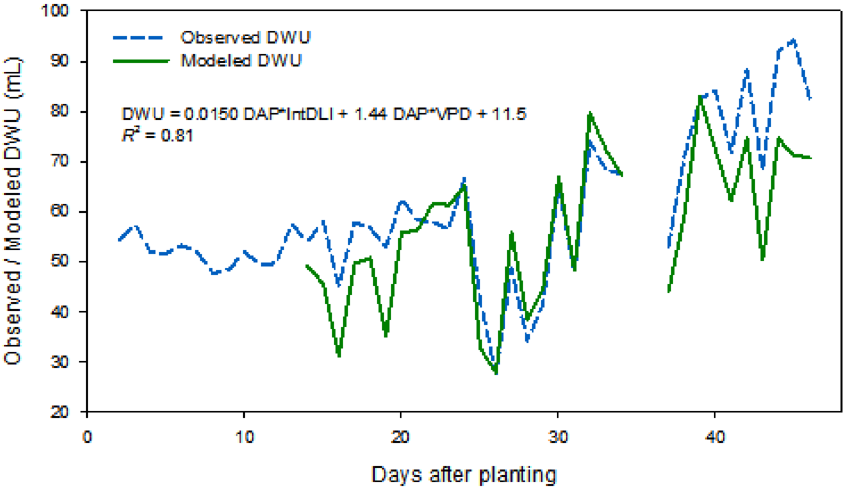


Fig. 42. Daily water use of snapdragon 'Opus Fresh White'. Fluctuation of daily water use follows daily light integral (DLI) fluctuation as well as intercepted DLI.

Monitoring and Control Network: During Fall, 2011, eight new NR5 nodes were installed in another dense network (not shown). This enlargement of the network has the primary objective to independently monitor and control irrigation events on two production beds within the greenhouse, being monitored and controlled using the sensorweb software (Fig. 43), using VWC and EC measurements from the EC-5 sensors in the bags.

Additional results:

- Wireless sensor network for EC measurements of nutrition tanks proved very useful to monitor changes in the nutrient solution with changing light levels, and troubleshoot nutrient deficiencies up to two weeks before visible plant symptoms.
- New GS3 sensors have been installed to monitor the changes in substrate EC over the growing period (Fig. 43).

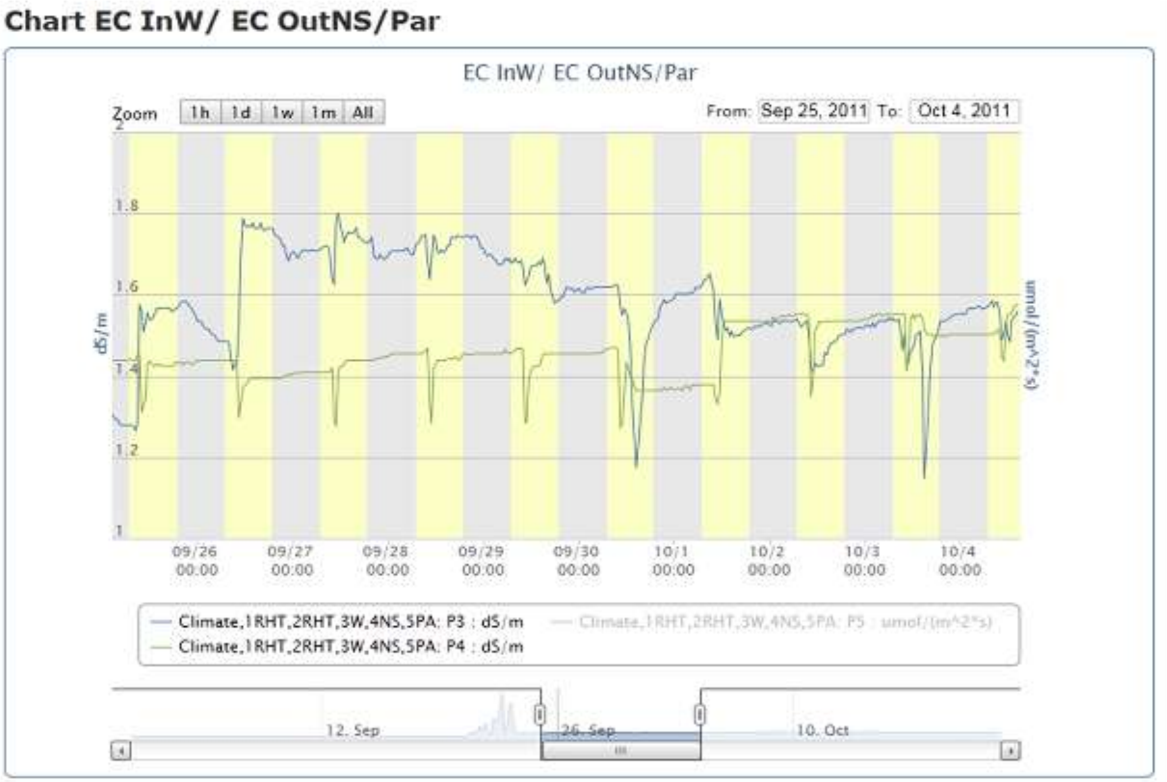


Fig. 43. EC chart from Carnegie Mellon sensorweb site (http://sensorweb.frc.ri.cmu.edu:3101).

2. Raemelton Farm – Adamstown, MD

We have deployed four individual wireless sensor networks (Decagon Devices Inc.) of various sizes, on four blocks of trees at Raemelton Farm, a commercial tree nursery near Adamstown, MD. Currently, there are 50 acres of trees under production (2010). The entire farm is on drip irrigation; each block is controlled by solenoid, timed by a central programmable irrigation scheduler in the pumphouse.

Since the farm is currently limited by water supply (72 gal per minute from two wells), it is imperative that this information is provided on a daily basis. This water supply equals 2034 gal water / acre per day for the farm if the pumps run 24 hours per day. At an average of 500 trees per acre, this water supply equates to a little more than 4 gals water /day / tree.

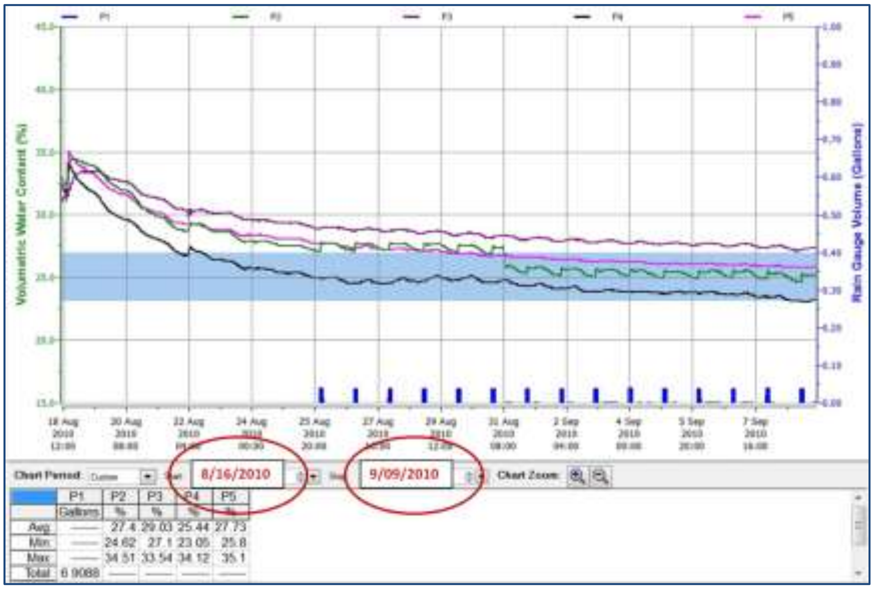
The ultimate objectives of this research are to determine whether these irrigation management systems are cost-effective in reducing input costs (including labor), and whether they improve water and nutrient application efficiency and minimize the environmental effects of production practices.

