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ARSPIVOT, A SENSOR BASED DECISION SUPPORT TOOL FOR THE INTEGRATED IRRIGATION MANAGEMENT OF VRI CENTER PIVOT SYSTEMS

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ABSTRACT

Advances made by scientists with the USDA-ARS Conservation & Production Research Laboratory, Bushland, TX, can provide farmers with site-specific irrigation scheduling tools based on plant stress to assist the management of Variable Rate Irrigation (VRI) center pivot systems. A software, named ARS-Pivot (ARSP), was developed for the seamless operation of a complex network consisting of VRI center pivot systems and embedded Supervisory Control and Data Acquisition (SCADA) controllers supporting their irrigation scheduling by interfacing with weather, plant, and soil water sensing systems. This paper describes how ARSP can be used to assist the integrated irrigation management of VRI center pivot systems under a wide range of conditions. A post-harvest analysis of an experiment carried out near Bushland during the summer of 2016 using a three-span VRI center pivot is presented to illustrate the advantages of using ARSP as a decision support tool for irrigation management.

INTRODUCTION

Irrigation scheduling methods based on plant stress have been successfully integrated into the operation of center pivot variable irrigation (VRI) systems using a SCADA system patented (Evett et al. 2014) by scientists with the USDA-Agricultural Research Service (ARS) Conservation and Production Research Laboratory (CPRL). Previous versions of this Irrigation Scheduling-SCADA system (ISSCADAS) have been effectively used on a commercial scale for site-specific irrigation management of soybean (Peters and Evett, 2008), cotton (O'Shaughnessy and Evett, 2010; O'Shaughnessy et al., 2015), and grain sorghum (O'Shaughnessy et al., 2013) planted in experimental plots near Bushland, TX. These studies demonstrated that the ISSCADA system 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 ISSCADAS collects data from soil water, plant, and weather sensing systems and feeds those data to a computerized irrigation scheduling method based on plant stress to generate recommended site-specific prescription maps. The ISSCADAS also integrates software and hardware functions to manage the submission of prescription maps for application by VRI center pivot systems operated with a Pro2 control panel (Valmont Industries Inc., Valley, NE). A software, named ARS-Pivot (ARSP), was developed by ARS-CPRL scientists to simplify the management of the network of sensing systems and irrigation equipment. ARSP embodies the ISSCADAS by automating the collection of data from sensing systems and implementing site-specific irrigation scheduling methods. ARSP also incorporates a user friendly Graphical User Interface (GUI) that allows end-users (farmers or irrigation consultants) to visualize and modify prescription maps before they are submitted to the control panel.

Andrade et al. (2015) described core features of ARSP, such as the client-server architecture used in its development to allow the control of multiple center pivots using a single GUI, and the implementation of tools commonly found in Geographic Information System (GIS) software to assist in the spatial and temporal analysis of data collected by the ISSCADAS. Andrade et al. (2016) described new features of ARSP and showed how its GIS-based GUI can be used as a decision support tool to improve irrigation management. This study is focused on illustrating how ARSP was designed as a flexible tool that can be used to assist the integrated irrigation management of VRI center pivot systems under a wide range of conditions. In particular, this paper describes how ARSP allowed the achievement of a singular experimental setup where one portion of the field was irrigated using VRI zone control and another portion was irrigated using VRI speed control. Special emphasis is placed on analyzing the yield and WUE of experimental plots in the latter portion of the field to compare the performance of the canopy temperature based method with a hybrid method using soil water depletion and canopy temperature to schedule irrigations.

MATERIALS AND METHODS

The irrigation scheduling method implemented in ARSP is based on plant stress, specifically the Integrated Crop Water Stress Index (iCWSI) approach described by O'Shaughnessy et al. (2013). The estimation of an iCWSI value for a given control zone is based on the calculation of a normalized difference between the crop canopy temperature T_c and air temperature T_a (Jackson et al. 1981):

$$\mathrm{CWSI} = \frac{(T_c - T_a) - (T_c - T_a)_{ll}}{(T_c - T_a)_{ul} - (T_c - T_a)_{ll}} \tag{1}$$

where $(T_c - T_a)_{ll}$ is the 'lower limit' of the difference between T_c and T_a, occurring for a well-watered crop; and $(T_c - T_a)_{ul}$ is the 'upper limit' of the same difference, occurring for a severely-stressed crop. The equations used to calculate both $(T_c - T_a)_{ll}$ and $(T_c - T_a)_{ul}$ can be found in O'Shaughnessy et al. (2012). ARSP calculates the iCWSI for each control zone in a field as the total sum of the theoretical CWSI obtained with Eq. (1) every minute during daylight hours for the area (09:00 to 19:00).

