Site specific irrigation management of a center pivot irrigation system using a sensor based decision support system

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Abstract. For farmers to take full advantage of center pivot Variable Rate Irrigation (VRI) systems, a decision support system (DSS) incorporating site specific irrigation scheduling methods must be integrated into their operation. This can be done with a Supervisory Control and Data Acquisition (SCADA) system implementing irrigation scheduling methods based on plant stress. This Irrigation Scheduling SCADA System (ISSCADAS) has been effectively used for site specific irrigation management of center pivot VRI systems. The ISSCADAS automates the collection of data from plant and microclimate sensing systems, as well as the application of algorithms to process those data. A software, named ARSPivot (ARSP), has been developed to facilitate the irrigation management of VRI center pivots using an ISSCADAS. This paper describes how a sensor based DSS consisting of ARSP and the ISSCADAS was used in the summer of 2016 to operate a six-span VRI center pivot near Bushland, TX. Corn was planted on one half of the field (the other half was left fallow) with three deficit irrigation treatments: 100, 50, and 30% of full replenishment of soil water depletion to 1.5 m. Irrigations were scheduled using either manual weekly neutron probe readings or the irrigation scheduling method implemented by the ISSCADAS, which incorporated a set of thermal stress thresholds and varying irrigation amounts for each irrigation treatment. No significant differences were found between overall means of dry grain yield and crop water use efficiency at the higher irrigation levels. At the lowest irrigation level dry grain yield and water use efficiency of plots using the plant stress based method were greater and significantly different than those obtained with the neutron probe measurements.

Keywords: center pivot irrigation, sensors, software, site specific irrigation scheduling.

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Introduction

According to Evans et al. (2013), adoption of site specific VRI technology has been slow. Among other needs required for the sustained adoption of site specific VRI technology, they mentioned a need for "the development and testing of easy-to-use basic decision support systems for simple site specific irrigation scheduling scenarios." This paper describes the use of a sensor based Decision Support System (DSS) for the site specific irrigation management of a center pivot VRI system. At the core of the DSS lies an Irrigation Scheduling Supervisory Control and Data Acquisition System (ISSCADAS) developed and patented by scientists with the USDA-ARS Conservation & Production Research Laboratory, Bushland, TX (Evett et al. 2014). The ISSCADAS incorporates irrigation scheduling methods based on plant stress and functions to automate the collection and analysis of data required by these methods. The ISSCADAS has been used in previous studies near Bushland for irrigation management of center pivot VRI systems irrigating soybean (*Glycine max* (L.) Merr.) (Peters and Evett, 2008), cotton (*Gossypium hirsutum* L.) (O'Shaughnessy and Evett, 2010), grain sorghum (*Sorghum bicolor* (L.) Moench) (O'Shaughnessy et al., 2013), and corn (*Zea mays* L.) (O'Shaughnessy et al., 2017). Results from these studies demonstrated that the ISSCADAS can be used to intensely manage center pivot VRI systems with little labor, resulting in yield and Water Use Efficiency (WUE) values comparable to those obtained using labor-intensive neutron probe (NP) measurements, and greater than county-wide averages.

The DSS used in this study is accessible to users without in-depth knowledge of sensing systems or irrigation scheduling methods thanks to a user friendly software developed as an embodiment of the ISSCADAS. The software, named ARSPivot (ARSP), automatically collects and processes data from plant, soil, and microclimate sensing systems to generate site specific prescription maps that users can visualize and modify using ARSP's Graphical User Interface (GUI). ARSP incorporates multiple tools commonly found in Geographic Information System (GIS) software to assist in the spatial and temporal analysis of data collected from the sensing systems (Andrade et al., 2016), and is also a flexible tool that can be used under a wide range of conditions (Andrade et al., 2017). This paper presents the results of using a sensor based DSS for the integrated irrigation management of a VRI center pivot system located in a field planted with corn near Bushland, TX. Some of the key benefits of the DSS are illustrated by analyzing the performance of experimental plots for which irrigation was scheduled using a plant stress method implemented in ARSP and plots for which irrigation was triggered by NP measurements.