Existing Sensor Networks:

During year 2, the existing networks (3-4 year-old Maple and Dogwood blocks; 2-year old transplant blocks and rootbox study) were continuously used for irrigation scheduling (Figs. 44 and 45). We are also sensing soil temperature, soil electrical conductivity, rainfall, irrigation water applications, air temperature, relative humidity and photosynthetically active radiation (PAR) on a 15-minute time interval in two locations on the farm, to provide daily and seasonal microclimatic data.

We anticipated being able to install nR5 nodes in late summer 2011, but delayed this decision with the anticipated release of the nR5 latching solenoid in Spring 2012, as a better solution for monitoring and automatic control of irrigation events in field nurseries.

Fig. 44. Decagon EM50R network on *Cornus florida* trees at Raemelton Farm. Insert shows sensors located in PVC tube in the root zone.



Start 8/16/2010 End 9/09/2010

	P1	P2	P3	P4	P5
	Gallons	%	%	%	%
Avg	——	27.4	29.03	25.44	27.73
Min	——	24.62	27.1	23.05	25.8
Max	——	34.51	33.54	34.12	35.1
Total	6.9088	——	——	——	——

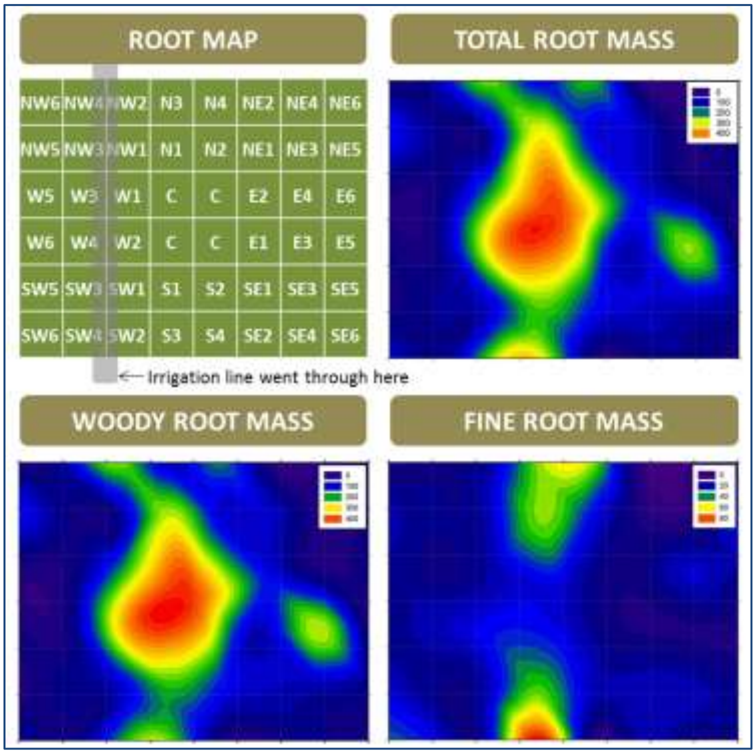
Fig. 45. Soil moisture data from the *Cornus florida* transplant network. Monitoring soil moisture allowed precision irrigation evens to be accurately timed, to maintain soil moisture in the target zone (blue horizontal bar).

Root Distribution Study: During Fall 2011, two red Sunset maple trees were destructively harvested at Raemelton farm, by air-spading the root systems. The root distributions were by measuring dry mass of the roots on a per square foot basis after air-spading the root systems to a depth of 12 inches (30cm).

Four-Year Old 'Red Sunset' Maple

The first tree was approximately 4 inch caliper, 20 foot tree, which had not been irrigated in two years.

All existing roots were harvested from the top 12" soil layer. Root dry mass was measured on a 8 x 6 square foot basis, as in the root map (at right, top left). Root densities are shown in the colorized figures, at right, partitioned by woody and fine root mass, at right.



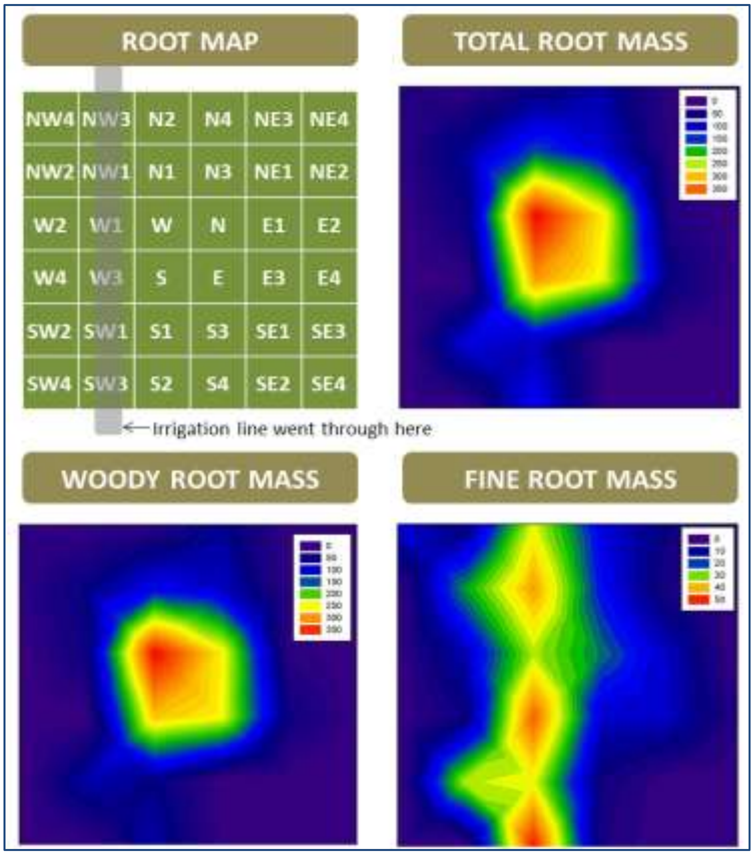
NW6	NW4	NW2	N3	N4	NE2	NE4	NE6
NW5	NW3	NW1	N1	N2	NE1	NE3	NE5
W5	W3	W1	C	C	E2	E4	E6
W6	W4	W2	C	C	E1	E3	E5
SW5	SW3	SW1	S1	S2	SE1	SE3	SE5
SW6	SW4	SW2	S3	S4	SE2	SE4	SE6

← Irrigation line went through here

Two-Year Old 'Red Sunset' Maple

A second tree was also destructively harvested, which had been irrigated the past two seasons whenever the soil VWC fell below 25 $m^3 \bullet m^{-3}$.

Similar to the 4-year old tree, roots were harvested from the top 12" soil layer, from a 6 × 6 square foot area (below) and at right.



NW4	NW3	N2	N4	NE3	NE4
NW2	NW1	N1	N3	NE1	NE2
W2	W1	W	N	E1	E2
W4	W3	S	E	E3	E4
SW2	SW1	S1	S3	SE1	SE3
SW4	SW3	S2	S4	SE2	SE4

← Irrigation line went through here

Conclusions:

- The mature tree had not been irrigated in two years, but there was a clear (legacy) difference in root density on the irrigated side of the tree.
- This irrigation effect was even more pronounced with the 2-year-old tree that has been irrigated since transplanting in April, 2009.
- With the 2-year-old tree, it was very evident that the majority of roots were directly under the drippers (white tape in the photos). The only roots that extended downwards ('peg' roots) appeared to follow water channels in the soil below the drippers.
- The root charts clearly showed the distribution of fine roots under the irrigation drip emitters.
- In general root architecture was not affected by irrigation. Both trees had excellent root systems, but almost all roots were confined to the top 12" of soil. We checked this by air-spading the area after we had completed the root mass of the large tree.
- We are fairly confident that our 6" and 12" sensors in PVC columns were positioned well to measure soil water content where the majority of feeder roots were located (close to the drip emitters).
- This is only anecdotal data (n=1) at this point, but the three replicate root-box trees (in the same row as the 2-yea-old tree) will be air-spaded during Fall 2012.

3. Waverley Farm – Adamstown, MD

Similarly to Raemelton Farm, three individual Decagon sensor networks were deployed in 2010 in three blocks of trees at Waverley Farm, a commercial nursery near Adamstown, MD. Waverley is a 200-acre facility with approximately 50 acres of permanent cover crop buffer strips (tall fescue) and 150 acres of plant production (2011). The entire farm is entirely on drip irrigation, but blocks are controlled by manual irrigation valves. Irrigation events are very different at Waverley compared to Raemelton Farm. The owner, Mr. Jerry Faulring typically schedules longer (12-hour) irrigation events, but on a much less frequent basis.

