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A Dynamic Variable Rate Irrigation Control System

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Abstract. *Currently variable rate irrigation (VRI) prescription maps used to apply water differentially to irrigation management zones (IMZs) are static. They are developed once and used thereafter and thus do not respond to environmental variables which affect soil moisture conditions. Our approach for creating dynamic prescription maps is to use soil moisture sensors to estimate the amount of irrigation water needed to return each IMZ to an ideal soil moisture condition. The UGA Smart Sensor Array (UGA SSA) is an inexpensive wireless soil moisture sensing system which allows for a high density of sensor probes. Each probe includes three Watermark sensors. We use a modified van Genuchten model and soil matric potential data from each probe to estimate the volume of irrigation water needed to bring the soil profile of each IMZ back to 75% of field capacity. These estimates are converted into daily prescription maps which we downloaded remotely to a VRI controller thus creating a dynamic VRI control system. During 2015, we conducted an on-farm experiment to assess our system. We worked with a producer in a 230ac field in southwestern Georgia. The field was divided into alternating conventional irrigation and dynamic VRI strips with each strip 120 rows wide. The conventional strips were irrigated uniformly based on the producer's recommendations. We divided the VRI strips into IMZs and after planting we installed UGA SSA probes in each of the IMZs. The data from the probes were used to develop daily irrigation scheduling recommendations for each IMZ. The recommendations were converted into a daily prescription map and downloaded remotely to the pivot VRI controller. When an irrigation event was initiated, the VRI-enabled pivot responded dynamically to soil moisture conditions. We will present the design of our dynamic VRI control system and the results from the 2015 study.*

Keywords. *wireless, soil moisture sensors, real time, management zones, prescription maps, peanuts.*

Introduction

Irrigation is becoming an essential component of farming in many areas of the world because it is a tool for ensuring food security. Irrigation not only serves to reduce risk of crop loss but also to build resiliency to climate variability and yield stability in food production systems. Irrigated agriculture provides 40% of the world's food while being used on only 18% of the cultivated land (FAO, 2015). The United Nations Food and Agricultural Organization estimates that the world currently consumes about 70% of available fresh water for irrigation (FAO, 2015). This results in growing competition for available fresh water supplies between agriculture, industry and residential uses. An indicator of this competition is that during the last few decades, ground water is depleting at an alarming rate in many agricultural areas. In addition, agriculture will need to produce more food to address the needs of a growing population. If irrigated agriculture is to expand in order to meet growing demands for food, then new irrigation practices and tools must be developed for more efficient water use. Precision irrigation is one possible approach (Vellidis et al., 2013).

Precision irrigation, like many other aspects of precision agriculture, has the goal of applying inputs which in this case is irrigation water where needed and when needed. The when needed is a particularly important aspect of precision irrigation because timing of irrigation applications are equally, if not more important, than the amount of irrigation water applied during a growing season (Vellidis et al., 2016). Vories et al. (2006) found that improper timing of irrigation on cotton can result in yield losses of between USD 370/ha to USD 1850/ac.

Variable Rate Irrigation

Precision irrigation has its roots in variable rate irrigation (VRI) technology developed for center pivot irrigation systems by the University of Georgia (UGA) Precision Agriculture team in 2001 (Perry et al., 2002; Perry and Pocknee, 2003). The UGA Precision Agriculture team recognized that variable rate application of irrigation water was a key enabling technology for adoption of precision agriculture in the Southeast. This was because fields in this region are highly variable in soil type and texture, moisture holding capacity, and slope. Ignoring site-specific water needs while attempting to vary other inputs like fertilizers would not result in the desired efficiency gains theoretically possible by using precision agriculture. In the Southeast, irrigation of agronomic crops is now done mostly by center pivots. Conventional center pivots apply the same rate of water along the entire length of the pivot and cannot account for within-field variability or non-farmed areas. Because of this, the UGA Precision Ag team focused on developed VRI for pivots.

Several pivot irrigation manufacturers now offer their own VRI systems. VRI allows center pivots to vary water application rates along the length of the pivot by using electronic controls to cycle sprinklers and control pivot speed. Sprinklers are controlled individually or together typically in groups of 2 to 10 depending on the level of resolution desired by the farmer. Each group or bank of sprinklers represents a grid with a 1 to 10 degree arc in which the irrigation water application rate can be set as percentage of the normal application rate – for example from 0% to 200% of normal (Figures 1 and 2). The number of degrees in the arc is determined by the level of resolution desired.

