2010

SCRI-MINDS – YEAR 1 REPORT

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

WIRELESS SENSOR NETWORKS FOR FEEDBACK AND FEED-FORWARD CONTROL

JOHN LEA-COX
GEORGE KANTOR
WILLIAM BAUERLE
MARC VAN IERSEL
TARYN BAUERLE
DENNIS KING
DOUG PARKER
RICHARD BAUER
LAUREN BISSEY
TODD MARTIN

15TH NOVEMBER 2010

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Executive Summary

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

A. Project Management:

- Specific working group objectives for year 1 and future years were discussed and developed at the first annual group meeting in January 2010;
- Financial and matching accountability procedures and systems were established and implemented; all subcontracts are invoicing and reporting match on a quarterly basis;
- A virtual workspace (Traction) was established for working group discussions and project management purposes;
- A project website (http://www.smart-farms.net) was established to communicate project goals, participants and general reporting to the public.

B. Research Sites; Grower Sensor Networks:

- Eight University research sites (three at Maryland; three at Georgia; one at Colorado State and one at Cornell) were established to support intensive scientific research projects. Most of these sites are highly sensored to provide a level of replication and precision that is not possible with on-farm networks;
- Sensor networks of varying size and complexity were installed in seven commercial nurseries in Maryland (3), Tennessee (1), Ohio (1) and Georgia (2). These networks are already providing managers with information that is enabling more precise irrigation scheduling and having positive impacts on water use and crop growth (see results and impacts, page 5);

C. Hardware and Software Development:

- The design of the next-generation CMU/Decagon sensor node that will allow for both monitoring and control has been completed; The first prototype units are being manufactured and will be ready for deployment in March, 2011;
- The engineering group provided significant site support for various project networks, both at university research sites and commercial nurseries;
- An improved web-based graphic user interface (software GUI) was developed to provide access to the current generation CMU and Decagon networks; this GUI is under continuous development and is helping facilitate model development;
- A framework that will allow for the clean interface of the plant models with the sensor network data was developed.

D. Model Development:

- The system architecture for the first model (Petunia) was developed and the model parameterized. This model is currently being validated by the University of Georgia team.
- The model inputs for the MAESTRA-based tree models were parameterized.

E. Economic Research:

- The economic team reviewed the relevant literature and outlined potential methodologies, methods of analysis and related software for performing analyses and presenting results;
- Developed a preliminary economic and environmental profile of the overall industry;

- Interviewed and collaborated with industry partners to develop a reasonable strategy for defining and surveying the relevant segments of the industry;
- Designed a set of three survey instruments to use during Year 2 to develop subsector-level and establishment level impact analysis.

F. Results and Impacts:

- Sensor networks were used to actively schedule irrigations at Bauers Greenhouse, Waverley and Raemelton Farms, Hale and Hines and Evergreen Nurseries on a consistent basis during 2010. Changes in irrigation practice were implemented based upon these monitoring data, resulting in considerable water savings;
- In the case of Raemelton Farm (MD), showing that young transplants did not require as much water as thought allowed for the re-allocation of scarce water resources to a 10-acre block of trees that would not have been irrigated in this drought;
- Modifying rain gauges to catch leachate from pot-in-pot production at Hale and Hines nursery (TN) allowed for the precise monitoring of daily water applications, and the instantaneous calculation of daily tree water use by red maple trees;
- Volumetric water content data has allowed Charles Bauers (Bauers Greenhouse, MD) to reduce numbers of irrigations each day, which has reduced the incidence of post-harvest botrytis and increased the percentage of prime quality snapdragon cut-flowers during summer months (a target metric);
- Monitoring of vapor pressure deficit (a "virtual" sensor measurement) was achieved at Bauers using new prototype graphic user interface software, developed by the engineering team;
- Monitoring of volumetric water content at Evergreen Nursery (GA) actually resulted in increased irrigation water applications. The growth of *Gaura lindheimeri* plants was more uniform and time to flowering shortened, giving Will Ross the confidence to use sensor networks on a larger scale;
- Reductions in irrigation volumes resulting in reduced crop losses of *Gardenia* due to root disease at McCorkles Nursery in GA;
- Intensive measurements of ten indicator species were taken at Willoway Nursery (OH) in order to define parameters for the Macroscale MAESTRA model;
- Computerized tomography (CT) scans were done at Cornell of the root systems of the same species, to provide sequential non-destructive measurements of root growth and development;
- A green roof research site with 18 replicate platforms has been installed and intensively sensored at the University of Maryland and is already providing stormwater runoff and substrate temperature data;
- Each research team can remotely login to the irrigation sensor networks at the various nursery and greenhouse operations, to monitor the data in real-time. This greatly facilitates dialogue with the owner/managers and a continuous two-way learning process between researchers and practitioners.

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 product satisfaction of the next generation of hardware and software developed by our commercial partners.

The short and long-term goals of this project are to:

1. Develop and commercialize advanced wireless sensor networks and customizable software to meet the monitoring and control requirements for irrigation at a species level;
2. Determine the performance and utility of moisture and EC sensors for precision irrigation and nutrient management;
3. Address spatial and temporal variability issues to optimize the numbers of sensors;
4. Integrate micro-scale data with macro-scale models to predict short-term plant water use in various environments; provide real-time storm water runoff data from green roofs, to model system efficiency;
5. Quantify improvements in water and nutrient management, nutrient runoff, plant quality, and yield;
6. Evaluate the private and public economic and environmental impacts of precision sensor-controlled practices; identify barriers to adoption and implementation of these practices;
7. Engage growers and the industry in the operation, benefits and current limitations of the sensor / modeling approach to irrigation management;
8. Develop strategies and better management practices for irrigation and nutrient management monitoring, by working with growers with on-farm networks, to innovate and capture needs-based issues;
9. Provide web-based educational materials, focusing on the pros and cons of sensors networks, and the strategies, economics and impacts of this research;
10. Train undergraduate and graduate students in science and engineering.

Approach:

The project consists of seven transdisciplinary teams from five universities and two commercial companies. These teams are organized into six major working groups whose activities are integrated through intensive interaction at the commercial production and research test sites. Each test site is instrumented with a sensor network(s) to provide real-time environmental data for scientific and technological discovery. Data streams are monitored on a day-to-day basis by team members, which drives continuous interaction between scientists, engineers and growers.

The role of the engineering team is to develop, deploy and maintain the next generation of wireless sensor networks which fulfill the needs and expectations of nursery and greenhouse operations and green roof systems. Another major focus of the engineering team is the development of advanced monitoring and control software which will provide advanced data filtering and analysis components. This software will refine incoming data and provide an easy-to-use graphic user interface (GUI) for the end-user to visualize the real-time data and allow for daily management decisions.

The modeling group is developing crop-specific software (plug-in modules) for predictive (feed-forward) management of water use, based upon plant and environmental models developed by the scientific (microscale and macroscale) teams. These advanced software modules will interface with the GUI and the underlying database via an open application programming interface that provides access to all GUI monitoring and control functions.

The role of the science-based teams (micro- and macro-scale) are to ensure that the precision and accuracy of the data gathered, and hence the quality of the conclusions reached, are of the highest possible quality and reliability. The micro-scale effort will address three primary objectives, across disciplines: (a) characterize spatial and temporal variability, to place sensors for maximum precision and economic benefit; (b) sensor performance and placement, to match the right sensor with the right application; (c) monitoring and control capability, which will integrate the knowledge from (a) and (b) to ensure precision control of irrigation water applications, to satisfy plant water requirements in real-time.

The macro-scale effort will address three additional objectives: (d) model and calculate species specific whole tree transpiration in three dimensions to scale up to large production sites; (e) optimize the environmental sensing capability to match model data requirements across scales of production (f) develop and demonstrate an integrated sensing and modeling approach for precision irrigation management for large production scales.

The economic and environmental analysis team members will gather specific economic, resource use and environmental data from each production site through a series of on-farm visits and assessments. All teams will disseminate knowledge through peer-reviewed, trade journal articles and traditional extension presentations. Additional industry and public outreach will include development of an interactive website with podcasts and frequent research updates from the production sites, and on-line learning modules delivered through a Moodle™-based Knowledge Center.

Project Working Groups, Governance, Project Planning and Evaluation

A full description of the project teams and their members (excluding staff and graduate students) are given in Appendix A. Appendix A also provides an outline of how the project is organized into the various working groups (Appendix Table A1) and how the project is governed. Specific project objectives and goals are outlined by working group in a five-year Gantt chart (Appendix Table A2). A logic model provides an overview of the short, medium and long-term metric evaluations (Appendix Table A3). The projects advisory panel members are listed in Appendix A4.

First Annual Project Meeting – January, 2010.

The first annual project meeting was held in College Park, MD from 20-22 January, 2010. The team toured Bauers Greenhouse and Raemelton Farm on the first day, as an opportunity to meet and get to know the various team members and advisory panel members. The objective of the meeting was to revisit the various goals that were originally outlined in the submitted proposal, and specifically to *coordinate* the various team and working group objectives for the first year, as a prelude to future years' work.

Presentations of first year goals and objectives were made during the morning of 21st January:

- Project Objectives, Success Criteria, Working Group Structure – John Lea-Cox
- Administrative Goals – John Lea-Cox
- Engineering Goals – George Kantor
- Hardware and Software Design Goals – George Kantor, Todd Martin
- Micro-scale Objectives – Taryn Bauerle, Marc van Iersel
- Green Roof Objectives – Andrew Ristvey,
- Modeling Objectives – Marc van Iersel, Bill Bauerle, Richard Bauer
- Macro-scale Objectives – Bill Bauerle
- Socio-Economic Objectives – Dennis King, Doug Parker
- Education and Outreach Objectives – John Lea-Cox

Time was taken during the afternoon sessions on the 21 January to discuss the engineering, scientific and modeling teams objectives and goals, and to revise and adjust, where necessary. Similar discussions were had the morning of 22 January for the socio-economic and education / outreach goals. Good discussion was had with the various teams and advisory panel members. Consensus was reached on most major issues.

Sessions were videotaped using Adobe Connect and archived online for reference by the various working groups at later dates.

Project Management and Coordination

A. Fiscal Accounting and Matching Documentation

During year one, many steps were taken to ensure the successful administration of the project in accordance with USDA guidelines. In April 2010, a project Administrative Assistant, Gina Rodriguez, was hired. Administrative goals were set as part of the first annual project meeting.

Ms. Rodriguez has established contact with all of the subcontractors' financial personnel to set up systems for documenting and reporting SCRI expenses. Systems and templates for tracking SCRI participant's hours and activities were also established with all matching partners, to ensure that reports contain all of the information required. Templates for subcontract invoices were also developed to ensure that all invoices contain the required information.

Table 1. Administrative Goals

Activities	Deliverables	Success Criteria
1. Financial	Quarterly Financial and Matching Reports; Annual CRIS Report	Maintain budget goals; On-time reporting
2. Internal Communication	Facilitation Mechanisms - Discussion, Information Exchange - Effective Archival, Retrieval Annual Conference - WG Coordination - Yearly WG Goals and Deliverables	Organizational Mechanisms: - Working Group (WG) Communication and Productivity - WG Yearly Goals met - Advisory Panel (AP) Access and Input
3. External Communication	Public Information Exchange - Project Website; Press releases Education and Outreach - Presentations, Field Days - Knowledge Center	Effective Communication Mechanisms: - Website Establishment - Knowledge Center Establishment - Conference Presentations, Workshops, Field Days - Timely release of information

Systems for tracking and monitoring SCRI expenditures have been put into place 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.

Table 2. Administrative Deliverables

Quarter	Goals	Deliverables
1	Nov 30 - Quarterly report	Q1 – Subaward Financial, Matching Reports
2	Feb 28 - Quarterly report	Q2 – Subaward Financial, Matching Reports
3	May 31 - Quarterly report	Q3 – Subaward Financial, Matching Reports
4	Aug 31 - Year 1 Annual report	Q4 / Y1 – Yearly Financial and Matching Report

A full accounting of all project expenditure is available for year 1, along with matching reports and documentation from all sources. The Financial Reporting form (SF425) for year 1 is attached as Appendix E.

Year 1 invoices totaled $461,738.75 whereas total match amounted to $919,467.60. The matching numbers were largely on target for the year 1 budget, whereas invoiced amounts were low, since many subcontractors had start-up lags in expenditure (e.g. newly employed graduate students and staff were only invoiced for part of the year). We anticipate that expenditures and matching numbers will even out in year 2. Based on year 1 matching totals from our grower partners, we anticipate that these may exceed projected numbers in the year 2 budget.

B. Internal Communication

Another primary goal of the administrative team was to develop and maintain a set of tools for the project that facilitate communication and interaction, but save time and frustration for all project participants. Internal communication goals and deliverable dates were set during the January meeting (Table 3).

Table 3. Internal Communication

Quarter	Goals	Deliverables
1	- Project Management Software (Traction) evaluation by WG members - Establish Adobe Connect Webconferencing facility	- Working Groups Established - WG Communication mechanisms established
2	- Traction Server Upgrade (Full Access for WG + AP members) - Adobe Webconference Access and Use by all WG - Annual Conference (Jan 20-22, 2010) - Project Administrator Hired	- WG + AP access and communication - Weekly Traction Digests - Monthly Webconference - WG Yearly Goals set; Advisory Panel (AP) and Stakeholder Input
3	- Traction; Adobe Use - New Server Specifications	- Traction Digests; Monthly Webconferences - New Server Purchase and Installation
4	- Traction; Adobe Use - Knowledge Center Planning	- Traction Digests; Monthly Webconferences - Moodle Installation (MS Server 2008)

Traction software was purchased by UM to facilitate communication and knowledge-sharing amongst project participants (Figure. 1). This server based software provides an asynchronous (virtual) workspace for all working groups and provides some project management features. Spaces were set up for all working groups to add information at any time during the project.

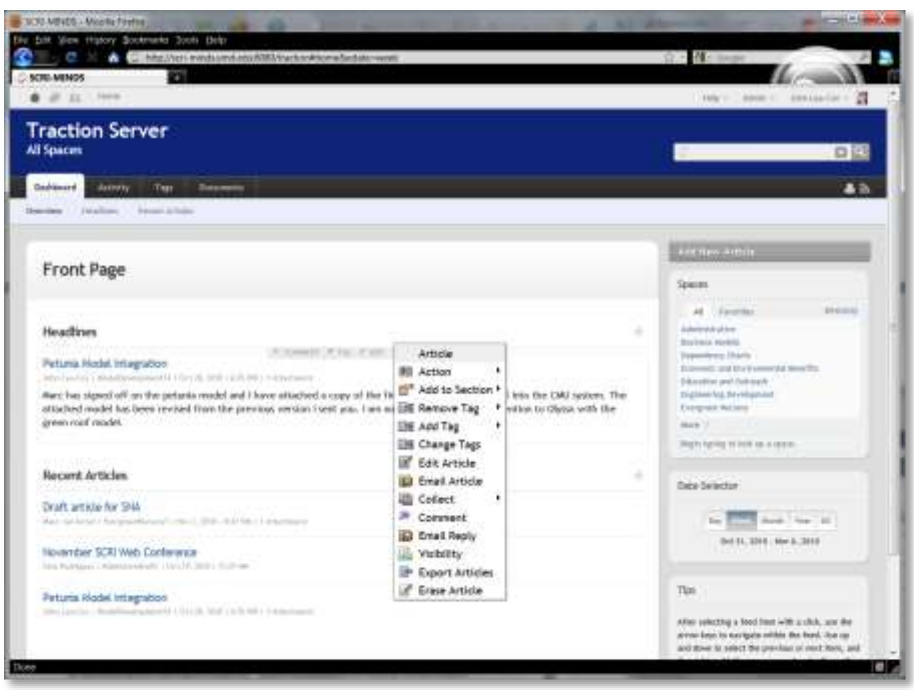


Figure 1. Traction Virtual Workspace.

This virtual workspace provides a mechanism to track notable project interactions and progress updates, and since it is asynchronous, it 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 (Appendix Table A3).

In addition to the traction workspace, monthly SCRI tele / webconferences are held to ensure communication and knowledge-sharing amongst project participants. These are held using Adobe Connect (Figure 2) and a dial-in 800 teleconference number.

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.

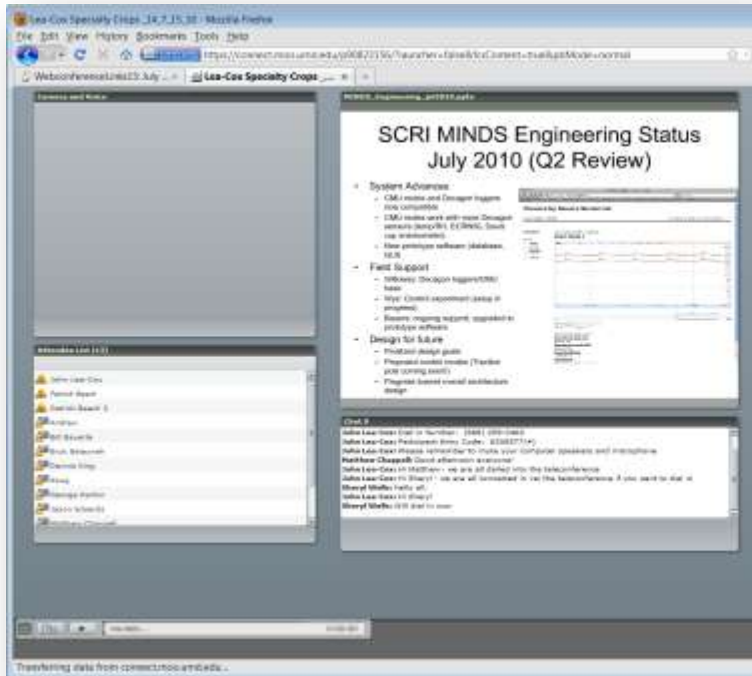


Figure 2. Adobe Connect Webconference Use

C. External Communication

External communication goals and deliverable dates were set during the January meeting (Table 4). The project 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 .org and .net domain names were purchased. The website can be viewed at http://www.smart-farms.org

Both domains mirror the same information at the present time, but there was initial thought that the .net site could become the knowledge center domain in due course. This URL has been publicized through various project press releases and trade articles during 2010. During the first year of the project, 2446 visits from 106 countries were registered on the website, with 332 returning visitors, who viewed an average of 3.5 pages per visit (Google Analytics). Most visits came from India, Canada, United Kingdom, Australia and Spain. Within the US, the most site traffic was from California.

The website is being redeveloped during winter, 2010 to include all the new project information given in this first annual report. The delay in this redevelopment was primarily due to the delay of a new server purchase, for budgetary reasons and prioritizing work schedules to complete the development of the UM research sites during Summer and Fall, 2010.

Table 4. External Communication Goals

Quarter	Goals	Deliverables
1	- Website URL Decision and Purchase - Project Website - Project Press Releases	- Project Acronym, Identity (Brand) - Public Website Established (smart-farms.org) - Project Exposure in Public Media
2	- Current Project Reports; Google Analytics - Website Upgrade Planning	- Website Visitor Metrics - Project Exposure in Public Media
3	- Current Project Reports; Google Analytics - Website Upgrade (smart-farms.net)	- Website Upgrade to include up-to-date project information
4	- Current Project Reports; Google Analytics - Website Update - Knowledge Center Established (smart-farms.org)	- Website Update (new project information) - Knowledge Center Launch (smart-farms.org)

Sensor Network Installations at University Research Sites and Commercial Operations

A. University of Maryland Research Facilities

1. UM Green Roof Research Site

During summer, 2010, 18 green roof platforms were built and sensored at the University of Maryland (Figure 3).
The 1.0m^2 platforms were constructed according to green roof standards and have 10cm of a commercial green roof (M2) shale and pumice substrate.
Each platform is sensored with a Decagon EM50R node, connected to four Echo-TM soil moisture / temp sensors positioned in the green roof substrate and one ECRN-50 rainfall sensor, which measures runoff collected by a gutter at the front of each platform (obscured by plastic cover; Figure 3).

Environmental variables including air temperature, wind speed, solar radiation, temperature/RH and precipitation are also collected at the study site every five minutes (weather station circled in Figure 3).

Figure 3. University of Maryland Green roof experimental site. Insert shows rain gauge installation on the gutter to collect stormwater runoff. Each replicate platform collects substrate moisture and temperature data from four Echo-TM sensors, with a substrate-specific calibration.

Four replicate platforms are each planted with one of the three most common greenroof *Sedum* species (Figure 4). Four substrate-only platforms and two no-substrate, no-plant platforms provide control treatments for stormwater runoff data.

Figure 4. Three common Sedum species: (A), *Sedum kamschaticum;* (B) S. *album* and (C) S. *sexangulare*

2. UM Snapdragon Research Network

A six-node, 30 sensor network was established to support the snapdragon water-use model research at the University of Maryland during Fall 2010. The experimental setup consists of 6 replicated 'troughs' that each rests on 2 load cells that are connected (12 in total) to a Campbell CX10 datalogger. These load cells monitor total trough weight on a continuous basis (Figure 6.)

Each trough supports a 6 foot bag of perlite substrate, exactly as used in the Bauers commercial greenhouse (see description below). Each bag is planted with56 snapdragon plants situated either side of a drip tape that runs along the center of the bag. Each trough drains into a gutter, which in turn drains through an ECRN rain gauge which monitors runoff on a 5-min basis. All troughs are sensored with 2x10-HS and 1 x EC-5 sensors to provide volumetric water content in the bag.