The primary objectives of these networks are to:

1. Evaluate the use of sensor networks to define timing of irrigation events with different indicator species (Leyland cypress and *Viburnum* species).
2. Compare different irrigation strategies on water content compared to Raemelton Farm (located less than 1.5 miles away)
3. Determine the effect of organic matter addition (sustainable practices) on irrigation requirements to maintain Leyland cypress plants over a 3-year period.

1. **Leyland Cypress Sensor Network:** A six-node Decagon network was established in early 2009 in a block of Leyland Cypress transplants. Decagon EC-5 sensors were installed at 6" and 12" depths (Figure 11), as previously described for Raemelton farm. This study was ongoing during 2010 and 2011. Data is currently being analyzed.

2. ***Viburnum* Sensor Networks:** Two additional 10-HS sensor networks were established in Spring, 2010 to provide additional scheduling information for two cultivars of *Viburnum*, namely *V. dentatum* 'Chicago Lustre' and *V. burkwoodii* x *V. carlesii* 'Mohawk' that are sensitive to water stress. These networks provide soil moisture information at 6" and 12" depths, together with volumetric irrigation data from an ECRN-50 rain gauge.

Tennessee

4. Hale and Hines Nursery, McMinnville, TN

We previously reported on the sensor networks installed at Hale and Hines in the year one report. Hale and Hines Nursery is located in McMinnville, TN – an area that is traditionally regarded as the "heart' of the nursery industry in the Eastern United States.

Hales and Hines is a major producer of Dogwood (*Cornus florida* cultivars), but also produces a wide range of shrubs and trees in 10, 15, 30 and 45-gallon containers. It is a 400+ acre field nursery operation, but in recent years, Mr. Terry Hines has converted about 180 acres to pot-in-pot (PnP) production (Fig. 46).

Since rooting volumes are more limited, and because of the pine bark soilless substrate they use, irrigation scheduling is much more rapid than in field soils. Leaching of nutrients from containers is likely without careful irrigation scheduling.

Fig. 46. Hale and Hines Pot-in-pot operation, showing trees growing in 30-gallon containers in the nursery.

By using the information from the sensor networks located in three indicator species -- Mr. Terry Hines as been able to simultaneously monitor irrigation water applications and leaching from various sized containers in the field during years 1 and 2 of the project.

In anticipation of the new nR5 monitoring and control nodes being available in mid-2011, the decision was taken to completely reconfigure these sensor networks in early spring, 2011 to compare 'normal' (i.e. manually-configured irrigation) vs. set-point irrigation control (determined by substrate soil moisture availability).

The three reconfigured networks are located in Red Maple, Dogwood and River Birch (indicator species) blocks. Two 10-HS sensors were installed in treatment (five replicate trees per treatment) within the red maple and Dogwood blocks (Fig. 47).

Fig. 47. The Dogwood monitoring and control block installed in March, 2011

The global study objectives are to:

1. Monitor Soil Moisture at 2 Depths (6" and 12")
2. Monitor Irrigation Applications; Leachate Volumes
3. Monitor pore water EC in control trees (by integrating the new GS3 sensor)
4. Determine set-point control strategies
5. Measure growth (shoot vs. root) differences in each block.

A Birch block sensor network was also reconfigured, but somewhat differently to answer some specific (within block) irrigation issues (Fig. 48).

Sensor networks were installed at the mid- and end point of a single lateral, to investigate perceived differences in water application due to pressure loss down the length of the lateral.

Single node installations at each point monitored 3 replicate trees for soil moisture, one tree for leachate and irrigation application, using ECRN-50 tipping gauges (as detailed in the first year report).

Fig. 48. Birch block single node installation, with the three sensed trees and tipping rain gauges monitoring irrigation applications and leaching (white bucket in foreground).

Results: Unfortunately the nR5 node and GS3 sensor production was delayed in 2011, such that implementation of the monitoring and control strategy was not possible.

Nevertheless, with the anticipated release of the latching nR5 in Spring 2012, we are in a good position to install these and the new GS3 sensors to monitor and control irrigation and EC in both red maple and dogwood.

Good data was derived from the existing networks in 2011, such that Terry Hines was able to 'fine-tune' his manual irrigation scheduling, using the data gathered on a daily basis (Fig. 49).

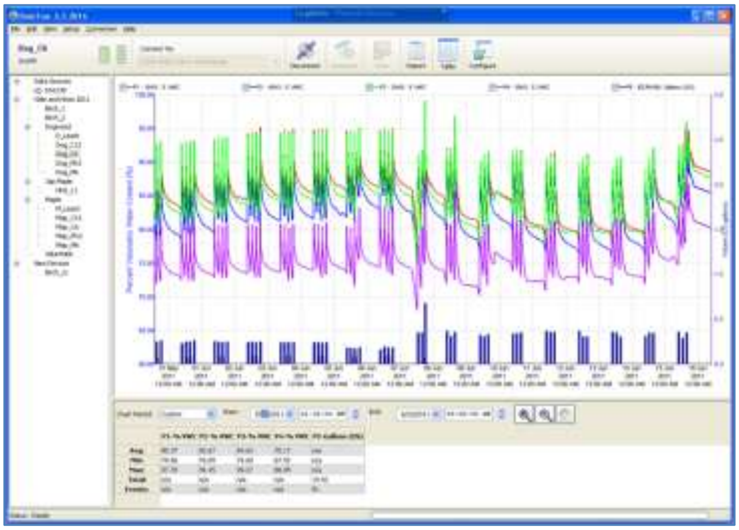


Fig. 49. Soil moisture measurement and irrigation volumes applied to the Dogwood block, showing adjustments to schedules during the season.

Data derived from monitoring the Birch block during 2011 confirmed significant differences in irrigation volumes being applied at the mid- and end points of the block, such that Mr. Hines may decide to reconfigure the irrigation main line in this block in 2012.

B. Georgia

1. Evergreen Nursery – Chatham, GA

The wireless sensor network at Evergreen consists of four Decagon EM50R loggers that are transmitting data to a Base Station at the nursery office, with data displayed on a laptop in Will Ross' office. One of the EM50R loggers functions as a weather station with a temperature and humidity sensor, light (*PPF*) sensor and rain gauge. The other three loggers are used to monitor substrate water content in several different crops (e.g. gaillardia, Heuchera, and ferns).

Will Ross, the grower at Evergreen, monitors the system and utilizes the information to help him make daily irrigation decisions. From looking at the data, Will noticed that some of his crops (e.g. gaillardia) were drying out faster than he realized. To reduce drought stress and improve plant growth, he changed irrigation practices for his gaillardia crop from once a day to twice a day (with smaller amounts). This allows him to better meet the water demands of the crop while minimizing leaching.

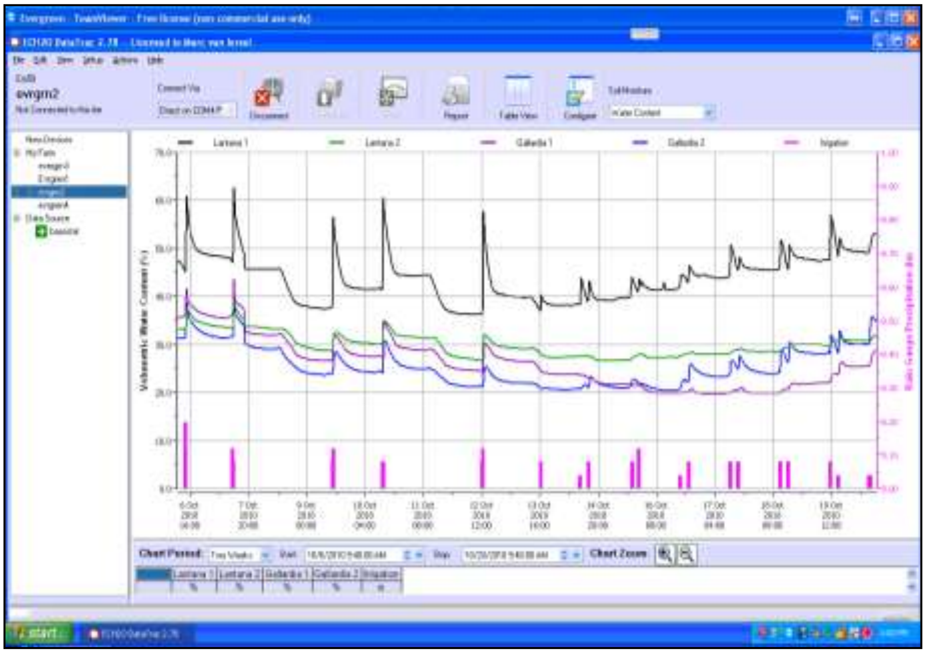


Fig.50. A screenshot for the computer at Evergreen displaying substrate water content measurements (lines) and irrigation (pink bars). Note the switch to irrigation twice daily during the latter part of this period.

