

Using Wireless Sensor Networks for Precision Irrigation Scheduling

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1. Introduction

Worldwide, irrigation uses about 69% of available freshwater resources (Fry, 2005). In the United States, 82% of freshwater resources are used for irrigation purposes. Major concerns on future planetary freshwater resources are the effects of climate change on changing sea temperature and levels, annual snowpack, drought and flood events, as well as changes in water quality, and general ecosystem vulnerabilities (US Global Change Research Program, 2011). Changes in the extreme climatic events are more likely to occur at the regional level than show in national or global statistics. The unpredictability of climatic events is of key concern to farmers in all countries, since the availability and cost of irrigation water is likely to be compounded by increased regulations and competition. Over the past 50 years, the urban demand for freshwater in the United States has also been increasing (Hutson et al. 2004), while the quality of both surface and groundwater has been decreasing due to pollution from both point and nonpoint sources (Secchi et al. 2007). Nitrogen, phosphorus and many other inorganic and organic pollutants such as pesticides and herbicides are being found at increasing concentrations in groundwater under agricultural areas (Guimerà, 1998). As demands on water and the cost of purification increase, the cost of freshwater resources will increase and the availability will likely decrease for agriculture. Population growth in the 20th century increased by a factor of three while water withdrawals increased by a factor of seven during the same time, with little hope of these rates slowing in the near future (Agarwal et al. 2000).

In view of increased competition for resources and the need for increased agricultural production to ensure national and global food security, it is clear that we need to increase our efficiency of irrigation water use, to adapt to these changing conditions. Not only do we need to increase the overall efficiency of irrigation water use to optimize crop yields, but there is also a need to provide farmers with better information on root zone water availability and daily crop water use, especially at critical times during flowering, fruit set and fruit or seed development. Although crop yield is oftentimes related to water use, most growers don't know the water requirement of the crop they grow at any real level of precision. Since irrigation costs in developed countries are usually a small fraction of total production costs, there are few incentives for growers to optimize their use of irrigation water. Therefore, the amount of water applied is mostly based on the availability, rather

than actual crop water needs (Balendock et al., 2009). The development of precision (low volume) irrigation systems has played a major role in reducing the water required to maintain yields for high-value crops, but this has also highlighted the need for new methods for accurate irrigation scheduling and control (Jones, 2008). For high-value horticultural crops, there is also significant interest in using precision irrigation as a tool to increase harvest quality through regulated deficit irrigation, and to reduce nutrient loss and fungal disease pressures. In the near future, farmers will likely have to make decisions on how to optimize water use with crop yield, in order to remain competitive. Achievement of any optimal irrigation capability will depend not only on the use of precision irrigation systems, but also on the tools that can help the farmer monitor and automate irrigation scheduling, applying water precisely to satisfy crop water requirements.

1.1 Scope of the chapter

The intent of this chapter is not to provide the reader with an exhaustive review of the sensor network development literature. A simple online search of the keywords “wireless, sensor, network, irrigation” provides links to over 1500 journal articles just within the engineering and biological fields. However, two recent articles do provide excellent current reviews (Ruiz-Garcia et al., 2009) and practical advice (Barrenetxea et al., 2008) for readers wanting more explicit engineering and technical advice on the development and deployment of wireless sensor networks for irrigation, environmental and other (animal and food safety) applications. It is apparent from these and many other articles that the development of operational wireless sensor networks (WSNs) for large-scale outdoor deployment has many challenges; an excellent discussion of many of the pitfalls is given by Barrenetxea et al., (2008). For many of the reasons they and others have outlined, most research in the field of sensor networks for irrigation scheduling has focused on the technical challenge of gathering reliable data from wide area networks. Barrenetxea et al. (2008) note that there are two primary components for successful WSN deployments: (1) gathering the data and (2) exploiting the data. Generally, the engineering component of any WSN project is tasked with providing hardware that reliably accomplishes the first task. However, understanding the biological and/or environmental domain is vital to maximize the trustworthiness of sensor data. Interdisciplinary projects and partnerships are more likely to have a greater chance of success, since the primary objective of all WSN's is to gather data for a specific use, and all partners are focused on that task. However, if we are going to successfully commercialize and deploy sensor networks on farms, the *end-user* must be involved during all stages of the project: from node deployment, to sensor placement and calibration, through to data analysis and interpretation (Tolle et al, 2005; Lea-Cox et al., 2010a). It is this part of the process that has often received scant attention from researchers and developers; the successful integration of sensor networks and decision support systems (software tools) is probably one of the greatest barriers to successful implementation and adoption of these systems by farmers. For this reason, any tools that are developed should be thoroughly vetted by the end-user for ease-of-use, interpretation and applicability. Perhaps most importantly, we should learn from past mistakes where various water-saving technologies have often not achieved any real economic benefit for the grower, in terms of water savings, improved yield, labor cost or other use. Sometimes technology merely adds another “management layer” that requires additional expertise to interpret and

use the information, in order to make a decision. We therefore need to bear these considerations in mind when we develop any irrigation scheduling system that aims to improve upon current irrigation management techniques.

This chapter will firstly summarize the pros and cons of certain sensors and techniques that provide promise for use in WSNs for precision irrigation. It will review WSN deployment and progress, but focus primarily on intensive nursery and greenhouse production, since these environments provide some extreme challenges with spatial and temporal sensor measurement, to accurately predict plant water use. We recognize that there are many aspects of plant physiology that provide both feedback and feedforward mechanisms in regulating plant water use, and these may radically change in a crop, pre- and post-anthesis. This chapter is not focused on these challenges; it will however attempt to illustrate the potential of sensor networks to provide real-time information to both farmers and researchers – often at a level of precision that provides keen insights into these processes. Our research and development team (Lea-Cox et al, 2010b) is actively working on deploying and integrating WSNs on farms, but concurrently developing the advanced hardware and software tools that we need for precision irrigation scheduling in intensive horticultural operations. We will illustrate some of our progress with these WSN's in container-production and greenhouse environments, as well as in field (soil-based) tree farms which have soil water dynamics more akin to field orchard environments. Finally, we will discuss challenges and opportunities that need to be addressed to enable the widespread adoption of WSN's for precision irrigation scheduling.

1.2 Intensive production system irrigation scheduling

The most widespread use of automated irrigation scheduling systems are in intensive horticultural, and especially in greenhouse or protected environments (Jones, 2008). Currently, many greenhouse and nursery growers base their irrigation scheduling decisions on intuition or experience (Bacci et al., 2008; Jones, 2008; Lea-Cox et al., 2009). Oftentimes the most basic decision is – “do I need to irrigate today?” While this question could seem trivial, plant water requirements vary by species, season and microclimate, and depend upon any number of environmental and plant developmental factors that need to be integrated on a day-to-day basis. Add to these factors the number of species grown in a ‘typical’ nursery or greenhouse operation (oftentimes >250 species; Majsztrik, 2011), the variety of container sizes (i.e. rooting volume, water-holding capacity) and the length of crop cycles (a few weeks to several years), it quickly becomes obvious why precision irrigation scheduling in these types of operations is extremely difficult (Lea-Cox et al., 2001; Ross et al, 2001). If done well, daily irrigation decisions take a lot of time and an irrigation manager often faces complex decisions about scheduling, which requires integrating knowledge from many sources. Although these intuitive methods for irrigation scheduling can give good results with experience, they tend to be very subjective with different operators making very different decisions. Many times, even experienced managers make an incorrect decision, i.e., they irrigate when water is not required by the plant. It is also surprising how many “advanced” irrigation scheduling systems automate irrigation cycles *only* on the basis of time, without any feedback-based sensor systems. Thus, even with advanced time-based systems, the decision to irrigate is again based solely on the operator's judgment and the time taken to evaluate crop water

use and integrate other information, e.g. weather conditions during the past few days and immediate future.

There are many sensor technologies that have been used over the years to aid this decision process. Various soil moisture measurement devices are available, e.g. tensiometers, gypsum blocks and meters that directly sense soil moisture; additionally pan evaporation, weather station or satellite forecast data can be incorporated into evapotranspiration (E_T) models. However, the widespread adoption of most of this technology has not occurred in the nursery and greenhouse industries, for good reasons. Many sensing technologies which were originally engineered for soil-based measurements have been applied to soilless substrates. Many have failed, largely because these sensors did not perform well in highly porous substrates, since porosity is an important physical property that is necessary for good root growth in containers (Bunt, 1961). Even when a technology has been adapted successfully to container culture (e.g. low-tension tensiometers), often the technology has been too expensive for wide-scale adoption, difficult to incorporate into WSNs, or there have been precision or maintenance issues. Cost and ease of use are key aspects to the adoption and use of any tool by growers, who are often time-limited.

1.3 Wireless sensor network development objectives

It was imperative to establish a list of global objectives for the development of WSN tools and strategies for our project (Lea-Cox et al, 2010b). Jones (2008) documented the features of an 'ideal' irrigation scheduling system for intensive horticultural production systems. He noted that any system should be (1) sensitive to small changes, whether in terms of soil moisture content, evaporative demand, or plant response; (2) respond rapidly to these changes, allowing for continual monitoring and maintenance of optimal water status and responding in "real time" to changing weather conditions; (3) readily adaptable to different crops, growth stages or different horticultural environments without the need for extensive recalibration; (4) robust and reliable; (5) user-friendly, requiring little user training; (6) capable of automation, thus reducing labor requirements, and (7) low cost, both in terms of purchase and running costs.

In addition to these universal requirements, Lea-Cox et al. (2008) proposed a number of more specific WSN requirements, where (1) users should be able to rapidly deploy sensors in any production area, to maximize utility and minimize cost; (2) sensor networks should be scalable, thereby allowing an operation to begin with a small, low-cost system and expand/improve the network over time; (3) nodes (motes) should have low power (battery) requirements, preferably with rechargeable power options; (4) sensor data should be reliably transmitted using wireless connections to the base station computer (or internet) with little or no interference over at least 1000m; (5) the software interface should automatically log and display real-time data from the sensor nodes, in a form that provides the user with an easily interpreted summary of that data, preferably as a customizable graphical output (6) any software control functions should include relatively sophisticated decision tools and discretionary options, to allow for maximum flexibility in scheduling / actuating irrigation solenoids or other control devices.

