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A real-time wireless smart sensor array for scheduling irrigation

G. Vellidis, M. Tucker, C. Perry, C. Kvien, C. Bednarz*

National Environmentally Sound Production Agriculture Laboratory (NESPAL), University of Georgia, Tifton, GA, USA

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ABSTRACT

A prototype real-time, smart sensor array for measuring soil moisture and soil temperature that uses off-the-shelf components was developed and evaluated for scheduling irrigation in cotton. The array consists of a centrally located receiver connected to a laptop computer and multiple sensor nodes installed in the field. The sensor nodes consist of sensors (up to three Watermark® soil moisture sensors and up to four thermocouples), a specially designed circuit board, and a Radio Frequency IDentification (RFID) tag which transmits data to the receiver. The smart sensor array described here offers real potential for reliably monitoring spatially variable soil water status in crop fields. The relatively low cost of the system (∼USD 2400 for a 20-sensor node system) allows for installation of a dense population of soil moisture sensors that can adequately represent the inherent soil variability present in fields. This paper describes the smart sensor array and testing in a cotton crop. Integration of the sensors with precision irrigation technologies will provide a closed loop irrigation system where inputs from the smart sensor array will determine timing and amounts for real-time site-specific irrigation applications.

1. Introduction

Irrigation is an essential component of crop production in many areas of the world. In cotton for example, recent studies have shown that proper timing of irrigation is an important production factor and that delaying irrigation can result in losses of between USD 62/ha and USD 300/ha (Vories et al., 2003). Yet there are few practical and cost-effective technologies that can assist producers with irrigation scheduling. Existing technologies vary from the water balance or check book method to sophisticated sensor-based systems like those provided by Adcon Telemetry® (Adcon, 2004) and Automata® (Automata, 2004). Current sensor-based technologies marketed as wireless are quite expensive because they require conventional radio transmitters, usually require a government license for use of the radio frequency, and still require extensive cabling if multiple sensors are used. These products generally have high-energy requirements and need regular maintenance during the growing season.

Allen (2000a) evaluated an irrigation management system that can provide continuous real-time or near real-time soil water content information to the irrigation system operator. This system used two different data loggers to collect and store data from Watermark® soil moisture sensors (Irrometer Co., Riverside, CA, USA). The data loggers were installed in the field in close proximity to the sensor and wired to the sensors. However, this system required the operator to visit the data loggers for data downloading and thus did not provide a wireless solution. Shock et al. (1999) used a similar approach but transmitted data from the data loggers to a central data logging site via radio. This system allowed up to 16 Watermark® soil moisture sensors to be wired into a

* Corresponding author. Tel.: +1 229 386 3377.
E-mail address: yiorgos@uga.edu (G. Vellidis).
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proprietary data logger/transmitting box. But, unless all the sensors were placed in close proximity to the data logger, this system still required extensive cabling. The expense of the data loggers prevents a dense population of sensors in the field. King et al. (2000) and Wall and King (2004) proposed the architecture for a distributed sensor network which included controls for a variable rate irrigation system. Although this approach may accommodate a large number of sensors, at this point, it is still a theoretical system. Hamrita and Hoffacker (2005) explored Radio Frequency IDentification (RFID) technology as a solution to wireless real-time monitoring of soil properties. In a laboratory setting they demonstrated that RFID technology was feasible for wireless real-time communication with a soil temperature sensor.

Inexpensive, real-time soil moisture sensing is needed to improve irrigation automation and performance. This paper describes a prototype real-time, wireless smart sensor array for measuring soil moisture and soil temperature using off-the-shelf components. The system allows for a large number of sensors to be installed in a field and provide data wirelessly to a centrally located receiver.

Fig. 1 – A smart sensor node which includes three soil Watermark® sensors and two thermocouples installed in the NESPAL field a few weeks after planting of cotton.