A 50% application rate is half the normal rate and is achieved by cycling the sprinklers on and off every 30 seconds. A 150% application rate is achieved by leaving the sprinklers on continuously while decreasing the travel speed of the pivot by 50%. If other grids along the length of the pivot require lower application rates, the VRI controller adjusts the sprinkler cycling pattern within those grids

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Fig 1. VRI-enabled pivot at UGA's Stripling Irrigation Research Park being used to vary irrigation application rates over research plots.

accordingly. VRI can be installed retroactively on most existing pivots. Installations costs range vary widely by brand and are also a function of the length of the pivot and the level of resolution desired by the farmer to address the variability of the field. Application rates are determined from an application or prescription map.

The prescription map for each field is typically developed jointly by the farmer and VRI dealer on desktop software (Figure 2) and then downloaded to the VRI controller on the pivot. The field is divided into irrigation management zones (IMZs) and application rates assigned to each of the IMZs using whatever information is available. At the moment, the prescription maps are static. In other words, they are typically developed once and used thereafter. Static prescription maps do not respond to environmental variables such as weather patterns and other factors which affect soil moisture condition and crop growth rates. So although VRI is a great leap forward in improving water use efficiency, the system could be greatly enhanced by having real-time information on crop water needs to drive the application rates. One approach for creating *dynamic* prescription maps is to use soil moisture sensors to estimate the amount of irrigation water needed to return each IMZ to an ideal soil moisture condition (Figure 2). The goal of this work was to develop a dynamic variable rate irrigation control system by coupling real-time soil moisture sensing networks with an irrigation scheduling decision support tool and VRI.

Methods

The operational paradigm for our dynamic VRI control system is that the field is divided into IMZs and a soil moisture sensing network with a high density of sensor nodes is installed to monitor soil condition within the zones and provide hourly soil moisture measurements to a web-based user interface. At the interface, the soil moisture data are used by an irrigation scheduling model running in the background to develop irrigation scheduling recommendations by IMZ. The recommendations are then approved by the user (farmer) and downloaded wirelessly the VRI controller on the center pivot as a precision irrigation prescription. When the center pivot irrigation system is engaged by the farmer, the pivot applies the recommended rates.

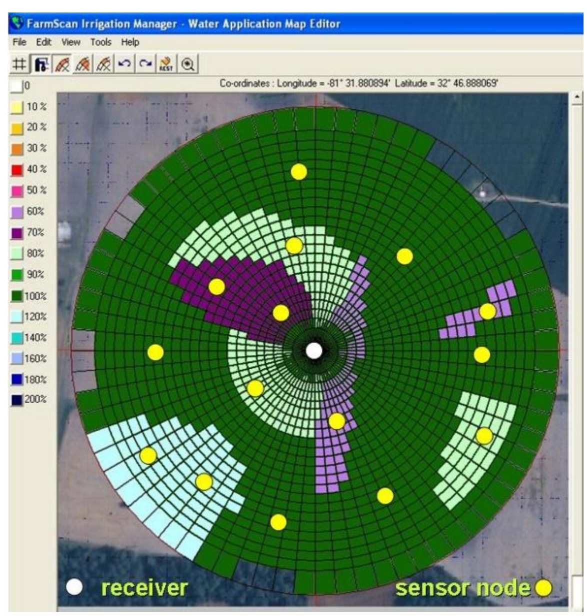

Fig 2. VRI prescription map for a 51ha field in Georgia. Grids represent discreet areas which can receive unique application rates. The yellow circles represent potential locations of soil moisture sensor nodes.

The UGA Smart Sensor Array (UGA SSA)

The UGA SSA is an inexpensive wireless soil moisture sensing system which allows for a high density of sensor nodes – a feature needed to account for soil variability and enable dynamic prescription maps. The UGA SSA was developed by the UGA Precision Ag

Fig 3. A UGA SSA sensor node has a low profile when installed in the field. The flexible whip antenna allows field vehicles to pass directly over the node.

Team and licensed to Advanced Ag Systems (Dothan, Alabama) during 2014. It became commercially available on a limited scale during 2015.