These engineering objectives are the foundation for our specific scientific, engineering and socio-economic objectives (Lea-Cox, 2010b), to: (1) further develop and adapt commercially-available wireless sensor network hardware and software, to meet the monitoring and control requirements for field (soil-based), container (soilless) production and environmental (green roof) systems; (2) determine the performance and utility of soil moisture and electrical conductivity sensors for precision irrigation and nutrient management; (3) determine spatial and temporal variability of sensors, to minimize the numbers of sensors required for different environments at various scales; (4) integrate various environmental sensors into WSNs to enable real-time modeling of microclimatic plant E_T ; (5) integrate soil and environmental data into species-specific models to better predict plant and system water use; (6) develop best management practices for the use of sensors, working with commercial growers to capture needs-based issues during on-farm system development; (7) quantify improvements in water and nutrient management and runoff, plant quality, and yield; (8) evaluate the private and public economic and environmental impacts of precision sensor-controlled practices; (9) identify barriers to adoption and implementation of these practices; and (10) engage growers and the industry on the operation, benefits and current limitations of this sensor / modeling approach to irrigation scheduling and management.

2. Irrigation sensing approaches

The main approaches to irrigation scheduling in soils and the techniques available have been the subject of many reviews over the years. Specific reviews have concentrated on measuring soil moisture (e.g. Dane & Topp, 2002; Bitelli, 2011), physiological measurements (e.g. Jones, 2004; Cifre et al., 2005) or water balance calculations (e.g. Allen et al., 1998). The conventional sensor-based approach has typically scheduled irrigation events on the basis of soil moisture status, whether using direct soil moisture measurements with capacitance or TDR-type sensors (Topp, 1985; Smith & Mullins, 2001), tensiometers (Smajstrla & Harrison, 1998) or soil-moisture water balance methods using daily E_T estimates (Allen et al., 1998). Some automated greenhouse systems have used load cells for the estimation of daily plant water use (Raviv et al., 2000). However, these load cell systems have to be programmed to accurately correct for increasing total plant mass over the crop cycle, or to adjust to changes in wind and temperature changes, if deployed in outdoor environments. Nevertheless, if operated correctly, most of these systems enable much greater precision and improved water use efficiency over traditional time-based irrigation scheduling methods.

Jones (2004) summarized the main sensor techniques that are currently used for irrigation scheduling or which have the potential for development in the near future in some detail (Table 1). The current debate centers around using soil moisture sensing techniques, plant water sensing techniques or a combination of both techniques. Soil irrigation sensing approaches (Table 1) can either be based on direct measurement of soil moisture content (or water potential), or by using sensors to provide data for the water balance method, which accounts for inputs (rainfall, irrigation) and losses (E_T , run-off and drainage) from the system. The emphasis on using soil moisture content for irrigation decisions has been based on the perception that water availability in the soil is what limits plant transpiration, and that irrigation scheduling should replace the water lost by plant water uptake and evaporation from the rootzone (Jones, 2008).

Measurement Technique	Advantages	Disadvantages
I. Soil water measurement		
(a) Soil water potential (tensiometers, psychrometers, etc.)	Easy to apply in practice; can be quite precise; at least water content measures indicate 'how much' water to apply; many commercial systems available; some sensors (especially capacitance and time domain sensors) readily automated	Soil heterogeneity requires many sensors (often expensive) or extensive monitoring program (e.g. neutron probe); selecting position that is representative of the root-zone is difficult; sensors do not generally measure water status at root surface (which depends on evaporative demand)
(b) Soil water content (gravimetric; capacitance / TDR; neutron probe)		
II. Soil water balance calculations (Require estimate of evaporation and rainfall)	Easy to apply in principle; indicate 'how much' water to apply	Not as accurate as direct measurement; need accurate local estimates of precipitation /runoff; evapotranspiration estimates require good estimates of crop coefficients (which depend on crop development, rooting depth, etc.); errors are cumulative, so regular recalibration needed
III. Plant 'stress' sensing (Includes both water status measurement and plant response measurement)	Measures the plant stress response directly; integrates environmental effects; potentially very sensitive	In general, does not indicate 'how much' water to apply; calibration required to determine 'control thresholds'; still largely at research/development stage; little used for routine agronomy (except for thermal sensing in some situations)
(a) Tissue water status	Often been argued that leaf water status is the most appropriate measure for many physiological processes (e.g. photosynthesis), but this argument is generally erroneous (as it ignores root-shoot signaling)	All measures are subject to homeostatic regulation (especially leaf water status), therefore not sensitive (isohydric plants); sensitive to environmental conditions which can lead to short-term fluctuations greater than treatment differences
(i) Visible wilting	Easy to detect	Not precise; yield reduction often occurs before visible symptoms; hard to automate
(ii) Pressure chamber (ψ)	Widely accepted reference technique; most useful if estimating stem water potential (SWP), using either bagged leaves or suckers	Slow and labor intensive (therefore expensive, especially for predawn measurements); unsuitable for automation
(iii) Psychrometer (ψ)	Valuable, thermodynamically based measure of water status; can be automated	Requires sophisticated equipment and high level of technical skill, yet still unreliable in the long term
(v) Pressure probe	Can measure the pressure component of water potential which is the driving force for xylem flow and much cell function (e.g. growth)	Only suitable for experimental or laboratory systems

(vi) Xylem cavitation	Can be sensitive to increasing water stress	Cavitation frequency depends on stress prehistory; cavitation-water status curve shows hysteresis, with most cavitations occurring during drying, so cannot indicate successful rehydration
(b) Physiological responses	Potentially more sensitive than measures of tissue (especially leaf) water status	Often require sophisticated or complex equipment; require calibration to determine 'control thresholds'
(i) Stomatal conductance	Generally a very sensitive response, except in some anisohydric species	Large leaf-to-leaf variation requires much replication for reliable data
- Porometer	Accurate: the benchmark for research studies	Labor intensive so not suitable for commercial application; not readily automated (though some attempts have been made)
- Thermal sensing	Can be used remotely; capable of scaling up to large areas of crop (especially with imaging); imaging effectively averages many leaves; simple thermometers cheap and portable; well suited for monitoring purposes	Canopy temperature is affected by environmental conditions as well as by stomatal aperture, so needs calibration (e.g. using wet and dry reference surfaces)

Table 1. A summary of the main classes of irrigation scheduling techniques, indicating the major advantages and disadvantages (from Jones, 2004). Reproduced with kind permission of the author and Oxford University Press.

2.1 Measuring soil moisture

2.1.1 Water potential or volumetric water content?

Soil (substrate) water content can be expressed either in terms of the energy status of the water in the soil (i.e. matric potential, kPa) or as the amount of water in the substrate (most commonly expressed on a volumetric basis; % or $\text{m}^3 \cdot \text{m}^{-3}$). Both methods have advantages and disadvantages. Soil/substrate matric potential indicates how easily water is available to plants (Lea-Cox et al, 2011), but it does not provide information on how much total water is present in the substrate. Conversely, volumetric water content indicates how much water is present in a substrate, but not if this water is extractable by plant roots. This is especially important for soilless substrates, since mixtures of different components means that substrates have very different water-holding capacities and moisture release curves (deBoodt and Verdonck, 1972). Sensors that estimate water content (e.g. capacitance and TDR-type sensors) tend to be more reliable than those sensors measuring water availability (tensiometers and psychrometers); (Jones, 2008; Murray et al, 2004). A major disadvantage of almost all soil sensors, however, is their limited capability to measure soil moisture heterogeneity in the root zone, since they typically only sense a small volume around the sensor. Variation in soil water availability is well known, primarily as a function of variation in soil type, soil compaction and depth, among many sources of variation (e.g. organic matter content, porosity and rockiness). The use of large sensor arrays which may be necessary to get good representative readings of soil moisture tends to be limited by cost, but this could be overcome by sensor placement strategies.

Soilless substrates are used by the nursery and greenhouse industry for a multitude of reasons, primarily to reduce the incidence of soil-borne pathogens, increase root growth, and reduce labor, shipping and overall costs to the producer (Majsztik et al., 2011). Over the years, many studies have shown large differences between soil and soilless substrates in the availability of water to root systems (Bunt, 1961; deBoodt and Verdonck, 1972). Soilless substrates, which in most cases have larger particle sizes and porosity, tend to release more water at very low matric potentials ($\Psi_m = -1$ to -40 kPa) which is 10 to 100 times lower than similar plant-available water tensions in soils (Lea-Cox et al., 2011). Plant-available water (PAW) is the amount of water accessible to the plant, which is affected by the physical properties of the substrate, the geometry (height and width) of the container and the total volume of the container (Handreck and Black, 2002). Container root systems are usually confined within a short time after transplanting, and shoot : root ratios are usually larger than those of soil-grown plants, for similarly-aged plants. For all these reasons, maintaining the optimal water status of soilless substrates has been recognized as being critical for continued growth, not only because of limited water-holding capacity, but also because of the inadequacies of being able to accurately judge when plants require water (Karlovich & Fonteno, 1986). Although it is likely that mature plant root systems can extract substrate moisture at Ψ_m less than -40 kPa, Leith and Burger (1989) and Kiehl et al. (1992) found significant growth reductions at substrate Ψ_m as small as -16 kPa (0.16 Bar). This has major implications for choosing appropriate sensors for use in soilless substrates (see next section), as well as the measurement and automatic control of irrigation in these substrates.