2. Methods

2.1. *Smart sensor array description*

The smart sensor array consisted of a centrally located receiver connected to a laptop computer and multiple sensor nodes installed in the field. The sensor nodes consisted of sensors (soil moisture sensors and thermocouples), a sensor circuit board, and an active RFID transmitter, referred to as a tag, which transmitted data to the receiver. The smart sensor circuit board is shown in Fig. 1. At user-defined intervals, the smart sensor board acquired sensor values and wirelessly transmitted those values to a centrally located radio frequency (RF) receiver. The board can read up to three Watermark® granular resistive-type soil moisture sensors and up to four thermocouple temperature sensors. We chose Watermark® sensors for this system because of their low cost, dependability, ease-of-use, and because they are commonly used by the agricultural community for scheduling irrigation. Past research has evaluated the Watermark® sensors and found them to respond well to the wetting and drying cycles for most soil types (Thomson and Armstrong, 1987; Spaans and Baker, 1992; Eldredge et al., 1993; Shock et al., 1998, 2003; Allen, 2000b; Thomson et al., 2002).

The smart sensor circuit board was designed to excite the Watermark® sensors separately with a dc voltage, rather than the ac voltage as recommended by the manufacturer (Allen, 2000a). Analog multiplexers, an instrumentation amplifier, and various other active and passive electronic components conditioned the sensors' output signals before they were input to a microcontroller. The node's microcontroller program (programmed in C language) corrected and formatted sensor values then output results to the onboard RF transmitter.

WhereNet® active RFID tags (WhereNet®, Santa Clara, CA, USA) were used to provide a wireless interface between the circuit board and the receiving station. These tags were developed for tracking inventories and transmit in the 2.4 GHz radio frequency range. At each transmission, the tags send a unique identifier code (node ID) and 12 bytes of user data. In our application, the 12 bytes of user data were the sensor values which consisted of three soil moisture values and two temperature values. The tags have a line-of-site transmission range of up to 0.8 km (0.5 miles). Hereafter, the combination of the electronics board, RFID tag, and sensors will be referred to as a "smart sensor node".

During preliminary field testing, plant biomass, terrain, and man-made objects caused some wireless transmission problems. Plant biomass greatly attenuates radio frequency signals, particularly in the 2.4 GHz range. To overcome this issue, transmitters (tags) were removed from the smart sensor electronics boards and mounted on hollow, flexible fiberglass rods approximately 1.2 m above ground level and covered with water proof material (Fig. 2). The flexible rods allowed field equipment, such as sprayers, to pass over the sensors without damaging them throughout the growing season.

The smart sensor boards used in the project were powered with single 9 V lithium batteries. To optimize battery life, the microcontroller was programmed to place itself in a low-current sleep mode between sensor readings and data transmissions. It was also programmed to cycle the sub-circuits on and off as needed when acquiring sensor values. The current drawn by each node during sleep mode was 150 μA. Nodes acquired soil moisture sensor values and transmitted the data to the receiver once per hour. The duration of the reading and transmission interval was 250 ms per sensor and drew 22 mA or a total of 1.25 s per node per hour. The smart sensor operating voltage was 3.3 V dc. The microcontroller program monitored battery voltage and transmitted an alarm code when the voltage dropped below an acceptable thresh-

Fig. 2 – Modified smart sensor node with raised transmitter in a peanut field.

old, thus eliminating the need for regular inspection. Battery life easily exceeded the duration of the growing season.

2.2. *Field testing of the smart sensor array*

A 2.3 ha National Environmentally Sound Production Agriculture Laboratory (NESPAL) field, located on the University of Georgia's Tifton Campus, was used for testing and demonstration of the smart sensor system. The field is equipped with a center-pivot variable-rate irrigation (VRI) system. The WhereNet® RF receiver was installed at the irrigation pivot point and used two omnidirectional antennae to receive incoming sensor node signals. A notebook computer, housed in a metal enclosure, was used to run the WhereNet® acquisition software and to log, timestamp, and store the smart sensor data (node identifiers and the sensor values) in a comma delimited file. The data were transferred from the receiver to the laptop via a wireless Ethernet connection.

