Automating Prescription Map Building for VRI Systems Using Plant Feedback

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Abstract. Prescription maps for commercial variable rate irrigation (VRI) equipment direct the irrigation rates for each sprinkler zone on a sprinkler lateral as the lateral moves across the field. Typically, these maps are manually uploaded at the beginning of the irrigation season; and the maps are based on prior yield, soil texture, topography, or soil electrical conductivity data. Producers are now beginning to make changes to their initial maps during the growing season based on visual observations, aerial imagery, and/or soil moisture sensors. In this study, plant feedback monitoring with infrared thermometers mounted on a moving sprinkler irrigation system was used to develop dynamic daily prescription maps for VRI sprinkler systems to aid in site-specific irrigation delivery. It was hypothesized that the plant feedback response can be used for site-specific control of crop water use efficiency. Here we discuss the application of a plant feedback algorithm combined with a variable rate irrigation system to implement site-specific irrigation management of sorghum throughout a growing season, and preliminary results to include examples of daily prescription maps, crop biophysical responses, and the average soil water content for the different irrigation treatments grouped by irrigation method. The methods used in this study provide one possible framework for establishing and integrating dynamic prescription maps into automatic control of irrigation scheduling.

Keywords: center pivot system, integrated CWSI, prescription maps, variable rate irrigation

Introduction. Commercial variable rate irrigation systems for zone control are designed to regulate flow to individual nozzles or banks of nozzles allowing for site-specific delivery of irrigation water along a pivot or linear move lateral as well as in the direction of sprinkler movement. A bank of nozzles under the control of a single solenoid valve is referred to as a zone. Prescription maps direct irrigation rates for each sprinkler zone on a sprinkler lateral as the lateral moves across the field. The initial irrigation patterns of VRI systems that are prescribed at the beginning of the growing season are manually uploaded at the beginning of the irrigation season, and can be based on, for example, one or more of the following: prior yield, soil texture, topography, rock outcrops, waterways and soil electrical conductivity information. Some producers are changing their initial maps during the growing season based on visual observations, aerial imagery, and/or soil moisture sensors (J. LaRue 2012, personal communication. It is problematic that these initial prescription maps are static for the irrigation season, which means that spatiotemporal variability of crop water stress throughout the growing season is disregarded.

One method to assess variability of crop water stress on a large scale and on a frequent basis is to use wireless sensor network systems to monitor crop canopy temperature and microclimatological parameters. Canopy temperature-based algorithms have been used to effectively control irrigation scheduling and crop water use efficiency. Two examples of thermal stress indices derived from canopy temperature are the Biologically-Identified Optimal Temperature Interactive Console (BIOTIC, Patent No. 5,539637; Upchurch et al., 1996) and the theoretical crop water stress index (CWSI) developed by Jackson et al., 1981. The BIOTIC method led to the time-temperature threshold (TTT) algorithm that has been used to automate irrigation for corn and soybeans using drip irrigation (Evett et al., 2000, 2006) and, using center pivot irrigation, soybeans (Peters and Evett, 2008), cotton (O'Shaughnessy and Evett, 2010), and forage sorghum (O'Shaughnessy et al., 2012a). A time-integrated CWSI algorithm was also used to successfully schedule irrigations for forage sorghum. Details of calculations for the upper (severely stressed) and lower (well-watered) limits of the CWSI are described in O'Shaughnessy et al. (2012b).

Both of these algorithms rely on a network of infrared thermometers to remotely monitor crop canopy temperature and were adapted for use with moving sprinkler systems by including a Global Positioning Sensor (GPS) on the lateral and integrating a scaling method (Peters and Evett, 2004) to estimate diel temperatures at remote locations using a one-time-of-day temperature reading at those locations and a reference diel temperature curve. If prescription maps can be constructed automatically based on spatiotemporal crop water stress data, then plant feedback algorithms for moving sprinkler systems can be integrated with commercial VRI systems. These daily prescription maps could direct site-specific irrigation according to crop water needs, which has the potential to improve crop water productivity and farm profitability by decreasing excessive irrigations, runoff, and deep percolation.