In the summer of 2016, ARSP was used for the integrated irrigation management of a three-span center pivot (131 m) equipped with a Pro2 control panel and a commercial VRI system (Valmont Industries, Inc., Valley NE). The center pivot was located at the USDA-ARS CPRL in Bushland, TX. The ARSP software was executed in an embedded computer located at the pivot point. A midseason corn hybrid, Pioneer® P1151AM, was planted on May 13, day of year (DOY) 134. Experimental plots used in this study were located within the six outermost sprinkler zones in the field (see Fig. 1). Each sprinkler zone was 6 drops wide and each drop was ~1.52 m (5 ft) apart and plumbed with a hydraulic valve. Irrigations were applied using a low elevation spray application (LESA) method with nozzles approximately 45.7 cm (18 in) above the ground.

VRI zone control was used for the North-Northwest (NNW) side of the field, which was divided into six sectors of 28° each and six concentric plots with a width of ~9 m (30 ft) each, for a total of 36 experimental plots (Fig. 1). VRI speed control was used for the South-Southeast (SSE) side of the field, which was divided into eight sectors of 20° each and a single concentric plot with a width of 54.9 m, for a total of 8 experimental plots (see Fig. 1). For the purposes of the experiment, each of the 44 plots (36 in the NNW side and 8 in the SSE side) constituted a control zone. A user-friendly selection tool implemented in ARSP's GUI was used to set up these two contrasting sets of plots and control zones.

The irrigation of plots in the NNW side was triggered by either the iCWSI method described above or by weekly neutron probe (NP) (model 503DR1.5, Instrotek, Campbell Pacific Nuclear, Concord, CA) measurements. Each of these plots was assigned one of the following irrigation levels: 80, 50, or 30%. For plots irrigated using the former method, a set of iCWSI thresholds was used to determine the prescription assigned to each plot, according with its irrigation level (Table 1). For example, a plot with the highest level (80%) would receive no irrigation if its iCWSI were lower than (or equal to) 100 (dimensionless unit), or it would receive the maximum water depth of 25.4 mm (1 in) if the representative iCWSI value were greater than 250. Small and medium depths of 12.7 mm (0.5 in) and 19.05 mm (0.75 in), respectively, would be applied if the iCWSI of such plot fell between these values (Table 1). The maximum water depth in this study was approximately 2.5

times the daily peak water use for corn in this region and was determined by the frequency of irrigation.

To calculate iCWSIs over daylight hours, ARSP uses climatological data as discussed by O'Shaughnessy et al. (2013), and a temperature scaling algorithm (Peters and Evett, 2004) to estimate the crop canopy temperature at any given location in the field through daylight hours using a one-time-of-day measurement taken at such location. A network of 12 wireless infrared thermometers (IRTs) was mounted on the center pivot's lateral to measure canopy temperature. Reference canopy temperatures for a well-watered crop were obtained by placing two IRTs in a well irrigated area in the NNW side of the field (see Fig. 1). The IRTs were developed by ARS scientists at Bushland, TX, and are now offered commercially (model SapIP-IRT, Dynamax, Inc., Houston, TX). Infrared thermometers on the pivot lateral were located forward of the drop hoses, at an oblique angle from nadir. The average of data from two IRTs with opposing views of a zone was the primary datum every minute for each control zone. Details of these wireless sensors and additional hardware required by the plant feedback system used by the iCWSI method can be found in O'Shaughnessy et al. (2013).

For plots in the NNW side irrigated using the NP method, irrigation levels represented the percentage of replenishment of soil water depletion (SWD) to field capacity in the top 1.5 m of soil. NP measurements were taken in 0.2 m increments from 0.1 to 2.3 m inside of plots in the NNW side with the highest irrigation level (80%). 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.

Plots in the SSE side were all assigned a single irrigation level of 80%. Their irrigation was triggered by either the iCWSI method, or by a hybrid method using the iCWSI method and an average soil water depletion in the root zone (SWDr) calculated from NP measurements. The latter method, referred heretofore as the NP+iCWSI method, used a two-step approach to prevent under- or over-irrigation. During the first step, the SWDr estimated for a plot was compared with lower and upper SWDr thresholds to determine if such a plot should receive no irrigation or the greatest depth, respectively (Table 1). If the SWDr estimated for the plot fell between these values, its iCWSI was compared with iCWSI thresholds during a second step to determine its prescription (Table 1).