2.1.2 Types of soil moisture sensors

Jones (2004) noted the various types of soil moisture sensors available at that time. The variety of soil moisture sensors (tensiometric, neutron, resistance, heat dissipation, psychrometric or dielectric) has continually evolved since then; the choices are now overwhelming, since each sensor may have specific strengths and weaknesses in a specific situation. Tensiometers have long been used to measure matric potential in soils (Smajstrla & Harrison, 1998) and in soilless substrates (Burger and Paul, 1987). Although tensiometers have proven to be valuable research tools, they have not been adopted widely in greenhouse and nursery production, mainly because of the problems with using them in highly porous soilless substrates. Tensiometers rely on direct contact between the porous ceramic tip and substrate moisture. If the substrate shrinks, or the tensiometer is disturbed, this contact may be disrupted. Air then enters and breaks the water column in the tensiometer, resulting in incorrect readings and maintenance issues (Zazueta et al., 1994). A number of next-generation soil moisture sensors have become available in the past decade from various manufacturers., e.g. Theta probe and SM200 (Delta T, Burwell, UK) and EC5, 5TM and 10HS sensors (Decagon Devices Inc., Pullman, WA, USA) which provide precise data in a wide range of soilless substrates. These sensors determine the volumetric moisture content by measuring the apparent dielectric constant of the soil or substrate. These sensors are easy to use and provide highly reproducible data (van Iersel et al., 2011). The Decagon range of sensors are designed to be installed in soils or substrates for longer periods of time and all interface with Decagon's range of EM50 nodes, datastation and Datatrac software (<http://decagon.com/products>). Dielectric sensors generally require substrate-specific calibrations, because the dielectric properties of different soils and substrates differ, affecting sensor output. The conversion between water potential and volumetric water

content (VWC) varies substantially with soil type. It is possible to inter-convert matric potential to volumetric water content (Lea-Cox et al., 2011) for various sensors using substrate moisture release curves. However, such release curves are substrate-specific, and may change over time as the physical properties (e.g. pore size distribution) of the substrate changes (van Iersel et al., 2011) or root systems become more established. Fortunately, in most irrigation scheduling applications, the objective is simply to apply a volume of water that returns the soil moisture content to its original well-watered state. Changes in this total water-holding capacity (i.e. the maximum VWC reading) can easily be monitored for changes over time, i.e. after significant rainfall events or by periodically saturating the container with the embedded sensor.

More recently, hybrid 'tensiometer-like' sensors have been developed which use the principle of dielectric sensors to determine the water potential of substrates (e.g., Equitensiometer, Delta T; MPS-1, Decagon Devices) (van Iersel et al., 2011). An advantage of such sensors is that they do not require substrate-specific calibrations, since they measure the water content of the ceramic material, not that of the surrounding soil or substrate. Unfortunately, the sensors that are currently available are not very sensitive in the matric potential range where soilless substrates hold most plant-available water (0 to -10 kPa; deBoodt and Verdonck, 1972). In addition, it is not clear whether these sensors respond quickly enough to capture the rapid changes that can occur in soilless substrates (van Iersel et al., 2011).

2.2 Measuring plant water status

Automated irrigation techniques based on sensing plant water status are mostly in the developmental stage, in large part because of the variability of sensor readings and the lack of rugged sensors and reliable automated techniques (Table 1). It is usually necessary to supplement indicators of plant stress with additional information, such as crop evaporative demand (Jones, 2008); it is also hard to scale up these automated systems for many horticultural applications, since a detailed knowledge of crop development is required. Plant water use (transpiration) is a key process in the hydrologic cycle, and because photosynthetic uptake of CO₂ and transpiration are both controlled by stomata, it is strongly linked to plant productivity (Jones & Tardieu, 1998). Models that can accurately predict transpiration therefore have important applications for irrigation scheduling and crop yield. However, previous evidence (Jones, 2004) suggests that leaf water status is not the most useful indicator of plant water stress, and cannot therefore be used as the primary indicator of irrigation need as has sometimes been suggested. In fact leaf water status depends on a complex interaction of soil water availability and environmental and physiological factors (Jones, 1990). It is now clear that in some situations soil water status is sensed by the roots and this information is signaled to the shoots, perhaps by means of hydraulic signals (Christmann et al., 2009) and chemical messengers such as abscisic acid (Kim & van Iersel, 2011). Another general limitation to plant-based methods is that they do not usually give information on 'how much' irrigation to apply at any time, only whether irrigation is needed or not. None of the plant-based methods illustrated in Table 1 are well-adapted for automatic irrigation scheduling or control because of the difficulties measuring each variable (Jones, 2008). Typically, the use of any plant-based indicator for irrigation scheduling requires the definition of reference or threshold values, beyond which irrigation

is necessary. Such threshold values are commonly determined for plants growing under non-limiting soil water supply (Feres and Goldhamer, 2003), but obtaining extensive information on the behavior of these reference values as environmental conditions change will be an important stage in the development and validation of such methods.

2.3 Hybridizing sensing and modeling techniques for precision irrigation scheduling

Water budget calculations are relatively easy to use in scheduling irrigations, since there are simple algorithms available to calculate crop E_T (typically using Penman-Monteith or other methods) that use local meteorological station or pan evaporation data (Feres et al., 2003). All methods are based on calculating a reference E_T that is multiplied by an empirically-determined crop coefficient (K_c) for each crop. At present there are good estimates of K_c values for many horticultural crops, even though most research has been conducted on the major field crops (Allen et al., 1998). However, there are virtually no K_c values for ornamental species and most estimates of woody perennial crop water use are quite variable. Inaccuracies in K_c values can result in large potential errors in estimated soil moisture contents (Allen et al., 1998). The approach therefore works best where it is combined with regular soil moisture monitoring techniques that can help reset the model (e.g. after rainfall). A particular strength of book-keeping and volumetric soil-based approaches is that they not only address scheduling issues about "when to irrigate" but also about "how much to apply". Although useful for soil-based irrigation scheduling, there may be limitations on how quickly these calculations can be manually performed. This is especially important for greenhouse and container-nursery operations who may be cyclic irrigating containerized plants from 4-8 times per day (Tyler et al., 1996) to maintain available water in the root zone on hot, sunny or windy days.

Previous studies with a variety of crop, ornamental and turf species have reported that the use of appropriate scheduling methods and precision irrigation technologies can save a significant amount of water, while maintaining or increasing yield and product quality (Bacci et al., 2008; Beeson & Brooks, 2008; Blonquist et al., 2006; Feres et al., 2003). Many of these empirical approaches have successfully incorporated environmental variables into various models, to further increase the precision of irrigation scheduling (e.g. Treder et al., 1997). It is imperative that we connect our capability for precision water applications with a knowledge of real-time plant water use. We need to improve our ability to predict plant water use in real-time using various technologies. As an example of this approach, van Iersel and his group have shown with various studies (Burnett and van Iersel, 2008; Kim and van Iersel, 2009; Nemali and van Iersel, 2006; van Iersel et al., 2009; 2010; 2011) that automated irrigation using soil moisture sensors allows for the very precise irrigation of greenhouse crops in soilless substrates. In addition, they maintained very low substrate moisture contents at very precise levels which advances our capability to use precision irrigation scheduling for regulated deficit irrigation (RDI) techniques (Jones, 2004), to increase fruit crop quality (Feres et al., 2003), and aid in precision nutrient (Lea-Cox et al., 2001; Ristvey et al., 2004) and disease management (Lea-Cox et al., 2006).

Most recently, Kim and van Iersel (2011) have demonstrated that the measured daily evapotranspiration of petunia in the greenhouse can be accurately modeled with measurements of crop growth (days after planting, DAP), daily light integral (DLI), vapor pressure deficit (VPD) and air temperature. All these environmental fluxes obviously affect

transpiration on a continuous basis. Ambient light affects plant water use due to its effects on evaporation and stomatal opening (Pieruschka et al., 2010). Vapor pressure deficit is the driving force for transpiration and also affects stomatal regulation (Taiz and Zeiger, 2006) while temperature affects E_T and plant metabolic activity (Allen et al., 1998; van Iersel, 2003). The importance of Kim & van Iersel's empirical modeling approach is how they have demonstrated the sensitivity of plant water use to these four easily-measured variables. Thus, with a few inexpensive sensors (temperature, relative humidity and photosynthetic photon flux, PPF) and some simple software tools that can integrate these variables on short time-scales, it now appears possible to predict hourly plant water use for greenhouse crops with real precision. It should be noted however, that these models still require rigorous validation for production conditions.

However, for these types of models to work in an external environment, it is likely that the complexity of our predictive water use models will have to increase, to incorporate additional variables. Water use by perennial woody crop species is much more complicated due to external environmental conditions (for example how VPD and leaf temperature are affected by wind speed and boundary layer effects on canopies; LAI effects on PPF interception). For example, Bowden et al. (2005) outlined an automated sensor-based irrigation system for nurseries that could calculate plant water consumption from species and genotype-specific plant physiological responses. The MAESTRA [Multi-Array Evaporation Stand Tree Radiation A] model (Wang and Jarvis, 1990) is a three-dimensional process-based model that computes transpiration, photosynthesis, and absorbed radiation within individual tree crowns at relatively short time (15-minute) intervals. The model is described more fully by Bauerle & Bowden (2011b) and has been modified and previously validated to estimate deciduous tree transpiration (Bauerle et al., 2002; Bowden & Bauerle, 2008) and within-crown light interception (Bauerle et al., 2004). The model applies physiological equations to sub-volumes of the tree crown and then sums and/or averages the values for entire canopies. Additionally, species-specific physiological values can be incorporated into model calculations, potentially yielding more accurate estimates of whole tree transpiration. The model holds potential advantages for nursery, forest, and orchard water use prediction in that structural parameters such as tree position, crown shape, and tree dimensions are specified.

Bowden et al. (2005) briefly illustrated how the model estimates of water use and plant water requirements are outputted from MAESTRA and used to both make irrigation decisions (command executed by a sensor node) and visualize model updates via a graphic user interface (Bauerle et al., 2006). Within each 15-minute time step, the model adjusts transpiration based on interactions between environmental, soil moisture, and plant physiological response. The substrate moisture deficit calculation is described in Bauerle et al. (2002). An updated substrate moisture value is carried into the next time step for input into the substrate moisture deficit sub-routine. The calculated moisture deficit value is one of the input values required to calculate the amount of stomatal conductance regulation and hence, interacts with other equations to derive whole plant water use. Overall, this GUI (Bowden et al., 2005; Bauerle et al., 2006) provides a user friendly interface to a complex set of calculations. In this way, whole tree water use estimates can be rapidly visualized for either sensor node or human based irrigation decision management. Bauerle and his group are actively working to further refine the MAESTRA model for incorporation into the irrigation scheduling decision support system in our current project (Lea-Cox et al., 2010b).