The UGA SSA consists of smart sensor nodes and a base station. The term sensor node refers to the combination of electronics and sensor probes installed within a field (Figure 3). The electronics include a circuit board for data acquisition and processing and a radio frequency transmitter. In the current design, the UGA SSA supports Watermark® soil moisture sensors. Each soil moisture probe integrates up to three Watermark sensors as shown in Figure 3. In addition, each node supports two thermocouples for measuring soil and/or canopy temperature. For field crops like cotton or maize, the sensors on the probe are arranged so that when installed they are at 20, 40, and 60 cm below the soil surface although any combination of depths is possible. Soil moisture is measured in terms of soil matric potential and reported in units of kPa. A Synapse brand radio frequency (RF) transmitter is responsible for transmitting sensor data. The transmitter is an intelligent, cheap, and low-power 2.4 GHz radio module. At the center of each field, a base station receives the data from all nodes at hourly intervals. The base station stores the data on a solar-powered netbook computer and transmits the data via cellular modem to a FTP server hourly.

A wireless mesh network is used for communication between the nodes. Data are passed from one node to the other through the RF transmitter which also plays the role of a repeater. If any of the nodes stop transmitting or receiving, or if signal pathways become blocked, the operating software reconfigures signal routes in order to maintain data acquisition from the network. The published range of the RF transmitter is 500m although we have observed its range to exceed 750m under field conditions.

To overcome the attenuating effect of the plant canopy, the RF transmitter antenna is mounted on spring-loaded, hollow flexible 6mm diameter fiberglass rod (Figure 3). Variable antenna heights are used to ensure that the antenna is always above the crop canopy. Rods which are 2.5m long are used for low-growing crops like cotton, soybeans, and peanuts and rods which are 4.5m long are used for tall crops like corn. This design allows field equipment such as sprayers and tractors to pass directly over the sensors without damaging them. This is a feature that is typically not found on other wireless soil moisture sensors as most of those require a solar panel to power the sensor and telemetry. The UGA SSA nodes are powered by two 1.5 V alkaline batteries which in our system have a life of more than 150 days. This typically spans an entire growing season. To optimize battery life, the nodes are programmed to be in a low-current sleep mode when not transmitting. The UGA SSA is described in detail by Vellidis et al. (2013) and Liakos et al. (2015).

To date the UGA SSA has been used primarily in farm fields irrigated by center pivots. The fields have been delineated into IMZs and one to three sensor nodes installed in each IMZ to characterize soil moisture during the growing season. Ten to 12 sensor nodes are typically installed in each field. The base station is usually located at the pivot point for easy access. The base station sends the node data to an FTP server hourly using a cellular modem. The data are also stored on commercial server space which can manage geographic data with different formats including the GeoJSON (Geographic JavaScript Object Notation) format. GeoJSON is used for visual representation of the data. The FTP server stores the raw soil moisture data while the commercial server manipulates and processes the raw data, stores them after applying a classification process, and serves as the interface with users through a dedicated website (www.ugassa.org).

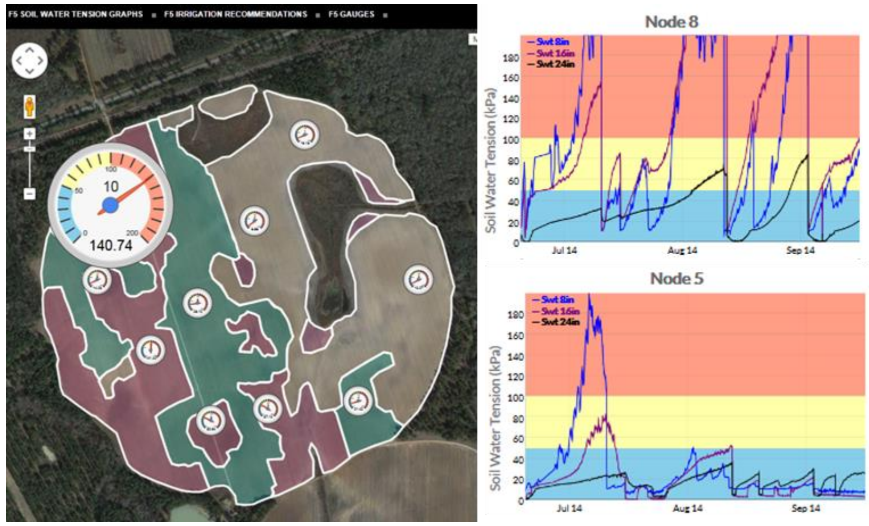

Fig 4. Two different visualizations of UGA SSA soil moisture data. On the left is current soil water tension displayed through color-coded gages. Touching the gages with the cursor or finger enlarges them. On the right are soil water tension curves for the entire growing season. Note the dramatic difference in response between two nodes in the same field.