Figure 5. The Snapdragon research network in the University of Maryland greenhouse complex

An additional node is monitoring electrical conductivity (EC) with four of the new prototype EC sensors from Decagon. One last node monitors temperature, relative humidity and PAR at two positions in the row. The entire system is fertigated with the same nutrient solution as used by Charles Bauers. He is providing us ongoing support to provide as near matching cultural conditions (temp, RH and Fertigation management) to the commercial conditions at Bauers greenhouse.

Both the UM Green roof and UM-snapdragon nodes have been recently connected to the Carnegie Mellon server (refer to the Engineering report) which will facilitate the charting of virtual sensors (for example Vapor Pressure Deficit) and the model development for both these projects.

3. Wye Container-Nursery Research Sensor Network

The Wye sensor network was originally established in 2008 with Carnegie Mellon University nodes, to support a research project that quantified nitrogen (N) and phosphorus (P) runoff from 4 native plant species. Twelve replicated platforms (Figure 6) compares sensor-controlled irrigation events (based upon a set-point of -10kPa in the pine substrate) vs. timed cyclic irrigation events that are scheduled with a programmable controller on 12 other platforms. Runoff from each platform is monitored using flow meters and collection barrels (not shown) on a continuous basis.

Figure 6. The Wye Carnegie Mellon network, showing the latest version of the CMU Node (insert, upper left).

Data from four 10HS sensors (placed in random plants on the platform) are averaged on a continuous basis by the node; when the lower matric potential setpoint is reached, a solenoid is activated, turning on the irrigation. When the containers reach container capacity (-1 kPa), the sensors direct the solenoid to switch off. A "micro-pulse" routine was successfully programmed into the software in 2009 which applied 10-15 ml of water per irrigation event, thus applying very small quantities of irrigation water, with almost zero leaching to small 2-gallon containers.

This network is in a fairly remote location on the Wye research farm, about 1 mile from the nearest building. Data is transmitted over that distance to an antenna located on a barn close to the office buildings, and then via the internet, to a server located at CMU in Pittsburgh. We have experienced baffling network interference with the base station during the entire time this network has been active. It has been established that there is apparently a (we think DOD) network in the area that is interfering with the 900 mHZ signal. There was no issue with the CMU nodes, which performed very well scheduling automatic irrigations. However, when they attempted to communicate with the base station, they would often make repeated attempts, shortening the battery life, with no data relaying. Much time and effort was made during 2010 to resolve the issue, with little progress. We decided in late summer to make the Wye site a priority for the next generation Decagon nodes, to be installed in early 2011.

B. Bauers Greenhouse – Jarrettsville, MD

The 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.

Bauers Sensor Network Description:

A six-node Carnegie Mellon wireless sensor network was established in three zones in the Bauers production greenhouse in early 2009. These zones are related to the growth stage of the crop, since the greenhouse is in continuous production, each crop taking between 14 weeks (summer cultivars) and 20 weeks (winter cultivars) to produce. Decagon EC-5 and Echo-TM sensors are monitoring the substrate water content at three positions within each 72" x 12" bag of perlite, which is used as the substrate. Current plant density is 56 plants per bag. Additionally, we are sensing soil temperature, canopy air temperature and relative humidity and photosynthetically active radiation (PAR) on a 5-minute time interval for each block.

The greenhouse is a closed hydroponic system, so they have the ability to fertigate as frequently as necessary, without compromising efficiency. The ultimate goal is to maintain an optimal water and nutrient status for different stages of crop growth, with as little human intervention as possible.

Figure 7. A Carnegie Mellon sensor node in Bauers greenhouse.

Production Objectives: The primary production objectives of this study are to improve the quality of cut-flower snapdragons, particularly those produced during summer months. Maintaining the water and nutritional status of the crop during the summer months is the ultimate challenge, given the growing conditions in the greenhouse at that time of the year. An economic test of the sensor network will be to increase the percentage of No.1 quality cuts from an average of 80% in summer to about 92%, which is the current average for the rest of the year.

Additional benefits have accrued from using the sensor networks during 2010. These results are discussed in the microscale working group report.

C. 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.

The primary objectives of these networks are to:

1. Evaluate the performance of these sensors and the capability and stability of the system to provide real-time data to Mr. Steve Black (the owner) to make more precise irrigation decisions. 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.
2. The ultimate objectives of this research are to determine whether these 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.
3. Additionally, Mr. Black would like to explore extending the life of the tree inventory on the farm, by optimizing initial growth rates, and at the appropriate time, to minimize water and nutrient inputs to slow tree growth and extend the "marketing window" of saleable trees.

1. Mature Maple and Dogwood Sensor Networks:

We established two, four-node wireless sensor networks (Decagon Devices), in two blocks of 'indicator' trees in 2008. We now have three years of data from these networks.

The sensor networks are monitoring the soil water status at two depths (at 6" and 12") within the root zone of ten *Acer rubrum* 'Franksred' Red Sunset® and ten *Cornus florida* 'Cherokee Princess' trees at 15-minute intervals (Figure 8). These specific blocks of trees were chosen since *Acer rubrum* represent a species with one of the largest water and nutrient requirements on the farm, while *Cornus florida* represent a slow-growing model species. As such, the average data from the sensors in each block are used to make irrigation scheduling decisions for similar species on a daily basis.

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 proide daily and seasonal microclimatic data.

Figure 8. Decagon EM50R network on *Cornus florida* trees at Raemelton Farm. Insert shows sensors located in PVC tube in the root zone.

2. Rootbox (3-year) Study Network:

We have a very dense (12 nodes; 60 sensors) network installation on three *Acer rubrum* ‘Franksred’ Red Sunset® trees that was installed in May, 2009. This study is monitoring soil moisture at 3 depths in two dimensions (in-row and across row) over time (Figure 9). Irrigation events are quantified using a ECRN-50 rain gauge on each tree. The network is providing replicated temporal and spatial information on water movement from the two drip emitters either side of each tree, on a 15-minute basis. A Decagon “weather station” node is installed by this rootbox study to provide microclimatic data (windspeed and direction, air temp/RH, rainfall, PAR and leaf wetness). Some initial results from this study are presented in the Microscale working group report.

Figure 9. Decagon EM50R network on one of three *Acer rubrum* ‘Franksred’ Red Sunset® trees with 18 x10HS soil moisture sensors at three depths (6”, 12” and 18”) at 6 positions around each tree.

3. New Transplants Network (2010):

We established two, one-node (five sensor) network in a newly tranplanted *Acer rubrum* and *Cornus florida* block in late June, 2010. Four 10HS Decagon sensors were placed at a 6” depth directly in the root zone of each tree, to monitor soil moisture ***in*** the rootball, rather than under the drip emitter, as had been done previously. This was done to directly monitor how long it took for an irrigation event to move into the root zone, and provide Steve Black with a capability to monitor the soil moisture status of his newly transplanted blocks which are irrigated daily. Irrigation events were again captured with a ECRN-50 rain gauge (with a rain cover) under a dripper in the row (sensor in ground container, shown without lid in Figure 10).

This network had an immediate impact on scheduling irrigation on this 10-acre block and the entire farm during this drought year in 2010. Preliminary results are discussed in the Microscale working group report and the Economic working group report.

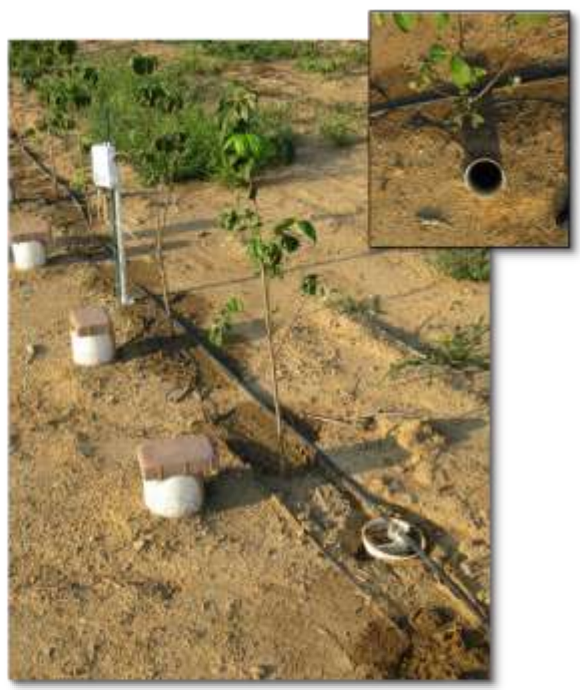


Figure 10. One-node network on four *Cornus florida* transplants; note the surface drip irrigation pattern from two emitters (top inset).

D. Waverley Farm – Adamstown, MD

Similarly to Raemelton Farm, we have deployed three individual Decagon sensor networks 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 (2010). The entire farm is again 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. This reflects another major irrigation philosophy used by ornamental producers in soil systems (i.e. longer irrigation times to replenish the volumetric water in deep soil layers).

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. Three rows of Leyland cypress are being monitored in this block, since each row has a different rate of organic matter incorporation (Figure 11). Mr. Faulring is interested in ascertaining whether these varying incorporation rates have any effect on increasing soil water holding capacity, with a concommittant reduction in irrigation water requirements over the long-term. Environmental data are also being monitored on a 15-minute basis at the Leyland site.

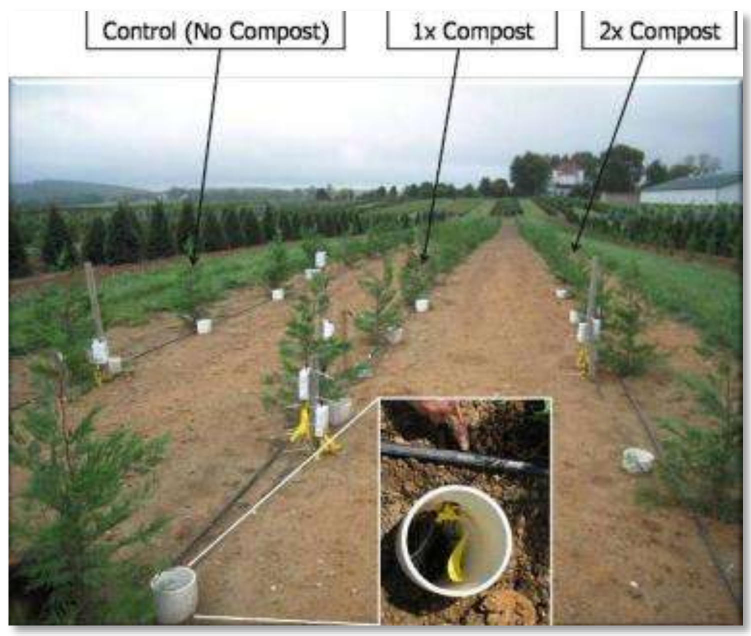


Figure 11. Leyland Cypress study network, indicating the control, 1x and 2x compost incorporation rates.

***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.

E. Hale and Hines Nursery, McMinnville, TN

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 US. 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 (Figure 12).

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. They use a 75% pine bark: 25% recycled waste paper substrate in his containers. Since rooting volumes are more limited, and because of the soilless substrate, irrigation scheduling is much more rapid than in field soils. Leaching of nutrients from containers is likely without careful irrigation scheduling.

Figure 12. Hale and Hines Pot-in-pot operation, showing trees growing in 30-gallon containers in the nursery.

Mr. Terry Hines installed his own sensor network in 2009 with the assistance of John Lea-Cox, to monitor substrate water content primarily in his Dogwood blocks. In spring 2010, these networks were reconfigured and an intensive 6 node (30-sensor) Decagon network was installed on three Red Maple 'Sunset Flame' trees (Figure 13).

Eight 10-HS sensors were placed in each rootball, positioned as shown in Figure 13. Additionally two ECRN-50 rain gauges were placed on each tree (Figure 14) to measure (A) the applied irrigation volume from the irrigation emitter (rain cover not shown) and (B) the leachate volumes obtained from each 30-gallon container.

The tree container was modified to catch the leachate from the outer socket pot, directed through the ECRN-50 rain gauge (see Figure 15.)

Figure 13. Red Maple network (at right) showing 10-HS sensor placement in the container.

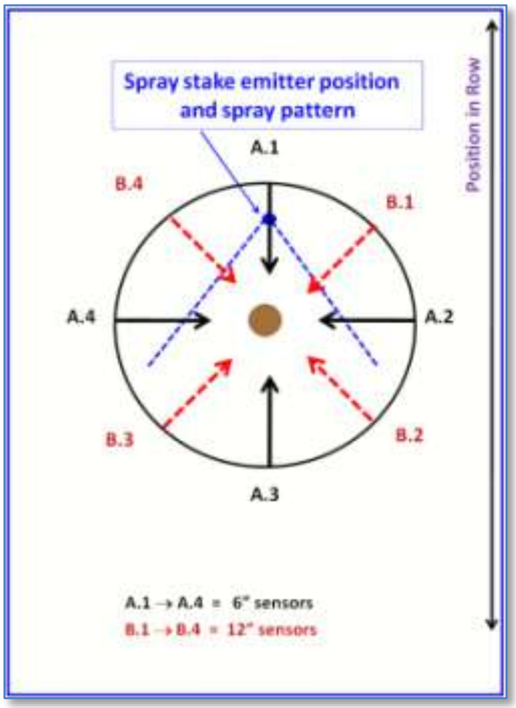


Figure 14. Cross-section of 10-HS sensor placement in 30-gallom Maple tree rootballs.

Figure 15. Installation of ECRN-50 rain gauges to measure (A) applied irrigation volume and (B) leachate volumes from the 30-gallon container.

In this way, Terry Hines could accurately monitor irrigation water applications and leaching simultaneously, providing him with a very sensitive indicator of when the substrate was saturated. By monitoring the eight sensors placed in the upper and lower quadrants of these trees, we could map spatial and temporal water movement in real-time and relate that to irrigation volume and periodicity of applying water.

Terry Hines reconfigured some other nodes in May, 2009 to provide him similar data for other indicator species, including *Betula nigra* (River Birch) and various *Cornus florida* (Dogwood) cultivars. Some initial results are discussed in the micro-scale working group report. The innovative thinking shown by Mr. Hines demonstrates the power of partnering with growers in this research, since they understand the potential application of these sensor networks much better than researchers, in many instances.

F. University of Georgia Research Facilities

Research at the University of Georgia is performed at several different locations, with the nursery component of the work being conducted at two different localities, one in North Georgia (UGA Horticulture farm in Watkinsville, GA) and one in Tifton (UGA's Tifton campus). Greenhouse research is conducted at the Riverbend research greenhouses on the UGA campus in Athens, GA.

1. Riverbend research greenhouse complex.

These are the main research greenhouses for the horticulture department. Facilities include glass-covered greenhouses with computerized environmental controls, growth chambers, and a headhouse with laboratory space. Most of the MINDS research is conducted in the greenhouses.

Several systems have been set up for our research. The largest of our systems is a 32-plot irrigation system with two EC-5 soil moisture sensors in each plot. These sensors are connected to a Campbell Scientific data logger using multiplexers. The datalogger measures those sensors, averages the readings of the two sensors in each plot, and then compares those averages to plot-specific set points. If the substrate water content drops below the set point, the datalogger uses a relay driver to open the irrigation valve for that plot, applying a small amount of water. This allows for precise control of substrate water content.

Figure 16. ***Overview of the 32-plot sensor-controlled irrigation system at the UGA Riverbend research greenhouses.***

This system has been used for studies looking at the effect of substrate water content on growth, water use, physiology, and gene expression of various crops, to do a study comparing responses of different species to drought stress, and to look at interactive effects of substrate water content and fertilizer rate on plant growth, flowering, and water use.

Other facilities available at the research greenhouses include an 8-chamber whole plant gas exchange system, which allows us to monitor whole plant CO_2 exchange and transpiration over long periods, and a load cell system that allows us to monitor plant water use of up to 24 plants precisely and over long periods.

We recently used a similar approach to automate irrigation of 10 ebb-and-flow benches (3' x 5' each). We use three EC-5 sensors per bench, and irrigation is triggered based on the average reading of those three sensors. This system has been tested in a study looking at growth of *Hibiscus acetosella* and performed well.

Control of substrate water is not precise since the pots are subirrigated and we have no control over the amount of water that gets taken up by the substrate during an irrigation event. Thus, we can control precisely at which water content plants get irrigated, but not how much water is applied.

Figure 17. Sensor controlled subirrigation system at the UGA research greenhouses in Athens.

A third automated irrigation system is designed for control of both substrate water content and substrate EC (either bulk or pore water EC). Using sensors that can measure both substrate water content and EC, a datalogger can decide when a particular plot should be irrigated, and whether plants should be irrigated using plain water or fertilizer solution.

We have tested this system using 5-TE sensors and noticed that these sensors were not optimal for soilless substrates. We are currently testing Decagon's new GS-3 soil moisture and EC sensor and hope that this new sensor will be a better fit for this system.

Figure 18. Irrigation System controlled by Electrical conductivity (EC) and water content at the UGA research greenhouses in Athens.

2. Nursery plots. Two identical soil moisture sensor-controlled irrigation systems were installed on the horticulture farm in Watkinsville, GA (near Athens) and on the UGA campus in Tifton. Both of these research sites allow for irrigation control of 16 plots, using 10HS soil moisture sensors. Like the greenhouse systems, these irrigation systems are controlled using a CR10 datalogger and relay driver. We used these sites during summer, 2010 to look at the effects of substrate water content on growth and water use of *Hibiscus acetosella*. Both of these irrigation systems performed very well, with good control over substrate water content.

Figure 19. S sensor-controlled irrigation systems in Nursery plots at Watkinsville, GA (near Athens) and at the UGA Research and Education Center campus at Tifton, GA.

G. Evergreen Nursery – Chatham, GA

Evergreen Nursery is a family-owned and operated nursery in Statham, GA, just outside of Athens. The nursery specializes in groundcovers and perennials. Container sizes range from cell packs to two gallons, and the nursery produces a wide variety of plants. They are a grower partner in the MINDS project, and the University of Georgia uses the site for their research. Research has included comparative water use of soil moisture sensor controlled irrigation and 'standard' irrigation practices, as well as the use of wireless Decagon network to allow Will Ross to monitor substrate water content in selected crops. Currently, Will Ross uses the wireless network to monitor substrate water content in three different hoop houses twice daily. The three crops that are monitored are hellebores (Lenten rose), delosperma (ice plant), sedum, gaillardia, and lantana.

1. Comparing water use with sensor-controlled versus standard irrigation. In this study we compared the water use of *Gaura lindheimeri* plants that were irrigated either using standard practices (Will Ross watered these plants as he usually does) or using soil moisture sensors (10HS, Decagon Devices) connected to a datalogger (CR200, Campbell Sci.). Three sensors were installed in the sensor-controlled plot and the datalogger averaged to soil moisture readings of the two sensors reading highest. The sensor with the lowest reading was ignored to prevent erroneous sensor readings turning the irrigation system on. Plants were irrigated when the average of the two sensor readings dropped below 0.35 m^3/m^3. Surprisingly, sensor-controlled irrigation resulted in 18% higher water use than 'standard' irrigation. Substrate water content was more stable, and higher, in the plot were irrigation was controlled using soil moisture sensors. Also surprising was the clear visual difference between the crops, with plants in the sensor controlled plot flowering much better (see picture). Perhaps the most important outcome here was that the grower, Will Ross, gained confidence in soil moisture sensor-controlled irrigation, and is willing to try this out on a larger scale.

Figure 20. Visual appearance of plants grown using standard irrigation practices (left) versus sensor-controlled irrigation (right) at Evergreen Nursery.

2. *<u>Monitoring substrate water content</u>*. We have been monitoring substrate water content in three hoop houses since late spring. Will Ross monitors the data twice daily and is using that information to decide whether to irrigate those houses or not.

Figure 21. A Decagon EM50 datalogger is suspended above a lantana crop (left). Substrate moisture content in the crop is monitored using EC-5 sensors, while irrigation is monitored using a rain gauge (left) at Evergreen Nursery.

One thing we noticed was that there seemed to be a fair amount of leaching following irrigation, and to try to reduce, Will Ross changed the irrigation in the house with the lantana and gaillardia from one 15-minute irrigation to two 8-minute irrigations. A screenshot from the period this change was made is shown below. The much slower decrease in substrate water content after an irrigation suggest that this change in irrigation practices did indeed reduce leaching.

Note that we access to this wireless system over the internet, using the Teamviewer software.