To evaluate the performance of the smart sensor array, we established two different irrigation scheduling strategies for the field. A north-south berm which traverses the field (top to bottom in Fig. 3) was used to delineate the two scheduling strategies. In the western (left) half of the field, irrigation was scheduled using a traditional assessment of the crop (plant wilting, days since last irrigation, rainfall, and weather forecast) by a staff member with many years of experience growing cotton. Three sensor nodes were installed here strictly for monitoring purposes.

In the eastern half of the field, irrigation was scheduled using the smart sensor array. Four different irrigation management zones were delineated based on soil type, apparent soil electrical conductivity, and historic yield maps (Fig. 3). Two or three sensor nodes per zone were installed to characterize soil moisture conditions within the zone. Each smart sensor node consisted of three Watermark® soil moisture sensors installed within the row at depths of 0.2, 0.4, and 0.6 m.

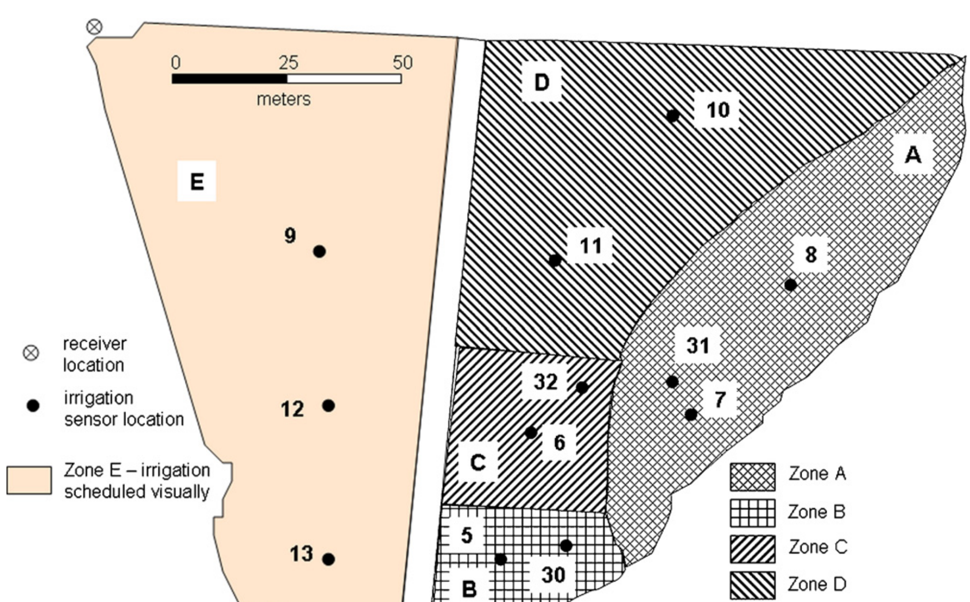

Fig. 3 – Irrigation management zones created for the NESPAL field based on scheduling strategies and inherent field properties.

Two thermocouples were also installed, one for soil temperature at 0.2 m and the other loosely wrapped around the stem of the nearest cotton plant to monitor ambient air temperature within the canopy. Irrigation was scheduled in the zones on this side of the field when soil water tension approached predetermined trigger points—when average soil water tension exceeded 40 kPa at 0.2 m depth, or when soil water tension exceeded 50 kPa at either the 0.4 or 0.6 m depth. These trigger points were selected based on published data (Flynn and Barnes, 1998; Thomson et al., 2002) and the experience of the authors. Average soil water tension was determined by averaging the results from all sensors at a given depth within a zone. The VRI pivot allowed each zone to be irrigated individually if necessary. The depth of water applied was determined by the amount of water required to reduce soil water tension to below 10 kPa. This amount varied from 13 mm of water to 25 mm of water.

The field was planted to Round-Up Ready 555 DPL cotton on 27 April 2004. Between planting and May 31, regular uniform irrigation applications were applied to ensure germination and a uniform stand. The smart sensor nodes were installed in May and began recording data in June at which time the predetermined irrigation scheduling protocols were initiated. Ample rainfall in June and September obviated the need for irrigation during those months.