Web-Based User Interface and Decision Support Tool

The purpose of the web-based interface is to allow users to visualize their soil moisture data and to make irrigation recommendations. The PHP (Personal Home Page) and Javascript programming languages were utilized to create different visualizations of the soil moisture data (Figure 4). The different visualizations provide users and especially farmers with the opportunity to better understand the soil condition and IMZ delineation within their fields. The website is smartphone compliant. To avoid the confusion of using negative numbers to report matric potential, data are reported in terms of soil water tension on the website.

In addition to data visualization, the web-based user interface incorporates a decision support tool which offers irrigation recommendations for each IMZ. We use a modified Van Genuchten model to convert the soil matric potential data to volumetric water content (Liang et al., 2016). The strength of the method is that it can use data readily available from USDA-NRCS soil surveys to predict soil water retention curves and calculate the volumetric water content and soil water tension of a soil at field capacity. Those parameters are then used to translate measured soil water tension into irrigation recommendations which are specific to the soil moisture status of the soil. Soil properties for each IMZ are extracted from the NRCS web soil survey. Our application of the Van Genuchten model uses mean hourly soil matric potential data measured between 07:00 and 09:00 by all nodes within an IMZ to calculate the volume of irrigation water needed to bring the soil profile back to the desired soil moisture condition which could be field capacity or a percentage of field capacity (for example 75% of field capacity) (Figure 5). Each node's soil water tension value is a weighted average of the soil water tension values of the three Watermark sensors of the node. At this point, our irrigation recommendations use the same soil water tension threshold across all of the crop's phenological stages although that will be adjusted as more information becomes available from crop physiologists who are researching different irrigation thresholds (Meeks et al., 2016)

Field Testing of the Dynamic VRI Control System

During 2015, we initiated a dynamic VRI "proof-of-concept" study. We identified a producer who has fields equipped with VRI in southwestern Georgia. We used the 93ha field shown in Figure 6 to conduct our study. The field was planted to peanuts (*Arachis hypogaea*). We divided the field into alternating conventional irrigation and precision irrigation strips with each strip 120 rows wide (Figure 6). We used aerial photographs, soil maps, soil electrical conductivity, topography, yield history, producers' knowledge of the fields and geostatistical software to develop irrigation management zones (IMZs) in the precision irrigation strips. After planting and establishment we installed UGA SSA sensor probes in each of the IMZs. Each probe contained three Watermark sensors. When the probes were installed the sensors were located at 10, 20, and 40cm below the soil surface.

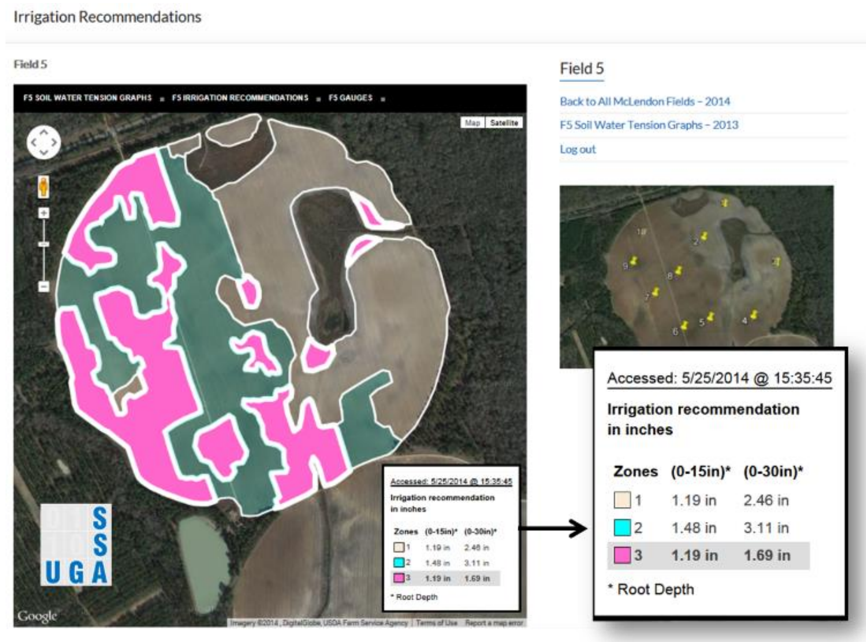

Fig 5. Irrigation recommendations are available daily for each IMZ through the UGA SSA web-based user interface.