The computer screenshot (Fig. 50) shows that Will changed the manner that he irrigated this crop on October 14, 2010. The pink bars show irrigation events, and while he initially irrigated once a day, you can see that he switched to watering twice a day while reducing the amount of water applied at each irrigation.

Will Ross also has focused on trying to reduce leaching. We have worked together on interpreting the data, and have looked specifically at the rate of decrease in substrate water content following irrigation (Fig. 51).

Since Evergreen uses relatively small containers, we feel confident that a rapid decline in substrate water content following irrigation is indicative of leaching (rather than the water draining to part of the substrate below the sensor).

We have recently introduced Will Ross to the 'Delta VWC' tool that has been incorporated into DataTrac at our request. Delta VWC shows the change in substrate water content since the previous measurement and is ideally suited for monitoring leaching.

Fig. 51. Will Ross, grower at Evergreen, in a cold frame at the nursery. Note the wireless node above his head, and the rain gauge among the plants used to monitor irrigation. Four pots have sensors to measure substrate water content.

2. McCorkle Nursery

We conducted a study at McCorkle Nurseries, Inc. to try to quantify water savings that can be attained using sensor controlled irrigation (August 2010 –May 2011), but did not get usable data on water savings. For our study, we had 10 plots, with five of the plots irrigated using sensors (MoistureClick) and five irrigated by McCorkle Nurseries Inc.

McCorkle Nurseries, Inc., unbeknown to us, decided to change their irrigation practices to try to match those to the sensor-controlled irrigation. They did so very successfully, and irrigation was very similar in the sensor-control plots versus the plots irrigated by McCorkle's. Although this negated the main objective of this study, it yielded very interesting and unexpected results.

First, the study clearly showed that sensor-controlled irrigation can be used to educate growers how to irrigate more efficiently. Secondly, these improved irrigation practices improved plant growth and reduced disease occurrence, yielding great information on the potential economic impact of more efficient irrigation (see below).

We have had three to four wireless nodes monitoring substrate water content in various gardenia crops throughout the year. Most of the crops are grown inside a large greenhouse (Fig.52), with one crop grown outdoors on a gravel pad.

A total of four EM50R dataloggers are deployed, and those loggers are sending data to a basestation and laptop in the McCorkle office at their Neals Mill farm. One of these loggers is configured as a weather station (temperature, RH rainfall and light), while the other three loggers have four soil moisture sensors connected to them. A rain gauge was added to these loggers, to monitor irrigation rates.

Fig. 52. An overview of the study with gardenia 'Heaven Scent' at McCorkle Nursery

To control irrigation we used MoistureClick irrigation controllers (Dynamax, Houston, TX) (Fig. 53, at right).

We compared water use of plants irrigated with these controllers to water use in plots irrigated by McCorkle’s irrigation manager. Surprisingly, we found that water use was similar. Unbeknown to us, McCorkle’s adjusted the irrigation in their plots to match what the volume of water that was applied in plots controlled by MoistureClick controllers.

Fig. 53. A MoistureClick irrigation controller with soil moisture sensor.

The most interesting results from our work at McCorkle’s came from a study with gardenia ‘Heaven Scent’, a problem crop for this and many other nurseries. This cultivar is very susceptible to a variety of pathogens and growers typically lose about 30% of the crop to water molds (root pathogens). By controlling irrigation using soil moisture sensors we minimized overwatering and reduce disease. Although this study appeared to be a total loss from that perspective, we then noticed that disease was not a problem in this crop. Additionally, plants grew much faster than normal and the production time of a salable crop took much less time than usual: 8 months instead of the typical 14 months, a 6-month or 43% shortening of the production cycle (Fig. 54). While the exact cause of the reduction in production cycle duration is not clear, we hypothesize that lower volumetric water content increased substrate temperature, reduced pathogen pressure, and decreased fertilizer leaching; and that these factors increased plant growth rates.

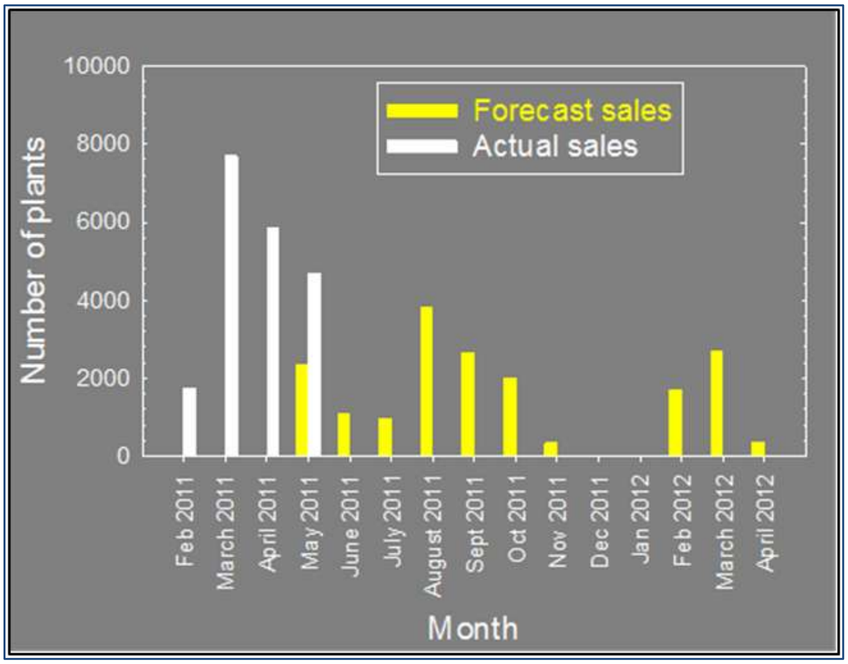


Fig. 54. Forecast and projected sales of gardenia 'Heaven Scent'. Note that better control of irrigation resulted in much improved growth and quicker sales. The sorter production cycle reduced production costs.

Economic Cost Projections: The reduction in production time decreased production costs (including elimination of some fertilizer and fungicide applications and associated labor costs); these avoided costs amounted to roughly $7,700. Finally, the reduction in growing time lowered the interest cost of holding growing plants in inventory by approximately $500, assuming simple interest at a rate of 8% per year.

Impact: The total increase in profits from reduced production time and elimination of shrinkage thus totaled $21,200, corresponding to $1.06 savings per ft^2 per production cycle or $0.90 per plant per production cycle. This estimate does not include the potential profits associated with initiating a new production cycle in the same growing area earlier than projected due to the time reduction in the production cycle. At this level of savings, the $3,000 precision irrigation system installed in this study would have a payback period of less than 2 months.

Wireless networks are currently being upgraded with control capability. We are testing the CMU base station and new nR5 nodes at UGA. As soon as the testing is complete, we will install these systems at Evergreen Nurseries and McCorkle Nurseries, Inc. This is planned for Fall, 2011, which will allow us to monitor the performance of these networks during winter, when little irrigation is needed. This should put us in a great position to actively control irrigation from the beginning of the spring 2012 growing season.