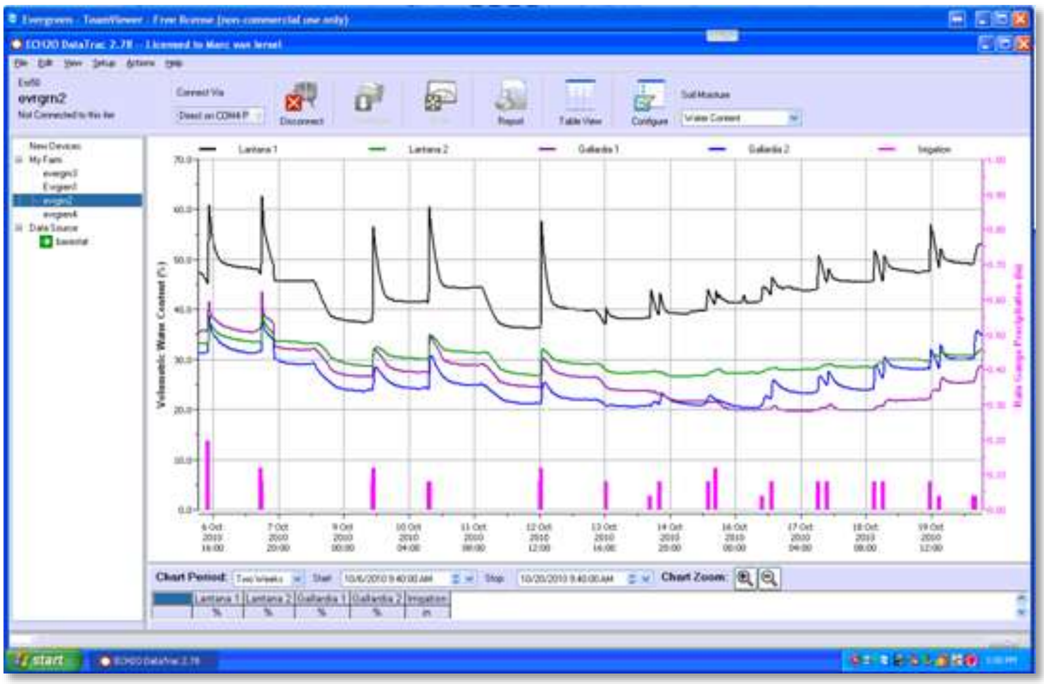


Figure 22. Screenshot from Evergreen Nurseries, showing the period that irrigation of the lantanas and gaillardias was changed from one 15-minute period to two 8-minute periods. The black and green lines show substrate water content of lantanas, while the purple and blue line show Gaillardia data. The pink bars indicate irrigation. Note that the decrease in substrate water content became much less following this change, suggesting that leaching was reduced.

H. McCorkles Nursery, GA

McCorkle Nurseries is a large family-owned nursery in Dearing, GA, close to Augusta. The nursery has been in business since 1942. They are among the largest nurseries in Georgia, producing over 4,000,000 plants per year, in pots ranging from 1 to 15 gallons. Production focuses on woody plants and herbaceous perennials. Plants are produced in two locations, the Luckey's Bridge and Neals Mill farms. The Luckey's Bridge farm alone requires up to 3 – 4 million gallons of water per day.

The UGA research is located on the Neals Mill farm , where two different projects are ongoing. The first project is a comparative study looking at irrigation water use of gardenia when irrigated according to 'standard' practices as compared to soil moisture sensor-controlled irrigation.

Figure 23. Aerial view of part of the Neal's Mill production facility.

The sensor controlled irrigation is achieved using MoistureClick irrigation controllers (Dynamax). There are five plots controlled using MoistureClick controllers and five plots irrigated according the McCorkle's standard practices. Water use in each plot is monitored using flow meters. We are using gardenia as a model crop here, because it is very susceptible to root diseases, especially when the crop is overwatered. This causes significant plant and financial losses at McCorkle's each year. Interestingly, there has been no disease in this crop so far. In plots irrigated using MoistureClick, the lack of disease may be due to the fact that we are not overwatering. And we suspect that the gardenias that are supposedly being irrigated using 'standard' practices get much less water than gardenias normally do in this nursery.

Figure 24. A MoistureClick irrigation controller

Interestingly, we have seen that a neighboring crop of gardenias did suffer from severe disease problems. That crop was not part of our study and likely watered more according to their regular practices. In short, it appears as if the 'standard' irrigation was reduced, simply because those plants were part of a water use study.

Our other project at McCorkle Nurseries is the use of a wireless Decagon network to monitor substrate water content in various crops. Data collection here also is focused on gardenia, because of the potential benefits of improved irrigation practices for this crop. A total of four EM50R dataloggers are deployed, and those loggers are sending data to a basestation and laptop in the McCorkle office at Neals Mill. One of these loggers is configured as a weather station (rain, temperature, light, RH), while the other three loggers have four soil moisture sensors connected to them. We will add a rain gauge to these three loggers soon, so that we can monitor irrigation as well.

Figure 25. The production area used for a study looking at water use of gardenias. Out of 10 plots, five are watered according to standard practices, while the other five are irrigated using MoistureClick irrigation controllers.

McCorkle personnel have real-time access to the data, while we are able to access the computer over the internet. Although these data are not yet used to alter irrigation practices, growers are monitoring the data, and hopefully will become comfortable with having this type of information.

McCorkle Nurseries already has expressed interest in trying sensor-controlled irrigation for some of their crops. We have done several studies here in the past where we have been able to show that this is a feasible approach.

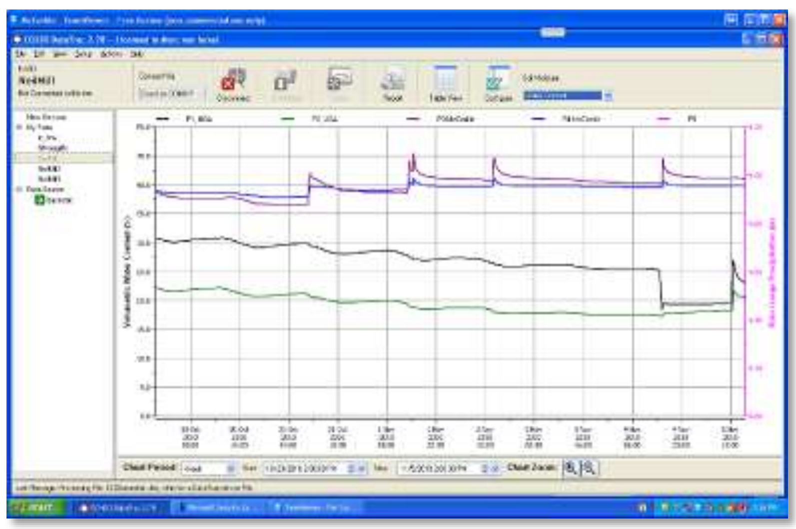


Figure 26. Screenshot from the computer at Neals Mill farm running DataTrac to display the data from the wireless Decagon network.

Although technically not a part of our SCRI-MINDS research at McCorkle's, we are also conducted related research at the Center for Applied Nursery research which is located on the Luckey's Bridge farm. The CANR is an industry supported research site for applied projects that can be conducted under realistic nursery conditions.

In 2010, two MINDS-related studies were conducted at this site. One of these projects was aimed at quantifying daily water use of two hydrangea cultivars. To do so, plants were placed on load cells and weighed at midnight and at 10 pm. The decrease in weight was the daily water use of that plant. The second MINDS-related study at CANR looked at the effects of irrigation practices on leaching, substrate EC, and plant growth. We hope to continue conducting MINDS-related projects at CANR in the future.

Figure 27. A hydrangea plant on a load cell to determine its daily water use.

I. Colorado State University Research Site

In spring of 2010, we installed a 100-socket, 57-L, pot-in-pot research plot at our macro-scale replicate research site in Fort Collins, Colorado. Ten replicate trees of ten commercially popular tree species were installed and connected to a pressure regulated micro-spray emitter irrigation system. Each of the ten species were irrigated separately (Figure 28A) and irrigation was measured per species with in-line paddlewheel flow meters (Omega FP-5300, Omega Engineering Inc. Stamford, CT, USA) (Figure 28B) connected to a data logger (Campbell CR1000x). Trees were fertilized once in May with a 19-6-12 timed-release fertilizer. Meteorological data was continuously measured, averaged over a five minute period and recorded (EM50 R, Decagon Devices Inc., Pullman, Washington, USA).

Throughout the growing season, the ten species were used for supplemental acquisition of gas exchange data (details described in Willoway section) to quantify parameters used in a three-dimensional, spatially-explicit, canopy transpiration model (MAESTRA). These parameters include measurements of enzyme limitations to photosynthetic rates, dark respiration, and photosynthetic response to changes in temperature and vapor pressure deficit. We also used this plot to implement a three-dimensional array of soil moisture sensors. At 20, 40 and 60 cm depths from the soil surface we installed four 5TM soil moisture sensors (Decagon Devices, Pullman WA, USA), one in each of the four cardinal directions (n = 12 sensors per container). The data from these sensors will be used to model the movement and distribution of soil moisture within the nursery container using a species specific spatially explicit substrate moisture model (HYDRUS-3D).

Figure 28 (A) Species specific solenoid irrigation control and (B) in-line species specific irrigation measurement.

J. Willoway Nursery, Avon, OH

In May of 2010, ten experimental macro-scale plots were established within a one hectare parcel at Willoway Nurseries Inc. L.L.C. in Avon, OH (41° 25' 30" N, 82° 2' 59" W). Trees were grown pot-in-pot in 57-L containers. Plants within each plot were spaced 1.5 m center-to-center and irrigated twice daily to container capacity with spray stakes (Netafim Inc., Israel). Five to seven replicate trees (n = 5-7) per species were randomly selected for repeated sampling of substrate moisture and temperature within each plot.

Substrate volumetric water content (VWC, $m^3\,m^{-3}$) and temperature was measured in replicate containers using model 5TM sensors (Decagon Devices Inc., Pullman, Washington, USA). Sensors were inserted horizontally through the side of the pots through a circular cut of sensor width. Hence, each container replicate had one sensor 20 cm below the soil surface and equidistant from the three container walls. One replicate per plot was randomly chosen and additional sensors were placed at depths of 10cm and 30cm to create a vertical soil moisture profile. Substrate sensors were sampled at 1 min intervals and 5 min averages were computed and stored (EM50R, Decagon Devices Inc., Pullman, Washington, USA) from May 21 to September 15, 2010.

Figure 29. Decagon Nodes at Willoway Nursery in Avon, OH.

Substrate sensor VWC readings were factory calibrated to our specific substrate. In addition, an independent micro-weather station was installed in each species plot (e.g. Figure 29). We measured air temperature, humidity, wind speed and direction, and precipitation for direct model input.

One objective of this study was to develop an understanding of substrate moisture distribution patterns within container-grown plant material. By focusing on ten commonly cultivated tree species (T. Demaline, personal communication), our analyses attempt to isolate and quantify different deterministic sources of substrate moisture variability. Specifically, we are analyzing the variation in substrate moisture within blocks of trees of the same species, determining the variation among different species, and exploring the change in substrate moisture variation over a growing season. We hypothesized that the optimum number and arrangement of substrate moisture sensors varies among species and changes with time. After establishing the spatial and temporal variation, we are determining the minimum number and arrangement of substrate moisture sensors for each of our ten study species.

Figure 30. Duel gas exchange systems were used to collect the seasonal change in physiological parameters (model input) for ten species. Cuvette close up at right illustrates environmental control (e.g. light) for the characterization of species responses across variable environmental conditions.

Over the course of the growing season, we also measured variables for a species specific transpiration model to include: gas exchange (Figure 30), leaf spectral characteristics, wind speed attenuation, growth attributes, and remote sensing characteristics (Figures 31A and B) on a monthly basis. The data from these measurements are currently being used to parameterize a 3D canopy transpiration model (MAESTRA) for an entire growing season. In 2011, it will be used to provide estimates of water usage per species and remotely schedule irrigation on a species basis.

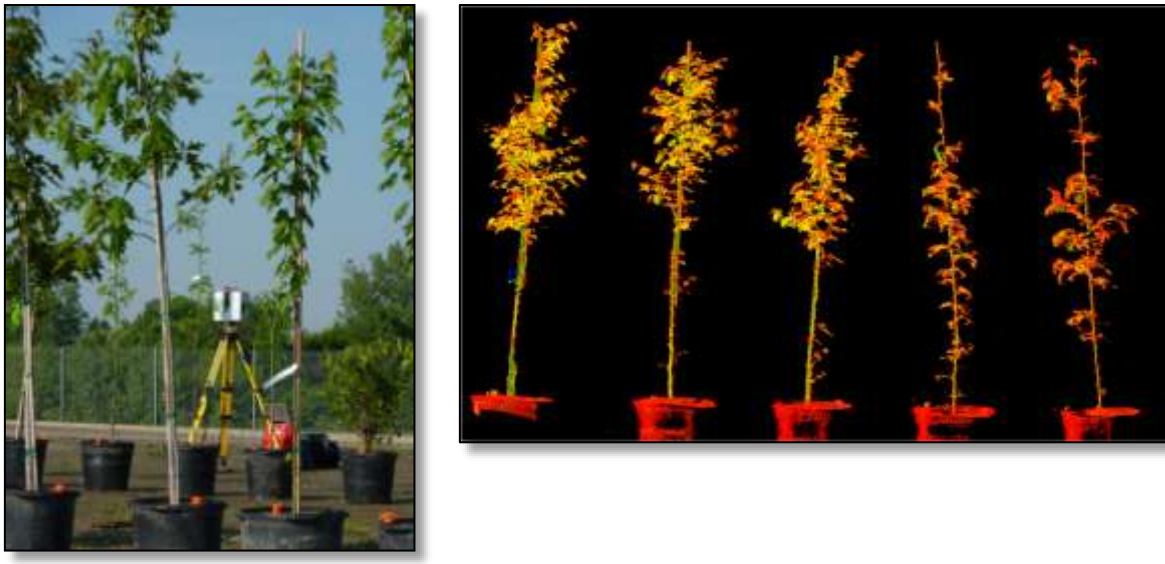


Figure 31 (A) Light detection and ranging (LiDAR) scanner was deployed over the course of the season to remotely measure individual tree dimensional characteristics (e.g. leaf area, height, and caliper) and (B) LiDAR imagery of the trees.

Engineering Working Group Report

Carnegie Mellon University and Decagon Devices

Engineering team activities and associated objectives in Year 1 fell into three basic categories: Supporting field work with existing equipment, beginning the process of model development, and designing a future iteration of the proposed wireless sensor network and control system. The specific objectives in these areas were

- Field Support
  - Maintain and upgrade current CMU sensor network at Bauers Greenhouse (Jarrettsville, MD)
  - Install and support closed loop irrigation experiment at UMD Wye site (Queenstown, MD)
  - Install CMU/Decagon hybrid system at Willoway Nursery (Avon, OH)
- Model Development
  - Determine requirements for interfacing to plant physiology models
  - Develop initial off-line prototype model for one crop
- Design
  - Identify design goals for next iteration system
  - Design hardware and software components for next iteration

1. *Design Activities*

The primary result of Y1 design activities is a documenting that describes the design of the prototype system that will be made available to the MINDS team in early 2011 (see "Design of the 2011 Generation MINDS Wireless Sensing and Control System" attached in Appendix B of this report). However there were two notable accomplishments that led up to this document, including both the development of ideas and the demonstration of some basic technical components that will go into the 2011 system.

- **CMU/Decagon Compatibility:** The designs of the existing CMU node and basestation were modified to make the CMU system over-the-air compatible with the Decagon EM50R system. Changes to the hardware (installing a different radio on base and node) and software (new data packets and implementation of Decagon's confirmed delivery protocol on the CMU base). The result is that CMU and Decagon equipment can now be used together in the same network using the CMU basestation. Additionally, software was developed to convert data collected by the CMU basestation into a format that can be viewed in Decagon's DataTrac software.
- **Web-based GUI Prototype:** An improved web-based user interface was developed to provide access to data from the hybrid Decagon/CMU system. The functionality of this interface is described in detail in the design document in Appendix B. The interface to the Bauer site provides a good example of the current state of this interface (see http://68.25.208.149:3000, username:guest, password: guest) A few of the highlights include:
  - Map-based status page shows node locations
  - Charting tool allows customizable interactive time-series plots
  - Node configuration tools that allow a user to manage sensor types and control functions.

2. *Model Development*

One of the most important activities in the area of model development was communication: engineers (primarily Richard Bauer and George Kantor) had many long discussions with plant scientists (primarily Marc van Iersel and Bill Bauerle) to determine the technical constraints and requirements associated with implementing plant physiology models with sensor network data. This resulted in two primary achievements.

- **Model Interface Specification:** A framework for implementing models that will allow them to be cleanly interfaced with sensor network data was developed and communicated with the team. In particular, the requirements for model inputs, model parameters, and model outputs were determined for the van Iersel petunia model and MAESTRA-based tree models.
- **Initial Model Prototype:** An off-line version of the petunia model was implemented in a format compatible with the framework mentioned above. This model is nearly ready for test. A detailed outline of the model is shown in Appendix C.

3. ***Field Support***

Significant engineering effort was spent in year 1 on field support of research sites. In addition to providing MINDS scientists with the data they need, these activities provide a setting in which we can both stress test more well-developed mature technologies and as well as try out new experimental ideas.

- **CMU Testbeds:** Two testbeds were set up in Pittsburgh to support engineering development and testing. A small (4-node) indoor irrigation experiment was set up in a CMU lab for to provide CMU engineers with a local testbed to develop and explore. Currently, micro-pulse set-point irrigation is being used to automatically irrigate a small collection of plants that are being grown in a variety of substrates under artificial lighting. A second small (3-node) outdoor network was set up at CMU's Robot City test site.
- **Wye site:** Unfortunately, not much progress was made at the Wye site in spite of concentrated effort. Much of the summer of 2010 was spent troubleshooting Internet communication issues, which were finally solved with the installation of a cellular modem at the site. In addition to problems with Internet access, there is a large amount of RF interference from an unknown source near that site, which causes the sensor network communications to be unreliable. Initial testing with a point-to-multipoint sensor network shows promise for overcoming these issues, and that will guide our activities at that site for the 2011 growing season.
- **Willoway site:** Year 1 activities at the Willoway site relied exclusively on the Decagon EM50Rs for data collection. The engineering team developed means for providing remote Internet access to Decagon-only test sites such a Willoway. This approach uses the modified CMU base station to collect data from Decagon EM50Rs, which is then served over the web. In May 2011, a 21-node Decagon network was installed at Willoway using this method of remote access. It has provided continual, reliable remote access since installation.
- **Bauer site:** the Bauer greenhouse test site, which had been instrumented with a CMU sensor network before the project started, was maintained and expanded. Two nodes were added. The network was upgraded to use the newly developed database/GUI system. New sensors have been added, including PAR sensors and temp/RH sensors.

Microscale Working Group Report

A. University of Maryland

Our research, which is initially focused at the microscale has five primary (ongoing) objectives:

1. Quantify temporal and spatial soil or substrate moisture variability, to optimize the placement of sensors, and minimize the cost of sensor networks
2. Formulate best management strategies for the installation and use of sensor networks, to include the use of various sensors in different environments, for maximize utility.
3. Quantify (reduced) water and nutrient use and reduction in leaching losses from container production
4. Quantify parameters for green roof stormwater modeling
5. Quantify parameters for snapdragon water use and modeling

With regard to these objectives, we demonstrated the following results during year 1 of this project:

1. Bauers Greenhouse

- Volumetric water content of the perlite substrate has been better optimized based on soil moisture sensor data, and has provided Charles Bauers with insight into the effects of high morning turgor pressure in his crop, with regard to the development of post-harvest *Botrytis* infections
- The development of the prototype Carnegie Mellon graphic user interface has allowed for the instantaneous calculation of vapor pressure deficit, and more felixible charting options, which allows Charles Bauers to better gauge water use by the crop.
- The percentage of primary quality (#1) snapdragons increased during summer 2010 (a target metric).

With regard to system improvements and challenges, Charles has indicated these priorities:

- Improved system network reliability
- Improved power management on the nodes
- Expanded monitoring capability (additional sensors)
- Streamline the graphical user interface functionality

2. Raemelton Farm

- Based on data analyzed from the root box study gathered during Fall 2009, it was determined that 4 short cyclic irrigations per day provided more lateral water movement in the soil profile than 2 longer irrigations of the same volume.
- Newly transplanted blocks are ***the*** most important priority for irrigation during any year for a number of reasons. Thus, in times of water shortages, transplants typically received at least 2 hours of water per day. By providing precise soil moisture data (Figure 32) to Mr. Black from these transplant blocks, he was able to maintain his target root zone moisture content (Blue horizontal bar) from 23-27% VWC with only 1 hour of irrigation per day.
- He could then reallocate this water to another 10-acre block of trees (see Figures 33 and 34).
- We are following up with an economic case-study of this situation (see Economic team report)

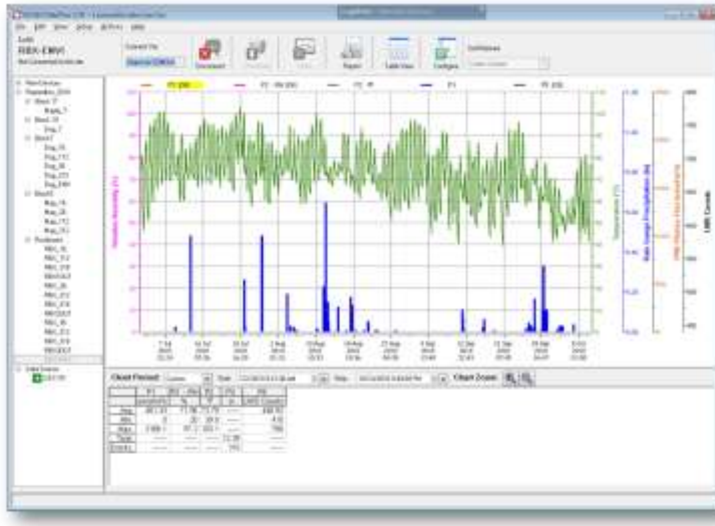


Figure 32. 2010 Rainfall and soil temperature data for Raemelton Farm. 2010 was a drought year, with just 12.4” inches of rain between July and September.

Consequently, with a high irrigation water demand, scheduling irrigations was a challenge.