The data from the sensors was used to dynamically develop irrigation scheduling recommendations for each IMZ. A 50kPa weighted mean soil water tension (SWT) was used to trigger irrigation in the VRI strips. The weighting function was (0.5×SWT at 10cm) + (0.3×SWT at 20cm) + (0.2×SWT at 40cm). At each irrigation event, the mean SWT sensor data from each IMZ were automatically converted into irrigation recommendations using the decision support tool (Figure 7). The tool calculated the volume of irrigation water needed to bring the soil profile of each IMZ back to 75% of field capacity. The irrigation recommendations for each IMZ were then manually coded to the prescription map which was wirelessly downloaded to the pivot VRI controller prior to an irrigation event. In this field, approximately 72 hours were required for the center pivot irrigation system to circle the field. Because of this, a new prescription map was downloaded to the VRI controller every morning during an irrigation event. However, it was possible to download new prescription maps more frequently at hourly intervals.

Fig 6. VRI Zones and field used for the 2015 on-farm VRI evaluation of dynamic VRI. The gages indicate the location of UGA SSA sensor nodes.

UGA SSA sensor probes were also installed in the conventional irrigation strips to monitor soil moisture conditions. The conventional strips were irrigated uniformly by the producer using Irrigator Pro (Davidson et al., 2000) for irrigation decisions.

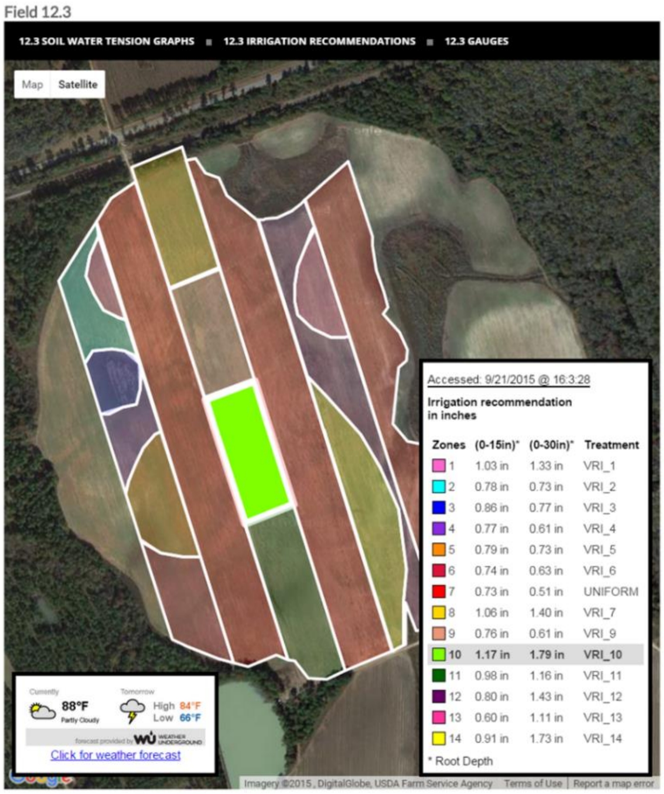

Fig 7. Dynamically developed irrigation scheduling recommendations for each IMZ. Clicking on either the zone or the recommendation will highlight both. In the figure, zone 10 is highlighted. The recommendations are to bring the soil profile to within 75% of field capacity.