3. Results and discussion

3.1. Soil water tension

Fig. 4 (sensor-based scheduling strategy) and Fig. 5 (traditional scheduling strategy) contrast soil water tension over the growing season at the three monitored depths. Each tension line on the graphs represents the average soil water tension at that depth in the given zone. The length of the vertical bars descending from the upper x-axis of the graphs represents the amount of rainfall or irrigation events. The location of the bar along the upper x-axis represents the time the event began.

The graphs illustrate that the smart sensor array was able to successfully monitor soil water tension as measured by the Watermark® sensors. Because performance of Watermark® sensors has been thoroughly evaluated previously (Thomson and Armstrong, 1987; Eldredge et al., 1993; Shock et al., 1998; Irmak and Haman, 2001; Allen, 2000b; Thomson et al., 2002), no alternative method was used to verify soil moisture during this study. To ensure that the smart sensor array system was properly reading the Watermark® sensors, all sensors were read with the manufacturer's handheld digital meter on a weekly basis. Without fail, the data collected by the wireless sensor system matched the data collected with the handheld meter.

With a few exceptions, soil water tension did not surpass established trigger points in the east side of the field. Because it takes many hours for a center pivot irrigation system to apply water to even a small field, we found that once soil water tension begins to increase sharply and approach the trigger point, irrigation must begin almost immediately or else soil water tension will climb well above the trigger point. It is also clear that the amount of water added during each irrigation event did not, in all cases, return the entire soil profile to below 10 kPa soil water tension. This may have been a function of not adding enough water but also a function of the low permeability of the lower soil profile.

On the west side of the cotton field (Fig. 4), irrigation was triggered based on traditional assessment of the crop (no sensors). This irrigation scheduling strategy resulted in much higher soil water tensions at 0.4 and 0.6 m depth than any observed in the eastern half of the field. In some instances, measured tension was more than double the trigger points established for the smart sensor scheduling protocol. It is also evident that the amount of irrigation water applied only served to momentarily reduce soil water tension below 0.2 m depth.

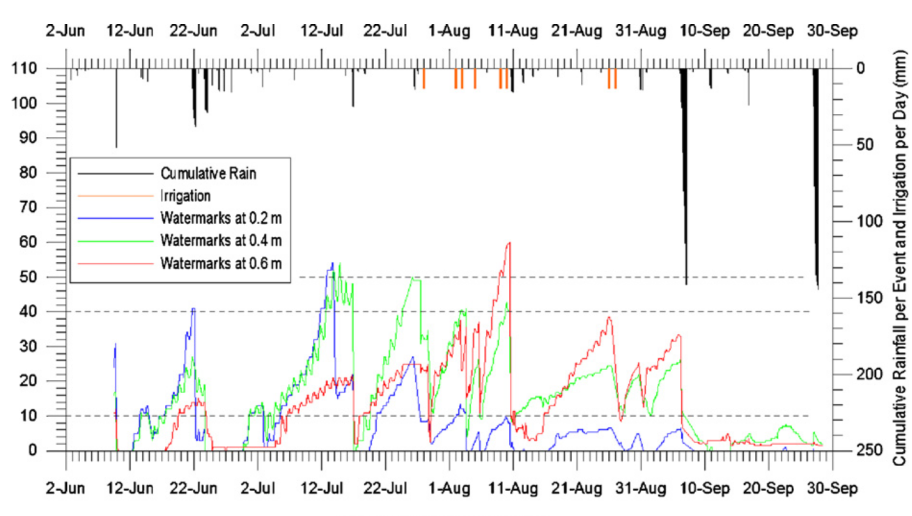

Fig. 4 – Soil water tension recorded in Zone C (see Fig. 3) representing sensor-based irrigation scheduling. The data are an average of soil water tensions recorded at nodes 6 and 32. The two top horizontal broken lines indicate the irrigation trigger points. The lower broken line indicates the target soil water tension following irrigation.