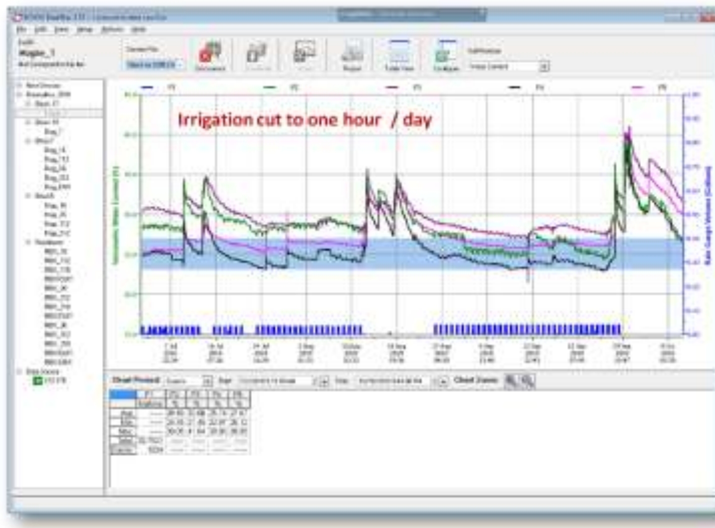


Figure 33. 2010 Maple Transplant Block Sensor Data

By providing precise soil moisture data in the 2010 transplant block, Steve Black was able to halve his normal irrigation frequency from 2 to 1 hour per day on these 10 acres. This amounted to a water savings of 30,240 gals of water per week (1 hour x 7days), which allowed him to then reallocate this water to another 10-acre block of 2-year-old trees (see Figure 34).

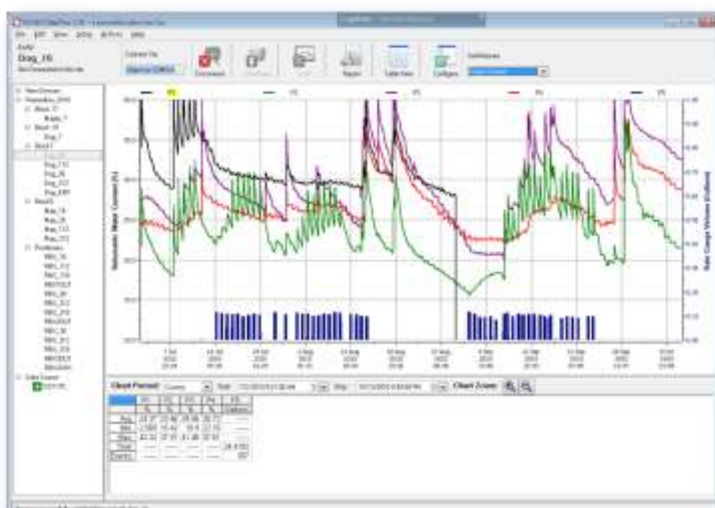


Figure 34. 2010 Dogwood Block soil moisture data at 6” depth. Irrigation volumes indicated by blue bars. Increases in soil moisture at other times are due to rainfall events (refer Figure 32).

If the irrigation water had not been available, these trees would not have been irrigated, likely causing a reduction in growth and longer production times.

3. Waverley Farm

- Mr. Faulring was able to monitor and schedule irrigations based on data from the Leyland and especially the new *Viburnum* networks.
- The Leyland cypress network data has yet to show any conclusive differences between compost treatments. Further specific soil calibrations were done during summer, 2010. We will use these calibrations with 10-HS sensors in 2011. We think this will give us better soil moisture data precision.
- We are trying to ascertain if there is any difference in irrigation application volumes between the two different irrigation strategies (short and frequent vs. long and infrequent) between Raemelton farm and Waverley farm.

4. Hale and Hines Nursery

- As previously mentioned in the Hale and Hines site description, the ability to measure daily water applications and leaching losses from both Maple and Birch blocks was a major innovation. The following figures provide some data from these sensor networks.

Figure 35. 2010 Rainfall and air temperature data for Hale and Hines nursery. The summer was extraordinarily hot, with daily temperatures above 90F from June through August. Rainfall totaled 23.6" between April and September, but the majority of that rain occurred in about 10-12 events (Figure 35).

Consequently, irrigation water demand was high for the pot-in-pot operation.

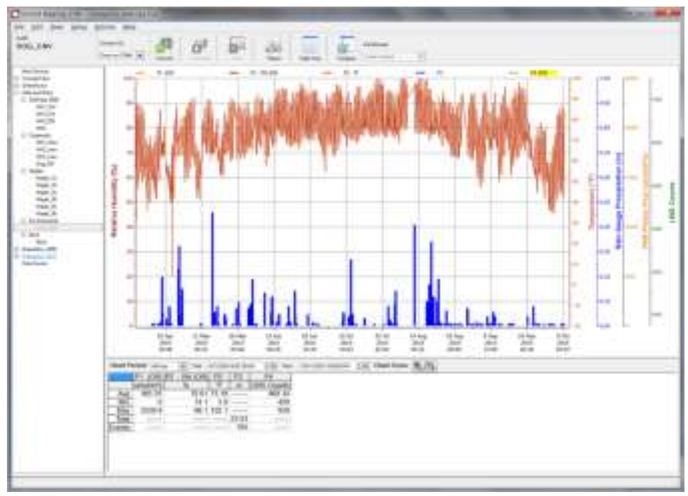


Figure 36. 2010 Maple Sensor Data (Tree #3; top quadrant)

Blue bars indicate irrigation applications; 200 gals of water was applied to this tree from May through October (not including rainfall).

Red lines are from the sensor directly under the dripper. Other sensors (e.g. black and green lines) are in the "irrigation shadow" of the trunk or side of the container; lower volumetric substrate contents were often seen. These trees were destructively harvested in October 2010. Shoot, leaf and root dry mass will be reported and analyzed, by quadrant.

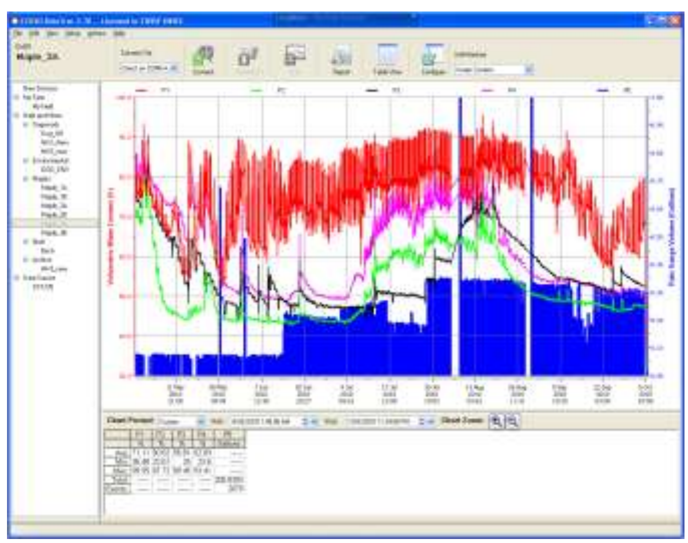


Figure 37. 2010 Maple Sensor Data (Tree #3; lower quadrant)

Blue bars indicate leaching volumes; 51 gals of water leached from this tree from May through October. The majority of this leaching appeared to be associated with increased irrigation volumes and additional rainfall in early July. This may have also been associated with reduced transpiration due to high daily temperatures. Note that irrigation volumes were adjusted down by Terry Hines after 16 July (refer to Figure 36).

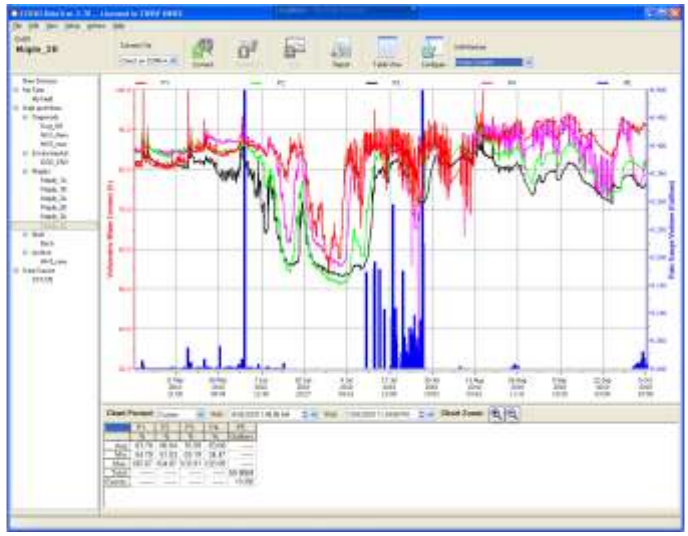
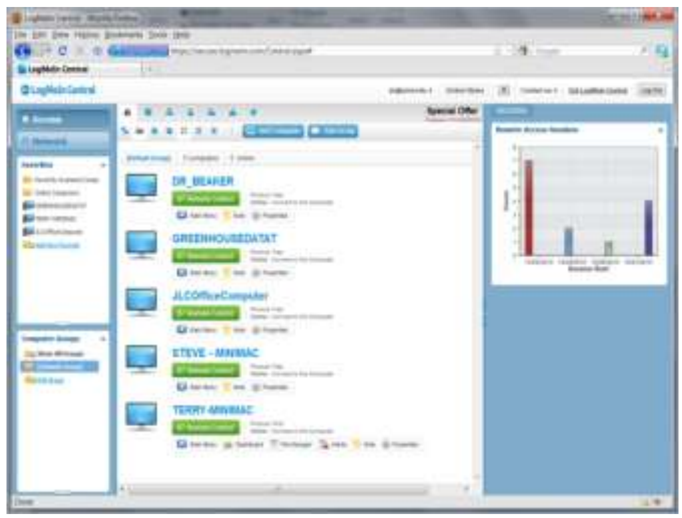


Figure 38. The logmein program (remote access) has provided John Lea-Cox, Terry Hines and Steve Black with the ability to remotely connect to the irrigation computers both at Hale and Hines, Raemelton Farm and the UM greenhouse networks.

This functionality has proven to be a major time saver for everyone, allowing remote access from anywhere with an internet connection. It has also allowed John Lea-Cox to troubleshoot network and sensor issues with Terry Hines and Steve Black.



5. Green Roof Research Site

- The construction and sensing of the green roof research site was a major accomplishment during summer, 2010. This puts this project well ahead of schedule and Olyssa Starry, the PhD graduate student on the project has already begun to analyze some initial stormwater runoff data.
- Example substrate moisture and temperature data from a green roof platform are shown in Figure 39.
- A green roof model (Figure 40) has been parameterized and is being validated with ongoing research and replicated environmental data from the green roof platforms.

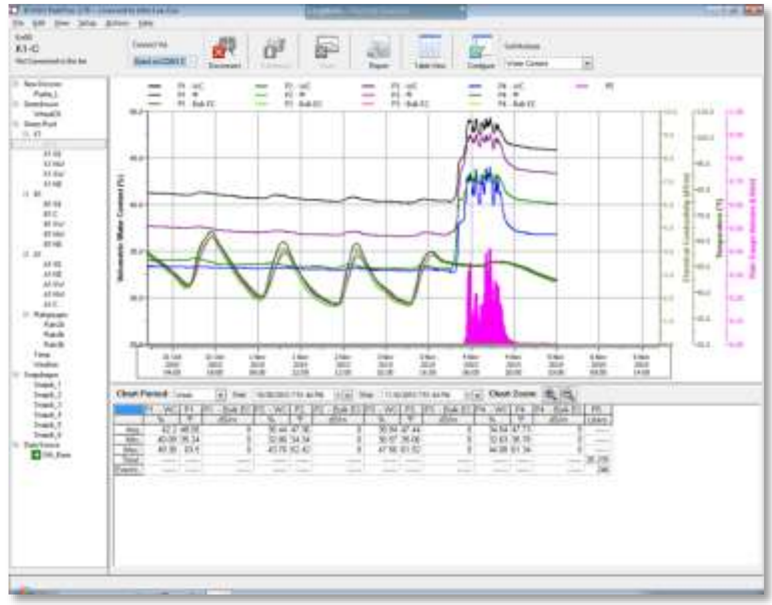


Figure 39. Green roof substrate moisture, soil temperature and stormwater runoff data (in pink) from one of the replicated green roof platforms

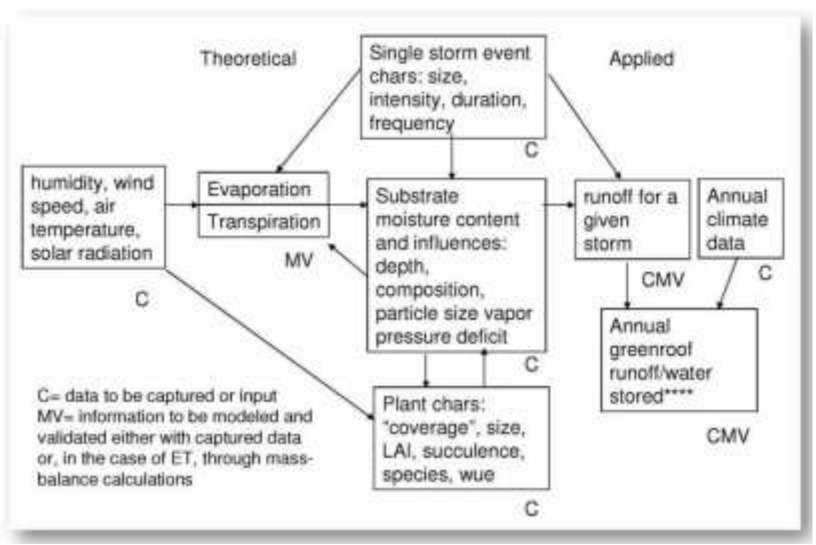


Figure 40. Conceptual Green Roof Stormwater Runoff Model (Olyssa Starry, 2010).

C =data to be captured or inputted.

MV = information to be modeled and validated either with captured data, or in the case of ET, through mass-balance equations.

6. Snapdragon Research Site

- As previously noted in the research site description, the snapdragon research facility has just been completed and planted in October, 2010. This research facility will allow us to quantify water use by snapdragons and relate that to environmental parameters.
- We are closely consulting with Dr. Marc van Iersel and Charles Bauers with this project, and our first objective is to accurately quantify light relationships in the canopy, over the development cycle of the crop and relate that to daily water use.

7. Wye Research Site

- Our inability to gather any usable sensor and runoff data from the Wye research site as we described in the site description and the engineering report was a major disappointment in 2010. However we have learned much from the situation and we have every confidence that we will overcome the transmission issues with the new advanced nodes in 2011.

8. People Involved

In addition to the four faculty members at UMD (Drs. John Lea-Cox, David Ross, Andrew Ristvey and Steven Cohan) Mr. Bruk Belayneh (research technician) has greatly assisted with this research in 2010. Ms. Olyssa Starry has worked tirelessly on the green roof project since starting at UMD in May, 2010. We also acknowledge the assistance of Clark de Long, undergraduate research assistant and the contributions of Mr. Felix Arguedas, a prior MS student with Dr. Lea-Cox whose research provided some of the foundational work with his research on sensor calibrations.

9. Communication and Outreach

Numerous outreach and conference presentations were made by our team.   A combined list of these is listed at the end of this report on pages 54-57.

B. Cornell University

Whole root system architecture and inherent growth rate of a species vastly affects root system ability to forage for resource such as water. While root system architecture and growth are genotypically driven, constraints to root growth and variation in growing conditions can alter root system development. Root growth and development of the finest first order lateral roots may also play a role in how species deal with their use of water.

1. Year One Objectives

The Cornell teams first year objective were to:

1. Investigate and characterize ten ornamental tree and shrub species for root development patterns in containerized systems using standardized soil media.
2. Develop a non-destructive" technique to monitor temporal tree root systems including horizontal and vertical roots in order to reconstruct a 3D model of root system development.
3. Meet with growers of containerized nursery stock to determine normal management practices and then to emulate nursery layout and design on a smaller scale at Cornell in order to provide the most accurate account of tree root growth.

2. Accomplishments

Early in 2010, Dr. Taryn Bauerle traveled to Willoway nurseries in Avon, OH to meet with Tom Demaline, his staff and tour the site.

Ten common ornamental tree and shrub species were chosen for research on root development and shipped to Cornell in the same soil as used at the nursery.   A plot was established with 4 replicates of each tree species using the same spacing and irrigation practices as found at Willoway nursery (Figure 41).   X-ray computer tomography technology trails at the Cornell University Veterinarian College were completed and evaluated for resolution and size capacity to ensure reproducible data sets would be obtained from sample trees (Figure 42).

Figure 41. Pot-in pot research site at Blue Grass Lane research facility, Cornell University.

Figure 42. Example of tree scanning using a Toshiba Aquillion 16-slice large-bore CT.

On arrival of the trees from Willoway nurseries, newly planted trees were immediately scanned to provide baseline data. Once a month thereafter three replicate trees of each species were transported to the Veterinarian College for scanning. Each tree was scanned for approximately 5 minutes. Data produced include approximately 350 one millimeter horizontal and 150 vertical high resolution slices through each container (Figure 43).

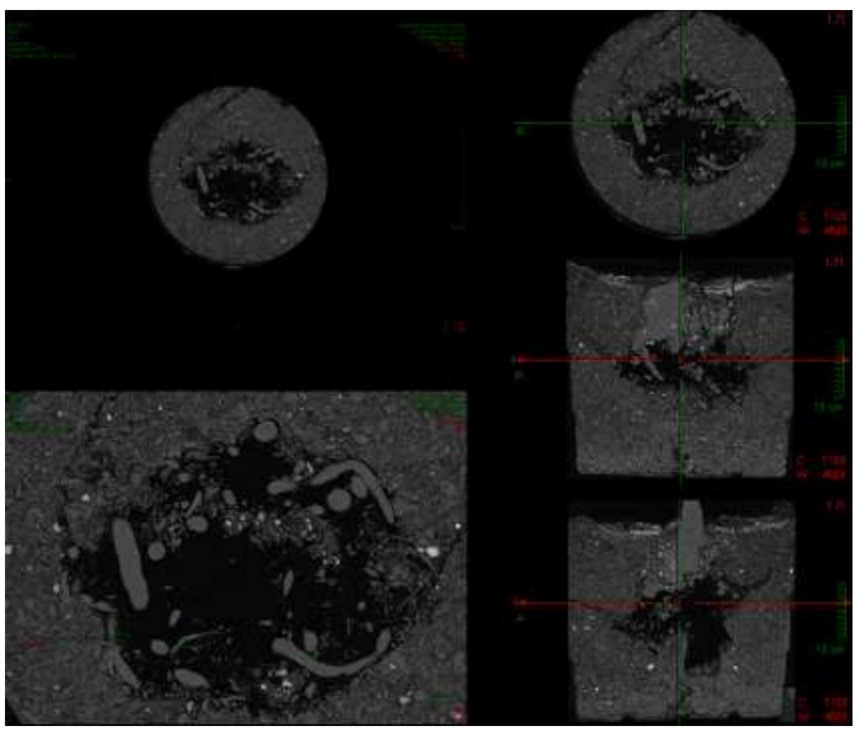


Figure 43. Example of an x-ray computer tomography section demonstrating 3 planes of view through an approximately 18 month old tree growing in a 15-gal container. Also noticeable is a large air space surrounding the root system (A).

Our next step is to Integrate 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 in order to conserve water and maximize yield.

3. Communication and Outreach

A number outreach and conference presentations were made by Dr. Bauerle and the team. A combined list of these is listed at the end of this report on pages 54-57.

C. University of Georgia

Progress for year 1 is listed by objective, as outlined in the University of Georgia statement of work.

1. Best Management Practices for Greenhouse Irrigation

Objective 1: Start greenhouse research to develop best management practices for greenhouse irrigation using soil moisture sensors.

The first phase of this part of the project was the design and construction of research equipment that can irrigate multiple plots based on substrate water content readings in that plot. We now have multiple systems in place:

- a 32-plot drip irrigation system for small plants in a greenhouse. Irrigation in each plot can be controlled separately, based on plot-specific set points.
- a 16 plot irrigation/fertigation system for small plants in a greenhouse. The ultimate use of this system will be to control irrigation and fertigation, based on water content and EC measurements, using Decagon's new greenhouse VWC/EC sensor. Until those sensors are available, we will use this system mainly to just control irrigation.
- a 10-bench, sensor controlled subirrigation setup. Water content in three pots on each bench is monitored, and those readings are averaged. The average VWC is then used to control when each of the 10 benches is subirrigated.
- two 16-plot, sensor controlled irrigation system for nursery crops. One of these systems is in Watkinsville, GA, the other one in Tifton. This will allow us to run identical experiments in different locations, and thus better quantify the effect of environmental conditions on plant water use and growth.

2. Effect of Substrate Water Content on Various Greenhouse Crops

Objective 2. Determine effects of substrate water content on physiology, growth, and quality of different greenhouse crops.

Multiple studies were conducted to quantify water use of bedding plants, as well as their responses to drought stress. Physiological responses of petunia to different severities of drought stress, as well as the effect of the rate at which this drought stress is imposed have been quantified and work to quantify changes in gene expression under drought is currently underway. We have also compared the response of four different bedding plants (impatiens dianthus, petunia, and ageratum) to different substrate water content.