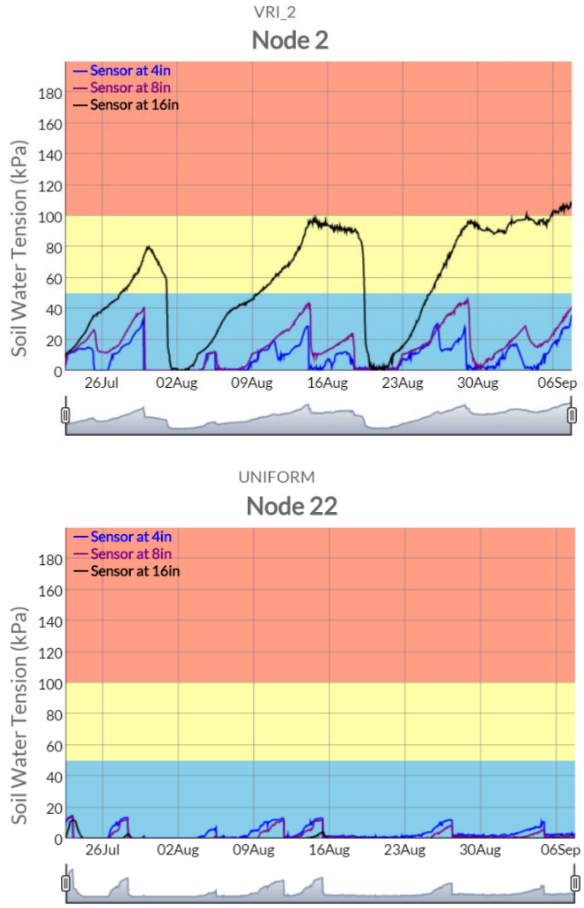

Fig 8. Season-long soil moisture data graphs from the VRI strip (top) and Uniform strip (bottom). The soil in the uniform strips is being maintained much wetter than in the VRI strips.

Irrigator Pro is a public domain irrigation scheduling tool developed by USDA which utilizes soil temperature, ambient temperature, and precipitation to provide yes/no irrigation decisions for peanuts. Total yield from each strip were measured by aggregating the weights of the truckloads of peanuts harvested from the strips.

Results

Precipitation during the 2015 growing season was 559mm which is slightly below the long-term mean precipitation for the period. As a result, irrigation during 2015 was truly supplementary to precipitation. Over the entire growing season, the dynamic VRI system (sensors + van Genuchten model + VRI) recommended an average irrigation amount of 76 mm compared to 109 mm by Irrigator Pro with approximately the same overall yields for both methods. The average yield for the dynamic VRI system strips was 5543 kg ha^{-1} while the average yield for Irrigator Pro strips was 5552 kg ha^{-1}. However, there were yield differences between strips. The parallel strip design allowed us to directly compare yields between precision-irrigated and uniformly irrigated areas with similar soil and topographic properties and assess the benefits of dynamic VRI.

Because during the 2015 growing season, the field received near mean precipitation, the dynamic VRI system outperformed Irrigator Pro in yield by 8.4% in the wetter areas of the field which were mostly areas of lower topographical relief. In contrast, Irrigator Pro outperformed dynamic VRI yields in sandy areas with higher elevations by 9.6% indicating that the 50 kPa irrigation trigger may have been too dry for these areas. Because the amount of plant available soil water is very small above 50 kPa in