Fig. 1 shows the randomized arrangement of plots in the field. Plots in the NNW side irrigated with the iCWSI-based method are labeled C80, C50, or C30, where 'C' stands for iCWSI-based control and numbers correspond to irrigation levels. Similarly, plots in the NNW side irrigated with the NP method are labeled as U80, U50, or U30, where 'U' indicates that irrigation scheduling is controlled by the user. Plots in the SSE side are labeled as C80 or U80 if their irrigation was triggered by the iCWSI method or the NP+iCWSI method, respectively.

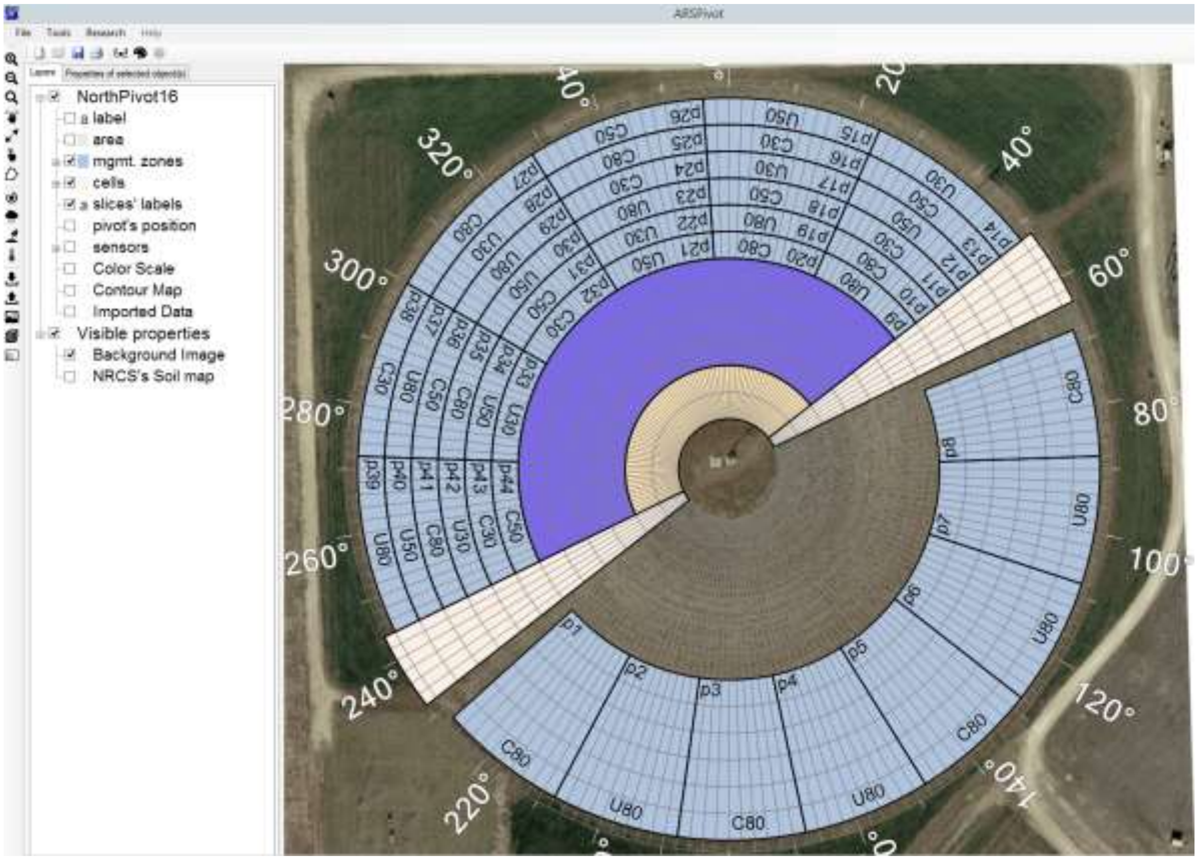

Fig. 1. Screenshot of ARSP's GUI displaying the experimental setup of 44 experimental plots in the three span center pivot irrigation system. Numbers inside of plots preceded by the letter 'p' indicate the numbers used to identify plots.