This study clearly showed that growth of impatiens and ageratum is much more affected by low substrate water content than growth of petunia and dianthus. This species differences appeared to be due to differences in the ability to extract water from relatively dry substrates, rather than differences in how efficiently water is used to produce biomass. Water uptake of plants was species-dependent, while water use efficiency (g biomass produced per gram of water) was not.

3. ***Quantify Water Savings***

Objective 3. Quantify water savings that can be obtained with soil moisture sensor controlled irrigation.

We conducted two studies at Evergreen Nurseries comparing water use of *Gaura lindheimeri* using a sensor-controlled irrigation setup to water use with their 'standard' irrigation practices. Surprisingly, we didn't see any water savings using sensors for irrigation control, but plants with sensor controlled irrigation flowered earlier and more prolific.

In an ongoing study at McCorkle Nurseries, we haven't seen any savings in water use with sensor-controlled irrigation in a *Gardenia* 'Heaven Scent' crop. This in sharp contrast to an earlier study where we saw an 84% decrease in water use when using sensors to control irrigation. Perhaps, they have since learned how to irrigate better? The main question we still have about this type of research is what to compare sensor controlled irrigation to. There is real industry standard for irrigation, and each grower is different. Should we make 20% leaching our 'standard'?

4. ***Environmental and Plant Water Use Data for Model Development***

Objective 4. Detailed environmental data will be collected for use in plant water use model development.

We are continuously collecting environmental data at all of our research sites, which includes the UGA research greenhouses, the UGA horticulture farms in Tifton, and Watkinsville, and at our grower collaborators (Evergreen Nurseries, McCorkle Nurseries, and Stacy's Greenhouses, see below for more information). These environmental data can later be used to develop and test predictive plant water use models.

Overall, model development is ahead of schedule. We have been working with Richard Bauer to develop a simplified model to predict petunia water requirements, and we expect the first version of this application to be ready soon. At this stage, the main goal is to develop the software structure to support water use models. As soon as this is completed, we will work on the development of more accurate water use models that take into account a wider range of environmental conditions. Currently, plant age and DLI are the only factors included.

5. ***Sensor Network Installations at Commercial Operations***

Objective 5. Install wireless networks at Evergreen and McCorkle Nursery.

We installed a Decagon wireless sensor network at Evergreen Nursery in July. This sensor network consists of 4 Decagon EM50R loggers which are transmitting data to BaseStation at the nursery, and data are displayed on 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 (lantana, gaillardia, sedum, delosperma, and hellebores). Will Ross, the grower at Evergreen, monitors the system twice data and uses the information to help him make irrigation decisions.

Similar systems were installed at McCorkle's Nursery in Dearing, GA and Stacy's Greenhouses in York, SC. Although Stacy's Greenhouses is not an official SCRI-MINDS partner at this point, they are very interested in this project, because they face a water crisis. The aquifer underlying this nursery is gradually being depleted, and water availability is a serious concern for this nursery. Thus, they are very interested in any measures they can take to conserve water.

We have access to all of these remote locations over the internet, allowing us to monitor the data from these nurseries from Athens, GA, and to provide feedback by e-mail or other electronic communications.

6. *Additional Progress*

The nursery part of our research is ahead of schedule. We have installed soil moisture sensor-controlled irrigation systems at nursery sites on the University of Georgia horticulture farms in Watkinsville, GA and Tifton, GA. These sites have been used for studies to determine the effect of substrate water content on the growth and water use of *Hibiscus acetosella*. These studies are currently approaching their end and will be harvested in the next few weeks. We also have conducted a companion study in the greenhouse. The greenhouse study was done, because control of substrate water content is easier, since the treatments are not affected by rain. In our plan of work, this was scheduled to be done in year 2 of the project.

The department of horticulture at UGA has made another graduate assistantship available for this project, which has allowed us to attract one additional M.S. graduate student. This will allow us to expand the scope of our work, and this study is currently focusing on hydrangea as a model crop, and has completed a study to determine the effect of environmental conditions on daily water use of hydrangea. This was not part of our original objectives.

7. *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 four graduate students working on this project (Jongyun Kim, Mandy Bayer, Alem Peter, and Lucas O'Meara), as well as one visiting PhD student from Brazil. Five undergraduates have been hired as part time workers, and they have gotten valuable research experience. Finally, two high school students, doing a summer internship at UGA, have been involved with some of the research, with one of these students taking the lead on our *Hibiscus acetosella* greenhouse study.

8. *Communication and Outreach*

Numerous outreach and conference presentations were made by our team. A combined list of these is listed at the end of this report on pages 54-57.

Macroscale Working Group Report

Colorado State University

1. *Year 1 Objectives*

The specific objectives of the Macroscale group were to:

- measure species-specific model parameters;
- deploy nodes with sensors;
- deploy lidar;
- parameterize and validate models; and
- calculate species-specific whole tree transpiration.

2. *Sites and Plant Material*

- Measurements were carried out during the 2009 growing season in Fort Collins, CO and Avon, OH as previously described.
- Ten species *Acer rubrum* cv. 'Franksred', *Acer Saccharum* cv. 'Green Mountain', *Betula nigra* cv. 'Cully', *Carpinus betula* cv. 'Columnaris', *Cercis Canadensis*, *Gleditsia triacanthos* var. inermis cv. 'Skycole', *Magnolia* s. cv. 'Royal Star', *Platanus* a. cv. 'Bloodgood', *Quercus rubra* , and *Thuja plicata* cv. 'Green Giant' were measured in both locations in 57 L plastic pots. Trees were spaced ~1.5 m center-to-center.

3. *Atmospheric and Rhizospheric Sensing*

Substrate volumetric water content and temperature was monitored every minute (5-TM, Decagon Inc., Pullman, WA) in ≥ 5 containers per species and 5 minute averages were stored on EM50R wireless nodes. From physical characteristics of the substrate, we calculated the maximum and minimum soil moisture holding capacity to estimate substrate volumetric water content.

Meteorological data (air temperature, precipitation, relative humidity, photosynthetic active radiation (PAR), and wind speed just above the canopy) were collected using atmospheric sensors logged by the wireless node (remote weather stations) located in the middle of each species experimental plot. Horizontal wind speed was collected along a canopy depth profile per species with a mobile tower of anemometers.

In addition, we geo referenced every measured tree and atmospheric and/or substrate sensor in our study using a combination of GPS data and ground based surveying. Using this information we built maps of all of our atmospheric and soil sensor data collection locations.

4. *Whole Canopy Measurements*

From the wind speed depth profile measurements we calculated the wind speed extinction per species on a monthly basis. In addition, leaf area index was measured monthly per species plot.

5. *Whole Tree Morphology Measurements*

Monthly, three dimensional above ground biometric characteristics were measured on individual trees per species and used for model. Specifically, diameter at 10 cm from the substrate surface, height, length of canopy, *x*-radii, and *y*-radii were measured monthly on the same trees measured for gas exchange and lidar. Lidar was collected monthly in conjunction with gas exchange and physical biometric measurements (Figure 44).

Figure 44. Example of lidar returns to remotely measure diameter, height, length of canopy, x-radii, y-radii, and leaf area of study species.

6. Leaf Level Measurements

Leaf gas exchange was quantified with Ciras-2 portable photosynthesis systems. Sections of the leaves were enclosed in a cuvette. We varied the CO_2 concentration, light level, and temperature within the cuvette to create response curves.

H_2O loss and CO_2 uptake were measured from which we calculated the following parameters: convexity parameter of the light response, the maximum rate of electron transport, activation energy of the temperature response of the maximum rate of electron transport, the entropy term of the maximum rate of electron transport temperature response, the quantum yield of electron transport, the maximum rate of Rubisco carboxylation, activation energy of the temperature response of the maximum rate of Rubisco carboxylation, the entropy term of the maximum rate of Rubisco carboxylation temperature response, dark respiration, CO_2 compensation point, genotype stomatal conductance slope coefficient, and minimum stomatal conductance.

Immediately afterwards, five SPAD readings were measured on each gas exchange leaf and averaged. The SPAD value (unitless), was used to estimate leaf absorption in the PAR wavebands, PAR transmittance, and PAR reflectance for the calculation of quantum yield. Leaf width was measured for boundary layer conductance characteristics.

7. Spatial Distribution and Movement of Water in Soilless Substrates

We implemented an array of 12 soil moisture sensors (5-TM, Decagon Inc., Pullman WA.) in one 57 L container from each of the ten tree species. We arranged the sensors into three layers of 4 sensors each that were inserted into the substrate at a distance equal to one-half the radius in the four cardinal directions. We placed the layers at 4, 8 and 12cm below the substrate surface with the irrigation emitter placed on the south side of the container. Soil moisture was recorded at min intervals from which 5 min averages were logged onto data nodes (EM50 and EM50R, Decagon Inc., Pullman, WA). A minimum of 8 irrigation events (4 events per day) were recorded before the irrigation emitter was moved to the opposite (north) side of the container and then an additional eight events were recorded.

Volumetric flow rate during irrigation events were measured concurrently with an in-line, paddle-wheel, flow meter (Omega FP-8500a Omega Inc., Stamford, CT, USA). These data will soon be combined with the tree species specific transpiration estimates in an effort to further define the movement and spatial distribution of water within the container using a 3-dimensional hydrologic model (Hydrus 3D).

8. Sensitivity Analysis

To separate the influence of the coupled photosynthesis, stomatal conductance, radiation, and leaf energy balance, a sensitivity analysis was undertaken to quantify the relative effects foliage input parameters have on transpiration estimates (Figure 45). The sensitivity analysis was used to assess the variability in transpiration along a vertical profile caused by variation in 16 parameter values and among three different leaf area index values. The analysis revealed six of 16 leaf traits had a 5% or greater impact on transpiration (Figure 45).

The parameters tested included the following complement of leaf level input that could potentially affect transpiration: PAR transmittance, PAR reflectance, leaf width, convexity parameter of the light response, the maximum rate of electron transport, activation energy of the temperature response of the maximum rate of electron transport, the entropy term of the maximum rate of electron transport temperature response, the quantum yield of electron transport, the maximum rate of Rubisco carboxylation, activation energy of the temperature response of the maximum rate of Rubisco carboxylation, the entropy term of the maximum rate of Rubisco carboxylation temperature response, dark respiration, CO_2 compensation point, genotype stomatal conductance slope coefficient, and minimum stomatal conductance. Although increases and decreases to all parameters were tested (resulting in 8,064 parameter % change regression contrasts), only those with $\geq$ 5% change in transpiration are reported (Figure 45).

Panel A shows results for variation in microclimate wind speed (0.2 -10 m s^{-1}), B) photosynthetic active radiation (0 - 1500 µmol m^{-2} s^{-1}), C) relative humidity (5 - 100%), and D) air temperature (20 - 40 ^{o}C). One microclimate condition (e.g., wind speed) was varied per panel (see above) while all others were fixed as follows: wind speed (5 m s^{-1}), photosynthetic active radiation (1500 µmol m^{-2} s^{-1}), relative humidity, (60%) and air temperature (25 ^{o}C).

9. Initial Species-specific Transpiration Model Parameterization

We scaled up leaf transpiration and estimated crown layer, whole crown and canopy transpiration. To do so, we divided the crown into layers, with each layer forming numerous equal sub-volumes (Figure 46). To facilitate leaf-to-crown layer scaling, leaf area density within each plot was based on measured leaf area index and the volume of individual crowns. Morphological and physiological attributes described above were parameterized on a species basis. Thus, we scaled-up each species' genetic difference with species-specific leaf-level values and control equations. The wind speed extinction coefficients were specific to the species and growth stage.

10. Impacts and Changed Practice

We specifically asked the Willoway personnel to not change their practices during year 1. In year 2, we will make species specific irrigation recommendations on a sub daily basis and control irrigation solenoids via wireless nodes. At that time, we can quantify the difference in irrigation and schedule species specific watering events.

11. Communication and Outreach

A number of outreach and conference presentations were made by the Colorado State University team. A combined list of these is listed at the end of this report on pages 54-57.

Figure 45. Parameter sensitivity analysis results for model transpiration estimates under different climate forcing scenarios.

Parameter abbreviations: Genotype slope coefficient (g_1), the maximum rate of carboxylation (V_{cmax}), leaf width (L_w), minimum stomatal conductance (g_o), dark respiration (R_d), and quantum yield of electron transport (α; absorbed PAR - PAR_a). Canopy vertical position (upper, middle, and lower) results are indicated by shaded bars: the light shade area indicates upper, medium shade indicates middle, and dark shade the bottom; the longer the bar, the more sensitive the parameter. In the case of L_w and R_d the ◀◀ symbol indicates a reversed response direction from all other parameters (i.e. an increase in L_w results in a decrease in transpiration). LAI results (1, 5, and 10) are indicated by the three separate horizontal bars within a parameter (e.g. L_w labeled).

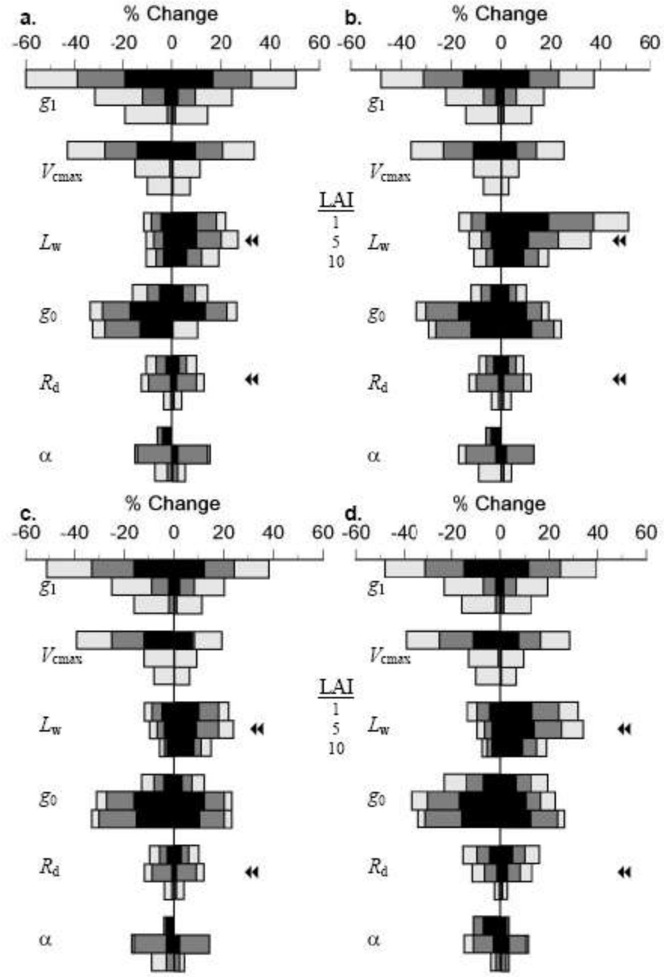
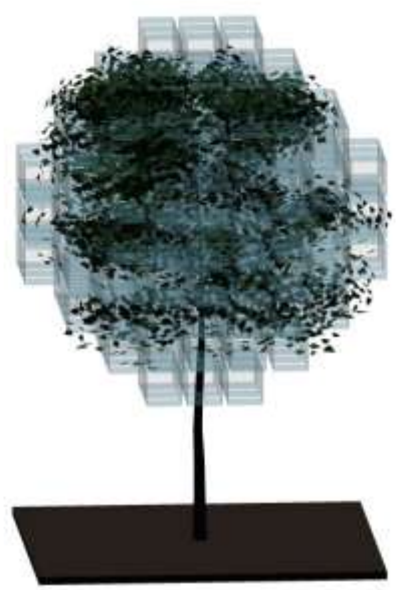


Figure 46. Three-dimensional representation of discrete within crown vegetation calculations. The crown is divided into grid cell volumes with known x, y, and z direction i.e. grid points calculations with the spatial position relative to the tree crown.



Modeling, Software Integration Working Group Report

Carnegie Mellon University and Antir Software

As previously noted, model development is ahead of schedule. Marc van Iersel has been working with Richard Bauer to develop a simplified model to predict petunia water requirements (see Appendix C). The model is currently being encoded and we expect to start validating the first version of this model with research datasets from Marc van Iersel's group. At this stage, the main goal is to develop the software structure to support water use models. As soon as this is completed, we will work on the development of more accurate water use models that take into account a wider range of environmental conditions. Currently, plant age and DLI are the only factors included.

A green roof stormwater model has been conceptualized (see Figure 40) and work has started on developing a database to support the data integration from the green roof experimental site. There are a number of sub-models within this model that need to be integrated (CAM water use and ET) during year 2 as part of this overall development. The snapdragon research site has now been established and work on the first part of the Snapdragon model (PAR and LAI in mature canopies) has started.

With regard to software development and integration, a numerous discussions were held between Richard Bauer, George Kantor, Marc van Iersel and Bill Bauerle to determine the technical constraints and requirements associated with implementing plant physiology models with sensor network data.

As previously noted in the Engineering report, this resulted in two primary achievements.

- **Model Interface Specification:** A framework for implementing models that will allow them to be cleanly interfaced with sensor network data was developed and communicated with the team. In particular, the requirements for model inputs, model parameters, and model outputs were determined for the van Iersel petunia model and MAESTRA-based tree models.
- **Initial Model Prototype:** An off-line version of the petunia model was implemented in format compatible with the framework mentioned above.

Economic and Environmental Benefits Working Group Report

University of Maryland AREC; UM – Center for Environmental Studies

The installation and implementation of wireless sensor networks in precision irrigation systems for nursery and horticulture operations are expected to reduce water, energy, fertilizer and chemical use, as well as generate higher quality products, alter plant growth rates – and thus marketing windows - and increase crop yields. Therefore, this technology has the potential to generate significant private (financial) and public (environmental) benefits. However, the benefits that accrue to the public will only be realized if private businesses adopt the technology. This will require the economic gains from installing and operating wireless sensor networks to exceed the costs.

The economic research undertaken as part of the SCRI-MINDS project will estimate changes in private sector costs and revenues, and quantify, and where possible monetize environmental benefits of installing wireless sensor networks at the establishment and industry scale, and will also examine any related changes in business risks. This will involve developing estimates of installation and operating costs and comparing them with expected cost reductions associated with more efficient use of inputs and labor and with higher earnings associated with increased yields and higher quality products. The research will also involve examining the duration of the payback period following transition from traditional operational practices to sensor-based techniques which can affect the rate of adoption even if long term benefits exceed costs. Some of the public benefits of shifting to sensor-driven "water on demand" irrigation, such as reductions in water use and carbon and nutrient discharges, may have potential to provide additional economic returns by generating marketable air and water emission offset credits in emerging air and water "cap and trade" programs. The study is also examining the possibilities that the shift to these systems may also generate private economic benefits by reducing the cost of emission taxes or penalties and/or by generating revenues via government-run economic incentive programs to promote environmentally conscious management practices. Additionally, more efficient water, chemical and nutrient usage as a result of sensor-based precision irrigation may generate multiple environmental benefits. Reduced water use from the new irrigation technology may ease water demand in water scare areas, reduce discharges of nutrients, chemicals and sediments to nearby water bodies, reduce energy use and decrease emissions of pollutants and greenhouse gases. Our analysis will quantify and, where possible, monetize the value of these indirect and induced environmental benefits to the public as well as determine where and how they might be used to increase private sector incentive to make the transition to the new technology.

The overall economic analysis will provide a comprehensive assessment of economic and environmental costs and benefits associated with a shift to new wireless sensor-based irrigation systems in nurseries, greenhouses, and other horticulture and floriculture operations.

1. Year 1 Objectives; Results to Date

Year 1 objectives for the economics and environmental benefits analysis have focused on obtaining baseline information regarding characteristics of nursery and greenhouse operations in the United States. Our ultimate goal is to comprehensively describe baseline factors such as current water, nutrient and chemical usage, emissions and discharges, economic input-output relationships, and industry attributes such as output, size, product types and irrigation techniques. Additionally, we aim to gauge the heterogeneity of these characteristics throughout the industry in order to determine when impacts from sensor-based precision irrigation can be applied generally to all operations within certain industry sectors and when more sub-sector and regional breakdowns should be used.

Appendix Table D1 summarizes the overall size of the greenhouse industry in the U.S. by state and Appendix Table D2 summarizes the direct, indirect, and induced economic output generated by the industry in each state, and nationally. Appendix Table D3 summarizes industry average natural resource use and environmental emission coefficients (use/emissions per $ million in sales) for the greenhouse industry. We are in the process of developing more detailed estimates of economic impacts (e.g., output, employment, value added, taxes generated, etc.) and resource use and emission coefficients for subsectors of the industry relevant to our study. This will provide a context for examining the overall scope of potential costs and benefits.

We are also developing frameworks for examining sub-sector level and establishment level economic and environmental impacts of sensor-based irrigation. Appendix Table D4 illustrates one establishment level cost/benefit worksheet we plan to use. This will be developed using the results from our survey (discussed later) and interviews with collaborating industry experts and team partners. Information from this worksheet will be input into a protocol budget spreadsheet we have created in Excel format. The spreadsheet will allow us to categorize various operational costs and estimate grower cost savings as a result of new irrigation technology.

As more information is obtained from our colleagues on the project regarding changes in product yield, quality and pricing in response to the new precision irrigation technology, output parameters and emission coefficients can be changed in our economic impact software (IMPLAN) and industry emissions software (EIO-LCA) to provide a more precise picture of potential impacts.

As more detailed data are collected from project research and industry partners, we will analyze how these environmental outputs will change under various assumptions regarding potential product yield and quality increases and more efficient use of water and related resources.