3. Utilizing the power of sensor networks

3.1 Wireless Sensor Networks

A WSN is typically comprised of radio frequency transceivers, sensors, microcontrollers and power sources (Akyildiz et al., 2002). Recent advances in wireless sensor networking technology have led to the development of low cost, low power, multifunctional sensor nodes. These nodes can be clustered in close proximity to provide dense sensing capabilities, or deployed in a more distributed fashion (Fig. 1). We shall describe the commercially-available Decagon Devices WSN, since we have the most experience with that system, although there are other commercial companies that have similarly available irrigation and environmental WSN systems, e.g. Adcon Telemetry Int. (Klosterneuburg, Austria; <http://adcon.at>), Delta-T Devices (Cambridge, UK; <http://delta-t.co.uk>) and PureSense (Fresno, CA; <http://puresense.com>).

Figure 1 shows the type of WSN that we have deployed in multiple research and commercial sites. Whenever necessary, the accumulated data is transmitted from each of the sensor nodes in the production area using a 900 MHz radio card (although other companies use other frequencies), to a 'base' datastation connected to a personal computer on the farm. Incoming data is inputted into a software program (e.g. DataTrac v.3.2; Decagon Devices) that is installed on a low-cost computer. The software then plots and displays the sensor information from each of the nodes. Data is appended to existing data, so information can be graphically displayed over multiple time scales, depending on user preference. Alternatively, data from a field node can be transmitted directly to a server via the internet using a 3G wireless node (e.g. EM50G, Decagon Devices). The logged data is then accessed from the server over an internet website, using the same DataTrac software previously described. In this way, a grower can develop a scaleable network of sensors that allows for the monitoring of soil moisture and environmental data, in real time. The advantages of these WSN's are fairly obvious - they provide information at the "micro-scale" which can be expanded to any resolution, determined for a specific production operation, for specific needs. This system also provides a mechanism for local (i.e. a decision made locally by the node, based on local sensor readings /setpoints) or the global control (information relayed to the nodes from an external database) of irrigation scheduling (Fig. 1) , depending upon grower preferences and needs (Kohanbash et al, 2011). We are currently in the process of deploying and testing next-generation nodes with these various capabilities.

Any combination of environmental sensors, including soil moisture and electrical conductivity, soil and air temperature, relative humidity, anemometer (wind speed and direction), rain gauge and light (PPF and net radiation) sensors can be connected to the nodes, according to user needs. Decagon nodes collect data every minute, which is averaged and logged on a 1, 5- 15-min or greater time scale, according to required precision. Longer sampling times result in a considerable increase in battery life, but power consumption will also vary greatly with different systems. With Decagon EM50 nodes, a 15-min average setting typically results in > 12-month battery life from 5 'AA' batteries under normal temperature (-5 to 40°C) conditions (J.D. Lea-Cox, *pers. obs.*). Battery life is also affected by the number of times the field nodes are downloaded and the settings employed; typically nodes are downloaded 1-10 times a day.

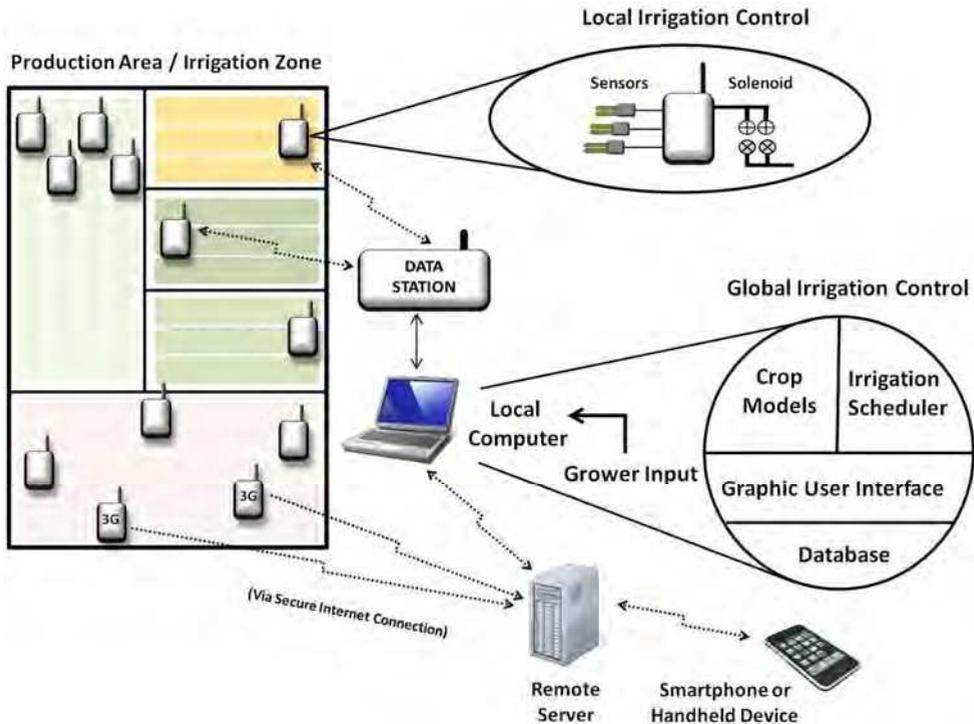


Fig. 1. A schematic of a farm-scale WSN for precision irrigation scheduling (adapted from Balendock, 2009), to illustrate networks deployed by our group (Lea-Cox et al., 2010b).

3.2 Scalable, adaptable and reconfigurable capabilities

One of the most important features of these WSNs is that a grower can purchase a small network and scale up and/or reconfigure the sensor network to meet specific needs, over time. These networks can provide a fixed capability, but networks can be more fully utilized if a “nimble networks” concept is used. In this way, growers can move sensor nodes quickly and easily within the production area for shorter periods of time, to address current issues and problems, e.g. to address the water requirements of a specific indicator species in a drought, or to monitor irrigations to reduce the incidence of disease in a crop (Lea-Cox et al., 2006). This nimble network approach can more fully utilize WSN capabilities and is one of the most powerful ways of realizing a quick return on investment in equipment. We think that there are many situations where a grower could have a payback period for a small network within a single crop cycle, if the information is utilized for better irrigation and crop management decisions.

3.3 Wireless sensor network development for irrigation scheduling

A number of WSN's with various topologies (e.g. star, mesh-network) have been developed and investigated by different researchers in the past decade (Ruiz-Garcia et al., 2009), including WSN's for irrigation scheduling in cotton (Vellidis et al., 2008), center-pivot

irrigation (O'Shaughnessy & Evett, 2008) and linear-move irrigation systems (Kim et al., 2008). The first reported greenhouse WSN was a bluetooth monitoring and control system developed by Liu & Ying (2003). Yoo et al. (2007) describes the deployment of a wireless environmental monitoring and control system in greenhouses; Wang et al. (2008) also developed a specialized wireless sensor node to monitor temperature, relative humidity and light inside greenhouses. Our group (Lea-Cox et al., 2007) reported on the early deployment of a WSN within a cut-flower greenhouse, where a number of soil moisture and environmental sensor nodes were deployed for real-time monitoring of crop production by the grower.

With regards to large on-farm WSN deployments, Balendonck et al., (2009) reported on the FLOW-AID project that has many of the same objectives that we are focused upon, i.e., providing growers with a safe, efficient and cost-effective management system for irrigation scheduling. The FLOW-AID project is integrating innovative monitoring and control technologies within an appropriate decision support system (Balendonck et al., 2007; Ferentinos et al., 2003) that is accessible over the internet, to assist growers in long-term farm zoning and crop planning. It is especially focused on providing growers with regulated deficit irrigation and soil salinity management tools. To support shorter-term irrigation scheduling, a scheduling tool is being developed which allocates available water among several plots and schedules irrigation for each plot (Stanghellini et al., 2007; Anastasiou et al., 2008). To assist this advanced scheduling tool, a crop response model is being developed and used to predict crop stress (Balendonck et al., 2009).

We outlined the major engineering and scientific goals of our WSN project earlier in this chapter (Lea-Cox et al., 2010a). To explain further, this interdisciplinary project is taking a commercially-available WSN product (Decagon Devices, Inc.) and retooling it to support the irrigation scheduling requirements of field nurseries, container nurseries, greenhouse operations and green roof systems, as analogs for many intensive agricultural production and environmental management systems. Our global goals are to develop a more integrative and mechanistic understanding of plant water requirements, to more precisely schedule irrigation events with WSN technology. We are working across various scales of production, using small and large commercial farms which allow us to take a systems approach to defining the hardware and software required to meet the needs of these highly intensive specialty crop systems. In addition to the ornamental industry, there are many parallel needs that we are addressing for WSN adoption by field-grown fruit, nut and berry production, as well as field and greenhouse vegetable production. As part of the project, economic, environmental and social analyses will identify costs and benefits of WSN technology to the industry and society, including barriers to adoption. The project directly involves commercial growers throughout the process, using deployments in commercial operations as test sites. This will help ensure product satisfaction of the next generation of hardware and software developed by our various teams (Lea-Cox et al., 2010b; <http://www.smart-farms.net>). Each farm and research test site is instrumented with a sensor network(s) to provide real-time environmental data for scientific and technological development. Data streams are monitored on a day-to-day basis by growers, engineers and scientists, which drives a daily dialogue between the growers and various working groups.

The role of the engineering team is to develop, deploy and maintain the next generation of wireless sensor networks (Fig. 1). Their major task is to develop the hardware and software

capable of supporting advanced monitoring and control of irrigation scheduling, implementing a hybrid sensor and modeling approach. A major focus of this effort is the development of advanced software which will provide advanced user control, in addition to database filtering and analysis. The software will refine incoming data and provide an easy-to-use computer program for a non-expert user to easily visualize the information from the WSN, and schedule irrigation events based on user preference, or utilizing automatic (set-point) control. The scientific modeling group (Bauerle et al., 2011a; Kim and van Iersel, 2011; Starry et al., 2011) are developing and validating the various models, which form the basis of the species- and environmental-specific software. These models interface with the WSN database via an open application programming interface, which integrates the models with the irrigation scheduling monitoring and control functions. This will enable more predictive (feed-forward) management of water use, based upon the underlying plant and environmental water-use models.