Table 1. iCWSI thresholds used to trigger the irrigation of plots using the iCWSI method; and SWDr and iCWSI thresholds used to trigger the irrigation of plots using the NP+iCWSI method.

		Plots in NNW side		
Irrigation Level (%)	**No irrigation**	**Low depth 12.7 mm (0.5 in)**	**Medium depth 19.05 mm (0.75 in)**	**High depth 25.4 mm (1 in)**
80	iCWSI <= 100	100 < iCWSI <= 150	150 < iCWSI <= 250	iCWSI > 250
50	iCWSI <= 150	150 < iCWSI <= 250	250 < iCWSI <= 300	iCWSI > 300
30	iCWSI <= 250	250 < iCWSI <= 300	iCWSI > 300	N/A
		Plots in SSE side		
Irrigation scheduling method	**No irrigation**	**Low depth 12.7 mm (0.5 in)**	**Medium depth 19.05 mm (0.75 in)**	**High depth 25.4 mm (1 in)**
iCWSI method	iCWSI <= 100	100 < iCWSI <= 150	150 < iCWSI <= 250	iCWSI > 250
NP+iCWSI method (0.2 <= SWDr <=0.5)	iCWSI <= 100	100 < iCWSI <= 150	150 < iCWSI <= 250	iCWSI > 250
NP+iCWSI method (otherwise)	SWDr <= 0.2	N/A	N/A	SWDr > 0.5

RESULTS

A scaled representation of the three-span center pivot and the experimental setup described, as displayed in ARSP's GUI, is presented in Fig. 1. ARSP uses the Universal Transverse Mercator (UTM) projection to geo-reference the information presented in its GUI. Users can modify the magnification and position of elements in the GUI through zoom in, zoom out, zoom extent, custom zoom, and pan functions. A hierarchical tree view groups elements in the GUI into layers that users can show or hide (Fig. 1). Background satellite images of the terrain can be displayed in the GUI using Google Maps application programming interface (API) (Fig. 1). A detailed description of additional GIS tools implemented in ARSP can be found in Andrade et al. (2015) and Andrade et al. (2016).

Fig. 2 shows a prescription map generated by ARSP on August 17 (DOY 230), using the irrigation scheduling methods described in the previous section for the SSE side of the field. The maximum depth of 25.4 mm was assigned to all plots with the iCWSI method (p1, p3, p5, and p8), which indicates that iCWSI values estimated inside of those plots were predominantly larger than 250 (Table 1). For plots with the NP+iCWSI method, the maximum depth was assigned to plots p6 and p7, and a medium depth of 19.1 mm was assigned to plots p2 and p4. Hence, for the latter plots, SWDr was larger than 0.2 but less than (or equal to) 0.5, and iCWSI values estimated inside of these plots were predominantly larger than 150 but less than (or equal to) 250 (Table 1). To apply the prescription map in Fig. 2 using VRI speed control, ARSP operated the center pivot using a constant flow (hydraulic valves remained open) for sprinklers irrigating experimental plots in the SSE side of the field, and a variable speed that was adjusted to meet the irrigation depth assigned to each plot. Once the center pivot left this portion of the field, ARSP operated the center pivot using VRI zone control.