A database is currently under development to consolidate information on field nursery, container nursery and greenhouse ornamental operations. Information in the database is being obtained from national and state government statistics, published scientific articles, trade literature and other sources. The purpose of the database is to allow the economics and environmental benefits team to comprehensively characterize and examine the ornamental industry by various attributes such as output, size, type, products produced, etc. at various spatial scales (nation, region, state). This characterization will describe the heterogeneity of ornamental operations which will allow us to better identify and assess the potential impacts of adoption of sensor-based irrigation technology within various segments of the industry.

Additional research was performed to review the economics literature on water and irrigation adoption, and production theory. A good review of the water and irrigation adoption literature can be found in Sunding and Zilberman's (2001) chapter in Handbook of Agricultural Economics. Follow up papers that add to the literature are: Schuck, et. al. (2005), Schuck and Green (2003), Verma, Tsephal and Jose (2004), Schuck and Green (2001), Uri, Tsur, Zemel, and Zilberman (2009) and Negri, Noel and Allery (2005).

Part of the literature directs efforts towards understanding the adoption mechanism through the role of diffusion models and the influence of risk, uncertainty, and other dynamic factors. Also, the literature analyzes the influence of institutions and government interventions on adoption. It describes models of induced innovation and experimentation and considers the political economy of public investments in agricultural research.

Other papers are concerned with estimating the impact of climate change on the discrete choice decision to adopt irrigation. This is important since irrigation adoption is a way to adapt to climate change. Not least, the monetary values of the benefits associated with the irrigation adoption are considered from a benefit-cost analysis perspective.

Closely related to the irrigation adoption question is the production perspective. This should not be neglected due to its overall importance in the design of viable economic models. The economics literature abounds on projects that have based their conclusions on ill understood production theoretical grounds (i.e. rigid assumptions of the production technologies or inflexible parameterization of production functions to name a few). Since production economics represents the base on which other economic models are built, it is imperative to have a sound understanding of the hypotheses on which the theoretical foundation is rooted. For instance, it is important to know and to understand the consequences of assuming that the production technology of a greenhouse operation has weak versus free disposability of inputs when considering the impact of its irrigation and water usage practices on outputs and revenues. Another example is the choice of economic tools. For instance, one has to understand both the pros and cons when deciding between data envelopment analysis and the stochastic frontier approach to the estimation of operation efficiency.

In terms of production theory, Chambers (1988) and Chambers and Quiggin (2000) represent a natural start. Chambers (1988) provides examples and intuition cast in an agricultural context, surveying the literature of production economics seen through the perspective of an agricultural economist. Chambers and Quiggin (2000) is a continuation of Chambers (1988). It picks up on the theory where Chambers (1988) left it and takes it one step further by introducing ways to model production decision making under risk and uncertainty**.**

A beta survey of grower characteristics and grower practices has been developed. This survey has been customized for different types of ornamental operations; container, greenhouse and in-ground (field). The survey will allow us to assess current management practices and grower interest in adoption of sensor technologies. We will be beta testing the survey in an oral or interview process with several local participants in the project. Once tested, the survey will be refined for broader application. It may be modified to operate as a stand-alone mail or internet survey. A draft of the field ornamental beta survey can be found in Appendix Table D4.

2. ***Personal Contacts***

In addition to the preliminary development of sector-wide economic and environmental profile, literature review and survey development and pre-testing, the economic and environmental benefits team has also conducted personal communications with various experts in the industry to obtain information pertaining to the day-to-day operation of nursery and greenhouse facilities, characteristics of consumers purchasing sensor-based irrigation technology, and current water and nutrient use. We have also reviewed the agricultural economics literature to identify useful models for assessing and comparing changes in costs and benefits associated with changes in irrigation methods. Along with other colleagues on the project, we participated in a tour of Moon Nurseries in Chesapeake City, MD. The purpose of this tour was to examine and get a better understanding of large-scale nursery and greenhouse operations firsthand, and to directly interact and communicate with growers in order to more fully understand the complexities of this typical operation and how we should reflect them in our analysis. Additionally, to better understand potential limitations in the adoption of new precision irrigation technology, the team conducted telephone interviews with representatives from Decagon Devices, Inc. that focused on the characteristics of the current consumer-base for agricultural sensors. This information will allow us to better assess demand and adoption of future sensor-based irrigation technology. Additional interviews were conducted with Cooperative Extension personnel in several states. While these interviews were very preliminary and open ended, we were able to gain a brief picture of irrigation practices in some parts of the country.

Based on our field survey, we managed to gather a number of qualitative and quantitative observations which we believe will help us to cross check the results that will be obtained later in the project. This information should be viewed as a short snapshot and not an exhaustive data collection exercise. The information will help us in the design of our other survey instruments.

We observed that few greenhouse operations use hydroponic systems or greenhouse sensors. Strawberry and tomato growers are the most likely growers to be using soil moisture sensors. As such, many strawberry farmers tend to over-irrigate their fields. These growers are using the sensors to ensure that their soils are completely saturated.

Greenhouse growers perceive sensor technology to be too expensive and most of the growers' irrigation systems are on timed controllers. Occasionally, growers will use irrigation systems that take sunlight levels into account.

In terms of irrigation decisions, growers consult with one another and rely on their experience. Many rarely look at the soil at all. Occasionally, they will check their plants for wilting and other practices. Outdoor nursery growers are using similar practices. There seems to be very little concern for over-irrigation. The same amount of water is often applied each day, regardless of circumstances. Finally, we found that vegetable production systems are more complex and have more automation.

A meeting was held between the economics and environmental benefits team, project leader John Lea-Cox and his Ph.D. student John Majsztrik to discuss greenhouse-, container nursery- and field nursery-specific water and nutrient use models. During this meeting, John Majsztrik provided an overview of irrigation and fertigation pathways in these operations. Also, discussed was a plan for future collaborations between Majsztrik and members of the team to utilize his models, which among other things, will estimate product yield, product quality, and water and nutrient usage and discharges based on changes in management practice. This data could be valuable in our estimates of private and public benefits from precision irrigation.

3. *Case Study*

Presently, we have the opportunity to work out and test a number of hypotheses that pertain to water usage and irrigation practices. More specific, we are working on a case study with the owner of one of our project partner's tree farms, Mr. Steve Black at Raemelton Farm. This tree farm is of average size and faces water constraints on the short to medium time frame due to pumping equipment limitations. Mr. Black must ensure no water stress in the first year of planting in order to keep loss rates to a minimum. The operation sells trees with trunks that are between 2 and 4 inches in diameter. The market for 2 inch products is larger than the market for 4 inch products; however, 4 inch products have a greater profit margin than 2 inch products. In terms of market forecast, the supply side can be relatively well estimated (i.e. business shows, etc), however the demand side is not well known.

Dr. Lea-Cox installed water sensors in the youngest block of trees to measure soil moisture at a depth of 6 inches. A target for soil moisture was set and Mr. Black was able to monitor moisture to ensure that it did not fall below the target range. Mr. Black was consequently able to decrease water applications to this block from 2 hours per day to 1 hour per day. This case study seeks to estimate the impact of this reduction in irrigation.

We will first seek to estimate the potential reduction in costs to the grower for reducing irrigation. This potential reduction in costs will be equal to the pump energy savings plus any reduced depreciation of pumping and irrigation equipment. We are working with the grower to estimate these parameters.

Of most interest to this project will be the opportunity cost of reducing the irrigation event from 2 hours per day to 1 hour per day. Because the grower's water supply is limited by pumping capacity, the opportunity cost is the value that the grower may obtain by using this 1 extra hour of water elsewhere in the operation.

The grower can choose to speed up and slow down growth rates for some plants compared to others in the context of present and future market conditions. The opportunity cost of using water in quantity **q** on plant **x** rather than plant **y,** is the margin that could be obtain from selling plant **y** if the **q** units of water would have been used for plant **y** rather than plant **x**. It should be noted that the opportunity cost is calculated with respect to other farm activities, more specific with respect to other farm products. For now we are ignoring the opportunity cost of this water with respect to outside farm activities (i.e. selling the water rights to municipality). This is a reasonable assumption as this area is not currently water constrained.

Speeding up the growth rate for a plant has an intertemporal component. More specific, reducing the production cycle creates the opportunity to sell the plants sooner which increases immediate sales for the operation. In this case, the margins would have to be actualized in order to have meaningful comparisons of the decision to speed up plant growth in block **y** through the usage of water. A working hypothesis would be to use the saving account interest rate and to assume it is constant across time. In this case, a possible formula could be:

$$PV = FV *(1+i)^{(-n)}$$

More robust models can also be used. However, given the level of detail involved in this case study, we do not believe they will bring more insights to the process.

The value of information associated with the decision to re-allocate water comes from two sources. First, the time required by the plants to reach the marketable frame will decrease. This will move sales to an earlier date as the plants mature earlier. Second, the re-allocation of water usage will reduce the length of the production cycle. More specifically, in a given time frame the operation could have more production cycles due to the re-allocation of water.

The value of the information gained from the installation of the water sensors and subsequent re-allocation of water can be explained via a simple example. Suppose the operation has a 50 years business planning horizon and that a normal production cycle is 5 years. In this case, the operation will have 10 cycles in 50 years. Now, assume that because of the improved information and water re-allocations this cycle can be reduced to 4.5 years. In this case, in the same time frame, the operation will have 11 cycles. Thus, in our simplistic example, the operation could benefit due to earlier sales (the operation will be able to sell the plants after 4.5 years compared to 5 years), as well as due to an extra production cycle (the operation will have 11 rather than 10 production cycles).

We believe that the insights gathered from this case study will enrich our results and conclusions obtained later on. In year 2 of this project, we will be gathering additional information on this case study to provide a financial analysis to our partner grower.

In summary, during Year 1 the economic and environmental benefits team:

- Reviewed the relevant literature and outlined potentially useful methodologies and methods of analysis and related software for performing analysis and presenting results.
- Developed a preliminary economic and environmental profile of the overall industry.
- Interviewed and collaborated with industry partners to develop a reasonable strategy for defining and surveying the relevant segments of the industry,
- Designed a set of three survey instruments to use during Year 2 to develop subsector-level and establishment level impact analysis.
- Applied for IBR approval to conduct survey/interviews during Year 2.
- Developed working relationships with industry partners to facilitate the development and interpretation of regional and national establishment-level and subsector level industry cost and earnings estimates, sales estimates, and environmental interaction estimates.
- Initiated cooperative research projects with industry partners to assess private benefits of using sensor-based precision irrigation technology.

Communication and Outreach

Book Chapters

1. Majsztrik, J., A. G. Ristvey and J. D. Lea-Cox. 2010. Water and Nutrient Management in the Production of Container-Grown Ornamentals. In: Hort. Reviews J. Janick (Ed.). J. Wiley, NJ. 38:253-297.

Refereed Papers in press

1. Bauerle, W.L. and J.D. Bowden. 2010. Predicting transpiration response to climate change: Insights on physiological and morphological interactions that modulate water exchange from leaves to canopies. HortScience (In press).

Refereed Papers in review

1. 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.

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8. van Iersel, M.W., S. Dove and S.E. Burnett. 2010. The use of soil moisture probes for improved uniformity and irrigation control in greenhouses. *Acta Horticulturae* (in press).
9. van Iersel, M.W. and S.E. Burnett. 2010. Plant water use and drought stress physiology: Manipulating irrigation for efficient water use and high quality plants. *Proceedings of the Taiwan*

– *USA Symposium on Technology of Cultivation and Molecular Breeding for Ornamental Crops.* T.-F. Hsieh, T.-E. Dai and L.-J. Wang (eds.) Special publication of TARI No. 145. p. 31-54.

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2. Lea-Cox, J. D., G. F. Kantor, W. L. Bauerle, M. van Iersel, C. Campbell, T. Bauerle, D. S. Ross, A. G. Ristvey, D. T. Parker, D. M. King, R. Bauer, S. Cohan, P. Thomas, J. Ruter, M. Chappell. M. Lefsky, S. Kampf and L. Bissey. 2009. A Major Specialty Crops Research Initiative Grant Award for the University of Maryland. Maryland Nursery and Landscape Association. *FreeState Nursery News* 23(3): 14-15. http://mnlaonline.org/documents/2009-winter.pdf
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2. Bauerle W.L. 2010. Mechanistic models: Application in basic and applied woody ornamental water relations research. HortScience 45(8): S46.
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8. Miralles, J. M. van Iersel, S. Burnett. 2010. Controlling water content and electrical conductivity in soilless substrates using in situ sensors. HortScience 45(8):S102.
9. van Iersel, M.W. 2010. Integrated water and nutrient management in greenhouse production systems. Land grant and Sea Grant National Water Conference, p. 1-2.

Presentations

1. Bauerle. T., 2010. Cornell University Field Day; Cornell Cooperative Extension. Dr. Bauerle gave three guided tours of the Willoway site replicated field site and discussed the USDA SCRI program and the projects objectives and research to date (30 participants).
2. Bauerle., T. 2010. Empire State Green Industry Show, Rochester, NY. January 13, 2010 (Invited Presentation; 100 participants).
3. 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. 2010. Managing irrigation via distributed wireless sensing, prediction, and control: Overview for Denver Botanic Gardens. January 14th Denver Botanic Gardens, Denver, CO.
4. Bauerle, W.L., S. Kampf, M.A. Lefsky, and T.L. Bauerle. 2010. Managing irrigation from the plant to the production site: A macro-scale overview. January 21st University of Maryland, College Park, MD.
5. 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. 2010. Overview of a national coordinated agriculture project for precision irrigation at multiple scales: Overview for Department of Horticulture & Landscape Architecture. February 10th Colorado State University, Fort Collins, CO.
6. Bauerle W.L. 2010. Predicting transpiration response to climate change: Insights on physiological and morphological interactions that modulate water exchange from leaves to canopies. August 5th 107th Annual Conference of the American Society for Horticultural Science, Palm Springs, CA.
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9. Chappell, M. 2010. Understanding Efficiency vs. Uniformity in Irrigation: A Systems Approach. Coastal Green Educational Symposium. Savannah, GA.
10. Chappell, M. 2010. Efficient irrigation in nurseries. Georgia green Industry Association Meeting. Atlanta, GA.
11. Kantor, G. and A. G. Ristvey. 2010. Irrigating Based on Plant Water Need with Wireless Sensor Networks. Annual International Meeting. American Society Agriculture & Biological Engineers. 22 June, 2010 . Pittsburgh, PA.
12. Kanto, G. F. 2010. Distributed Sensing in Horticultural Environments (Invited talk) Colloquium 6: Technological Innovation in Horticulture. 28th International Horticultural Congress, 25 August 2010, Lisbon, Portugal.
13. Lea-Cox, J.D. and F. R. Arguedas-Rodriguez, 2009. Webinar: Using Decagon Moisture Sensors for the Precision Irrigation of Soilless Substrates. Decagon Devices, Inc. 11 Sept., 2009. Pullman, WA. http://www.decagon.com/soil_moisture/seminars/index.php?pg=1 .
14. Lea-Cox, J.D., 2009. Wireless Sensor Networks for Improved Irrigation and Production Efficiency. Int. Pl. Prop. Soc. – Eastern Region Meeting. Cleveland, OH. 16 Oct. 2009.

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16. Kim, J. and M.W. van Iersel. 2010. Photosynthesis and water use of vinca (*Catharanthus roseus*) during drought: the effect of different drying rates. 2010 *SNA research conference* (Mobile, AL).
17. Lea-Cox, J.D., G. Kantor, W. Bauerle, M. van Iersel, C. Campbell, T. Bauerle, D. Ross, A. Ristvey, D. Parker, D. King, R. Bauer, S. Cohan, P. Thomas, J. Ruter, M. Chappell, M. Lefsky, S. Kampf, L. Bissey, T. Martin. 2010. Precision irrigation and nutrient management for nursery, greenhouse and green roof systems: Wireless sensor networks for feedback and feed-forward control. Annual International Meeting. American Society Agriculture & Biological Engineers. June 23rd. Pittsburgh, PA.
18. Lea-Cox, J.D., G.A. Kantor, W.L. Bauerle, 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. 2010. Precision irrigation and nutrient management for nursery, greenhouse and green roof systems 107th Annual Conference of the American Society for Horticultural Science, Palm Springs, CA.
19. Lea-Cox, J.D., G.A. Kantor, W.L. Bauerle, M. van Iersel, C. Campbell, T. Bauerle, R. Bauer. 2010. SCRI-MINDS: Some management and communication strategies for a national coordinated agricultural project. ASHS 107th Annual Conference, Palm Springs, CA.
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21. Owen, J.S. S.A. White, W.L. Bauerle, J. Albano, C. Wilson, T. Yeager, T. Bilderback. 2010. Nursery production technologies for enhancing water quality protection and water conservation. Land Grant & Sea Grant National Water Conference. February 21-25, Hilton Head, SC.
22. Ruter, J. 2010. Ornamentals research at the UGA campus in Tifton. Annual Georgia Farm Bureau meeting.
23. van Iersel, M.W. 2010. Integrated water and nutrient management in greenhouse production systems. 2010 National Water Conference, Hilton Head, SC.
24. van Iersel, M.W. Floriculture production and physiology research at the University of Georgia. Presented to the Board of Directors of the American Floral Endowment. (25 people, 1/13/2010).
25. van Iersel M., W.L. Bauerle, J.D. Lea-Cox, A. Ristvey, and P.A. Thomas. 2010. Modeling. January 21st University of Maryland, College Park, MD.
26. van Iersel, M.W. 2010. Automation of greenhouse irrigation with soil moisture sensors. Cobb County Master Gardeners group.
27. van Iersel, M.W. and S.E. Burnett. 2010. Plant water use and drought stress physiology: Manipulating irrigation for efficient water use and high quality plants. *Taiwan – USA Symposium on Technology of Cultivation and Molecular Breeding for Ornamental Crops.* Taichung, Taiwan.
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29. van Iersel, M. 2010. Converting carbohydrates into biomass: the role of respiration and its importance in modeling plant carbon use. 107th Annual Conference of the American Society for Horticultural Science, Palm Springs, CA.

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1. Lea-Cox, J.D. and C. Zhao, 2009. Smart-farms: Managing Irrigation and Nutrients via Distributed Sensing - The Specialty Crops Research Initiative Project Website http://smart-farms.net

Appendix A: Project Organization, Governance, Plan of Work and Accountability

1. Project Team Members

The key project personnel, their roles and responsibilities are as follows:

A. University of Maryland

1. **Dr. John Lea-Cox:** *Overall Project Management; Sensor calibration, spatial and temporal variability assessment in soils and substrates; Implementation with growers; Data analysis; Environmental and sociological analysis; Undergraduate and graduate Advising; Education, outreach and extension; Project Administration and Reporting.*
2. **Dr. Andrew Ristvey:** *Green Roof Project Management; Water and Nutrient budgets; hardware and software development, spatial and temporal variability assessment in soils and substrates; Green roof deployment and evaluation; Data analysis; Implementation with growers and industry members; Undergraduate and graduate Advising; Education, outreach and extension.*
3. **Dr. Steven Cohan:** *Green Roof deployment and evaluation, Implementation with green roof industry; Education and Outreach, Undergraduate and Graduate Advising;*
4. **Dr. David Ross:** *Engineering issues; Spatial and temporal variability; Data analysis; Integration with existing controllers; Implementation with growers; Undergraduate and graduate Advising; Education, outreach and extension;*
5. **Dr. Doug Parker:** *Project Management; Economic and benefit-cost analysis; Economic impacts of changed practices and barriers to adoption; Implementation with growers and industry members; Graduate Advising; Education, outreach and extension*
6. **Dr. Dennis King:** *Project Management; Environmental and Issues Analysis; Environmental impacts of changed practices and barriers to adoption; Public and Private Benefits of Technology and Adoption*

B. Carnegie Mellon University

1. **Dr. George Kantor:** *Project Management; Sensor network (hardware) development; GUI software development; Implementation with growers; Data analysis; Undergraduate advising; Education, outreach and extension; Project Administration and Reporting*
2. **Engineering Specialist:** *GUI software development; Data analysis; Software support and troubleshooting with industry and research partners (test site networks). Software Support Documentation*

C. Colorado State University

1. **Dr. Bill Bauerle:** *Project Management; Integration of sensing data with plant environmental models; process modeling and implementation with growers; Macro-scale sensing network optimization; Environmental and sociological analysis; Undergraduate and graduate Advising; Education and outreach; Project Administration and Reporting*
2. **Dr. Michael Lefsky:** *lidar specialist; remote lidar data capture and analysis; Development of model parameters; Spatial analysis of optimal remote data collection*
3. **Dr. Stephanie Kampf:** *Hydrologist – Analysis of variation in water content in soils and substrates; development of model attributes; Hydrologic process modeling; Undergraduate and graduate Advising; Education and outreach.*

D. Cornell University:

Dr. Taryn Bauerle: *Project Management; Characterization of root structure attributes and morphological adaptation of root systems to water availability; Development of simple model parameters for indicator species; Undergraduate and graduate Advising; Education and outreach; Project Administration and Reporting*