Methodology

A DSS consisting of ISSCADAS/ARSP was used during the summer of 2016 for the site specific irrigation management of a six-span center pivot (260 m) equipped with a Pro2 control panel and a commercial VRI zone control system (Valmont Industries, Inc., Valley NE). Drought tolerant corn hybrid Pioneer® P0157AM was planted on the North-Northeast side of the field on June 16, 2016, day of year 168. The field was divided into six sectors of 28° each and six concentric plots spaced 18.3 m (30 ft) apart, for a total of 36 plots (Fig. 1). Irrigations were applied using low elevation spray application (LESA) and furrows were diked to reduce runoff. Plots were assigned one of three irrigation levels (100, 50, and 30%) and their irrigation was either scheduled by a plant stress method or by weekly NP measurements. The three irrigation levels were used in order to establish data for production functions of yield versus water use. For plots assigned the former method these levels represented percentages of a specified water depth of 38.1 mm (1.5 in), corresponding to 3.5 times the daily peak water use for corn in the region (assuming a 3.5-day return period for the center pivot). For plots assigned the latter method, irrigation levels represented percentages of replenishment of soil water depletion to field capacity in the top 1.5 m of soil. Irrigation scheduling of plots using this method was determined based on NP (model 503DR1.5, Instrotek, Campbell Pacific Nuclear, Martinez, CA) measurements in 0.2 m increments from 0.1 to 2.3 m (center of measurement) in treatment plots with the highest irrigation level. The NP was calibrated in the field using methods described by Evett (2008). Any precipitation occurring prior to irrigation was subtracted from the total amount required for the week.

The plant stress method implemented in ARSP is based on the estimation of an integrated Crop Water Stress Index (iCWSI) obtained as the sum of theoretical Crop Water Stress Indices (CWSIs) calculated at discrete intervals during daylight hours. ARSP estimates a CWSI for any given location in the field at time interval t using the normalized difference between the crop canopy temperature in the location and the air temperature at time t. Hence, values of CWSI so calculated range from 0 for well-watered crops to 1 for severely-stressed crops, and the iCWSI estimated for any location in the field can be described in an intuitive way as the total number of time intervals during daylight hours that the crop in that position experiences the most severe stress. Additional details of the iCWSI method and the formulas used for its calculation can be found in O'Shaughnessy et al. (2013) and O'Shaughnessy et al. (2017).

A network of 12 wireless infrared thermometers (IRTs) (model SapIP-IRT, Dynamax, Inc., Houston, TX) was mounted on the center pivot to measure crop canopy temperatures required by the iCWSI method. IRTs were located forward of the drop hoses, at an oblique angle from nadir and distributed along the center pivot in such a way that data from two IRTs with opposing views of a concentric plot were averaged to estimate the canopy temperature inside of the concentric plot. Six wireless IRTs were placed in the field to provide a reference canopy temperature for a well-watered crop. These IRTs were scattered in wetlands located in the inner and outer areas of the North-Northeast side of the field. Time intervals of one minute were used for the estimation of canopy temperatures using data collected from the IRTs. Scans of the field were performed periodically by running the pivot dry. Canopy temperatures collected within daylight hours during the scans (9 am to 7:30 pm – avoiding hours near sunrise and sunset per Peters and Evett, 2004) were used to schedule the irrigation of plots assigned the iCWSI method.