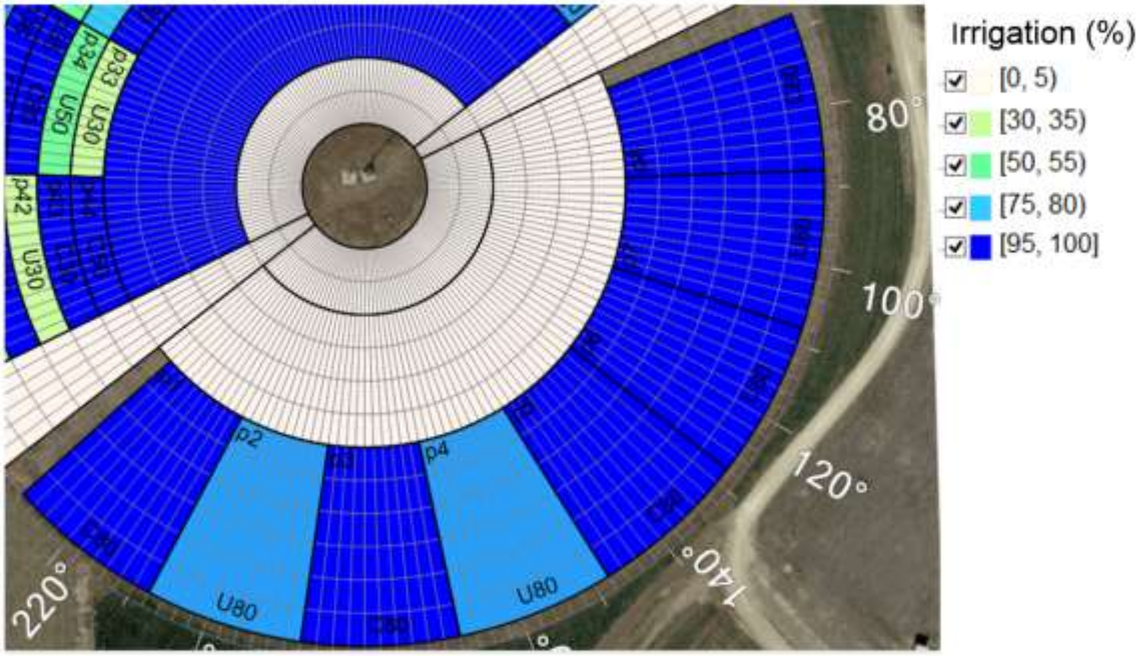

Fig. 2. Prescription map obtained by ARSP for the SSE side of the field on August 17, 2016. Irrigation depth is shown as a percent of a pre-specified maximum depth of 25.4 mm (1 in).

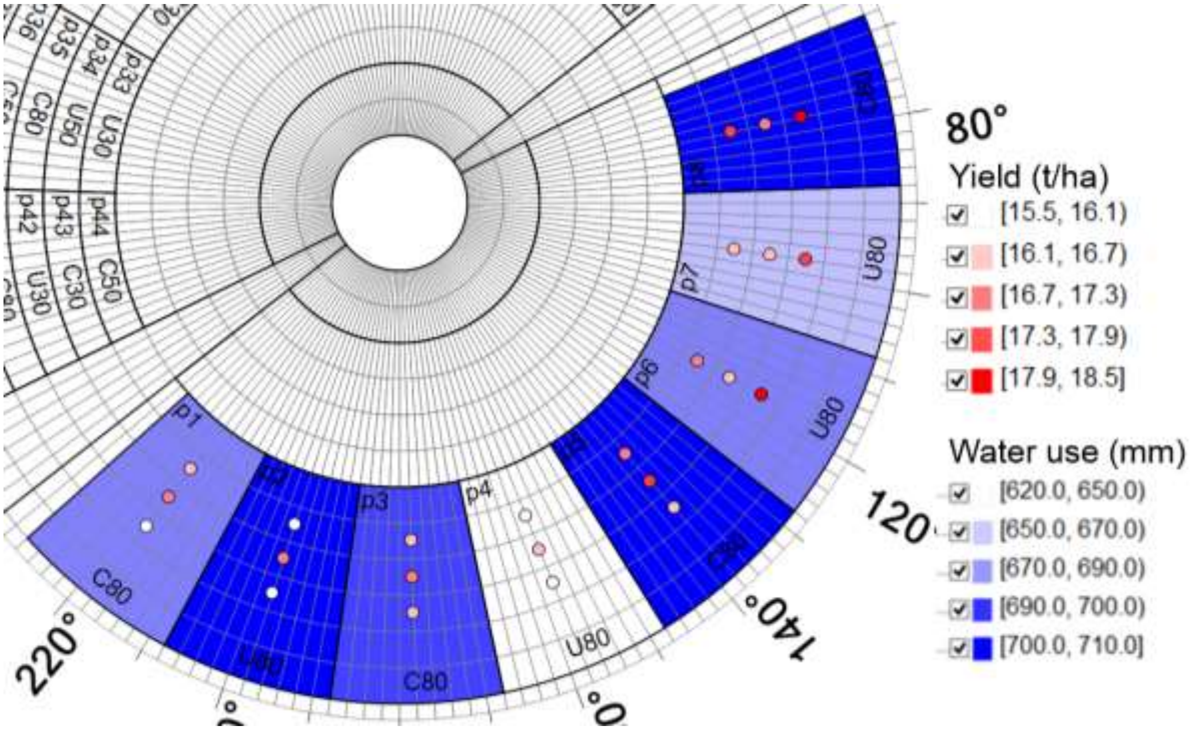

Fig. 3. Color scale map of yields (t/ha) and seasonal water use (mm) of plots in the SSE side of the field. Circles inside plots represent approximate locations where yields were estimated. Seasonal water use includes a total precipitation of 222 mm measured during the season (May 13 to October 1).