E. University of Georgia:
   1. **Dr. Marc van Iersel:** *Project Management; Physiological Research; GUI software development; Implementation with growers; Data analysis; Graduate and undergraduate advising; Education, outreach and extension; Project Administration and Reporting*
   2. **Dr. Paul Thomas:** *Physiological Research; software development; Sensor Network deployment and evaluation; Implementation and day-to-day interaction with partners (test site networks); Graduate advising.*
   3. **Dr. Matthew Chappell:** *Sensor Network deployment and evaluation; Implementation and day-to-day interaction with partners (test site networks); Implementation with growers and industry members; Education, outreach and extension; graduate advising.*
   4. **Dr. John Ruter:** *Physiological Research; Sensor Network deployment and evaluation; Data analysis; Implementation with growers and industry members; Education, outreach and extension; Undergraduate and graduate Advising*

F. Decagon Devices, Inc.
   1. **Dr. Colin Campbell:** *Project Management; Data analysis; Education and outreach. Project Administration and Reporting*
   2. **Ms. Lauren Bissey***: Sensor network (hardware) development; Hardware support and troubleshooting with industry partners (test site networks). Extension and outreach*

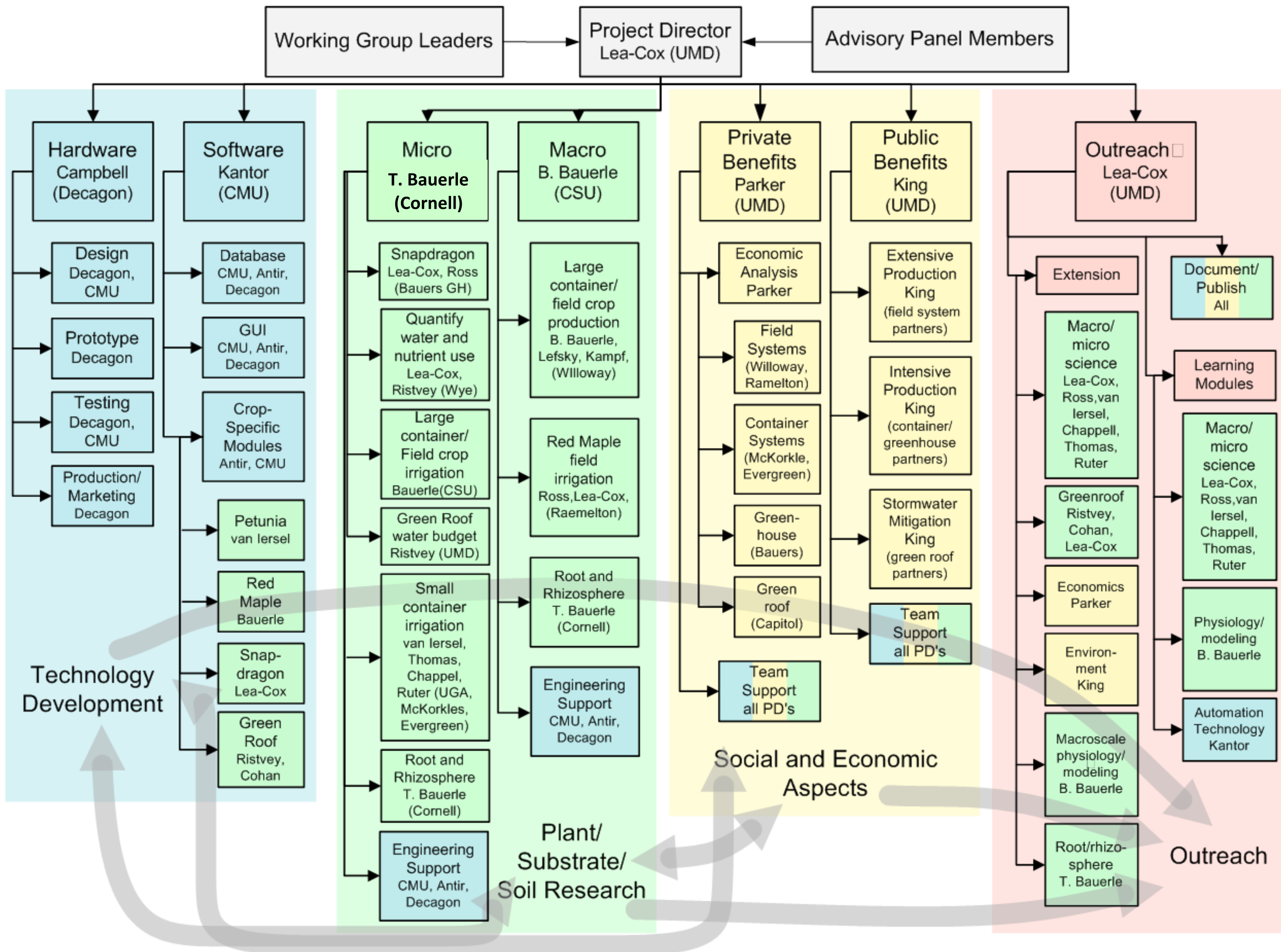
G. Antir Software, LLC.
   1. **Mr. Richard Bauer:** *Project Management; Crop Model software development; Data analysis; Software support and troubleshooting with research partner). Software Support Documentation.*

2. Project Organization

The project workload is divided and organized by seven working groups, i.e. hardware and software development, micro-and macro-scale research, social and economic aspects culminating in commercialization, extension and outreach (Appendix Table A1). Each University and Commercial partner has team members and responsibilities within each working group. Working group members report directly to the working group leader, on a quarterly basis to document their progress towards the specific scientific and engineering objectives of the working group. The working group leaders (Kantor, W. Bauerle,T Bauerle, van Iersel, Ristvey, Parker, King, Bissey, and R. Bauer) coordinate their respective university/company teams on a continuous basis and report progress via monthly tele/webconferences to the group, coordinated by the PI (Lea-Cox). This allows us to address inter-group issues on a continuous basis. Working group leaders will assure that their working group completes their part of the project on schedule, and will report to Lea-Cox when work is behind schedule.

Hardware development and support for the test site environments will be handled primarily by Campbell and Bissey (Decagon) in close cooperation with Kantor (Carnegie Mellon). Carnegie Mellon is leading the software development effort, with cooperation from Campbell (Decagon) and Bauer (Antir Software). Lea-Cox is coordinating the plant/substrate/soil research, with working group members from Colorado, Cornell, Georgia, and Maryland collaborating. Within this group, Ristvey is leading the green roof part of the work. Parker and King are coordinating the social and economic part of this project, with all working groups contributing needed information. Educational and extension programming (website and knowledge center activities) are coordinated primarily by Lea-Cox, Ross and Cohan (Maryland), but will include content from all University groups (CMU, Colorado, Georgia, Cornell). Extension (grower outreach) and traditional outreach (publications, conferences) will be done by all groups.

Appendix Table A1. Project Organization Chart Showing Project Goals, Working groups, Team Members and Project Responsibilities.



3. Project Governance

This project is intended to fulfill the expectations and needs of the industry. As such, the Advisory Panel will be our governing body, inasmuch as they will hold the working groups accountable for the development of the hardware, software, and BMPs that meet those needs. The scientist and engineers on the project hold an equally important role, in that they will provide the knowledge and guidance to develop these products within reasonable boundaries. Some ideas are difficult or not cost-effective to implement at this point. The social and economic team will provide vital information to both groups as to those aspects of the project that have the greatest impact, which may in turn influence hardware and software development decisions and priorities.

To ensure that the advisory board stays informed of the progress made by the various working groups, short quarterly reports from WG leaders, detailing progress and delays will be communicated to the Advisory Team through John Lea-Cox. Quarterly tele/webconferences will be held among the working group leaders and the Advisory team, to discuss these reports and adjust research and programmatic priorities. All PDs, graduate students, and members of the Advisory Panel will meet yearly at one of the locations where the research is performed. This will allow everyone to see some of the ongoing research and to efficiently address issues in break-out groups. At this meeting, the PDs will report on the progress from their respective working groups, and Advisory Panel members will provide feedback on the progress to date and make suggestions for potential changes and/or priority issues that need to be addressed by the various working groups. Following this feedback, working group leaders will revise their plans of work for the following year, and communicate those changes to Lea-Cox, who in turn will inform the Advisory panel of any substantial changes in the planned work.

4. Budgeted Project Management Plan, Administrative Timelines

The University of Maryland and each subcontract team (University and Company) has submitted a separate budget, budget justification and statement of work, which provides the detail of how each team and its members will function, working with their respective industry partners. Budgetary responsibilities rest with the lead PI at each institution/company, *i.e.*, Lea-Cox (Maryland and overall PD), Bauer (Antir), T. Bauerle (Cornell), B. Bauerle (Colorado State), Campbell (Decagon), and van Iersel (Georgia). The University of Maryland, as lead institution, will approve all expenditures for the project and is fiduciarily responsible for the entire grant.

Industry partners and growers have pledged a considerable amount of their own resources toward this project, indicating the importance of this project to their various businesses. The key to success of this project will be how the transdiscplinary teams (working groups) will coordinate and function, as detailed in the project Gantt chart (Appendix Table A2). This table documents the timeline of the various tasks and specific work objectives that will be met by each group, by year.

5. Short-, Medium and Long-Term Metric Evaluation

The logic model in Appendix Table A3 indicates the broad project short, medium and long-term evaluation metrics that will be achieved through the activities of this project. Short-term progress will be evaluated based on whether the activities and short term impacts, specified in Appendix Table A3, will be achieved according to the schedule presented in the Gantt chart (Appendix Table A2). We will continuously evaluate our short-term progress through our working group and advisory team activities, our annual meetings, and through formal and yearly reports to USDA-NIFA and other agencies. Medium term evaluation will be performed at the end of the project period by assessing whether the medium term impacts in Appendix Table A3 have been achieved. The long-term impact of the proposed research goes well beyond the 5-year project period, and is largely based on how our project outcomes change the management practices in greenhouse / nursery / green roof operations (medium to long term) as well as in other areas of specialty crop production (long term). Such evaluations are beyond the timeline of the current project, but will be assessed by PDs over the next 10 to 15 years. Especially PDs with extension/outreach responsibilities continuously monitor and quantify impacts of their outreach programs on the specialty crops industry, and they are in the perfect position to evaluate the long-term impact of this project.

6. Linkages to Existing Programs

Many of the PDs on this project work closely with specialty crop industry groups in their home states and around the country. These relationships will ensure that we can effectively integrate our findings into the educational programs of these industry groups. We will strive to involve other development groups in this effort through our external involvement in other groups such as USDA multistate groups NCERA101 and NC1186 . and through professional societies. There are many applications for this technology in the broad specialty crop community, especially the fruit production and landscape industries. Development of crop-specific models and software modules will allow us to engage and partner with interested parties in the future. We also have strong ties to other SCRI funded projects, including the SCRI "Comprehensive Automation for Specialty Crops (CASC)", led by Dr. Sanjiv Singh at Carnegie Mellon University, and the SCRI "Integrated management of zoosporic pathogens and irrigation water quality for a sustainable green industry " project led by Dr. Chuan Hong at Virginia Tech. We are actively working with these groups to integrate our technologies into the tree fruit and pathogen management arenas, and we will seek ways to incorporate results from CASC and IMP into our project.

Appendix Table A2. Project Research and Development Objectives, by Network Installation and Working Group

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

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

ID	PROJECT OBJECTIVES AND GOALS	WORKING GROUP	PROJECT ACTIVITIES BY QUARTER																			
			YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
			9-2009	12-2009	3-2010	06-2010	9-2010	12-2010	3-2011	06-2011	9-2011	12-2011	3-2012	06-2012	9-2012	12-2012	3-2013	06-2013	9-2013	12-2013	3-2014	06-2014
	Carnegie Mellon University																					
	Hardware Development																					
	Design	Decagon, CMU	team tech review	new node design			iterate design				iterate design					iterate design						
	Manufacture	Decagon				engineering prototype		build 50 field prototypes					build preproduction prototypes				produce/market sensor network system					
	Evaluate	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 Table A3: Logic Model – Wireless Sensor Networks for Precision Irrigation and Nutrient Management

Situation: This research and development program is directed at developing real-time wireless sensor networks that have the ability to monitor and control irrigation water applications in nursery and greenhouse production situations based upon immediate plant water use, reducing leaching of nutrients, increasing resource use, plant growth and the profitability of specialty crop producers

Outcomes: By providing real-time root and aerial microclimatic information with wireless sensor networks, we will provide specialty crop producers advanced tools for better daily management and economic decisions. During this grant, we will address deployment, operational and management issues with stakeholder involvement and participation, to produce a commercial system to implement into the nursery, greenhouse and green roof environments and spur further development in the future.

Inputs

What we invest:

- Research grant money
- Graduate student support and education
- Analytical and technical equipment and support
- Faculty time and expertise
- Grower collaboration, in-kind contributions of materials and support

Outputs

Activities

What we do:

- Deploy commercial and research sensor networks in the field
- Implement research-based knowledge (e.g. specific calibration curves)
- Develop robust operational systems that provide precision information about production scenarios
- Develop better irrigation and nutrient management practices
- Collaborate with the industry and other (national) researchers through this SCRI grant
- Disseminate research-based knowledge through extension programs, learning modules and peer-reviewed publications

Participation

Who we reach:

- Field, container-nursery and greenhouse growers
- Agency personnel (Departments of Agriculture, Environment, Cooperative Extension agents, NRCS technical service providers)
- Growers and Professionals throughout the US
- Researchers on a National and International basis
- Other State and National agencies (NRCS, EPA, USDA) and policy-makers
- Graduate and undergraduate students

Outcomes – Impact

Short Term

What the short term results are:

- Generation and evaluation of better management practices for water and nutrient management
- Economic and environmental management recommendations for the industry
- Increased awareness of the value of research-based information
- Research information development for extension education programming
- University graduates with expertise in transdisciplinary research
- Peer-reviewed journal and conference papers

Medium Term

What the medium term results are:

- Implementation of best management practices by individual growers
- Generate economic analyses of changed practices
- Monitoring of practices and runoff by growers
- Changed practices improve profitability and increase resource use efficiency
- Changed practices reduce impacts on local ecosystems
- Publication of policy / document changed practices by growers

Long Term

That the ultimate results are:

- Implementation of best management practices as standard practice by the industry on a state-wide and national basis
- Changed practices lead to significant conservation of resources and profitability
- Changed practices lead to significantly reduced nutrient and chemical impacts on local ecosystems and water bodies (e.g. the Chesapeake Bay)

Assumptions

- Adequate research funding is maintained
- Adequate research facilities, support services and technical help are available

External Factors

- Cost of inputs (fertilizer, water) and other resources will increase, giving an economic incentive for change and implementation
- Grower organizations continue to place a high priority on this research

Evaluation - How will you measure and report your outcomes?

Quantitative Outcomes: Document and communicate the science, private and public benefits to scientists, policy makers and the industry. Successful implementation and integration of the hardware and software into commercial use. Generation of knowledge with graduate students; Training and education of professionals and decision-makers with new information; Documentation of improved resource use and reduction of environmental impacts by growers.

Appendix Table A4: SCRI-MINDS Advisory Panel Members

Advisory Panel Member	Position	Expertise, Representation
Dr. Nick Place	Associate Dean of Extension University of Maryland. College Park, MD	Extension and Outreach, Administrative
Dr. Bruce Bugbee	Professor, Crop Physiology, Utah State University 1410 North 800 East Logan, UT; Apogee Instruments, Inc., Logan UT.	Research, Crop Physiology, Model Development; Commercial Industry
Mr. Marc Teffeau	Director, Research and Regulatory Affairs Horticultural Research Institute; American Nursery and Landscape Association, Washington, DC	National Industry Needs Research and Regulatory
Mr. Todd Martin	Decagon Devices, Inc. Pullman, WA	Hardware and Software Development
Mr. Terry Hines	Hale and Hines Nursery McMinnville, TN	Central Region Nursery / Industry
Mr. Tom Demaline American Nursery and Landscape Assoc.	Willoway Nursery Avon, OH	Central Region Nursery / Industry
Mr. Chris McCorkle	McCorkle Nursery Dearing, GA	Southern Region Nursery / Industry
Mr. Will Ross Georgia Green Industry Assoc.	Evergreen Nursery	Southern Region Greenhouse / Industry
Mr. Edmund Snodgrass	Emory Knoll Farms Addy, MD	Green Roof Plant Specialist; Green Roof Production and Installation
Mr. Gregory Long	Capitol Green Roofs Arlington, VA	Green Roof Construction and Integration
Mr. Charles Bauers Maryland Cut-Flower Assoc.	Bauers Greenhouses Jarrettsville, MD	North-East Greenhouse / Cut-flower Industry
Mr. Jerry Faulring Maryland Nursery and Landscape Assoc.	Waverley Farm Adamstown, MD	Mid-Atlantic Nursery Field Production
Mr. Steve Black Maryland Nursery and Landscape Assoc.	Raemelton Farm Adamstown, MD	Mid-Atlantic Nursery Field Production

Appendix B: Next-Gen MINDS Wireless Sensing and Control System Design (2011)

George Kantor (Carnegie Mellon University) and Todd Martin (Decagon Devices)

1. Overview

This document describes the wireless sensing and control prototype system that will be delivered in the Spring of 2011. This system is designed to simultaneously support the scientific investigations of the MINDS project and the needs of the commercial nursery, greenhouse, and green roof industries. Note that we expect the final commercial solution to be a subset of the research necessary options.

2. Hardware

The proposed system will have two primary hardware components: a *node* and a *basestation*. A node is a device that collects data from sensors that is it connected to and delivers those data wirelessly. A node also contains a relay that can be used to turn electrical devices such a solenoid valves on and off. A basestation is a device that receives information from and sends commands to one or more nodes.

3. The Nodes

The nodes in the 2011 system will closely resemble the Decagon EM50R wireless dataloggers, with the exception of the fact that each node will have a relay to provide the capability of control (the current EM50R is for sensing only).
Nodes will have five sensor ports, and will be compatible with any of the currently available sensors provided by Decagon. This list includes but is not limited to:

- Volumetric water content
- Air temperature and RH
- Electrical conductivity
- Micro environment (wind speed/direction, temp, RH, solar radiation, precipitation gauge)
- PAR
- Soil (media)
- Temperature
- Pressure switch
- Flow meter
- Leaf wetness

The power source for the nodes will be alkaline batteries with a standard form factor. They will have a battery life of at least six months. This battery life objective assumes a maximum sensor sampling rate of once every five minutes and a maximum of 20 control cycles per day. The nodes will support higher data rates (up to once per minute) and control cycle rates (up to once per minute) at the expense of a shorter battery life. Nodes will be equipped with radios and antennas the provide a communication range of 2 kilometers for outdoor line-of-sight transmission and 500 meters for indoor line-of-sight transmission. Radio options will be available that are legal for non-licensed use in U.S. and non-U.S. markets. The nodes will provide an easy means of determining the strength of telemetry links in the field. Nodes will be configurable with channels and subchannels so that adjacent networks will not interfere with one another. The nodes are not intended to be made commercially available, though they will be engineered with a target price comparable to that of the EM50R. Nodes will be configurable (sensor types, sensing parameters, control parameters) via a local, wired connection to a laptop computer. Nodes will also be configurable from a central location (the basestation) via the wireless network.

4. The Basestation

The basestation in the 2011 system has two components: a radio and a low-cost computer. The radio will connect to the low-cost computer via USB. Both components will be powered from standard 110VAC power, and both with be packaged for operation in an indoor environment.
Because the radio will communicate with the computer over USB, the computer will be available multiple form factors depending on the needs of the specific site. The computer will be either a netbook or a single-board computer mounted into an appropriate housing. The computer will run Ubuntu Linux operating system.

5. Information Flow

The information flow in the system will work in one of two ways, depending on whether the installation site has an internet connection.

A. Local Access Only Configuration

In the case where a site does not have access to the internet, the basestation serves as a server that will host the database and a web-based user interface to the local network via wired Ethernet or WiFi.

B. Remote Access Configuration

In the remote access configuration, the Ethernet port on the computer is connected to the internet. The database residing on the local computer is synced via the internet to a remote high-bandwidth server, which is likely hosted either at Carnegie Mellon University or Decagon Devices. Remote users can then access the system via a web-based user interface on the remote server. Local users will be able to access the system via either the local server or the remote server. Figure B1 depicts the local and global access configurations.

6. Control System

Nodes will provide a control capability via a relay that can be used to turn electrical devices on and off, though we focus on water. The control capabilities will combine open-loop scheduling with sensor based feedback. There will be two separate modes of the sensor feedback component: a local mode where the feedback loop is closed on the node itself, and a global mode where the feedback loop is closed over the wireless network and through the basestation.