Experimental plots were organized using a Latin square design shown in Figure 1, as they are displayed in ARSP's GUI. Plots irrigated with the iCWSI method are labeled as C100, C50, or C30, where 'C' stands for iCWSI-based control and numbers correspond to irrigation levels. Similarly, plots irrigated with the NP method are labeled as U100, U50, and U30, where 'U" indicates that irrigation scheduling is controlled by the user. Irrigation scheduling of 'C' plots was determined by comparing all the iCWSIs calculated inside of a plot with a set of pre-established thresholds (Table 1). These thresholds were determined from mean seasonal iCWSI values obtained by O'Shaughnessy et al. (2017) for two corn hybrids during the 2013 and 2014 growing seasons at Bushland. Irrigation was triggered for plots where most iCWSIs were greater than 100 and no irrigation was triggered otherwise. The irrigation amounts prescribed were then assigned based on the irrigation level of each plot and by the values of iCWSIs obtained inside the plot. A plot received a 'low' irrigation depth if most of its iCWSIs were higher than 100 but less than or equal to 150 (column 3 in Table 1), a 'medium' depth if most of its iCWSIs were larger than 150 but less than or equal to 250 (column 4 in Table 1), or a 'high' depth if most of its iCWSIs were larger than 250 (column 5 in Table 1).

ARSP consists of two programs running simultaneously on an embedded computer located at the pivot point. Both programs operate using a client-server architecture, where one program (named as the 'client') contains functions to collect data from sensing systems and to communicate with the Pro2 control panel; the other program (named as the 'server') incorporates ARSP's GUI and algorithms to process the data collected by the client program, such as the iCWSI irrigation scheduling method. Figure 2 illustrates the interaction of the DSS with its user and the VRI center pivot system for the generation and application of a site specific prescription map. The process occurs through the following stages (Fig. 2): once at the beginning of the season the user provides information of the field, crop, characteristics of the VRI center pivot system, etc., to the DSS through ARSP's GUI; the user then initiates ARSP to (1) collect data from a weather station, the wireless network of IRTs mounted on the center pivot, and the IRTs in the field is stored in the embedded computer; (2) those data are processed by the client program and then (3) sent to the server program that uses the iCWSI method to generate a site specific prescription map that is (4) presented in a friendly format to the user through the GUI implemented in the server program; (5) the user looks at the prescription map and, if needed, modifies it before it is (6) sent to the client program, which in turn (7) submits it to the Pro2 panel for its (8) application by the VRI center pivot; (9) the process starts again after the irrigation with the collection (1) of a new set of canopy temperatures and weather data. Additional details of how site specific prescription maps can be visualized and modified using ARSP's GUI, and how color scaled maps of iCWSIs can be generated to analyze such prescription maps can be found in Andrade et al. (2016).