Economic and Environmental Benefits Working Group Report

1. Economic Methodology Development

The overall goal of the SCRI-MINDS project is to quantify the private and public economic benefits and costs of a wireless sensor network supporting production requirements in field nurseries, container nurseries, greenhouse operations, and green roof systems. That sensor network provides real-time information on production conditions. That information is valuable when (1) it allows people to make better decisions and (2) the increase in value from better decision making exceeds the cost of acquiring and processing the information.

A major initiative of the economics team during year 2 of this project focused on developing a general conceptual framework for understanding how the information from sensor networks influences the decisions made by nursery growers with greenhouse, container, and field operations. An initial model of decision making in a field operation with water supply constrained by pump capacity was also developed. Preliminary analysis of that model indicated that information from soil moisture sensors could be used to increase profit by allowing reallocation of water from young to more mature trees while maintaining an adequate margin of safety to ensure young tree survival. Further elaboration of this and other models of nursery operations will be undertaken during year 3.

2. Survey Development

The economic team began development of a national nursery and greenhouse irrigation survey whose purposes are to (1) document current industry practices across the country, (2) better understand consumer perceptions of sensor-based irrigation technology, and (3) collect information for use in economic modeling of private and public costs and benefits. The team has received feedback about the design of the survey from our grower partners and from the Survey Methodology Department at the University of Maryland. The Survey Methodology Department has also provided advice on sampling techniques. A pretest of the survey using 15-30 growers will be conducted shortly.

We expect to finalize the survey design in early- to mid-December 2011 so that it can be administered during 2012. We will use a variety of means to disseminate the survey including attending industry trade shows and conducting outreach via state and federal grower organizations (i.e. Southern Nurseryman's Association, Maryland Nursery and Landscape Association, NC 1186 USDA Nursery and Greenhouse Working Group). Both hard copy and web versions are under consideration.
Collection and preliminary analysis of industry data using this survey will constitute the principal work of the economics team during year 3 of the project.

3. Human Subjects Review

The University of Maryland group received approval for a Human Subjects Review from the Institutional Review Board (IRB) at the University of Maryland. This consent form is used any time sensitive information is collected from individuals, and informs the participant of the liabilities and benefits of their participation in a particular project. The grower partners involved in this research will be required to read and sign this IRB. Our grower partners will be asked to give their informed consent about what information we are gathering, and how that information will be used. Most of the sensitive information will be gathered by the economic team in the near future, but also covers any operation specific information that is published by the research partners, and will be approved by that particular grower before the information is published.

4. Case Study: Reduced Losses of Gardenia

Many growers in the Southeastern U.S. suffer significant losses in *Gardenia*, typically 30% (but as high as 70%) crop shrinkage, due to root pathogens and associated mortality and reductions in quality. Our intention was to test whether sensor-controlled irrigation can reduce water use and shrinkage due to disease. Ten bays totaling approximately 20,000 ft^2 in an unheated greenhouse at a large commercial nursery were used for this research from late summer 2010 into spring 2011. Each bay (plot) contained approximately 2,340 *Gardenia augusta* 'Heaven Scent'™ in #2 containers filled with a bark-based substrate. Irrigation in five of the ten bays was controlled with a Moisture Clik irrigation controller (IL200-MC, Dynamax, Houston, TX), which uses a dielectric soil moisture sensor (SM200) to measure substrate water content.

Irrigation controllers were set to come on when the substrate water content dropped below approximately 20% soil moisture. To prevent irrigation at night, the Moisture Clik controllers were connected to a 24 hour timer to power the controllers only between 8 am and 5 pm. Irrigation in the other five bays was controlled by nursery personnel, who were asked to irrigate according to their regular practices. Each bay was equipped with a water meter, and irrigation volumes were recorded monthly. Other than irrigation, plants were produced using the standard nursery practices.

Based on previous studies with *Hydrangea macrophylla* in the same production facility, we expected to observe water savings as high as 83% over standard irrigation practices (5). Yet our results indicated that sensor-controlled irrigation reduced irrigation by only 1.2% (183, 219 gallons/plot with sensor controlled irrigation versus 185, 521 gallons in the control). The confounding results relating to water use between the two treatments were due to the irrigation technician's independent decision to mimic the precision control system in the "standard irrigation" treatment he was charged with irrigating. While this action by the irrigation technician negated the ability to determine differences in irrigation quantity between standard irrigation practices and a precision irrigation control system, it did show that sensor-controlled irrigation systems can be used to train people to irrigate more efficiently.

Economic Impacts: Within both treatments, there was zero mortality across the entire 23,400 units due to pathogen pressure. The projected, typical losses were 2,000 units; therefore at an industry standard $6.50/unit sale price, and given that 100% of the viable crop is usually sold, avoided losses due to a lack of shrinkage amounted to $13,000.

Also of note is that producing a salable crop took much less time than usual: 8 months instead of the typical 14 months, a 6-month or 43% shortening of the production cycle. While the exact cause of the reduction in production cycle duration is not clear, we hypothesize that lower volumetric water content increased substrate temperature, reduced pathogen pressure, and decreased fertilizer leaching; and that these factors increased plant growth rates.

The reduction in production time decreased production costs (including elimination of some fertilizer and fungicide applications and associated labor costs); these avoided costs amounted to roughly $7,700. Finally, the reduction in growing time lowered the interest cost of holding growing plants in inventory by approximately $500, assuming simple interest at a rate of 8% per year. The total increase in profits from reduced production time and elimination of shrinkage thus totaled $21,200, corresponding to $1.06 savings per ft^2 per production cycle or $0.90 per plant per production cycle. This estimate does not include the potential profits associated with initiating a new production cycle in the same growing area earlier than projected due to the time reduction in the production cycle.

At this level of savings, the $3,000 precision irrigation system installed in this study would have a payback period of less than 2 months.

Project Management, Coordination and Communication

1. Fiscal Accounting and Matching Documentation

Many steps were taken to ensure the successful administration of the project in accordance with USDA guidelines, as detailed in the first year report. More advanced systems for tracking and monitoring SCRI expenditures were implemented during year 2 at UMD. 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 and 2 totaled $1,544,593 whereas total match amounted to $2,358,154. In year 2, accrued match exceeded the projected matching totals by $363, 321.

2. 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, monthly SCRI webconferences are held to ensure communication and knowledge-sharing amongst project participants. These monthly 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.

3. Website and Knowledge Center Development

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 during 2011 to include all the new project information given in this first annual report (Fig. 55). The website has been publicized through various project press releases and trade articles during 2010 and 2011.

Fig. 55. The SCRI-MINDS website and knowledge center homepage

4. Second Annual Project Meeting

The second annual project meeting was held in Pittsburgh, PA from 22 – 24 June, 2011. In addition to the engineering and research scientist participants from all the Universities and companies, we were joined by Dr. Dan Schmoldt, USDA-SCRI co-program leader, eight of our advisory panel members and eight graduate students involved in various aspects of the project (Fig. 56).

Fig. 56. The SCRI-MINDS team participants at the 2nd Annual meeting at the Carnegie Mellon Robotics Institute in Pittsburgh, PA.

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 A), in anticipation of tighter integration of the engineering and scientific objectives during the third year.

The meeting also gave the group an opportunity to meet other members of CMU teams involved in other projects at a barbeque hosted at the CMU sensor test site at Robot City, where the sensorweb software and new nR5 were debuted for the first time. The Carnegie Mellon team were excellent hosts and the meeting was extremely productive.

Publications, Presentations and Outreach

Book Chapters

1. Lea-Cox, J. D. 2012. Using Wireless Sensor Networks for Precision Irrigation Scheduling. *T.S. Lee (Ed.) In:* Irrigation – Types, Sources and Problems (Book 3). InTech Press. Rijeka, Croatia. 26 p. (*In Press*).
2. Lea-Cox, J.D. and D. S. Ross. 2012. Managing Water and Nutrients to Reduce Environmental Impact. *In: Nutrient Management for Floricultural Crops.* D. Merhaut, K. M. Williams and S. Mangiafico. (Eds.). University California Press, CA. Chapter *13. 30 p. (In Press*).
3. Majsztrik, J., A. G. Ristvey and J. D. Lea-Cox. 2011. Water and Nutrient Management in the Production of Container-Grown Ornamentals. J. Janick (Ed.). *In: Hort. Reviews 38:253-297*. John Wiley, NJ. USA.