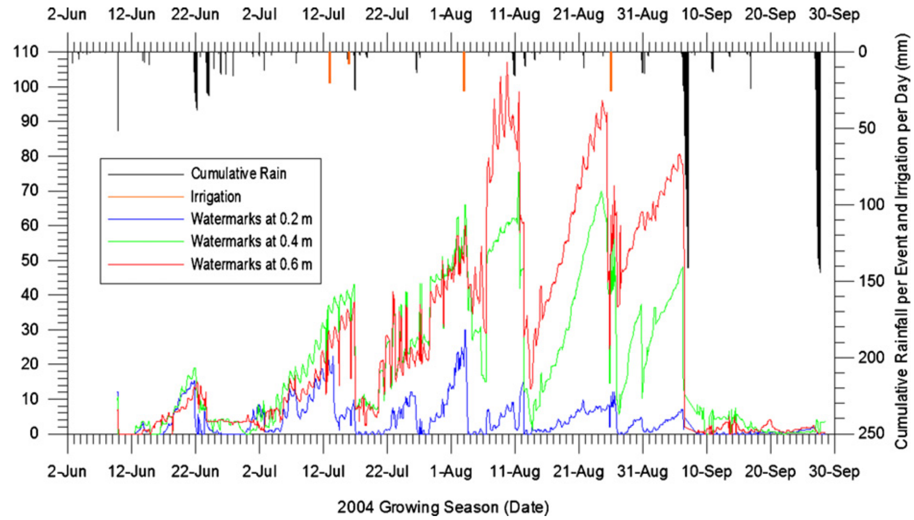

Fig. 5 – Soil water tension recorded in Zone E (see Fig. 3) representing traditional irrigation scheduling. The data are an average of soil water tensions recorded at nodes 9, 12, and 13.

3.2. *Thermocouple response*

Although soil and air temperature within the canopy were not used to make management decisions for the cotton crop at the NESPAL field, they are important parameters for peanut production and are key input parameters to the *Irrigator Pro* decision support software (Davidson et al., 2000) which is used by peanut producers. Thermocouple response was stable for the duration of the study which indicates that the smart sensor array can successfully record three soil moisture values as well as two thermocouple values at each node. Soil temperature at 0.2 m fluctuated between 24 and 28 °C with a gradual decline as the season progressed (Fig. 6). In contrast, air temperature within the canopy fluctuated between 20 and 40 °C during most of the season and even approached 44 °C during mid September. Canopy air temperature was compared weekly to readings from a mercury thermometer and was consistently within ±2 °C.

4. Ongoing and future work

Using a smart sensor array in conjunction with a conventional uniform-application irrigation system can aid in determining when to begin watering based on the driest zone in a field. The smart sensor array can also be used to determine the optimum amount of water to apply across the field. However, to optimize irrigation applications, the smart sensor array is best used in conjunction with a VRI system.

A VRI control system that enables a center pivot irrigation system to supply water at rates relative to the needs of individual areas within fields was developed through collaboration between the University of Georgia Precision Farming Team and the FarmScan Group (Perth, Western Australia). The VRI system varies application rate by cycling sprinklers on and off and by varying the center pivot travel speed. Details of the system were presented by Perry et al. (2003, 2002a,b). The VRI system