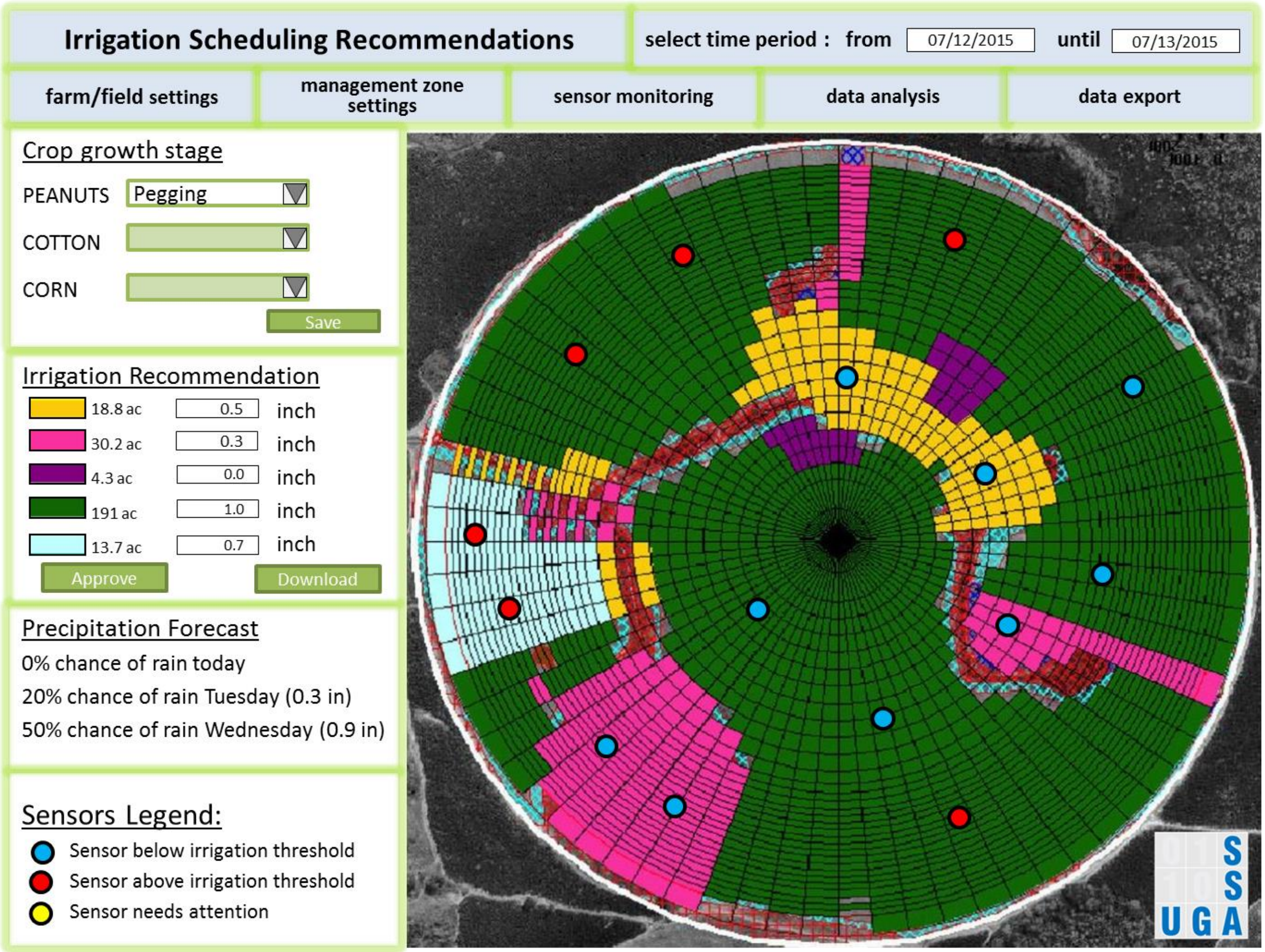

Fig 9. Mock-up of a dynamic VRI control system dashboard showing a prescription map of the field, location and status of soil moisture sensor nodes, irrigation recommendations for each IMZ, and approval and download buttons. Clicking the download button would send the prescription map wirelessly to the VRI controller.

sandy soils, any delay in irrigation results in the SWT increasing rapidly and the crop experiencing water stress. In retrospect, it appears that the threshold for these areas should have been lower to account for time to irrigation. Figure 8 shows SWT graphs from two nodes in the field. The top graph is from a node in the northwestern area of the westernmost VRI strip. The SWT data line at 40cm (16in – black line in Figure 8) clearly shows that for large periods of time, SWT at this depth was around 100 kPa and the plateaus on the graph indicate that the peanut roots were no longer able to extract water from the soil. In contrast, the lower graph which is from the easternmost uniform strip shows that the soil profile in this area was mostly saturated for the entire growing season.

Conclusions and Future Work

During 2015 we demonstrated that the technology and knowhow to implement dynamic VRI is available and feasible. The system performed well but our results indicate that we have more to learn about triggering irrigation in sandier soils. The harvest season was plagued by excessive rain which resulted in this field being harvested over a period of several weeks instead of 3 to 4 days. Consequently, the yield difference observed could also be an artifact of harvest conditions. The experiment will be repeated in 2016 to incorporate lessons learned and to collect more data about the performance of the dynamic VRI control system. Our research goal for the next two years is to fully automate the process so that each morning, a farmer is able to view a dashboard similar to the one shown in Figure 9 and with two clicks enable dynamic VRI. A short video describing VRI and showing the VRI-enabled pivot used in this study is available at https://www.youtube.com/watch?v=DgexX_IToI0.

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