The role of the scientific and extension teams is to ensure that the precision and accuracy of the data gathered (and hence the quality of the models incorporated in the decision support software) are of the highest possible quality and reliability. There are a number of critical research objectives that span the various production environments: (a) characterize the spatial and temporal variability of environmental parameters in both root and shoot canopies, since we need to place sensors for maximum precision and economic benefit; (b) characterize sensor performance and precision, so we match the right sensor with the right application; (c) integrate the knowledge gained from (a) and (b), to ensure that the irrigation scheduling decisions made (either manually or automatically) satisfy plant water requirements in real-time, while placing a minimum burden on the grower for managing the system. We elaborate further on some of these critical objectives below in section 3.4. However, our primary project objective is to provide a cost-effective WSN that provides quality data for minimal cost to growers, both small and large. Our grower's production areas range from 0.5 to over 250 ha in extent, with multiple irrigation zones / crop species. To that end, our economic and environmental analysis team members are gathering specific economic, resource use and environmental data from each production site through a series of on-farm visits and assessments. Larger outreach (survey) efforts across the United States will validate results from our intensive economic analysis of the commercial operations in the study. Some early WSN deployment strategies and results from the project are illustrated later in this chapter. Further project information, results and learning modules are available from our interactive website at <http://www.smart-farms.net>.

3.4 Sensor network deployment issues and strategies

3.4.1 Spatial and temporal variability

Understanding spatial and temporal variability of environmental data is one of the most important aspects of deploying WSNs in any real-world application, since these dynamics not only determine the appropriate position of a sensor, but the precision of the sensor data is of course greatly affected by the immediate environment and the forces acting on that environment. This is the realm of environmental biophysics (Campbell and Norman, 1998; Jones, 1992) and environmental plant physiology (Nobel, 2009) which forms the basis of our efforts to sense and model the environment.

Figure 2 illustrates soil moisture variability from 10HS soil moisture sensors at two depths (15 and 30cm below the soil surface) in five replicate *Acer rubrum* (Red maple) trees from May through Sept., 2009 (Lea-Cox, unpublished data). Sensors were calibrated to the specific soil type found on this farm (Lea-Cox, Black, Ristvey & Ross, 2008).

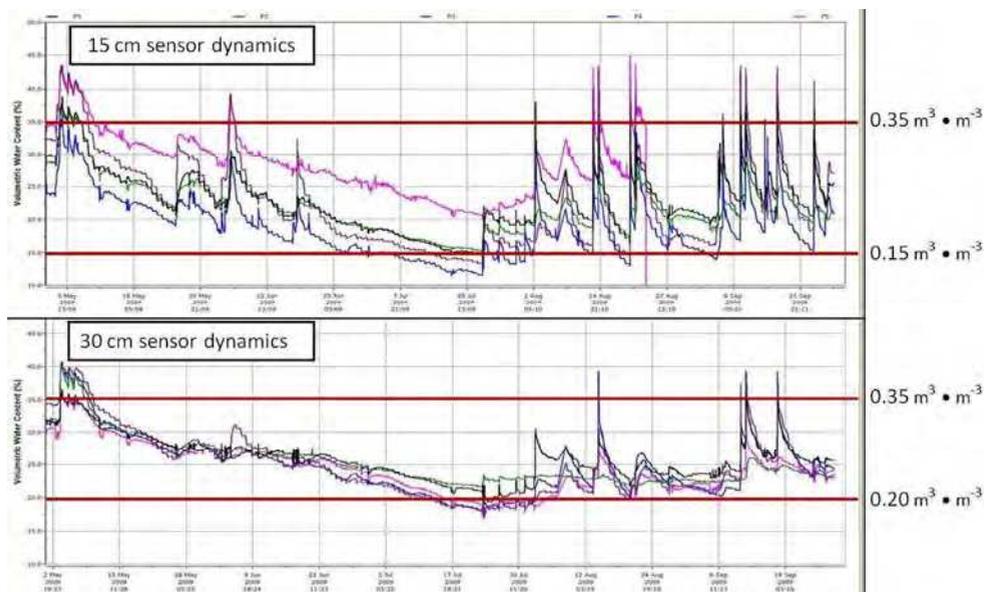


Fig. 2. Soil moisture dynamics at 15cm and 30cm depths in the root zone of five replicate *Acer rubrum* trees from May through September, 2009. Stacked data from two nodes is graphically displayed using an earlier version of DataTrac (v. 2.78, Decagon Devices).

As can be seen, 15cm data were more variable throughout the entire season (Fig. 2). Trees were irrigated for 1-2 hours with drip irrigation on a daily basis throughout most of the study (Lea-Cox, Black, Ristvey & Ross, 2008), except after major rainfall events restored the soil water contents above $0.25 \text{ m}^3 \cdot \text{m}^{-3}$ (Fig. 2). Changes in daily water content (tree uptake) are evident immediately after these rainfall events, particularly in the 15cm dynamics. Soil moisture dynamics at the 30cm depth were much less variable between trees at all times during the season, and soil moisture at this depth did not fall below $0.20 \text{ m}^3 \cdot \text{m}^{-3}$ during this year, despite relatively low rainfall totals during the summer (data not shown).

Figure 3 shows similar soil moisture data from 10HS sensors at 15cm depth from *Cornus florida* trees, but these trees were grown in a pine bark soilless substrate in 56-liter containers in a container-nursery operation. Firstly, note that the average substrate moisture is around $0.5 \text{ m}^3 \cdot \text{m}^{-3}$, since this organic substrate has a high water-holding capacity and also because this grower typically irrigates 2-3 times per day, with small low-volume microsprinkler events (1.5L in 6 minutes) during summer months.

Note also how quickly substrate moisture decreases with plant uptake when morning and early afternoon irrigation events are skipped, due to the relatively low amounts of total water in the container (Fig. 3). Note also that real-time irrigation applications per tree are

easily measured using a small tipping rain gauge with a rain cover, with an additional microsprinkler head inserted under the cover (Lea-Cox et al., 2010b). The volumes displayed (Fig. 3) give the grower instantaneous feedback and tie soil moisture contents directly to irrigation events and the volumes applied. We are using the same tipping rain gauges to give leaching volumes from pot-in-pot containers with an underground drainage system, to provide approximate daily irrigation water budgets (i.e. Irrigation + Rainfall - Leaching = $\delta VWC \approx E_T$) for additional indicator species on the farm (Lea-Cox et al., 2010b).

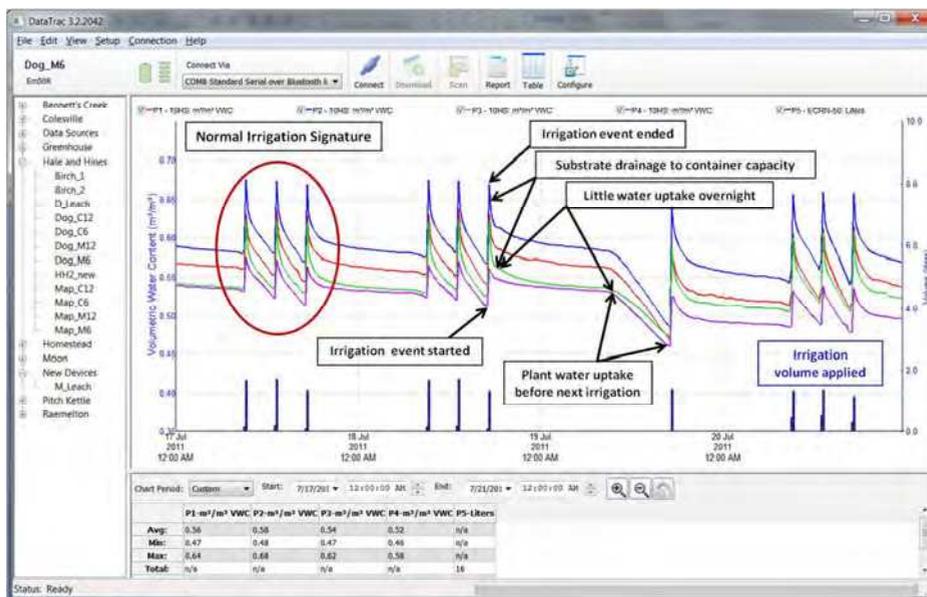


Fig. 3. Typical container moisture dynamics before and after irrigation events in four *Cornus florida* trees. Data is graphically displayed using the most recent version of DataTrac (v. 3.2).

3.4.2 Sensor placement

Changes in substrate VWC due to daily water use of a crop can be used to control irrigation events, but placement of sensors is very important in container production, because of the non-uniform distribution of water within a soilless substrate and container. van Iersel et al. (2011) illustrated this point, by calculating the *rate of change* in substrate VWC. They noted that the maximum rate of decrease in VWC occurred at the bottom of the container in a greenhouse study and closely followed changes in solar radiation, suggesting that changes in VWC were driven by root water uptake from the lower part of the container. However, the vertical gradient in substrate VWC also changed over time i.e., the VWC of the bottom layer decreased much more rapidly than that of the upper layers, likely because of the root distribution within the container. Apparently, the lack of roots in the upper part of the substrate resulted in little water uptake from that substrate layer, and vertical water movement in the container was not fast enough to prevent the middle layers from getting drier than the upper layer. If these findings can be generalized for other container-grown species, it would greatly increase our understanding for correct sensor placement in root

zones, simplifying placement and increasing the precision of information for controlling irrigation events. However, since root distribution is affected by irrigation method, optimal placement of soil moisture sensors for irrigation control may depend on how the crop is irrigated (van Iersel et al., 2011).

Sensor placement is especially challenging for crops grown in large containers over relatively long periods of time. Barnard et al. (2011) examined the spatial and temporal variation in VWC among 10 tree species in large containers in a container nursery, and found significant differences within containers and among species. Based on their initial results, they recommended species-specific sensor deployment. For such crops, where root distribution within the container may change dramatically throughout the production period, it may be necessary to move the soil moisture sensor as root distribution changes, or it may be possible to use a soil moisture sensor that can sense the substrate water content throughout most of the container. It is therefore likely that a hybrid sensor and crop water use model approach will have greater degree of precision for automated irrigation scheduling, a feature desired by many greenhouse and container-nursery growers.