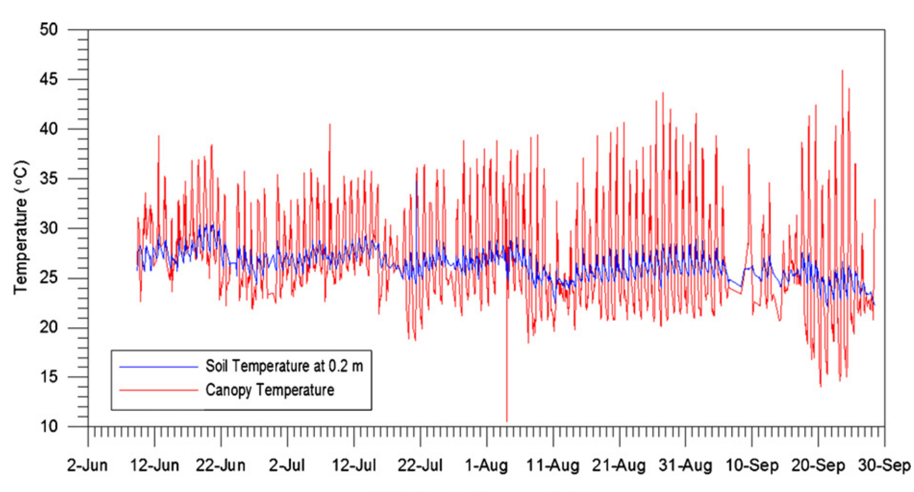

Fig. 6 – Soil temperature and air temperature within the canopy recorded at node 5 in Zone B. Soil and air temperature response was similar at the other nodes. Gaps in the data resulted from periods when the node was not operational.

is a retrofit package that can be installed on most existing pivots. It has been commercialized in the United States by Hobbs & Holder, LLC (Ashburn, GA, USA; www.betterpivots.com).

Irrigation water application maps for VRI equipped pivots are defined by the producer or operator of the VRI system, who delineates zones within the field requiring different water application amounts. These differences are generally based on the field's soil and topographic features but could also reflect different crops under the same pivot.

4.1. *Control of VRI with the smart sensor array*

With current VRI systems, application maps are typically static—they do not change during the growing season. Furthermore, VRI controllers generally do not accept sensor inputs. Our goal is to make irrigation dynamic and responsive to real-time plant water needs. To achieve this goal, we are in the process of developing a new VRI controller with accompanying decision making software which will accommodate a wide variety of control inputs, including data from the smart sensor array. The new VRI controller will monitor the sensor array's sensor values and initiate irrigation based on pre-determined irrigation scheduling strategies.

4.2. *Commercialization*

The smart sensor array design allows for a high population of nodes within a field because of the relatively low cost of the nodes. The cost of the node is primarily a function of the number of Watermark® soil moisture sensors used. In small quantities, the Watermarks® cost approximately USD 25 each. If purchased in large quantities, the price may be lower. The cost of the other node components is about USD 40. In the configuration used for this study, the cost of each node was approximately USD 115. For most crops, a node with two Watermark® sensors installed at different depths would adequately characterize the status of the soil at a given location. However, multiple nodes would be required to overcome the inherent variability that may be encountered within irrigation management zones. It is not unrealistic to expect that in production quantities, a two-sensor node would cost about USD 70. A population of 20 nodes, which should adequately instrument a 40 ha field with a moderate amount of variability would then cost about USD 1400. The life of a node is expected to be about 5 years.

Greater costs are associated with the WhereNet® receiver and acquisition software, approximately USD 4500. The receiver and software are designed for a much more complicated mission than for an irrigation management application. We are currently cooperating with WhereNet® company officials and technical staff to simplify the receiver and software with a target price of USD 1000 for agricultural applications. Simplifying the software will also allow it to operate on a smaller computing platform such as a personal digital assistant (PDA). If this objective is achieved, a producer could complete instrumentation of the wireless system for a 40-ha field for approximately USD 2700 (includes USD 300 for a PDA).

5. Summary

The smart sensor array described here offers real potential for reliably monitoring soil water status in crops. The system was able to successfully monitor soil water status and soil and air temperature within the canopy for the entire 2004 growing season with few technical difficulties. Equipment modifications resulting from encountered problems resulted in a more robust system that can be installed at the beginning of the season and left alone until harvest. The smart sensor array reliably recorded and transmitted the readings of the Watermark® sensors and allowed us to successfully implement our irrigation scheduling protocol. The relatively low cost of the sensor nodes allows for installation of a dense population of soil moisture sensors that can adequately represent the inherent soil variability present in any field.

Future work will involve developing a smart sensor array-to-variable rate irrigation system interface to provide a fully automated, closed-loop irrigation system. This will provide a dynamic system capable of addressing varying water needs in fields with diverse irrigation management zones.

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