Peer-Reviewed Journal Articles

1. Bauerle, W.L. and J.D. Bowden. 2011. Predicting transpiration response to climate change: Insights on physiological and morphological interactions that modulate water exchange from leaves to canopies. *HortScience* 46:163-166.
2. Bauerle, W.L. and J.D. Bowden. 2011. Separating foliar physiology from morphology reveals the relative roles of vertically structured transpiration factors within red maple crowns and limitations of larger scale models. *J. Exp. Bot.* 62:4295-4307.
3. Crespo, J. M. and M.W. van Iersel. 2011. Performance of a soil moisture sensor-based landscape irrigation controller for automated irrigation of container-grown plants. *HortScience* 46:889-894.
4. Daniels, A.B., D.M. Barnard, P. Chapman, and W.L. Bauerle. Optimizing substrate moisture measurements in containerized nurseries. *HortScience*. (In Press)
5. Kim, J, M.W. van Iersel and S.E. Burnett. 2011. Estimating daily water use of two petunia cultivars based on plant and environmental factors. *HortScience* 46:1287-1293.
6. Kim, J. and M.W. van Iersel. 2011. Slowly-developing drought stress increases photosynthetic acclimation of *Catharanthus roseus*. *Physiologia Plantarum* 143:166-177. DOI: 10.1111/j.1399-3054.2011.01493.x
7. Lea-Cox, J. D., F. R. Arguedas-Rodriguez, A. G. Ristvey and D.S. Ross. 2011. Relating Real-time Substrate Matric Potential Measurements to Plant Water Use, for Precision Irrigation. *Acta Hort.* 891: 201-208.
8. Lea-Cox, J. D., A. G. Ristvey, D.S. Ross and G. Kantor. 2011. Wireless Sensor Networks to Precisely Monitor Substrate Moisture and Electrical Conductivity Dynamics in a Cut-Flower Greenhouse Operation. *Acta Hort.* 893:1057-1063.
9. van Iersel, M.W., S. Dove and S.E. Burnett. 2011. The use of soil moisture probes for improved uniformity and irrigation control in greenhouses. *Acta Hort.* 893:1049-1056.

Non-Refereed Conference Proceedings

1. Kim, J., A. Malladi, and M.W. van Iersel, M.W. 2011. Abscisic acid-related gene expression and physiological responses of petunia at different substrate water contents. *Proceedings of the Plant Growth Regulation Society of America*. (In press).

2. Kohanbash D., A. Valada and G. F. Kantor. 2011. Wireless Sensor Networks and Actionable Modeling for Intelligent Irrigation. *Amer. Soc. Agric. Biol. Eng*. 7-12th August, 2011. Louisville, KY. Paper #1111174. 7p.
3. Wells. S., M. Chappell, J. Ruter, P. Thomas, and M. van Iersel. 2011. Monitoring substrate water content in nurseries: More efficient irrigation and reducing leaching and runoff. *Amer. Soc. Agric. Biol. Eng.* 7-12th August, 2011. Louisville, KY. Paper #1111254. 8p.
4. van Iersel, M., W. Ross, S. Dove, M. Chappell, P. Thomas, J. Ruter, and S. Wells. 2011. Substrate water content dynamics in nurseries: real-time monitoring can improve irrigation practices. *Proc. SNA Research Conf.* 56:173-179.
5. Bayer, A., I. Mahbub, M. Chappell, J. Ruter, and M. van Iersel. 2011. Growth of 'Panama Red' hibiscus in response to substrate water content. *Proc. SNA Research Conf.* 56:134-138.
6. Kim, J., A. Malladi, and M. van Iersel. 2011. Physiological responses of petunia to different levels of drought stress. *Proc. SNA Research Conf.* 56:46-51.
7. Peter, A., P.A. Thomas, and M.W. van Iersel. 2011. Growth of petunia as affected by substrate moisture content and fertilizer rate. *Proc. SNA Research Conf.* 56:167-172.
8. Soranz Ferrarezi, R. and M.W. van Iersel. 2011. Monitoring and controlling subirrigation with soil moisture sensors: a case study with hibiscus. *Proc. SNA Research Conf.* 56:187-191.
9. Starry, O., J.D. Lea-Cox, A.G. Ristvey and S. Cohan. 2011. Utilizing Sensor Networks to Assess Stormwater Retention by Greenroofs. *Amer. Soc. Agric. Biol. Eng.* 7-12th August, 2011. Louisville, KY. Paper #1111202. 7p.
10. O'Meara, L., M. Chappell, and M.W. van Iersel. 2011. Water consumption of *hydrangea macrophylla* as affected by environmental factors. *Proc. SNA Research Conf.* 56:162-166.

Trade Articles

1. Lea-Cox, J. D. 2011. Smart Irrigation Strategies: Growers get high-tech help with irrigation frequency and leaching reduction. *Nursery Management Pro*. April 2011. pp. 16-20.
2. van Iersel, M., S. Burnett, J. Lea-Cox, and P. Thomas. 2011. Improving irrigation with sensors. *Greenhouse Management* 31(9): 56-59.

Conference Abstracts

1. Barnard, D.M. and W.L. Bauerle. 2011. Variation in within canopy attenuation of wind speed in container grown trees: Measurement errors and their impact on canopy transpiration estimates. HortScience 46(9): S195.
2. Barnard, D.M., A.B. Daniels, and W.L. Bauerle. 2011. Optimizing substrate moisture measurements in containerized nurseries: Insights on spatial and temporal variability. HortScience 46(9): S207.
3. Bauerle, W.L. 2011. Separating foliar physiology from morphology reveals the relative roles of vertically structured transpiration factors within red maple crowns. HortScience 46(9): S146-147.
4. Bayer, A. J.M. Ruter, M. Chappell, and M. van Iersel. 2011. Growth of *Hibiscus acetosella* 'Panama red' in response to sensor controlled irrigation in two outdoor nursery settings. HortScience 46(9): S218.
5. Bissey, L., C. S Campbell and K. Dunne. 2011. Development of a Sensor to Measure Water Content and EC of Soilless Substrates HortScience 46(9): S347.
6. Kim, J., A. Malladi, and M. van Iersel. 2011. Gene expression and physiological responses of petunia at specific substrate water contents. HortScience 46(9): S105.
7. Lea-Cox, J. D. 2011. Project Design with the End in Mind. HortScience 46(9): S72.

8. Lea-Cox, J. D. 2011. Visualizing and Interpreting Large Sensor Datasets for Daily Specialty Crop Management Decisions. HortScience 46(9): S76.
9. Lea-Cox, J. D. and J. C. Majsztrik. 2011. Considering the Value of Real-Time Sensor Information. HortScience 46(9): S210.
10. Majsztrik, J., J. D. Lea-Cox, D. S. Ross and A. G. Ristvey. 2011. Modeling Nitrogen, Phosphorus, and Water Dynamics in the Nursery and Greenhouse Industry. HortScience 46(9): S160-161.
11. Majsztrik, J., J. D. Lea-Cox, D. S. Ross and A. G. Ristvey. 2011. An In-Depth Analysis of Water and Nutrient Management in the Nursery and Greenhouse Industry in Maryland. HortScience 46(9): S220-221.
12. O'Meara, L., M. van Iersel, M. Chappell. 2011. Water consumption of *Hydrangea macrophylla* as affected by environmental factors. HortScience 46(9): S219.
13. Peter A., R. Soranz Ferrarezi, P.A. Thomas , M. van Iersel. 2011. *In situ* measurements of the electrical conductivity of substrates: the relationship between bulk EC, pore water EC, and substrate water content. HortScience 46(9): 198-199.
14. Peter A., P.A. Thomas, and M. van Iersel. 2011. Growth of petunia as affected by substrate moisture content and fertilizer rate. HortScience 46(9): S295-296.
15. Soranz Ferrarezi R., M. van Iersel, and R. Tezteslaf. 2011. Soil moisture sensors for monitoring and controlling subirrigation: a case study with hibiscus. HortScience 46(9): S302.
16. Thomas, P.A., M. Chappell, J.M. Ruter, S. Dove and M. van Iersel. 2011. Monitoring environmental conditions and substrate water content for more efficient irrigation in nurseries. HortScience 46(9): S218.
17. van Iersel, M. 2011. Publish or perish: trials, tribulations, and triumphs. HortScience 46(9): S72.