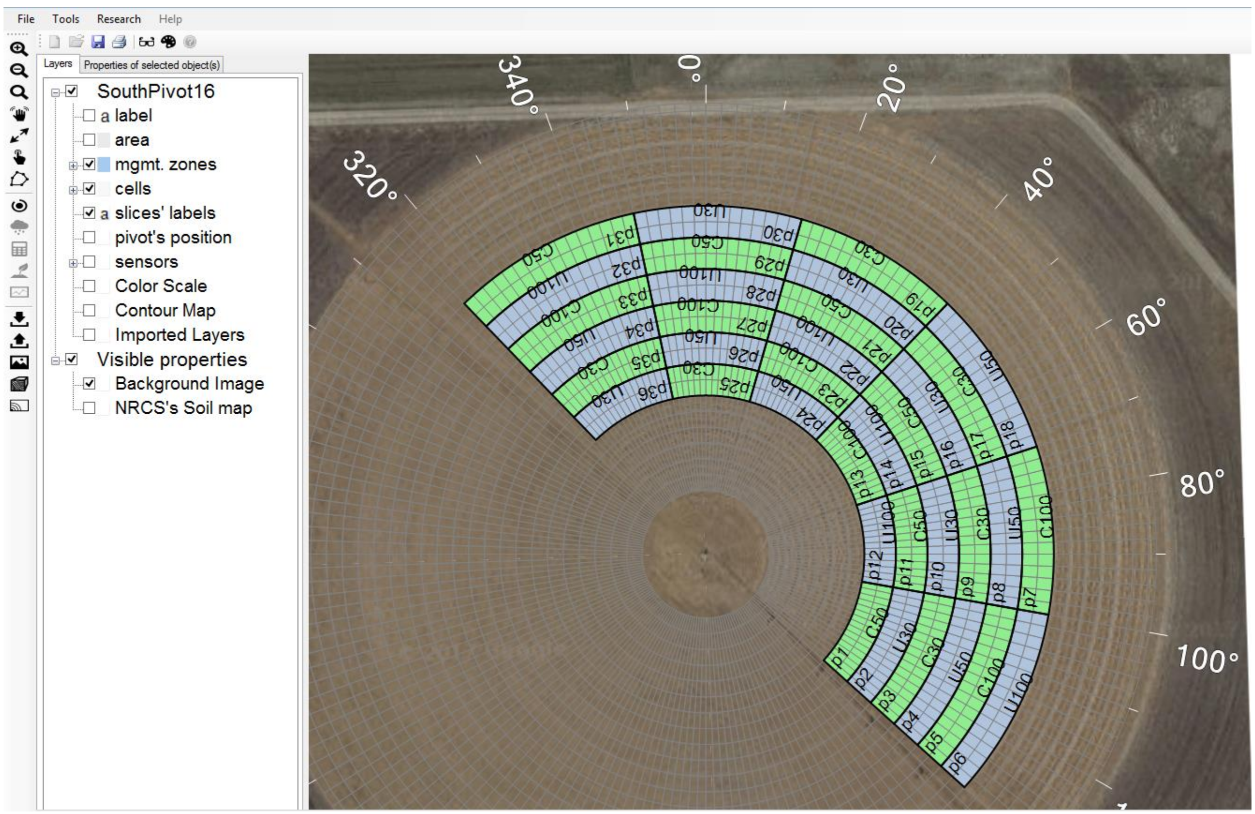

Fig. 1. Experimental setup of 36 plots in the six-span center pivot irrigation system, as displayed in ARSP's GUI. Letters C and U inside a plot indicate, respectively, that irrigation scheduling of the plot is CWSI-based (C) or controlled by the user (U) through weekly NP measurements. Similarly, numbers 100, 50, and 30 (located next to letters C or U) indicate the irrigation level assigned to the plot (100, 50, or 30%). Numbers inside plots preceded by the letter 'p' indicate the number of plot.