The goal of this study was to determine the feasibility of building dynamic prescription maps for a VRI equipped center pivot sprinkler system based on remotely monitored climatological and crop canopy temperature data. By imposing crop water stress using differing thresholds for irrigation scheduling, treatment plots with higher thresholds would receive irrigation signals less frequently than those plots with lower thresholds (Evett et al., 2002). This method would allow assessment of spatial and temporal crop water stress under the pivot field. Therefore, specific objectives were: (1) triggering irrigations for automatic treatment plots based on varying thresholds of an integrated CWSI; (2) developing a graphical user interface to integrate plant feedback with VRI hardware control to deliver irrigations when and where necessary; and (3) comparing crop biophysical and soil water measurements between scheduling methods (automatic and manual) across the same irrigation treatment level.

Materials and Methods

Experimental site and irrigation system

The experiment took place at the Conservation and Production Research Laboratory, Bushland, Texas [35° 11' N, 102° 06' W, 1141 m (3745 ft)] above mean sea level). The field soil was a Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (Soil Survey Staff, 2004). The field capacity (0.33 m^3 m^{-3}; 4.0 in. ft^{-1}) and wilting point (0.18 m^3 m^{-3}; 2.2 in. ft^{-1}) water contents were assumed uniform across the center pivot field. The climate is semi-arid with an average annual rainfall of 470 mm (18.5 in.). Early maturing sorghum, variety NC+5C35[1] was planted on June 27, 2012 (DOY 179) under an existing six-span center pivot system retrofitted with a variable rate irrigation (VRI) package (Valmont Industries, Valley, Nebr.). Irrigations were applied using low energy precision application (LEPA) drag socks (Lyle and Bordovsky, 1983) in every other furrow. Furrow dikes were placed in the furrows to reduce runoff and to provide the temporary detention required for LEPA irrigation in alternate furrows.

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[1] The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

Nozzle sizes were selected to apply water as uniformly as possible along the lateral length. Irrigation application zones along the lateral were configured as banks of six sprinkler drop hoses. Each sprinkler drop hose was connected to a hydraulically actuated valve, and outfitted with a polyethylene weight and a pressure regulator rated at 41.4-kPa (6-psi). Each zone was controlled by an electronic solenoid valve at a pivot control tower. The solenoid valve activated all hydraulic valves in the zone. One-half of the center pivot field was cropped and divided into seven sectors of 22°. Treatment plots were established in a split plot block design (Littell et al., 2006) consisting of four concentric zones, each comprised of two sprinkler banks (12 drop hoses). A WAAS corrected GPS, with differential position accuracy of ± 3 m, communicated with the programmable logic controller of the pivot's VRI system using power line carrier communication. Irrigation methods (manual and automatic) were randomized radially and concentrically over half of the pivot field (Fig. 1).