Invited Presentations

1. Bauerle, W.L., J.D. Lea-Cox, G.A. Kantor, M. van Iersel, C. Campbell, T. Bauerle, D.S. Ross, A. Ristvey, D. Parker, D. King, R. Bauer, S. Cohan, P.A. Thomas, J.M. Ruter, M. Chappell, S. Kampf, M.A. Lefsky, L. Bissey, and T. Martin. Overview of a national coordinated agriculture project for precision irrigation at multiple scales. Rocky Mountain Short Course, Colorado Nursery and Greenhouse Association. 21 October, 2010. Thornton, CO.
2. Lea-Cox, J. D. 2011. Implementing Wireless Sensor Networks in Intensive Horticultural Production Systems, for Precision Irrigation and Nutrient Management. Keynote Presentation. First International Symposium on Wireless Sensor Networks in Agriculture. China Agricultural University; Chinese Academy of Agricultural Sciences. 18-21 November, 2010. Beijing, China.
3. Lea-Cox, J. D. 2011. Measuring Spatial and Temporal Dynamics of Water in Soil and Soilless Substrates, to Enable Precise Scheduling of Irrigation Applications. *AGRI-SENSING 2011: International Symposium on Sensing in Agriculture in Memory of Dahlia Greidinger.* Technion-Israel Institute of Technology. 20 -24th February, 2011. Haifa, Israel.
4. Lea-Cox, J. D. 2011. Project Management and Outreach Using Web-Based Tools. SCRI Project Directors Workshop. 108th Annual American Society for Horticulture Science Conference. 25 Sept., 2011. Waikoloa, HI.
5. Lea-Cox, J. D. 2011. Project Design with the End in Mind. Graduate Student Workshop. 108th Annual American Society for Horticulture Science Conference. 26 Sept., 2011. Waikoloa, HI.
6. Lea-Cox, J. D. 2011. Visualizing and Interpreting Large Sensor Datasets for Daily Specialty Crop Management Decisions. Computer Applications in Horticulture Workshop. 108th Annual American Society for Horticulture Science Conference. 26 Sept., 2011. Waikoloa, HI.

7. van Iersel, M.W. 2011. New irrigation technologies. Moving nursery producers toward sustainability. University of Florida, North Florida Research and Education Center – Quincy, FL.
8. van Iersel, M.W. 2011. Water issues in the greenhouse industry. Annual Meeting of the National Greenhouse Manufacturers Association, Saint Louis, MO.
9. van Iersel, M. 2011. Publish or perish: trials, tribulations, and triumphs. Graduate Student Workshop. 108th Annual American Society for Horticulture Science Conference. 26 Sept., 2011. Waikoloa, HI.

Other Contributed Presentations

1. Bauerle W.L. 2011. Measurement and modeling physiological processes to determine optimal seasonal cycle metrics for deficit irrigation. USDA-ARS - Deficit irrigation and return flow maintenance. 15 June, 2011. Fort Collins, CO.
2. Bayer, A., I. Mahbub, M. Chappell, J. Ruter, and M. van Iersel. 2011. Growth of 'panama red' hibiscus in response to substrate water content. SNA research conference, Mobile, AL.
3. Bayer, A., I. Mahbub, M. Chappell, J. Ruter, and M. van Iersel. 2011. Growth of 'Panama red' hibiscus in response to substrate water content. CANR open house, GGIA Wintergreen, Duluth, GA.
4. Kim, J., A. Malladi, and M. van Iersel. 2011. Physiological responses of petunia to different levels of drought stress. SNA research conference, Mobile, AL.
5. Kim, J., A. Malladi, and M. van Iersel. 2011. Physiological responses of petunia to different levels of drought stress. CANR open house, GGIA Wintergreen, Duluth, GA.
6. Kim, J., A. Malladi, and M.W. van Iersel, M.W. 2011. Abscisic acid-related gene expression and physiological responses of petunia at different substrate water contents. Annual meeting of the Plant Growth Regulation Society of America, Chicago, IL.
7. O'Meara, L., M. Chappell, and M.W. van Iersel. 2011. Water consumption of *hydrangea macrophylla* as affected by environmental factors. CANR open house, GGIA Wintergreen, Duluth, GA.
8. Peter, A., P.A. Thomas, and M.W. van Iersel. 2011. Growth of petunia as affected by substrate moisture content and fertilizer rate. CANR open house, GGIA Wintergreen, Duluth, GA.
9. O'Meara, L., M. Chappell, and M.W. van Iersel. 2011. Water consumption of *hydrangea macrophylla* as affected by environmental factors. SNA research conference, Mobile, AL.
10. Peter, A., P.A. Thomas, and M.W. van Iersel. 2011. Growth of petunia as affected by substrate moisture content and fertilizer rate. SNA research conference, Mobile, AL.
11. Ruter, J.M. 2011. Water quality for ornamental production. Ohio Nursery Shortcourse, Central Environmental Nursery Trade Show, Columbus, OH.
12. Ruter, J.M. 2011. Water efficiency in the nursery. Ohio Nursery Shortcourse, Central Environmental Nursery Trade Show, Columbus, OH.
13. Soranz Ferrarezi, R. and M.W. van Iersel. 2011. Monitoring and controlling subirrigation with soil moisture sensors: a case study with hibiscus. SNA research conference, Mobile, AL.
14. Soranz Ferrarezi, R. and M.W. van Iersel. 2011. Monitoring and controlling subirrigation with soil moisture sensors: a case study with hibiscus. CANR open house, GGIA Wintergreen, Duluth, GA.
15. van Iersel, M., W. Ross, S. Dove, M. Chappell, P. Thomas, J. Ruter, and S. Wells. 2011. Substrate water content dynamics in nurseries: Real-time monitoring can improve irrigation practices. SNA research conference, Mobile, AL.
16. van Iersel, M.W. 2011. ABA research at the University of Georgia: water use, physiology and gene expression. Valent BioSciences, Long Grove, IL.

17. van Iersel, M.W. 2011. Annuals, perennials, and woody ornamantals: How much water do they need? GGIA Wintergreen, Duluth, GA.
18. van Iersel, M.W., M. Chappell, J. Ruter, P. Thomas, and S. Wells. 2011. Using soil moisture sensors for irrigation control: reducing nursery water use and increasing profits. Southern Region Water Conference, Athens, GA.

Websites, Impact Statements

1. Lea-Cox, J.D. and C. Zhao, 2011. Smart-farms: Managing Irrigation and Nutrients via Distributed Sensing - The Specialty Crops Research Initiative Project Website and Knowledge Center http://www.smart-farms.net
2. Lea-Cox, J. D., T. Rhodus, L. Brewer and M. Neff, 2011. American Society for Horticultural Science: Center for Horticultural Impact Statements. http://ashsmedia.org
3. Lea-Cox, J. D., G.A. Kantor, Bauerle, W.L., M. van Iersel, C. Campbell, T. Bauerle, D.S. Ross, A. Ristvey, D. Parker, D. King, R. Bauer, S. Cohan, P.A. Thomas, J.M. Ruter, M. Chappell, S. Kampf, M.A. Lefsky, L. Bissey, and T. Martin. Increasing the Efficiency of Irrigation Water Applications with Smart Sensor Technology. American Society for Horticultural Science: Center for Horticultural Impact Statements. http://ashsmedia.org/?p=62