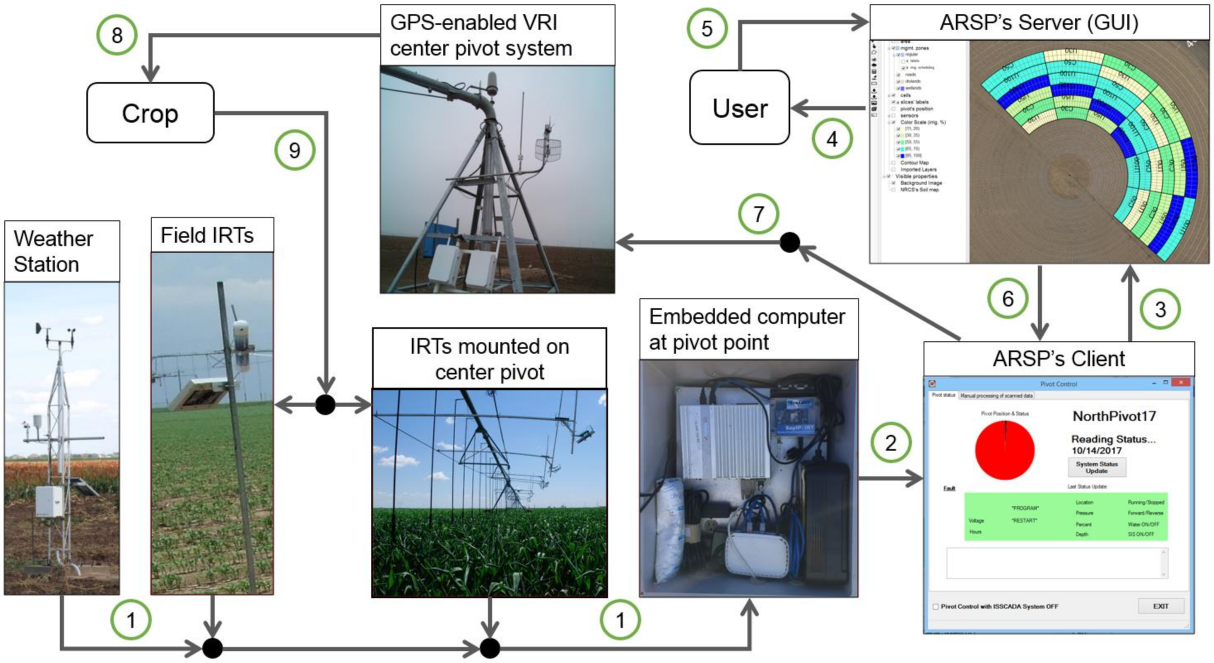

Fig. 2. Interaction of a sensor based DSS with its user and a VRI center pivot system for the generation and application of a site specific prescription map. The process occurs through nine stages noted by numbers.

Table 1. Irrigation depths and iCWSI thresholds used for the irrigation scheduling of experimental plots assigned the iCWSI method

Irrigation Level (%)	**No irrigation iCWSI<=100**	**Low depth 100<iCWSI<= 150**	**Medium depth 150<iCWSI<=250**	**High depth iCWSI>250**
100	0	19.1 mm (0.75 in)	25.4 mm (1 in)	38.1 mm (1.5 in)
50	0	12.7 mm (0.5 in)	19.1 mm (0.75 in)	25.4 mm (1 in)
30	0	6.4 mm (0.25 in)	12.7 mm (0.5 in)	19.1 mm (0.75 in)

Results

Tables 2, 3, and 4 summarize experimental results in terms of mean dry grain yield (Mg/ha), crop water use (mm), and WUE (kg/m^3). Crop water use displayed in these tables includes a total precipitation of 236 mm measured during the season. Crop response to irrigation scheduling methods is presented in Table 2. Larger mean yield and WUE were obtained from plots irrigated using the iCWSI method ('C' plots) and their values were significantly different than those obtained from plots irrigated with the NP method ('U' plots). Although the mean seasonal crop water use of the 'U" plots was smaller than the mean crop water use of ‘C’ plots, their difference was not significant. Crop response to irrigation levels is presented in Table 3. Mean yields and crop water use values increased with irrigation levels and their differences were significant. Mean WUE values, on the other hand, were not significantly different for any irrigation level, a result which may be explained by the use of a drought tolerant hybrid for the experiment.

Table 2. Mean dry grain yield (Mg/ha), seasonal crop water use (mm), and WUE (kg/m^3), grouped by irrigation scheduling method[(a)]

Irrigation Method	Dry grain yield (Mg/ha)	Crop water use (mm)	WUE (kg/m^3)
Neutron Probe (U)	10.95a	562a	1.95a
iCWSI (C)	12.11b	592a	2.05b

(a) Mean values in each column followed by a different letter are significantly different at p<0.05

Table 3. Mean dry grain yield (Mg/ha), seasonal crop water use (mm), and WUE (kg/m^3), grouped by irrigation level[(a)]

Irrigation Level (%)	Dry grain yield (Mg/ha)	Crop water use (mm)	WUE (kg/m^3)
100	12.86a	644a	2.0a
50	11.51b	569b	2.03a
30	10.22c	518c	1.97a

(a) Mean values in each column followed by a different letter are significantly different at p<0.05

Crop response to the six irrigation treatments resulting from the interaction of two irrigation scheduling methods and three irrigation levels is presented in Table 4. Mean yields of ‘C’ plots were consistently larger than mean yields of ‘U’ plots with the same irrigation levels. However, mean yields were only significantly different at the smallest irrigation level. Although mean crop water use was not significantly different at the largest irrigation level, at the smaller irrigation levels the mean crop water use of ‘C’ plots was larger and significantly different than the mean crop water use of ‘U’ plots. Mean WUE was only significantly different at the smallest irrigation level, where ‘C30’ plots obtained a larger mean WUE than ‘U30’ plots.