3.4.3 Using indicator plant species

For many ornamental operations, it is unlikely that we will be able to sense the water needs of all crop species being grown. Many growers however are familiar with the concept of using indicator species (i.e., species that have high and low water use, on average), which are used to inform irrigation schedules for similar types of plants (Yeager et al., 2007). For this reason, we are developing crop models which include a number of these indicator species in the decision support software. Part of this strategy is also to engage the larger research community in the development and incorporation of additional specific crop models (e.g. Warsaw et al., 2009) in future irrigation decision support systems.

3.4.4 Microclimatic data

The gathering and seamless integration of real-time environmental data is integral to the development and implementation of crop-specific (Bauerle et al., 2010; Kim and van Iersel, 2011) and environmental models (Starry, 2011). Typical microclimatic data which is gathered by “weather” nodes is displayed in Fig. 4. Tools within DataTrac v.3.2 now allow for the calculation and plotting of integrated data, such as vapor pressure deficit, daily light integral and accumulated degree days, as simple derivatives of this instantaneous data. Apart from the integration of this data into various crop, environmental and disease development models, this microclimatic data has many other direct practical benefits for producers, e.g. the use of real-time T/RH and wind speed data for precision timing of spray schedules in the field. Longer-term seasonal information for light, precipitation and maximum/minimum air and soil temperatures are very informative for growers to assess crop growth development and other production variables e.g. residual soil nutrient values.

3.4.5 Predictive irrigation scheduling

The integration of real-time microclimatic data into crop-specific and environmental water use models is the next step in our development path; we have successfully parameterized petunia (Kim and van Iersel, 2011), red maple (Bauerle et al., 2011b) and green roof

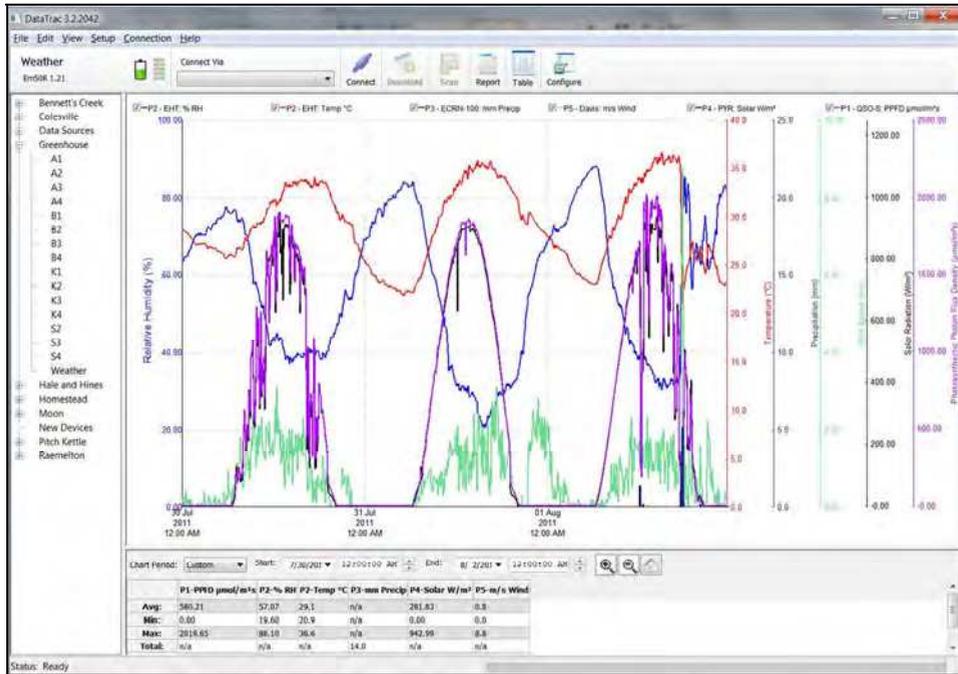


Fig. 4. Weather data from a sensor node with a typical suite of environmental sensors, including total radiation (black), photosynthetic photon flux (purple), relative humidity, RH (blue), air temperature, T (red) and wind speed (green).

stormwater runoff (Starry et al, 2011) models, and we are verifying and validating those models with current research projects. Our modeling and engineering teams are interfacing these models with a testbed sensorweb system (Kohanbash et al., 2011). In their paper, they present a framework for integrating physiological models into WSN for advanced irrigation scheduling. They note that the ability to gather high resolution data, interpret it, and create an actionable conclusion is a critical ability for a WSN.

Kohanbash et al. (2011) outlined our irrigation scheduling programming logic where growers create a schedule for when water needs to be applied, and then the schedule is interrupted as needed. This system provides growers with four operating modes: (1) a schedule-based controller very similar to what is commonly used in the industry. Within the schedule, there are two different options to over-ride the schedule to decrease the irrigation time (a) a local setpoint controller and (b) a global controller. The schedule + local setpoint controller enables the sensor node to make local control decisions based on sensors attached to the node. The schedule + global controller allows the grower to use data from *any* node in the network, calculated data or model data to control the irrigation and consequently determine if the schedule should be interrupted. The fourth mode is a manual override mode that allows the grower to water in traditional mode, for a given number of minutes. This irrigation scheduling flexibility gives a grower the ability to control how water gets applied to an irrigation zone, with various user-defined parameters. The user can choose between a mode where water will be applied slowly with small delays between irrigation

events to allow water to reach subsurface sensors (micro-pulse irrigation; Lea-Cox et al., 2009) or a mode in which water is applied continuously for a specified period of time.

4. Challenges, opportunities and conclusions

Of course there are many areas where we need additional research and development, to provide the maximum cost benefit of WSNs for growers. Challenges include standardizing WSN protocols and communication frequencies, as they can be confusing for growers and researchers alike. Nodes operating at lower frequencies (900 MHz) typically have an increased range and can penetrate tree canopies better than higher frequency (2.4 GHz) nodes with reduced packet loss. Battery-operated nodes are typical; integrating rechargeable capabilities into sensor nodes is important, especially if control capabilities are going to become standard, since this will greatly increase power requirements. Another challenge is working with large datasets. We have to educate ourselves as to the resolution required for optimum precision in each environment, keeping the ultimate use of the data in mind.

The maintenance and calibration of sensors and equipment is an ongoing concern, particularly for growers who may be uncomfortable with the technology and equipment. We definitely see an opportunity for paid consultants to maintain and remotely monitor WSNs for optimum performance. As part of our project, we are developing an online knowledge center, to provide assistance and guidance about various aspects of WSN deployment, sensor use, strategies and best practices. We need to integrate better data analysis tools to handle large volumes of data from sensor networks. We also need to do a thorough user interface study on how growers actually use computer interfaces and to determine what features are needed. Predictive models for plant water use, environmental and disease management tools are rapidly being developed for growers, but we need to validate and verify these models for use in different environments. Incorporation of models into WSNs for decision-making appears to be relatively easy, but there are many details which have yet to be worked out.

There are many layers to the socio-economic analysis our economic team is performing. Of course there are many direct benefits of precision irrigation scheduling that can be accrued by the grower, such as saving on water, labor, electricity, and fertilizer costs. However, there are many indirect (e.g. reduced disease incidence, fungicide costs) and societal benefits (reduced nutrient runoff, groundwater consumption) that may have much larger benefits over the long-term for all agricultural producers. Most importantly, we need to quantify the return on investment that a grower could expect to achieve, and to be able to scale those benefits for small producers, along with scaling WSN deployments. We are also interested in documenting perceived and real barriers to adoption. Our socio-economic team is actively surveying a large number of growers with a detailed survey, to compare the use of sensor technology and irrigation decisions by early and late adopters.

In conclusion, we believe that there have been some real advances in WSNs for precision irrigation scheduling in recent years. Of course many challenges still remain, but we believe that WSNs are a fast-maturing technology that will be rapidly adopted by many growers in the near future.

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6. References

- Anastasiou, A., Savvas, D., Pasgianos, G., Stangellini, C., Kempkes, F. & Sigrimis, N. 2008. Decision Support for Optimised Irrigation Scheduling. *Acta Hort.* 807:253–258.
- Agarwal, A., delos Angeles, M.S., Bhatia, R., Cheret, I., Davila-Poblete, S., Falkenmark, M., Gonzalez Villarreal, F., Jønch-Clausen, T., Kadi, M.A., Kindler, J., Rees, J., Roberts, P., Rogers, P., Solanes, M. & Wright, A. 2000. Integrated Water Resources Management. *Global Water Partnership*. Denmark.
- Akyildiz, I.F., Su, W., Sankarasubramaniam, Y. & Cayirci, E. 2002. Wireless Sensor Networks: A Survey. *Computer Networks* 38:393-422.
- Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. *FAO Irrigation and drainage paper no.56*. FAO, Rome, Italy.
- Bacci, L., Battista, P. and Rapi, B. 2008. An Integrated Method for Irrigation Scheduling of Potted Plants. *Sci. Hortic.* 116:89-97.
- Bauerle, W.L., Post, C.J., McLeod, M.E., Dudley J.B. & Toler, J.E. 2002. Measurement and Modeling of the Transpiration of a Temperate Red Maple Container Nursery. *Agric. For. Meteorol.* 114:45-57.
- Bauerle, W.L., Bowden, J.D., McLeod M.F. & Toler, J.E. 2004. Modeling Intracrown and Intracanopy Interactions in Red Maple: Assessment of light transfer on carbon dioxide and water vapor exchange. *Tree Physiol.* 24:589-597.
- Bauerle, W.L., Timlin, D.J., Pachepsky, Ya.A. & Anantharamu., S. 2006. Adaptation of the Biological Simulation Model MAESTRA for Use in a Generic User Interface. *Agron. J.* 98:220-228.
- Bauerle, W.L. & Bowden, J.D. 2011a. Predicting Transpiration Response to Climate Change: Insights on Physiological and Morphological Interactions that Modulate Water Exchange from Leaves to Canopies. *HortScience* 46:163-166.
- Bauerle, W.L. & Bowden, J.D. 2011b. Separating Foliar Physiology from Morphology Reveals the Relative Roles of Vertically Structured Transpiration Factors Within Red Maple Crowns and Limitations of Larger Scale Models. *J. Exp. Bot.* 62:4295-4307.
- Balendonck, J., Stanghellini, C., & Hemming, J. 2007. Farm Level Optimal Water Management: Assistant for Irrigation under Deficit (FLOW-AID). In: *Water Saving in Mediterranean Agriculture & Future Research Needs*, Bari, Italy, Lamaddalena N. & Bogliotti, C. (Eds.), CIHEAM, Bari, Italy. pp. 301-312.
- Balendonck, J., Stanghellini, C., Hemming, J., Kempkes F.L.K. & van Tuijl, B.A.J. 2009. Farm Level Optimal Water Management: Assistant for Irrigation under Deficit (FLOW-AID). *Acta Hort* 807: 247-252.
- Barnard, D.M, Daniels, A.B. & Bauerle, W.L., 2011. Optimizing Substrate Moisture Measurements in Containerized Nurseries: Insights on Spatial and Temporal Variability. *HortScience* 46(9): S207. (Abstr.)