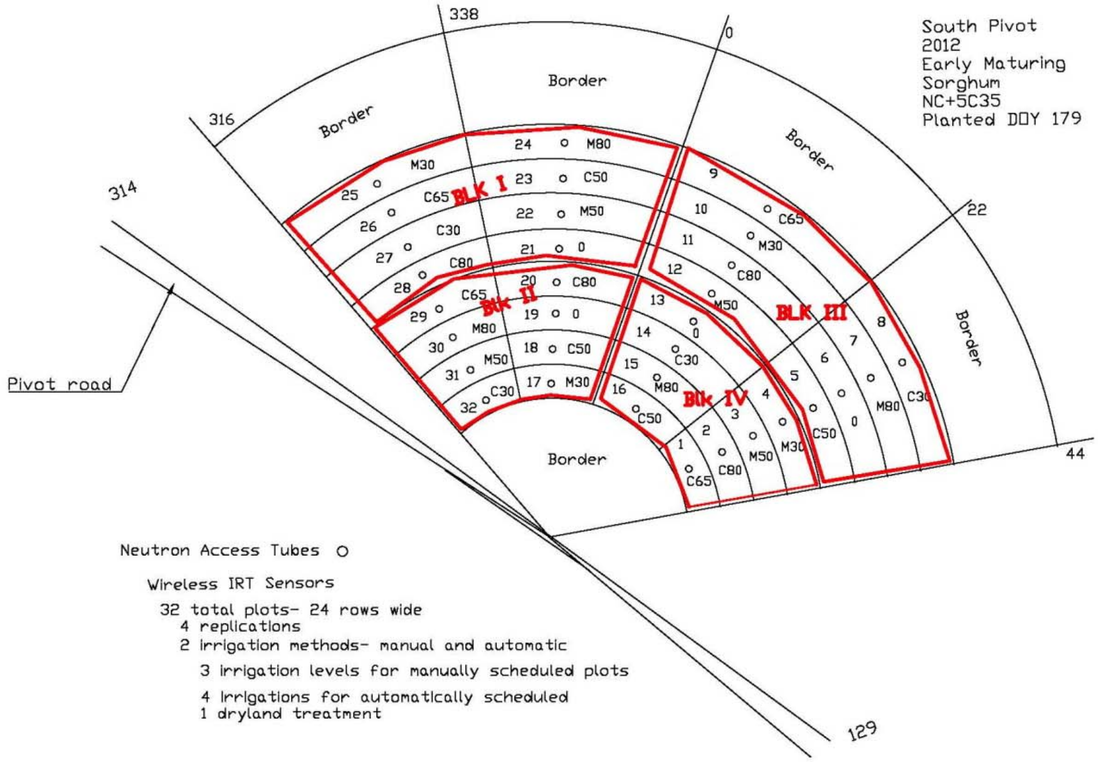


Figure1. Experimental field layout. The letter “M” in a plot indicates manual irrigation scheduling and the letter “C” in a plot indicates automatic irrigation scheduling using the integrated crop water stress index ($_i$CWSI).

Sensor Network Systems

A wireless sensor network (WSN) comprised of infrared thermometers was established on the pivot lateral and in the field below as described by O’Shaughnessy et al. (2012c). Sixteen sensors were mounted on masts hanging from the pivot lateral at the border of each concentric plot looking inwards at an oblique angle. The sensors viewed the cropped field forward of the irrigations. In addition, static “field” sensors were placed in 10 of the automatic irrigated plots (designated C80, C50, and C30) (fig.1) and two were placed in the manually scheduled M80 treatment plots to monitor well-watered canopy temperatures. Micrometeorological data (wind speed, relative humidity, air temperature and solar irradiance) were collected using a weather station located within the pivot field and transmitted hourly to the base station computer at the pivot.

Manual Irrigation Scheduling

Manual irrigations were scheduled over 3-4 days as needed in a 7-day period and based on 80%, 50%, and 30%, (designated $I_{80\%M}$, $I_{50\%M}$, and $I_{30\%M}$, respectively) of full replenishment of soil water depletion to field capacity in the top 1.5 m (4.9 ft) of soil. Soil water content was determined weekly using a neutron probe (NP) (model 503DR1.5, Instrotek (Campbell Pacific Nuclear), Martinez, Cal.) in 0.2-m increments from 0.10 m to 2.3 m (0.32 to 7.6 ft) in the $I_{80\%M}$ treatment plots. Access tubes were placed in a row in the center of each plot (24 rows wide). The neutron probe was field calibrated to accuracy of better than 0.01 m^3 m^{-3} (0.12 in. ft^{-1}), resulting in separate calibrations for three distinct soil layers, Ap, Bt and Btca, using methods described by Evett (2008). Irrigations for the manual and automatic control treatments were applied on the same day, over three days of the week if necessary. Any rainfall occurring prior to irrigation of the total amount for the week was subtracted from the required total.

Automatic Irrigation Scheduling

Irrigations in automatic control treatment plots were scheduled when pre-established threshold values were exceeded after the pivot scanned the field. Threshold values were 320, 380, and 450 for the automatic treatments corresponding to 80%, 50%, and 30% automatic control treatments and designated $I_{80\%C}$, $I_{50\%C}$, and $I_{30\%C}$. The integrated CWSI ($_i$CWSI) thresholds were calculated from canopy temperature and microclimatological data every minute over daylight hours for sorghum grown under a range of irrigation treatment levels at Bushland, Texas during the 2011 growing season (O'Shaughnessy et al., 2012a). In the case of extended cloud cover, irrigation was delivered to the automatic plots in the amounts of 80%, 50%, or 30% of 19 mm (0.76 in.) if estimated crop water use ($ET_c = K_c \times ET_o$) was greater than 0.76 inches. Percentages of the full amount were released to parallel the mechanism of irrigation threshold values, i.e. higher thresholds should result in less frequent irrigations and lessor amounts, while lower thresholds should result in more frequent irrigations or greater amounts. The full irrigation level and the threshold ET_c value for automatic treatments used on cloudy days was based on twice the peak daily crop water use rate of grain sorghum at the location (Steiner et al., 1991).