Table 4. Mean dry grain yield (Mg/ha), seasonal crop water use (mm), and WUE (kg/m^3), grouped by irrigation treatment[(a)]

Irrigation treatment	Dry grain yield (Mg/ha)	Crop water use (mm)	WUE (kg/m^3)
U100	12.43ab	646a	1.92ab
C100	13.29a	642a	2.07a
U50	11.02c	535c	2.06a
C50	12.0bc	603b	1.99ab
U30	9.4d	505d	1.86b
C30	11.04c	531c	2.08a

(a) Mean values in each column followed by a different letter are significantly different at $p<0.05$

ARSP's GUI incorporates multiple tools to assist the irrigation management of VRI center pivot systems. Among these tools is the generation of color scale maps of different numerical properties of management zones (experimental plots in this study). These maps are displayed in the GUI as layers drawn in top of (or below) other layers to facilitate the visual analysis of spatial information collected by the DSS. Layers of information can be overlaid because the GUI generates a scaled representation of center pivots and their management zones that is geo-referenced using the Universal Transverse Mercator projection (UTM). ARSP's GUI can also download and display other useful layers, such as a background satellite image of the terrain that is obtained using Google Maps application programming interface (API) (see Fig. 1 and Fig. 3), and a layer containing soil map units in the field obtained using the USDA-National Resources Conservation Service's Web Soil Survey website (USDA-NRCS, 2017).

Figure 3 shows color scaled maps of dry grain yield (Mg/ha) and seasonal crop water use (mm) obtained for all 36 experimental plots used in this study. These maps help to identify if particular conditions in portions of the field had an effect on crop performance. However, no spatial pattern seems to be involved in either yield or crop water use, since their values seem to be mainly influenced by irrigation level and (to a lesser degree) by the irrigation method assigned to each plot. Spatial distribution of dry grain yield is further explored in Figure 4, where a color scaled map of yield is displayed on top of an elevation contour map generated by ARSP using the kriging interpolation method. Elevations were obtained using Google Maps API through an external script written in the R programming language and the 'googleway' package for the same language (Cooley, 2017). Elevation doesn't seem to play a significant role in crop performance in terms of yield. If sectors are numbered in a counter-clockwise direction, sectors 4 and 6 are the sectors with the lowest and highest elevations in the experimental area, respectively. Nevertheless, a visual inspection of yields in these sectors shows that similar values were obtained from plots with the same irrigation treatments. Users of the DSS can perform similar analyses to assist the decision making process before the start of a growing season. For example, a soil contour map can be displayed in ARSP's GUI on top of yield and elevation contour maps to delineate the management zones that will be used during the season.