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

<table>
<tr><th rowspan="3">ID</th><th rowspan="3">PROJECT OBJECTIVES AND GOALS</th><th rowspan="3">WORKING GROUP</th><th colspan="20">PROJECT ACTIVITIES BY QUARTER</th></tr>
<tr><th colspan="4">YEAR 1</th><th colspan="4">YEAR 2</th><th colspan="4">YEAR 3</th><th colspan="4">YEAR 4</th><th colspan="4">YEAR 5</th></tr>
<tr><th>9-2009</th><th>12-2009</th><th>3-2010</th><th>06-2010</th><th>9-2010</th><th>12-2010</th><th>3-2011</th><th>06-2011</th><th>9-2011</th><th>12-2011</th><th>3-2012</th><th>06-2012</th><th>9-2012</th><th>12-2012</th><th>3-2013</th><th>06-2013</th><th>9-2013</th><th>12-2013</th><th>3-2014</th><th>06-2014</th></tr>
<tr><td></td><td>University of Maryland Greenhouse Research</td><td></td><td colspan="20"></td></tr>
<tr><td>1.6.1</td><td>On-campus research</td><td></td><td></td><td colspan="5">Begin plant physiological studies (water use) and verify sensor calibrations. Begin Model development.</td><td colspan="5">Integrate sensor physiological research to next iteration of node networks. Continue physiological greenhouse studies and validate Model design</td><td></td><td colspan="4">Finalize Model development and receive input from industry</td><td colspan="4">Resolve any industry issues and concerns with Model use</td></tr>
<tr><td>1.6.2</td><td>On-farm research</td><td></td><td></td><td colspan="5">Deploy present generation node networks at commercial farm with commercial greenhouse partners. Begin initial monitoring.</td><td colspan="5">Deploy next interation of node networks at commercial greenhouse. Begin to validate Model. Test monitoring and irrigation control capabilties</td><td></td><td colspan="4">Contiue research with node networks with commercial greenhouse partners. Resolve issues with Model and irrigation control capabilies</td><td colspan="4">Finalize Model and monitoring and irrigation control issues for commercialization.</td></tr>
<tr><td>1.6.3</td><td>Technology implementation</td><td></td><td></td><td colspan="5">Continue monitoring and begin irrigation control. Apply research data for Model development. Employ GUI.</td><td colspan="5">Refine GUI and Model. Continue monitoring and control research and develop baselines. Determine spatial and temporal probe requirements.</td><td></td><td></td><td colspan="3">Beta testing model/GUI software.</td><td></td><td colspan="3">Release of commercial product</td></tr>
<tr><td>1.6.4</td><td>Outreach</td><td></td><td></td><td></td><td colspan="2">Preliminary findings presented at local extension programs and national conferences.</td><td colspan="2"></td><td colspan="2">Write peer reviewed and trade journal manuscripts.</td><td></td><td colspan="3">Previous seasons findings presented at local extension programs and national conferences.</td><td colspan="2"></td><td colspan="2">Write peer reviewed and trade journal manuscripts.</td><td></td><td colspan="3">National conferences and extension programming.</td></tr>
<tr><td>1.6.5</td><td>Synergistic activities</td><td></td><td colspan="20">Share monitoring and control data with CMU,UG, Cornell, UC and Decagon to develop model crop software and GUI.</td></tr>
<tr><td>1.6.6</td><td>Software and Modeling</td><td></td><td colspan="3">Begin initial modeling research and develop baselines for Model GUI software development.</td><td></td><td colspan="5">Begin model validation. Varify GUI utility.</td><td colspan="4">Comntinue model validation and GUI utility.</td><td colspan="3">Beta testing model/GUI software.</td><td></td><td colspan="3">Release of commercial product.</td></tr>
<tr><td></td><td>In-Ground/Out of Ground Nursery Research</td><td></td><td colspan="20"></td></tr>
<tr><td>1.6.1</td><td>Field station research</td><td></td><td colspan="2">Deploy present generation node networks at Field Research Station. Varify probe calibrations. Begin initial monitoring and irrigation control.</td><td></td><td colspan="3">Deploy next interation of node networks at Field Station. Conitnue testing monitoring and irrigation control capabilties.</td><td></td><td colspan="3">Continue node network research at Field Station. Conitnue testing monitoring and irrigation control capabilties. Determine spatial and temporal variations for Model.</td><td></td><td colspan="3">Finalize node network research at Field Station. Wrap up monitoring and irigation control.</td><td></td><td colspan="3">Finalize Model development and receive input from industry.</td><td colspan="2">Resolve any industry issues and concerns with Model use.</td></tr>
<tr><td>1.6.2</td><td>Commerical farm Research</td><td></td><td colspan="2">Deploy present generation node networks at Commercial Farm. Begin initial monitoring.</td><td></td><td colspan="3">Conitnue research on node networks at Commercial Farm. Begin monitoring and initial irrigation control. Employ GUI.</td><td></td><td colspan="3">Deploy present generation node networks at Field Research Station. Begin initial monitoring and irrigation control.</td><td></td><td colspan="3">Deploy present generation node networks at Field Research Station. Begin initial monitoring and irrigation control. Employ GUI.</td><td></td><td colspan="3">Finalize Model development and receive input from industry.</td><td colspan="2">Resolve any industry issues and concerns with Model use.</td></tr>
<tr><td>1.6.3</td><td>Technology implementation</td><td></td><td colspan="2">Employ GUI at Reaserch Farm</td><td></td><td colspan="3">Validate GUI effectiveness and improve</td><td></td><td colspan="3">Determine GUI usefulness and improve</td><td></td><td colspan="3">Determine GUI usefulness and improve based on industry needs</td><td></td><td colspan="5">Release of commercial product</td></tr>
<tr><td>1.6.4</td><td>Outreach</td><td></td><td></td><td></td><td colspan="2">Preliminary findings presented at local extension programs and national conferences.</td><td colspan="2"></td><td colspan="2">Write peer reviewed and trade journal manuscripts.</td><td></td><td colspan="3">Previous seasons findings presented at local extension programs and national conferences.</td><td colspan="2"></td><td colspan="2">Write peer reviewed and trade journal manuscripts.</td><td></td><td colspan="3">National conferences and extension programming</td></tr>
<tr><td>1.6.5</td><td>Synergistic activities</td><td></td><td colspan="20">Share monitoring and control data with CMU,UG, Cornell, UC and Decagon to develop model crop software and GUI.</td></tr>
<tr><td></td><td>Software and Modeling</td><td></td><td colspan="3">Begin initial modeling research (Buaerle) and develop baselines for model/ GUI software development.</td><td></td><td colspan="5">Varify GUI utility.</td><td colspan="4">Begin model validation and GUI utility.</td><td colspan="3">Beta testing model/GUI software.</td><td></td><td colspan="3">Release of commercial product</td></tr>
</table>

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	Decagon, CMU				test/evaluate prototypes			collect engineering data from test sites						ollect engineering data from preproduction test site				collect engineering data on production units			
	Deployments	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	dababase	design GUI, refine database			final GUI design/development, develop supporting documentation				refine GUI									
	Evaluate	CMU, Decagon, Antir				evaluate database and GUI			collect user feedback, evaluate				collect user feedback, evaluate				collect user feedback, evaluate					
	Deployments	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			

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 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							

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
	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 incoproratation 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							

Appendix B:

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

8. Project/Grant Period From: (Month, Day, Year) 9/1/2009	To: (Month, Day, Year) 8/31/2014	9. Reporting Period End Date (Month, Day, Year) 8/31/2011

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	$1,297,556.70
b. Cash Disbursements	$1,356,733.97
c. Cash on Hand (line a minus b)	($59,177.27)
(Use lines d-o for single grant reporting)	
Federal Expenditures and Unobligated Balance:	
d. Total Federal funds authorized	$5,161,496.00
e. Federal share of expenditures	$1,356,733.97
f. Federal share of unliquidated obligations	
g. Total Federal share (sum of lines e and f)	$1,356,733.97
h. Unobligated balance of Federal funds (line d minus g)	$3,804,761.03
Recipient Share:	
i. Total recipient share required	$5,161,496.00
j. Recipient share of expenditures	$2,311,626.08
k. Remaining recipient share to be provided (line i minus j)	$2,849,869.92
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	8/31/2011	878,357	439,179	269,856
				g. Totals:	878,357	439,179	269,856

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 penalities. (U.S. Code, Title 18, Section 1001)

a. Typed or Printed Name and Title of Authorized Certifying Official **Sri Latha Nair, Senior Accountant**	c. Telephone (Area code, number and extension) 301-405-2617
	d. Email address snair@umd.edu
b. Signature of Authorized Certifying Official	e. Date Report Submitted (Month, Day, Year) 9/15/2015
	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.