Crop coefficients (K_c) were from those established for Bushland, Texas as a function of accumulated growing degree days (AGDD) (Table 1) (Howell et al., 2008). Reference evapotranspiration (ET_o) was calculated from microclimatological data using the ASCE standardized reference evaporation equation (ASCE-EWRI, 2004). The GDD were calculated using $GDD = (T_{max} + T_{min})/2 - 10.0°C$ where T_{max} and T_{min} are daily maximum and minimum air temperatures; and AGDD was the accumulated sum of daily GDD since emergence.

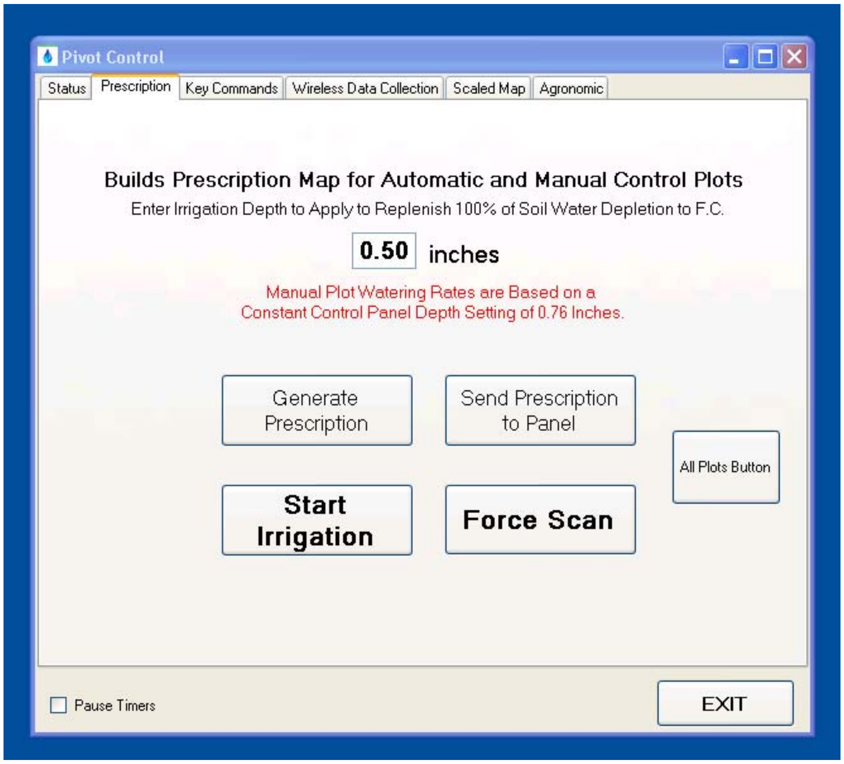
Table 1. Crop coefficients for sorghum grown in Bushland, Texas (Texas High Plains ET Network).

AGDD	Crop Coefficient (K_C)	General growth stage description
$AGDD \leq 265$	$= 0.10$	Through emergence
$265 < AGDD \leq 615$	$= (0.0026 \times AGDD) - 0.58$	Through Flag leaf
$615 < AGDD < 750$	$= 1.0$	Boot to Flowering
$AGDD \geq 750$	$= -0.00043 \times AGDD + 1.32$	Soft dough to Black layer

The pivot scanned the field on even days of the year (DOY); these data were used to build a prescription map to deliver irrigations to manual and automatic plots on the odd DOY. The maximum application depth (VRI system keeping nozzles on continuously) of the irrigation system was set at 19 mm (0.76 in.) by setting the pivot travel speed at the end tower to 46.4 m hr-1 152.4 ft hr^{-1} ;9.2° hr^{-1}. Each time a treatment plot designated as 80% irrigation under automatic control received an irrigation signal, 0.76 inches was delivered, i.e. the pulsing rate to that particular plot was programmed at 100%. Irrigation rates for the other automatic treatment amounts were reduced from this according to the relative percentages (50 or 30%). Irrigation depths delivered to the manual designated plots were achieved by pulsing the appropriate banks at rates that were equivalent to 80%, 50%, and 30% of the entered application depth. The pulsing rate for each manual treatment plot was calculated using eq.1:

$$\text{Pulsing rate}_i = (\text{Manual amount}/0.76) \times I_{i\%M}\ (\%) \qquad \text{(Equation 1)}$$

where manual amount = amount entered in the graphical user interface (Fig. 2), and i = 80, 50, or 30 for the plots $I_{80\%M}$, $I_{50\%M}$, and $I_{30\%M}$, respectively. These amounts of irrigation also limited “washing-out” the furrow-dikes throughout the course of the irrigation season.