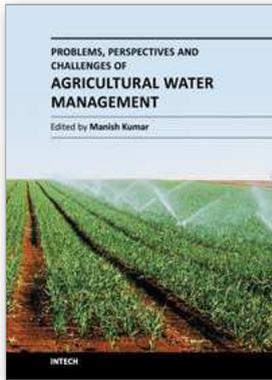
- Barrenetxea, G., Ingelrest, F., Schaefer, G., & Vetterli, M. 2008. The Hitchhiker's Guide to Successful Wireless Sensor Network Deployments. In: *Proc. 6th ACM Int. Conf. Embedded Networked Sensor Systems (SenSys)* Raleigh, NC, Nov. 5 -7, 2008. pp. 43-56.
- Beeson Jr., R.C. & Brooks. J. 2008. Evaluation of a Model Based and Reference Crop Evapotranspiration (ET_o) for Precision Irrigation using Overhead Sprinklers during Nursery Production of *Ligustrum japonica*. *Acta Hort.* 792:85-90.
- Bitelli, M. 2011. Measuring Soil Water Content: A Review. *HortTechnology* 21: 293-300.
- Blonquist, J.J.M., Jones, S.B. & Robinson. D.A. 2006. Precise Irrigation Scheduling for Turfgrass using a Subsurface Electromagnetic Soil Moisture Sensor. *Agricultural Water Management* 84:153-165.
- Bowden, J.D. & Bauerle, W.L. 2008. Measuring and Modeling the Variation in Species-Specific Transpiration in Temperate Deciduous Hardwoods. *Tree Physiol.* 28:1675-1683.
- Bowden, J. D., Bauerle, W.L., Lea-Cox, J.D. & Kantor, G.F. 2005. Irrigation Scheduling: An Overview of the Potential to Integrate Modeling and Sensing Techniques in a Windows-based Environment. *Proc. Southern Nursery Assoc. Res. Conf.* 50:577-579.
- Bunt, A.C. 1961. Some Physical Properties of Pot-Plant Composts and their Effect on Plant Growth. *Plant and Soil* 13:322-332.
- Burger, D.W. & Paul, J.L. 1987. Soil Moisture Measurements in Containers with Solid State, Electronic Tensiometers. *HortScience* 22:309-310.
- Burnett, S.E. & van Iersel, M.W. 2008. Morphology and Irrigation Efficiency of *Gaura Lindheimeri* Grown with Capacitance-Sensor Controlled Irrigation. *HortScience* 43:1555-1560.
- Campbell, G. S. & Norman. J. 1998. An Introduction to Environmental Biophysics. 2nd Ed. Springer New York, NY.
- Cifre, J., Bota, J., Escalona, J.M., Medrano, H. & Flexas, J. 2005. Physiological Tools for Irrigation Scheduling in Grapevine (*Vitis vinifera* L.). *Agric. Ecosys. Environ.* 106:159-170.
- Christmann, A., Weiler, E.W., Steudle, E. & Grill. E. 2007. A Hydraulic Signal in Root-to-Shoot Signaling of Water Shortage. *Plant J.* 52:167-174.
- Dane, J.H. & Topp, G.C. 2002. Methods of Soil Analysis. Part 4: Physical Methods. *Amer. Soc. Soil Sci.*, Madison, WI.
- deBoodt, M. & O. Verdonck. 1972. The Physical Properties of Substrates in Horticulture. *Acta Hort.* 26:37-44.
- Ferentinos, K.P., Anastasiou, A., Pasgianos, G.D., Arvanitis, K.G. & Sigrimis, N. 2003. A DSS as a Tool to Optimal Water Management in Soilless Cultures under Saline Conditions. *Acta Hort.* 609:289-296.
- Fereres, E.; Goldhamer, D.A. & Parsons, L.R. 2003. Irrigation Water Management of Horticultural Crops. *HortScience* 38:1036-1042.
- Fereres, E. & Goldhamer, D.A. 2003. Suitability of Stem Diameter Variations and Water Potential as Indicators for Irrigation Scheduling of Almond Trees. *J. Hort. Sci Biotech.* 78:139-144.
- Fry, A., 2005. Facts and Trends, Water. *World Business Council for Sustainable Development, Earthprint Ltd.* ISBN 2-940240-70-1.
- Guimerà, J. 1998. Anomalously High Nitrate Concentrations in Ground Water. *GroundWater* 36:275-282.

- Handreck, K. & Black, N. 2002. Growing Media for Ornamental Plants and Turf (3rd Ed.). *Univ. New South Wales Press*, Sydney, Australia.
- Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S. & Maupin, M.A. 2004. Estimated Use of Water in the United States in 2000. *Circular 1268. U.S. Geological Survey*, U.S. Dept. Interior. Reston, VA.
- Jones, H.G. 1992. Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology. (2nd ed.) *Cambridge University Press*. Cambridge. UK.
- Jones, H.G. 1990. Physiological-Aspects of the Control of Water Status in Horticultural Crops. *HortScience* 25: 19-26.
- Jones, H.G. 2004. Irrigation Scheduling: Advantages and Pitfalls of Plant-Based Methods. *J. Exp. Bot.* 55:2427-2436.
- Jones, H.G. 2008. Irrigation Scheduling - Comparison of Soil, Plant and Atmosphere Monitoring Approaches. *Acta Hort.* 792: 391-403.
- Jones, H.G. & Tardieu F. 1998. Modeling Water Relations of Horticultural Crops: A Review. *Scientia Horticulturae*. 74:21-46.
- Karlovich, P.T. & Fonteno, W.C. 1986. The Effect of Soil Moisture Tension and Volume Moisture on the Growth of *Chrysanthemum* in Three Container Media. *J. Amer. Soc. Hort. Sci.* 111:191-195.
- Kiehl, P.A., Liel, J.H. & Buerger, D.W. 1992. Growth Response of *Chrysanthemum* to Various Container Medium Moisture Tensions Levels. *J. Amer. Soc. Hort. Sci.* 117:224-229.
- Kim, Y., Evans, R.G. & Iversen, W.M. 2008. Remote Sensing and Control of an Irrigation System using a Distributed Wireless Sensor Network. *IEEE Trans. Instrum. Meas.* 57:1379-1387.
- Kim, J. & van Iersel, M.W. 2009. Daily Water Use of Abutilon and Lantana at Various Substrate Water Contents. *Proc. Southern Nursery Assn. Res. Conf.* 54:12-16.
- Kim, J., van Iersel, M.W. & Burnett, S.E. 2011. Estimating Daily Water Use of Two Petunia Cultivars Based on Plant and Environmental Factors. *HortScience* 46:1287-1293.
- Kim, J. & van Iersel, M.W. 2011. Abscisic Acid Drenches can Reduce Water Use and Extend Shelf Life of *Salvia splendens*. *Sci. Hort.* 127: 420-423.
- Kohanbash D., Valada, A. & Kantor, G.F. 2011. Wireless Sensor Networks and Actionable Modeling for Intelligent Irrigation. *Amer. Soc. Agric. Biol. Eng.* 7-12th August, 2011. Louisville, KY. Paper #1111174. 7p.
- Lea-Cox, J.D., Ross, D.S. and Tefteau, K.M. 2001. A Water And Nutrient Management Planning Process For Container Nursery And Greenhouse Production Systems In Maryland. *J. Environ. Hort.* 19:230-236.
- Lea-Cox, J. D., Arguedas-Rodriguez, F. R., Amador, P., Quesada, G. & Mendez, C.H. 2006. Management of the Water Status of a Gravel Substrate by Ech20 Probes to Reduce *Rhizopus* Incidence in the Container Production of *Kalanchoe blossfeldiana*. *Proc. Southern Nursery Assoc. Res. Conf.* 51: 511-517.
- Lea-Cox, J. D., Kantor, G. F., Anhalt, J., Ristvey A.G. & Ross, D.S. 2007. A Wireless Sensor Network for the Nursery and Greenhouse Industry. *Proc. Southern Nursery Assoc. Res. Conf.* 52: 454-458.
- Lea-Cox, J.D., Ristvey, A.G. Arguedas-Rodriguez, F.R., Ross, D.S., Anhalt J. & Kantor. G.F. 2008. A Low-cost Multihop Wireless Sensor Network, Enabling Real-Time Management of Environmental Data for the Greenhouse and Nursery Industry. *Acta Hort.* 801:523-529.