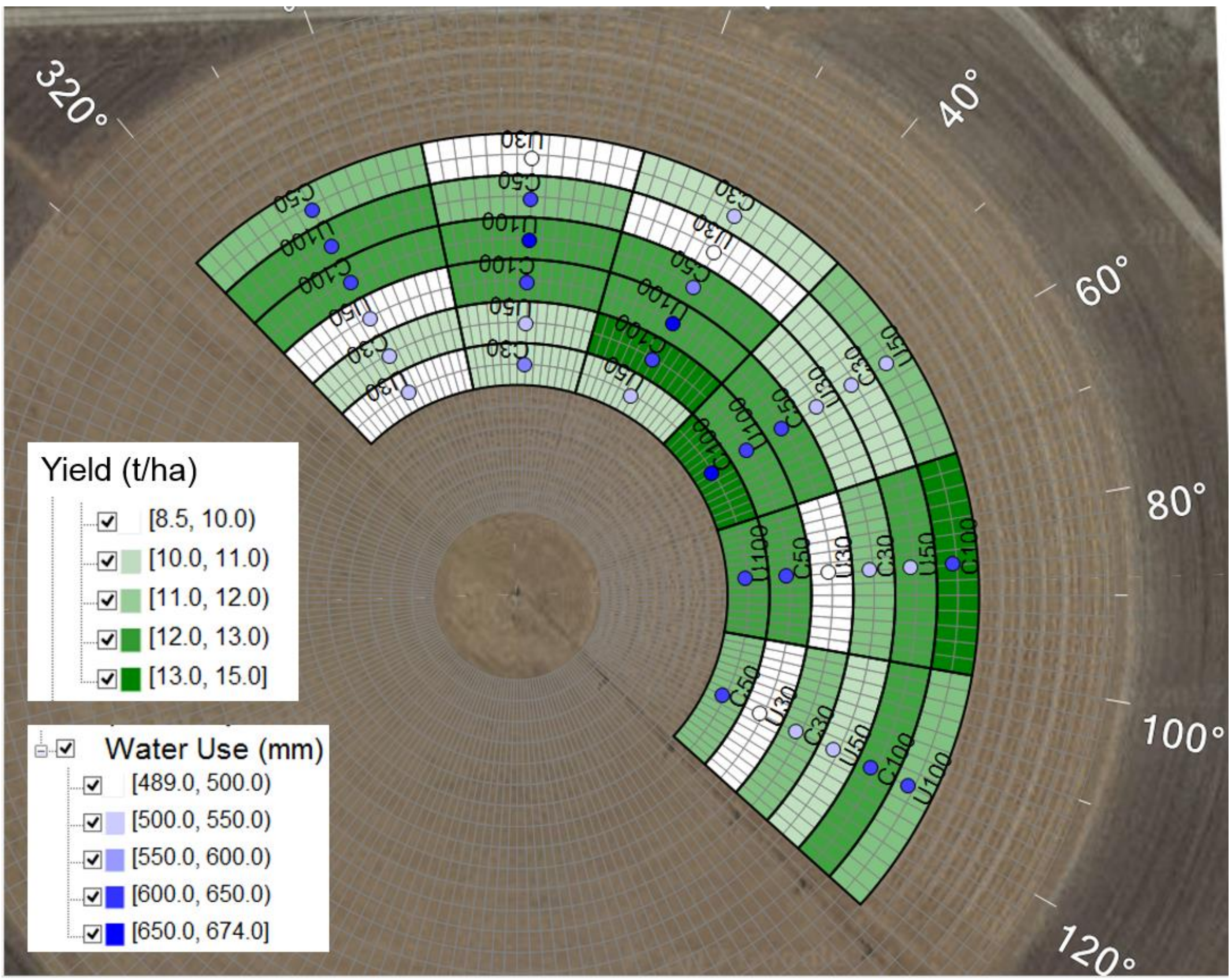

Fig. 3. Color scaled maps of dry grain yield (Mg/ha) and crop water use (mm) generated in ARSP's GUI. Yields are displayed using a color scale that progresses from white (least yield) to green (largest yield). Crop water use values are represented by circles inside plots; the color scale used for these circles progresses from white (least water use) to blue (largest water use).