Builds Prescription Map for Automatic and Manual Control Plots
Enter Irrigation Depth to Apply to Replenish 100% of Soil Water Depletion to F.C.
0.50 inches
Manual Plot Watering Rates are Based on a
Constant Control Panel Depth Setting of 0.76 Inches.

Figure 2. Graphical user interface constructed to deliver the appropriate irrigations depths to manual control plots (based on entered data) and exceeded thresholds for the automatic plots. The GUI uploads the prescription map to the pivot control panel and initiates irrigation when the respective buttons are pushed.

The prescription map was constructed using Visual Basic code. Treatment plot boundaries were static and defined by sectors and irrigation banks. Software previously developed by the USDA-Agricultural Research Service (ARS) was used to control the start and completion of irrigations, and recorded direction and speed of the pivot, angular location, and water pressure every minute. Plant height and width measurements were recorded approximately every 14 days throughout the growing season.

Statistical Analysis

Results from each year were analyzed separately using the Mixed Models procedure (Littell et al., 2006) with SAS statistical software (SAS 9.2, SAS Institute Inc., Cary, NC). The main factors of irrigation method (automatic and manual) and irrigation treatment (80%, 50%, 30%, 0%) were treated as fixed effects. Blocks were considered random effects. Differences among means of fixed effects were tested using least square mean differences and P values were adjusted for multiplicity with the least mean square difference student's t-test ($p < 0.05$).

Results

Results presented in this study were from data analyzed through DOY 255 when the sorghum was nearing the hard dough stage. On odd and even DOY, it was possible to consistently build a prescription map based on a mean calculated ${}_{i}$CWSI (Fig. 3a) specific to each automatic treatment plot, and information entered for irrigating manual treatment plots. The prescription maps were built using code specific to the commercial VRI software, and enabled a visual representation of spatial and temporal crop water stress throughout the irrigation season (Fig. 3b). The treatment plots where the thermal stress index was exceeded (${}_{i}$CWSI value shown in red) indicated the location of a management zone where the crop was stressed. This resulted in an automatic decision to irrigate that particular zone. The decision was implemented by the generation and uploading of the prescription map to the pivot control panel. Irrigation of sectors outside of the 44° to 316° pie-shaped field were controlled by ARS software.