- Lea-Cox, J.D., Black, S., Ristvey A.G. & Ross. D.S. 2008. Towards Precision Scheduling of Water and Nutrient Applications, Utilizing a Wireless Sensor Network on an Ornamental Tree Farm. *Proc. Southern Nursery Assoc. Res. Conf.* 53: 32-37.
- Lea-Cox, J.D., Ristvey, A.G., Ross, D.S. & Kantor. G.F. 2009. Deployment of Wireless Sensor Networks for Irrigation and Nutrient Management in Nursery and Greenhouse Operations. *Proc. Southern Nursery Assoc. Res. Conf.* 54: 28-34.
- Lea-Cox, J.D., Kantor, G.F., Bauerle, W.L., van Iersel, M.W., Campbell, C., Bauerle, T.L., Ross, D.S., Ristvey, A.G., Parker, D., King, D., Bauer, R., Cohan, S. M., Thomas, P. Ruter, J.M., Chappell, M., Lefsky, M., Kampf, S. & L. Bissey. 2010a. A Specialty Crops Research Project: Using Wireless Sensor Networks and Crop Modeling for Precision Irrigation and Nutrient Management in Nursery, Greenhouse and Green Roof Systems. *Proc. Southern Nursery Assoc. Res. Conf.* 55: 211-215.
- Lea-Cox, J.D., Kantor, G.F., Bauerle, W.L., van Iersel, M.W., Campbell, C., Bauerle, T.L., Parker, D., King, D., Bauer, R., L. Bissey & Martin, T. 2010b. SCRI-MINDS-Precision Irrigation and Nutrient Management in Nursery, Greenhouse and Green Roof Systems: Year 1 Report. Available from <<http://www.smart-farms.net/impacts>> Accessed 08/02/2011.
- Lea-Cox, J.D., Arguedas-Rodriguez, F. R., Ristvey A. G. & Ross. D. S. 2011. Relating Real-time Substrate Matric Potential Measurements to Plant Water Use, for Precision Irrigation. *Acta Hort.* 891:201-208.
- Leith, J.H. & Burger. D.W. 1989. Growth Of Chrysanthemum Using An Irrigation System Controlled By Soil Moisture Tension. *J. Amer. Soc. Hort. Sci.* 114: 387-397
- Liu, G. & Ying, Y. 2003. Application Of Bluetooth Technology In Greenhouse Environment, Monitor And Control. *J. Zhejiang Univ., Agric Life Sci.* 29:329-334.
- Majsztrik, J.C., A.G. Ristvey, and J.D. Lea-Cox. 2011. Water and Nutrient Management in the Production of Container-Grown Ornamentals. *Hort. Rev.* 38:253-296.
- Murray, J.D., Lea-Cox J.D. & Ross. D.S. 2004. Time Domain Reflectometry Accurately Monitors and Controls Irrigation Water Applications *Acta Hort.* 633:75-82.
- Nemali, K.S. & van Iersel, M.W. 2006. An Automated System for Controlling Drought Stress and Irrigation in Potted Plants. *Sci. Hortic.* 110:292-297.
- Nobel, P.S. 2009. Physicochemical and Environmental Plant Physiology 4th Ed. *Elsevier Inc.* Waltham, MA.
- O'Shaughnessy, S.A. & Evett, S.R. 2008. Integration of Wireless Sensor Networks into Moving Irrigation Systems for Automatic Irrigation Scheduling. *Amer. Soc. Agric. Biol. Eng.* 29 June - 2 July, 2008. Providence, RI. Paper # 083452, 21p.
- Pieruschka, R., Huber, G. & Berry, J.A. 2010. Control of Transpiration by Radiation. *Proc. Natl. Acad. Sci.* 107:13372-13377.
- Raviv, M., Lieth, J.H. & Wallach, R. 2000. Effect of Root-Zone Physical Properties of Coir and UC Mix on Performance of Cut Rose (cv. Kardinal). *Acta Hort.* 554:231-238.
- Ristvey, A.G., Lea-Cox, J.D. & Ross, D.S. 2004. Nutrient Uptake, Partitioning And Leaching Losses From Container-Nursery Production Systems. *Acta Hort.* 630:321-328.
- Ross, D. S., Lea-Cox, J.D. & Tefteau, K.M. 2001. The Importance of Water in the Nutrient Management Process. *Proc. Southern Nursery Assoc. Res. Conf.* 46:588-591.
- Ruiz-Garcia, L., Lunadei, L., Barreiro, P. & Robla, J. I. 2009. A Review of Wireless Sensor Technologies and Applications in Agriculture and Food Industry: State of the Art and Current Trends. *Sensors* 9: 4728-4750.

- Secchi, S., Gassman, P.W., Jha, M., Kurkalova, L., Feng, H.H., Campbell, T. & King, C.L. 2007. The Cost of Cleaner Water: Assessing Agricultural Pollution Reduction at The Watershed Scale. *J. Soil Water Conservation* 62:10-22.
- Smith, K.A. & Mullins, C. 2001. Soil and Environmental Analysis: Physical Methods. 2nd Ed. Marcel Decker, New York, NY.
- Smajstrla A.G. & Harrison, D.S. 1998. Tensiometers for Soil Moisture Measurement and Irrigation Scheduling. *Univ. Fl. IFAS Ext. Cir.* No. 487. 8p.
- Stanghellini, C. & van Meurs., W.T.M., 1989. Crop Transpiration: A Greenhouse Climate Control Parameter. *Acta Hort.*, 245: 384-388.
- Stanghellini, C., Pardossi, A. & Sigrimis, N. 2007. What Limits the Application of Wastewater and/or Closed Cycle in Horticulture? *Acta Hort.* 747:323-330.
- Starry, O., Lea-Cox, J.D., Ristvey, A.G. & Cohan, S. 2011. Utilizing Sensor Networks to Assess Stormwater Retention by Greenroofs. *Amer. Soc. Agric. Biol. Eng.* 7-12th August, 2011. Louisville, KY. Paper #1111202, 7p.
- Taiz, L. & Zeiger, E. 2006. Plant Physiology. *Sinauer Associates, Inc.* Sunderland, MA
- Testezlaf, R., Larsen, C.A., Yeager, T.H. & Zazueta, F.S. 1999. Tensiometric Monitoring of Container Substrate Moisture Status. *HortTechnology* 9:105-109.
- Treder, J., Matysiak, B., Nowak, J. & Treder, W. 1997. Evapotranspiration and Potted Plants Water Requirements as Affected by Environmental Factors. *Acta Hort.* 449:235-240.
- Tolle, G., Polastre, J., Szewczyk, R., Culler, D., Turner, N., Tu, K., Burgess, S., Dawson, T., Buonadonna, P. Gay, D. & Hong, W. 2005. A Macroscope in the Redwoods. *In: Proc. 3rd ACM International Conference on Embedded Networked Sensor Systems (SenSys)*, 2005. San Diego. Nov 2-4, 2005. pp. 51- 63.
- Topp, G.C. 1985. Time-Domain Reflectometry (TDR) and its Application to Irrigation Scheduling. *Adv. Irr.* 3:107-127.
- Tyler, H.H., Warren, S.L. & Bilderback, T.E 1996. Cyclic Irrigation Increases Irrigation Application Efficiency and Decreases Ammonium Losses. *J. Environ. Hort.* 14:194-198.
- United States Global Change Research Program. 2011. Overview: Water. Available from <<http://www.globalchange.gov/component/content/article/52-reports-and-assessments/481-overview-water>> Accessed 07/15/2011.
- van Iersel, M.W. 2003. Short-Term Temperature Change Affects the Carbon Exchange Characteristics and Growth of Four Bedding Plant Species. *J. Amer. Soc. Hort. Sci.* 128:100-106.
- van Iersel, M. W., Seymour, R.M., Chappell, M., Watson, F. & Dove, S. 2009. Soil Moisture Sensor-Based Irrigation Reduces Water Use and Nutrient Leaching in a Commercial Nursery. *Proc. Southern Nursery Assoc. Res. Conf.* 54:17-21.
- van Iersel, M.W., Dove, S. Kang, J-G. & Burnett, S.E. 2010. Growth and Water Use of Petunia as Affected by Substrate Water Content and Daily Light Integral. *HortScience* 45:277-282.
- van Iersel, M.W., Dove, S. & Burnett, S.E. 2011. The Use of Soil Moisture Probes for Improved Uniformity and Irrigation Control in Greenhouses. *Acta Hort.* 893:1049-1056.
- Vellidis, G., Tucker, M., Perry, C., Wen, C. & Bednarz, C. 2008. A Real-Time Wireless Smart Sensor Array for Scheduling Irrigation. *Comput. Electron. Agric.* 61:44-50.

- Wang, Y.P. & Jarvis. P.G. 1990. Description and Validation of an Array Model-MAESTRO. *Agricultural Forest Meteorology*. 51:257-280.
- Wang, C., Zhao, C.J., Qiao, X.J., Zhang, X. & Zhang, Y.H. 2008. The Design of Wireless Sensor Networks Node for Measuring the Greenhouse's Environment Parameters. *Computing. Technol. Agric.* 259:1037-1046.
- Warsaw, A. L., Fernandez, R. T., Cregg, B. M. & Andresen. J. A. 2009. Water Conservation, Growth, and Water Use Efficiency of Container-Grown Woody Ornamentals Irrigated Based on Daily Water Use. *HortScience* 44: 1308-1318.
- Yeager, T.H., Bilderback, T.E., Fare, D., Gilliam, C., Lea-Cox, J.D., Niemiera, A.X., Ruter, J.M., Tilt, K., Warren, S.L., Whitwell T. & Wright. R.D. 2007. Best Management Practices: Guide for Producing Nursery Crops. 2nd Ed. *Southern Nursery Assoc.*, Atlanta, GA.
- Yoo, S., Kim, J., Kim, T., Ahn, S., Sung, J. & Kim, D. 2007. A2S: Automated Agriculture System Based on WSN. In: *ISCE 2007. IEEE International Symposium on Consumer Electronics*. Irving, TX, USA.
- Zazueta, F.S., Yeager, T., Valiente, J.I. & Brealey, J.A. 1994. A Modified Tensiometer for Irrigation Control in Potted Ornamental Production. *Proc. Soil Crop Sci. Soc. Fla.* 53:36-39.



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Food security emerged as an issue in the first decade of the 21st Century, questioning the sustainability of the human race, which is inevitably related directly to the agricultural water management that has multifaceted dimensions and requires interdisciplinary expertise in order to be dealt with. The purpose of this book is to bring together and integrate the subject matter that deals with the equity, profitability and irrigation water pricing; modelling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation in a single text. The book is divided into four sections and is intended to be a comprehensive reference for students, professionals and researchers working on various aspects of agricultural water management. The book seeks its impact from the diverse nature of content revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.

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