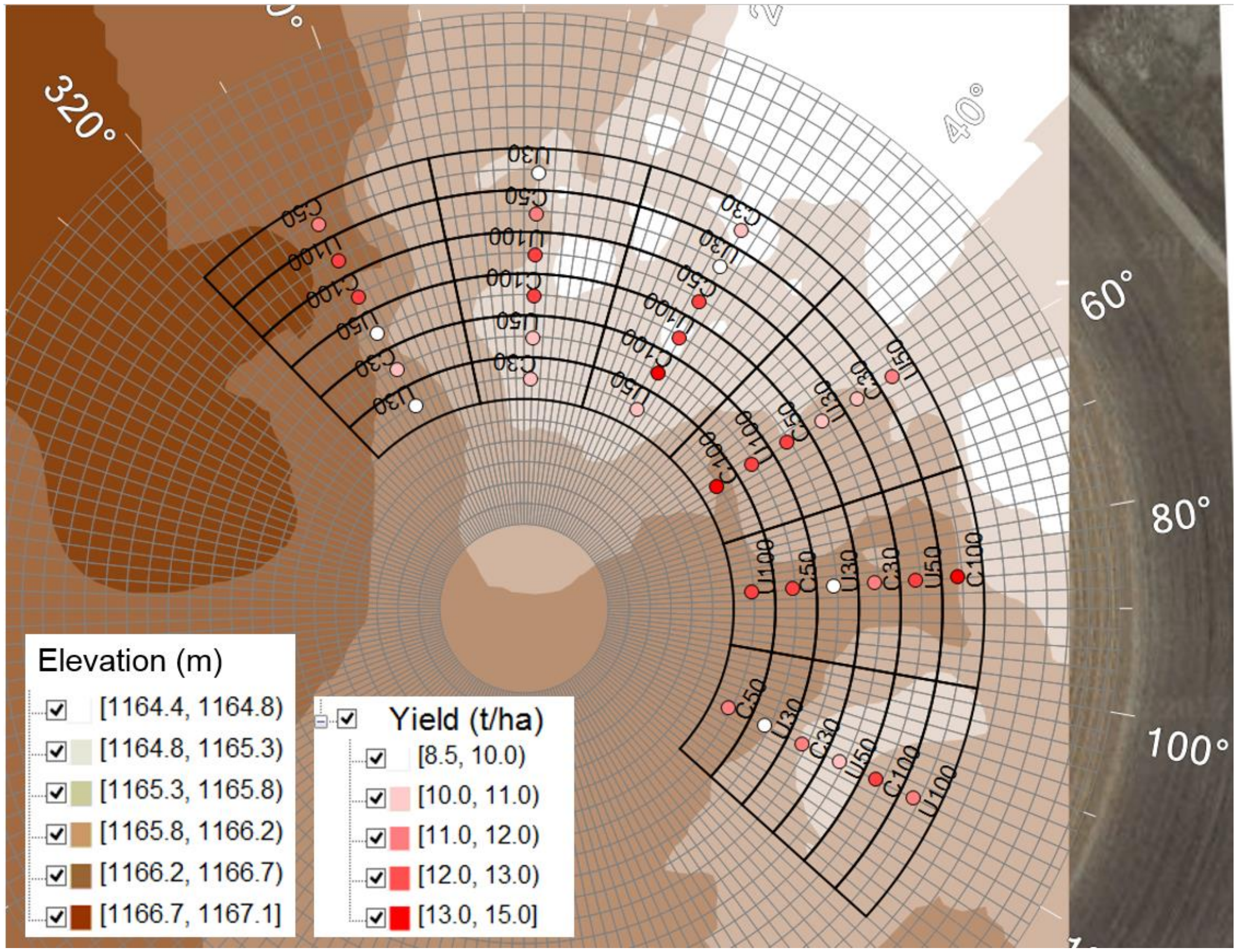

Fig. 4. Color scaled map of dry grain yield (Mg/ha) and elevation (m) contour map generated by ARSP using the kriging interpolation method.

Conclusions

A user-friendly DSS was applied to operate a complex system comprised of a VRI center pivot system and a network of plant and microclimate sensing systems supporting a site specific irrigation scheduling method based on plant stress. A software developed as part of the DSS allows the seamless operation of such a complex system. A post-harvest analysis of an experiment carried out in Bushland, TX, during the summer of 2016 demonstrated how the DSS can be used to assist the irrigation management of a VRI center pivot system. Results from this experiment showed that, at the higher irrigation levels, mean yield and WUE values obtained from plots using the iCWSI method were not significantly different than those obtained using the time consuming neutron probe method.

Acknowledgements

This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2016-67021-24420. Work reported in this paper was also accomplished as part of a Cooperative Research and Development agreement between USDA-ARS and Valmont Industries, Inc., Valley, NE (Agreement No.: 58-3K95-0-1455-M).

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