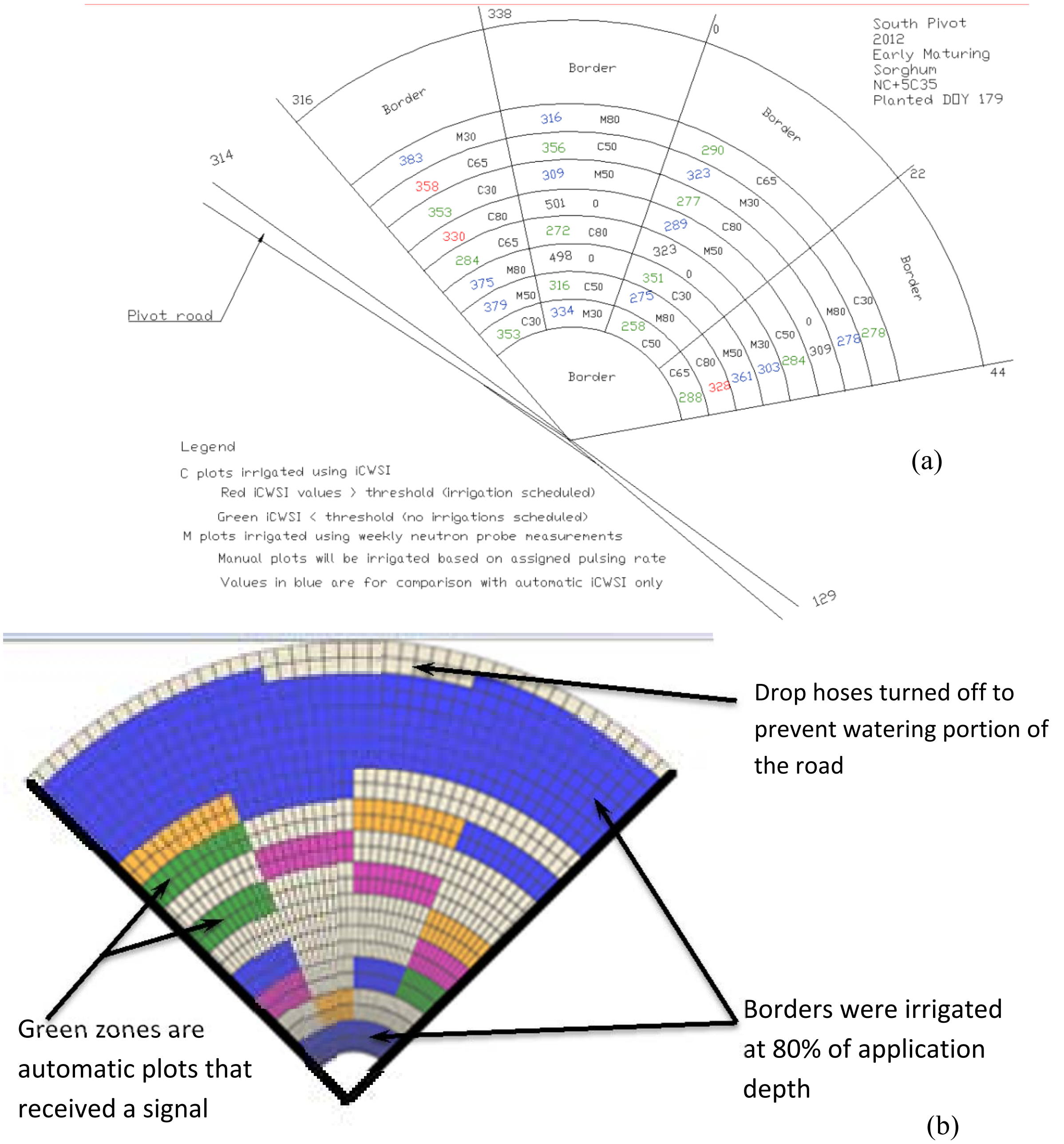


Figure 3. Examples of field treatment effects and treatment implementation illustrated respectively by: (a) integrated crop water stress index values ($_i$CWSI) calculated from field scan on DOY 254; and (b) prescription map built on DOY 255 based on $_i$CWSI values exceeding pre-established threshold values for treatment plots within sectors 44-316°.

Drought conditions prevailed in the 2012 growing season at Bushland, Texas, with total precipitation during the months of May through June amounting to 71.6 mm (2.82 in.), maximum daily temperatures averaging 31.6° C (89°F), and mean wind speeds of 4.1 m s^{-1} (9.15 mph) (Table 2).

Table 2. Climatological data for the 2012 growing season in Bushland, Texas, represented by monthly means of daily values.

Month	Min RH (%)	ET Ref mm	Max RH (%)	Min T (°C)	Max T (°C)	Precipitation (Total mm)	Wind speed (m s^{-1})	Max solar irradiance MJ m^{-2} d^{-1}
May	21.1	7.4	72.6	10.7	27.8	29	4.1	26.5
June	23.1	8.4	78.7	16.5	32.9	33	4.9	26.8
July	21.3	8.1	68.2	18.5	34.0	2	3.9	25.6
August	21.7	7.1	72.7	17.1	32.8	8	3.5	24.9

1 mm d^{-1} = 0.039 in. d^{-1}; 1°C = 1.8*(°C) + 32 in °F; 1 mm = 0.039 in.; 1 m s^{-1} = 2.24 mph; 1 MJ m^{-2} d^{-1} = 23.9 Langley d^{-1}.

Irrigation scheduling began on July 30, 2012 (DOY 211) and will continue until the grain reaches physiological maturity, which is expected to occur in 2-3 weeks. As of September 11, 2012 (DOY 255), the total amount of irrigation applied to manual treatment plots ($I_{80\%M}$, $I_{50\%M}$, and $I_{30\%M}$) was 361, 226, and 137 mm (14.2, 8.9, and 5.4 in.), respectively. Average irrigation amounts applied to the automatic control plots ($I_{80\%C}$, $I_{50\%C}$, and $I_{30\%C}$) were 279.4 ± 33, 218 ± 38.1, 173 ± 46 (11.0 ± 1.3, 8.6 ± 1.5, and 6.8 ± 1.8 in.), respectively. On DOY 254, the mean soil water content for the $I_{80\%M}$ treatment plots was 0.27 m^3 m^{-3} (3.2 in. ft^{-1}) and that for the $I_{80\%C}$ plots was 0.26 m^3 m^{-3} (3.1 in. ft^{-1}). The differences in irrigation amounts applied to the $I_{80\%M}$ and $I_{80\%C}$ plots produced observable differences in plant height that were significantly different (Table 3). However, irrigation amounts and plant heights were not significantly different at the 50% and 30% irrigation levels when compared across irrigation methods.