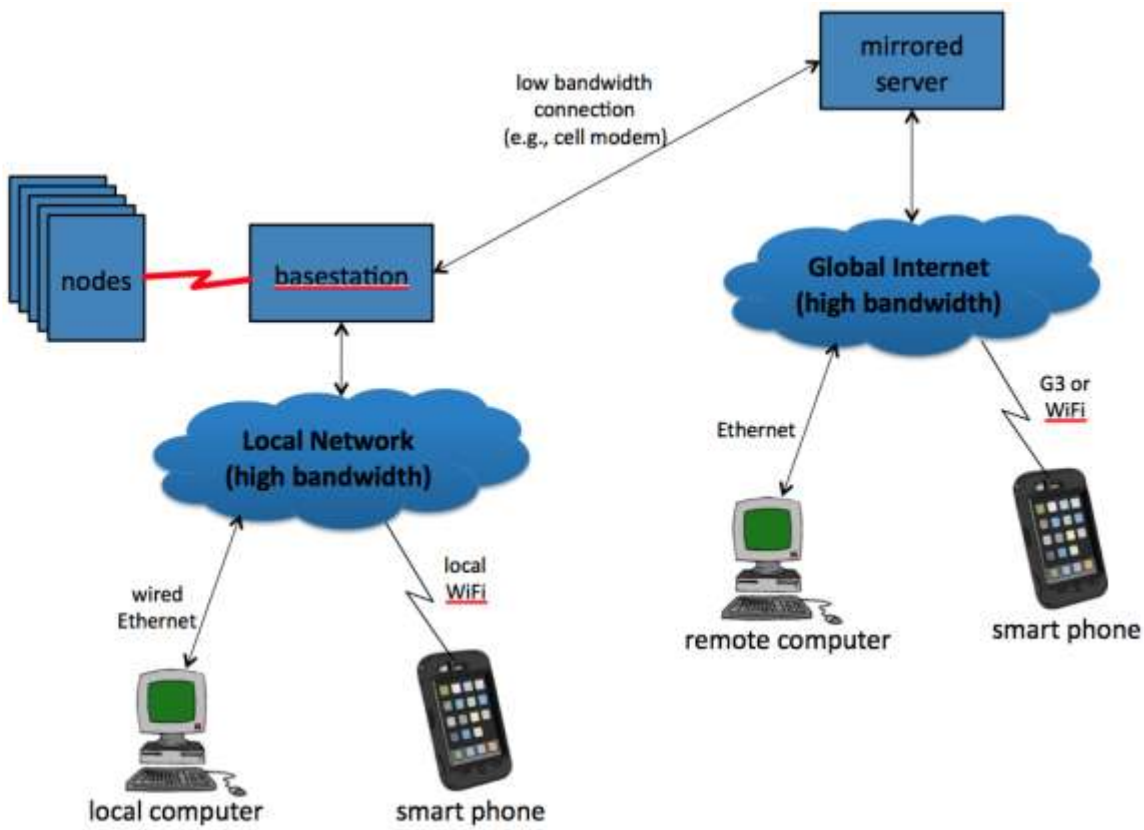
7. Assumptions

In order to come up with a feasible and cost-effective solution, it was necessary to place some limitations on the control capability and make some assumptions about the environments in which it can be used.

These assumptions are:

- There must be an external power source available for the device that is to be switched on and off by the relay.

- Relays will be sufficient
- Only controls "leaf" nodes of irrigation infrastructure. In other words, we are not designing for controlling large valves or pumps.
- One control point (relay) per node



Appendix Figure B1: Information flow diagram.

8. Control System Functions

The control system will have four basic functions: scheduling, feedback control, remote manual override, and local manual override. The use of each is described next.

A. Scheduling

The system will provide a means of implementing an irrigation schedule for each node that turns its relay on and off based on the node clock. A tool will be provided in the user interface that allows the schedule for each node to be configured and wirelessly transferred to the node. New schedules can be transmitted to a node at any time with a maximum latency of 10 minutes. The schedule resolution will be one second to allow for the possibility of scheduled "micropulse" irrigation.

B. Global Setpoint Control

In global setpoint control, an on/off control signal is generated by comparing the current reading of a single virtual control sensor to high and low setpoints. The virtual control sensor can be defined to combine inputs from any sensor on the network, hence the "global" designation. Note that due to the communication delays inherent in communicating over the wireless network, it will be impossible to close the loop at a rate faster than the sensor sample rate of the system (which is specified to be once per minute maximum, though we expect that the standard operational frequency will be once per five minutes). This may be exacerbated lost transmissions which are bound to happen occasionally. For these reasons, we expect that global setpoint control will be used only in combination with scheduling (see the section Combining Control Functions below).

The setpoint logic will be standard two-setpoint hysteresis. When the value of the virtual control sensor becomes lower than the low setpoint, the control signal will be set to on. Then it will stay on until the virtual sensor measurement reaches the high setpoint, at which point it will turn off.

The user interface will provide a tool for configuring setpoints and virtual control sensor for each node. Control logic will be implemented on the basestation computer.

C. Local Setpoint Control

The difference between global and local setpoint control is that the global approach can use sensor feedback derived from any sensor on the wireless network while local control can only use sensor feedback derived from the sensors directly attached to the same node as the relay that is being controlled. The primary benefit of this configuration is that the feedback does not need to be transmitted over the wireless network, which provides the ability to do control on smaller time scales and also allows the controller to continue to function in the case where the wireless connection fails.

Local setpoint control will be designed to work either in combination with the scheduler or independently. When working in combination with the scheduler, the setpoint logic will be identical to the logic used in the global setpoint control case. When working independently, the setpoint logic will be the same as the micropulse setpoint controller currently implemented on the CMU nodes. When the virtual control sensor goes below the low setpoint, the node goes into irrigation mode and stays in irrigation mode until either the high setpoint is reached or until a configurable maximum number of cycles is exceeded. In irrigation mode, the node goes into a loop where the relay is on for a configurable number of seconds (Seconds ON per cycle), waits for some configurable number of seconds (Seconds between consecutive cycles), then takes another measurement. Once irrigation mode is exited, the system waits for a configurable time (delay after watered) before it is allowed to enter irrigation mode again.

The user interface will provide a tool for configuring the setpoints, virtual control sensor, maximum number of cycles, seconds ON per cycle, seconds between consecutive cycles, and delay after watered.

D. Remote Manual Override

The system will provide a means for a user to remotely turn relays on and off. These manual commands will be subject to a delay of no more than 10 minutes between when they are issued by the user and when they are implemented at the node. The manual commands provided will be:

- Turn on for some configurable length of time
- Turn off (i.e., prevent any automatic control events) for some configurable length of time
- Disable, i.e., prevent any automatic control events from occurring until an "enable" command is received.
- Enable, i.e., allow automatic control algorithms to operate normally.

The user interface will provide tools to configure and send each of these commands.

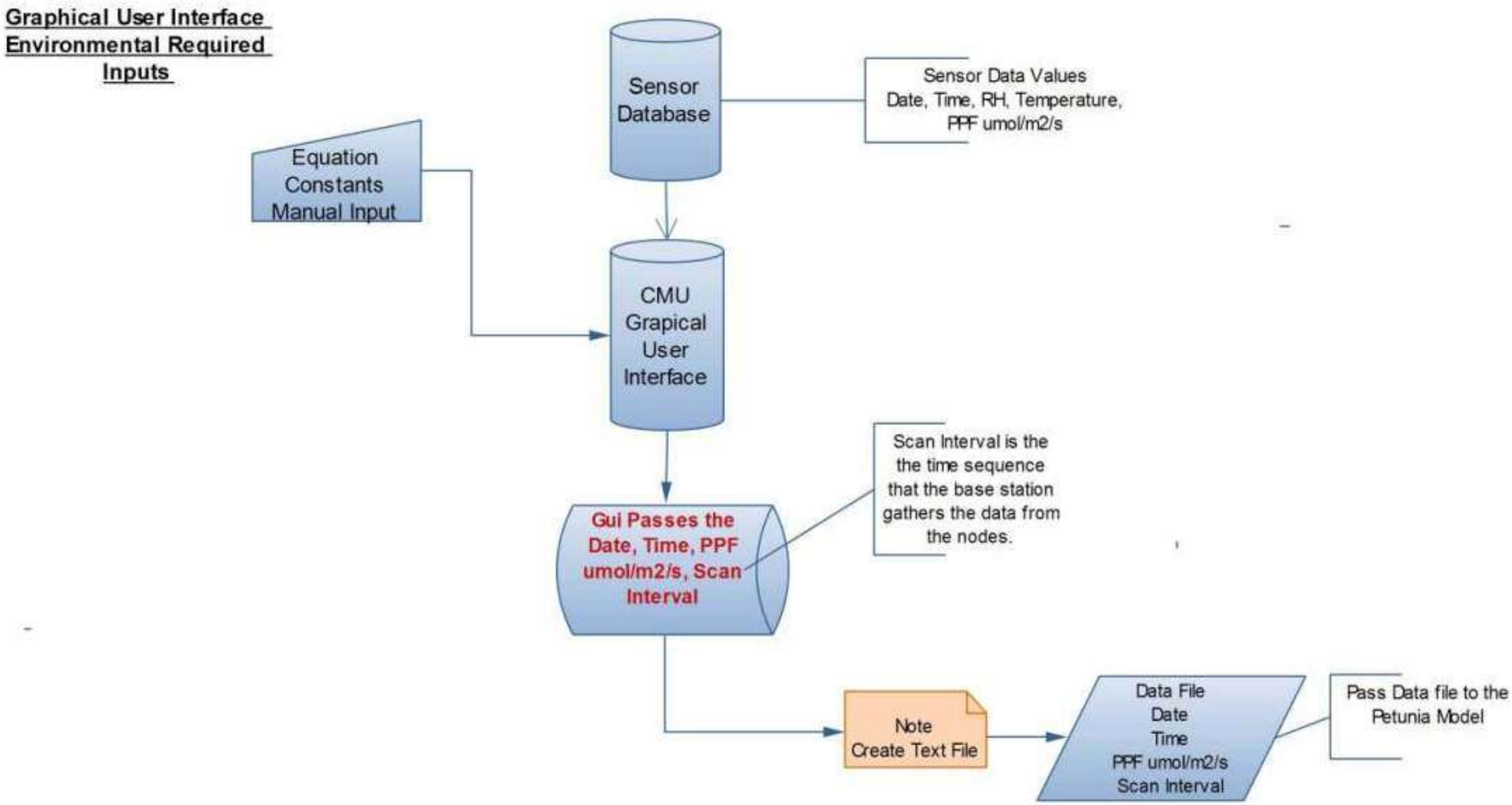
E. *Combining Control Functions*

It is anticipated that in typical operation, the schedule-based, setpoint-based, and override functions will be combined to provide the overall control capability.

The rest of this Appendix has been redacted from this public document, to protect Intellectual Property agreements between the project partners.

If you would like further information, please contact the authors of this report.

Appendix C: Petunia Model



The rest of this Appendix has been redacted from this public document, to protect Intellectual Property agreements between the project partners.

If you would like further information, please contact the authors of this report.

Appendix D: Economic Data

Appendix Table D1. Nursery and greenhouse economic data by state from the 2007 USDA Census of Agriculture

Nursery and greenhouse economic data by state (USDA Census of Agriculture 2007)			
State	**# of Establishments**	**Output ($1,000)**	**Output/Establishment ($1,000)**
United States	50,784	16,632,734	327.519
Alabama	675	264,807	392.307
Alaska	138	15,478	112.159
Arizona	281	417,792	1486.804
Arkansas	357	48,049	134.591
California	3,634	3,647,057	1003.593
Colorado	564	299,585	531.179
Connecticut	638	269,221	421.976
Delaware	175	17,114	97.794
Florida	4,778	2,115,641	442.788
Georgia	1,030	317,291	308.050
Hawaii	1,628	119,593	73.460
Idaho	548	87,373	159.440
Illinois	1,159	435,073	375.387
Indiana	888	126,241	142.163
Iowa	536	93,813	175.024
Kansas	399	77,031	193.060
Kentucky	1,191	87,748	73.676
Louisiana	498	103,154	207.137
Maine	676	51,687	76.460
Maryland	691	208,692	302.014
Massachusetts	814	169,167	207.822
Michigan	2,128	623,097	292.809
Minnesota	918	239,354	260.734
Mississippi	479	46,007	96.048
Missouri	913	121,280	132.837
Montana	367	29,472	80.305
Nebraska	371	41,215	111.092
Nevada	45	11,949	265.533
New Hampshire	382	65,554	171.607
New Jersey	1,682	442,953	263.349
New Mexico	231	60,267	260.896
New York	2,009	389,117	193.687
North Carolina	2,317	573,529	247.531
North Dakota	71	9,126	128.535
Ohio	2,104	444,855	211.433

Oklahoma	471	204,020	433.163
Oregon	2,583	989,483	383.075
Pennsylvania	2,719	892,279	328.164
Rhode Island	260	40,739	156.688
South Carolina	623	227,041	364.432
South Dakota	121	19,984	165.157
Tennessee	1,517	325,079	214.291
Texas	1,958	862,183	440.339
Utah	254	128,626	506.402
Vermont	437	24,795	56.739
Virginia	1,040	248,153	238.609
Washington	1,472	327,046	222.178
West Virginia	323	23,371	72.356
Wisconsin	1,635	244,216	149.368
Wyoming	56	6,339	113.196

Appendix Table D2. U.S. Nursery and Greenhouse Sector Direct, Indirect and Induced Economic Impacts from 2007 USDA Census Data and IMPLAN

U.S. Nursery and Greenhouse Sector Direct, Indirect and Induced Economic Impacts				
State	**Direct Output ($1,000)**	**Indirect Output ($1,000)**	**Induced Output ($1,000)**	**Total Output ($1,000)**
Alabama	264,807	95,900	391,821	752,528
Alaska	15,478	5,605	22,902	43,985
Arizona	417,792	151,303	618,185	1,187,280
Arkansas	48,049	17,401	71,096	136,546
California	3,647,057	1,320,782	5,396,361	10,364,199
Colorado	299,585	108,495	443,280	851,360
Connecticut	269,221	97,498	398,352	765,072
Delaware	17,114	6,198	25,323	48,635
Florida	2,115,641	766,179	3,130,404	6,012,224
Georgia	317,291	114,907	469,479	901,677
Hawaii	119,593	43,311	176,956	339,859
Idaho	87,373	31,642	129,281	248,296
Illinois	435,073	157,562	643,755	1,236,390
Indiana	126,241	45,718	186,792	358,751
Iowa	93,813	33,974	138,810	266,598
Kansas	77,031	27,897	113,979	218,907
Kentucky	87,748	31,778	129,836	249,362
Louisiana	103,154	37,357	152,632	293,143
Maine	51,687	18,718	76,479	146,884
Maryland	208,692	75,578	308,791	593,061
Massachusetts	169,167	61,264	250,308	480,738
Michigan	623,097	225,655	921,964	1,770,716
Minnesota	239,354	86,682	354,160	680,196
Mississippi	46,007	16,661	68,074	130,743
Missouri	121,280	43,922	179,452	344,653
Montana	29,472	10,673	43,608	83,753
Nebraska	41,215	14,926	60,984	117,125
Nevada	11,949	4,327	17,680	33,957
New Hampshire	65,554	23,740	96,997	186,291
New Jersey	442,953	160,415	655,415	1,258,783
New Mexico	60,267	21,826	89,174	171,267
New York	389,117	140,919	575,756	1,105,792
North Carolina	573,529	207,704	848,621	1,629,854
North Dakota	9,126	3,305	13,503	25,934
Ohio	444,855	161,104	658,229	1,264,188
Oklahoma	204,020	73,886	301,878	579,784
Oregon	989,483	358,341	1,464,087	2,811,911
Pennsylvania	892,279	323,139	1,320,259	2,535,677

Rhode Island	40,739	14,754	60,279	115,772
South Carolina	227,041	82,223	335,941	645,205
South Dakota	19,984	7,237	29,569	56,790
Tennessee	325,079	117,727	481,002	923,809
Texas	862,183	312,240	1,275,727	2,450,150
Utah	128,626	46,582	190,321	365,529
Vermont	24,795	8,980	36,688	70,462
Virginia	248,153	89,869	367,179	705,201
Washington	327,046	118,440	483,913	929,399
West Virginia	23,371	8,464	34,581	66,416
Wisconsin	244,216	88,443	361,354	694,013
Wyoming	6,339	2,296	9,379	18,014
United States	16,632,734	6,023,545	24,610,592	47,266,870

Appendix Table D3. United States nursery and greenhouse environmental outputs per $1 million in direct sales from EIO-LCA

United States nursery and greenhouse environmental outputs per $1 million in direct sales (EIO-LCA)			
Emissions	**Direct**	**Indirect**	**Total**
Sulfur dioxide (mt)	1.50656	0.25344	1.76000
Carbon monoxide (mt)	10.10080	1.69920	11.80000
Nitrogen oxide (mt)	1.79760	0.30240	2.10000
Volatile organic compounds (mt)	1.30112	0.21888	1.52000
Lead (mt)	0.00000	0.00000	0.00000
PM10 (mt)	1.16416	0.19584	1.36000
Global warming potential (mt CO2 equivalent)	655.69600	110.30400	766.00000
Carbon dioxide (mt CO2 equivalent)	452.82400	76.17600	529.00000
Methane (mt CO2 equivalent)	38.09200	6.40800	44.50000
Nitrous oxide (mt CO2 equivalent)	159.21600	26.78400	186.00000
Chlorofluorocarbons (mt CO2 equivalent)	5.01616	0.84384	5.86000
Energy usage	**Direct**	**Indirect**	**Total**
Energy (TJ)	6.89080	1.15920	8.05000
Electricity (MkWh)	0.28505	0.04795	0.33300
Coal (TJ)	1.66064	0.27936	1.94000
Natural gas (TJ)	1.78904	0.30096	2.09000
Liquid petroleum gas (TJ)	0.83974	0.14126	0.98100
Motor gas (TJ)	1.34392	0.22608	1.57000
Distillate (TJ)	0.61290	0.10310	0.71600
Kerosene (TJ)	0.06934	0.01166	0.08100
Jet fuel (TJ)	0.09159	0.01541	0.10700
Residual (TJ)	0.16692	0.02808	0.19500
Releases	**Direct**	**Indirect**	**Total**
Non-point air (kg)	9.75840	1.64160	11.40000
Point air (kg)	78.92320	13.27680	92.20000
Total air releases (kg)	89.02400	14.97600	104.00000
Water releases (kg)	10.44320	1.75680	12.20000
Land releases (kg)	76.18400	12.81600	89.00000
Underground releases (kg)	21.22880	3.57120	24.80000
Total releases (kg)	196.88000	33.12000	230.00000
Publicly owned treatment works transfers (kg)	7.96936	1.34064	9.31000
Offsite transfers (kg)	16.34960	2.75040	19.10000
Total rel/trans (kg)	220.84800	37.15200	258.00000

Appendix Table D4. Establishment-level impact worksheet for greenhouse and nursery operations

SCRI Impact of Precision Irrigation
Establishment Level Impact Worksheet Summary

Page 1 (of 2) Establishment Level Economic Impacts
Changes in Revenues, Costs, and Earnings

Legend:

Establishment

Type: ___________________________ Product Types: ___________________________ Size: _____________________________

Irrigation Type: ________________________ Location: ____

			Difference (Old – New)	
	Current Irrigation System	**Sensor-based Precision Irrigation System**	**Amount**	**% Change**
Annual Revenues				
Quantity				
Price				
Gross Revenues				
Operating Costs				
Input Costs				
Fertilizer				
Fungicides				
Pesticides				
Herbicides				
Water Purchases				
Other Materials				
Energy for Water Supplies				
Other Utilities				
Labor Costs				
Labor for Irrigation				
Labor for Other Tasks				
Equipment Costs				
Irrigation Equipment				
Other Equipment				
Other				
Overhead				
Other				
Total				
Operating Profit				
Capital Costs				
Net Profit				

SCRI Impact of Precision Irrigation
Establishment Level Impact Worksheet Summary

Page 2 (of 2) Other Establishment Level Impacts
Changes in Natural Resource Use, Emissions, and Other Factors

Legend:
Establishment
Type: ___________________________ Product Types: ___________________________ Size: _____________________________
Irrigation Type: ________________________ Location: ____

			Difference (Old – New)	
	Current Irrigation System	**Sensor-based Precision Irrigation System**	**Amount**	**% Change**
Summary Impact on Energy/Water Use and Environmental Emissions				
Resource Use				
Water				
Energy for Water Use				
Other				
Emissions and Releases				
Sulfur dioxide (mt)				
Carbon monoxide (mt)				
Nitrogen oxide (mt)				
Volatile organic compounds (mt)				
Lead (mt)				
PM10 (mt)				
Global warming potential (mt CO_2 equivalent)				
Carbon dioxide (mt CO_2 equivalent)				
Methane (mt CO_2 equivalent)				
Nitrous oxide (mt CO_2 equivalent)				
Chlorofluorocarbons (mt CO_2 equivalent)				
Point air (kg)				
Water releases (kg)				
Land releases (kg)				
Underground releases (kg)				
Other Impacts				
Production area size				
Yield loss due to water-related stress				
Yield loss due to pathogens				
Growing season duration				
Plant maturation timing				

Appendix E:

FEDERAL FINANCIAL REPORT

(Follow form instructions)

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

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

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

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

8. Project/Grant Period From: (Month, Day, Year)	To: (Month, Day, Year)	9. Reporting Period End Date (Month, Day, Year)
9/1/2009	8/31/2014	8/31/2010

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	$226,543.74
b. Cash Disbursements	$461,738.75
c. Cash on Hand (line a minus b)	($235,195.01)
(Use lines d-o for single grant reporting)	
Federal Expenditures and Unobligated Balance:	
d. Total Federal funds authorized	$5,161,495.00
e. Federal share of expenditures	$461,738.75
f. Federal share of unliquidated obligations	
g. Total Federal share (sum of lines e and f)	$461,738.75
h. Unobligated balance of Federal funds (line d minus g)	$4,699,756.25
Recipient Share:	
i. Total recipient share required	$5,161,495.00
j. Recipient share of expenditures	$919,467.60
k. Remaining recipient share to be provided (line i minus j)	$4,242,027.40
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	8/31/2010	354,378	177,189	114,076
				g. Totals:	354,378	177,189	114,076

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

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

a. Typed or Printed Name and Title of Authorized Certifying Official **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) 11/10/2010
	14. Agency use only:

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

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