A color scale map of yields and seasonal water use (mm) in the SSE side of the field (Fig. 3) shows no clear differences between yields and water use of plots assigned the iCWSI method and plots assigned the NP+iCWSI method. However, larger yields seemed to be obtained in plots p5 to p8, in comparison with yields obtained in plots p1 to p4 (Fig. 3). To further analyze this pattern, soil data were obtained from the USDA-National Resources Conservation Service's Web Soil Survey website (USDA-NRCS, 2017). ARSP can download these data automatically and display the geospatial vector data obtained as a layer in its GUI (Fig. 4). Soil in the SSE side of the field is a Pullman clay loam with 0 to 1% slopes (PuA) and 1 to 3% slopes (PuB) (Fig. 4). A yields contour map obtained using the kriging interpolation method implemented in ARSP is also displayed in Fig. 4 to assist with the analysis. From the soil data and yield contour map in Fig. 4, a moderate correlation seems to exist between larger yields (now clearly visible in plots p5 to p8) and the PuB soil map unit (predominant in plots p4 to p6) with a greater slope.

Mean yields (t/ha), seasonal water use (mm), and WUE (kg/m^3) of plots in the SSE side of the field are presented in Table 2, grouped by (i) irrigation scheduling method, (ii) predominant soil map unit in the plot, and (iii) location of plots. No significant differences were found in mean yields, seasonal water use, and WUE between irrigation scheduling methods or soil map units. A significant difference was found between mean yields of plots located in the Southwest (plots p1 to p4) and Southeast (plots p5 to p8) portions of the field. No significant differences, however, were found in mean seasonal water use and WUE between plots located in different portions of the field (Table 2).

Mean yields (t/ha), seasonal water use (mm), and WUE (kg/m^3) of plots in the entire field with the 80% irrigation level are presented in Table 3, grouped by type of (i) VRI control and (ii) irrigation scheduling method. No significant differences were found in mean yields, seasonal water use, and WUE between VRI zone and speed controls. No significant differences were found in mean yields and WUE between irrigation scheduling methods, but a significant difference was found in seasonal water use of plots using the iCWSI method. Average yields obtained from plots using the iCWSI, NP+iCWSI and NP methods are considerably greater than corn yields obtained from nearby irrigated fields (within 100 miles of Bushland, TX) that ranged from 13.5 t/ha (214 bu/ac) to 15.1 t/ha (240 bu/ac).