Table 3. Statistical comparison of plant height and cumulative irrigations through DOY 255 for grain sorghum for the 2012 growing season in Bushland, Texas. Values followed by the same letter in each column and grouped by effect, are not significantly different.

	Plant Height (cm/in)	Cumulative Irrigations (mm/in)
Irrigation Method		
Manual	93.2/36.7a	241/9.5a
Auto	88.6/34.9a	224/8.8a
	F=5.0, p =0.04	F= 2.89, p = 0.11
Irrigation Level		
$I_{80\%}$	100.0/39.4a	320/12.6a
$I_{50\%}$	86.6/34.1b	221/8.7b
$I_{30\%}$	82.0/32.3b	130/5.1c
$I_{0\%}$	66.6/26.2c	0/0d
	F=17.8, p <0.0001	F=87.9, p < 0.0001
Irrigation Method × Irrigation Level		
$I_{80\%M}$	106.9/42.1a	361/14.2a
$I_{80\%C}$	93.7/36.9b	279/11.0b
$I_{50\%M}$	89.4/35.2bc	226/8.9c
$I_{50\%C}$	83.6/32.9cd	218/8.6c
$I_{30\%M}$	81.5/32.1d	137/5.4d
$I_{30\%C}$	83.1/32.7bcd	142/5.6d
	F=2.7, p=0.09	F=11.1, p=0.001

Mean seasonal $_i$CWSI values calculated through DOY 254 (Table 4) grouped by irrigation level, compared well between irrigation methods. The average stress index values for the 50% and 30% treatment levels were lower than the threshold values, but in agreement between scheduling methods. This was likely due to soil background making surface temperatures read cooler immediately after irrigation from wet soil, and increasing surface temperatures when drier.

Table 4. Mean seasonal integrated crop water stress index values calculated for each irrigation treatment and method through DOY 254, 2012.

Irrigation Treatment Amount	Irrigation Method		
	Manual	Automatic	Threshold
80	324.4	322.9	320
50	342.2	344.1	380
30	391.4	393.5	450
0	468.8		

Conclusion and Discussion

In this study, prescription maps were based on the previous 24 hours of data. Preliminary results suggest that automatic irrigation scheduling using plant feedback methods can be integrated with VRI hardware and software to construct dynamic prescription maps and control crop water use efficiency. If the lesser irrigation amounts delivered to the $I_{80\%C}$ irrigation plots result in significantly reduced yields or water use efficiency values, the threshold can be reduced to increase the frequency of irrigations. In previous sorghum studies without VRI, however, the same threshold $_{i}$CWSI value used for the $I_{80\%C}$ treatment did not result in significantly different yields than did the corresponding manual irrigation treatment ($I_{80\%M}$).

This study demonstrates the ability to integrate sensor feedback with VRI equipment to assess spatiotemporal variability with greater frequency than weekly manual soil water readings. At harvest, grain yield and water use efficiency will be calculated from hand-samples to assess the overall effectiveness of using plant feedback methods for irrigation scheduling and controlling water use efficiency for forage sorghum.

The methods used in this study provide one possible framework for establishing and integrating dynamic prescription maps into automatic control of irrigation scheduling. In this study, spatiotemporal crop water stress was induced by establishing variable thresholds for irrigation scheduling. Irrigation management zones were established by defining the borders of each treatment plot by sector and sprinkler irrigation bank. A second fundamental element was to assess, on a regular basis, the performance of the crop in a management zone against a pre-defined performance index (i.e. a stress index threshold value). The third fundamental element was the implementation of a secondary decision support system to estimate crop water use to control irrigations in the case of extended periods of cloudy days with no precipitation. Future work will require correcting radiometric temperature measurements for cases in which the crop canopy is less than full, and the incorporation of other sensor network systems such as soil water sensors to overcome issues of inadequate temporal frequency due to the time it takes the pivot to move across the field.

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