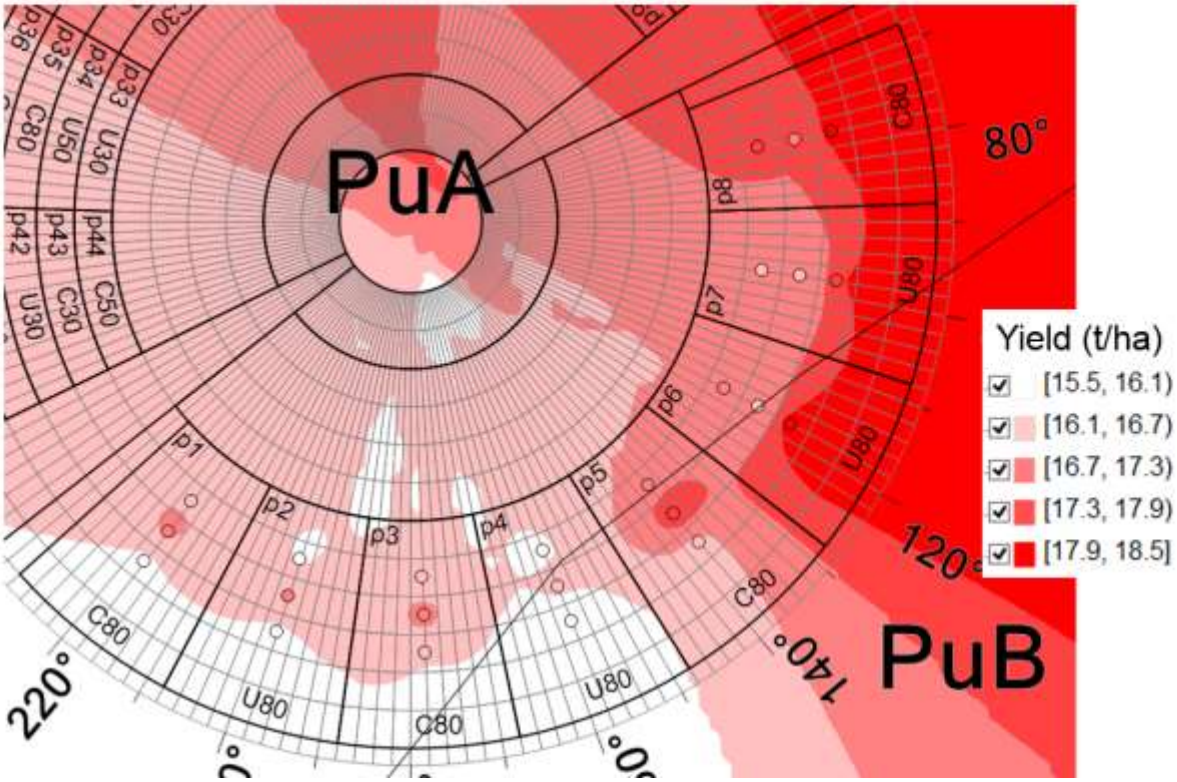

Fig. 4. Soil map units in the SSE side of the field obtained from the USDA-NRCS Web Soil Survey Website and yield contour map generated using the kriging interpolation method with an exponential semivariogram model. Soil in this portion of the field is a Pullman clay loam with 0 to 1% slopes (PuA) and 1 to 3% slopes (PuB). Yields are displayed using a color scale that progresses from white (least yield) to red (largest yield).

Table 2. Mean yields (t/ha), seasonal water use (mm), and WUE (kg/m^3) of plots in the SSE side of the field, grouped by (i) irrigation scheduling method, (ii) predominant soil map unit, and (iii) location of plots in the field[a].

(i) Irrigation scheduling method	**Yield (t/ha)**	**Seasonal water use (mm)**	**WUE (kg/m^3)**
iCWSI (p1, p3, p5, p8)	16.91a	700.6a	2.41a
NP+iCWSI (p2, p4, p6, p7)	16.54a	671.9a	2.46a
(ii) Soil Unit	**Yield (t/ha)**	**Seasonal water use (mm)**	**WUE (kg/m^3)**
PuA (p1, p2, p3, p7, p8)	16.72a	692.8a	2.41a
PuB (p4, p5, p6)	16.74a	675.3a	2.48a
(iii) Location of plots	**Yield (t/ha)**	**Seasonal water use (mm)**	**WUE (kg/m^3)**
Southwest (p1-p4)	16.27a	679a	2.4a
Southeast (p5-p8)	17.19b	693.5a	2.48a

[a]Values followed by the same letter in each column grouped by category were not significantly different.

Table 3. Mean yields (t/ha), seasonal water use (mm), and WUE (kg/m^3) of plots in the field assigned the 80% irrigation level, grouped by type of (i) VRI control, and (ii) irrigation scheduling method[a].

(i) VRI control	**Yield (t/ha)**	**Seasonal water use (mm)**	**WUE (kg/m^3)**
Zone Control	17.0a	682a	2.496a
Speed Control	16.73a	686.3a	2.439a
(ii) Irrigation scheduling method	**Yield (t/ha)**	**Seasonal water use (mm)**	**WUE (kg/m^3)**
iCWSI	17.0a	698.3a	2.44a
NP+iCWSI	16.54a	671.9b	2.46a
NP	16.8a	670.2b	2.51a

[a]Values followed by the same letter in each column grouped by category were not significantly different.

CONCLUSIONS

A user-friendly software, named ARS-Pivot was developed to operate a complex system comprised of a center pivot VRI system and an embedded SCADA controller interfacing with soil water, plant and microclimate sensing systems supporting site-specific irrigation scheduling methods based on plant stress. A GIS-based GUI incorporated in ARSP assists the design of control zones for VRI and the spatial and temporal analysis of data collected by these systems. A post-harvest analysis of an experiment carried out in Bushland, Texas during the summer of 2016 demonstrated how ARSP's GUI can be used to assist irrigation management using VRI zone and speed control under a wide range of conditions. Results obtained from this experiment showed that plots using the iCWSI method achieved yield and WUE values not significantly different from those obtained using time-consuming neutron probe methods, and considerably greater than nearby county-wide yields.

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