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ORIGINAL PAPER

Using an integrated crop water stress index for irrigation scheduling of two corn hybrids in a semi-arid region

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Abstract Different thermal-based plant feedback systems have been used for irrigation management of cotton and grain crops in the Texas High Plains region, producing yields that are similar or better than irrigation scheduling using the neutron probe. However, there are limited studies using plant feedback systems to actively scheduling irrigations for corn. In this 2-year study, a drought tolerant and a conventional hybrid were managed under a variable rate center pivot irrigation system. The main treatments were manual and plant feedback irrigation scheduling based on weekly neutron probe readings and an integrated crop water stress index (CWSI), respectively. In each main treatment, three irrigation treatment levels were established. Crop responses were compared between irrigation methods and levels. Results demonstrated that overall grain and biomass yields and grain WUE for the plant feedback-control plots were similar to those from the manual-control plots for both years. These results indicate that a plant feedback system using a CWSI could be used to manage corn in a semi-arid region and over a large-sized field. The plant feedback system could provide convenience and time savings to farmers who manage multiple center pivot fields.

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Introduction

Corn (*Zea mays* L.) is the most widely produced feed grain in the United States (USDA ERS 2016) and is grown in various climatic regions throughout the country. In Texas, corn grown for cattle feed is a major contributor to the state's economy, but water for agriculture is limited. Hence, it is worthwhile to investigate optimal irrigation-scheduling strategies for different corn hybrids, especially in areas, where water is limited. In 2013 and 2014, nearly, 50% of corn grown in Texas was irrigated, with the majority of irrigated acres located in the Texas and Southern High Plains regions of the state (USDA NASS 2016). Irrigated agriculture in this area draws water mainly from the Ogallala Aquifer, a non-renewable freshwater water source (Scanlon et al. 2012).

Although corn can use water efficiently (Hsiao and Acevedo 1974), the required amount of water (irrigation and rainfall) in a semi-arid region can be more than 800 mm per growing season (Howell et al. 1989, 1998, 2002). Improved irrigation management of corn could result in reduced water applied and improved crop water use efficiency. Over the past 20 years, various irrigation-scheduling methods have incorporated crop canopy temperature into an irrigation-scheduling scheme. These thermal-based plant feedback systems include the Biologically identified optimal temperature interactive console (BIOTIC) (Upchurch et al. 1996), the time temperature threshold (TTT), the crop water stress index and time threshold (CWSI-TT), and the integrated CWSI (iCWSI). The BIOTIC method contains dual thresholds of temperature and time. The temperature threshold uses a species-specific thermal range (optimal for enzyme kinetics, Burke et al. 1988), and a time threshold that is region specific. The BIOTIC method was used primarily to manage irrigation scheduling of cotton under subsurface drip and sprinkler irrigation (Wanjura et al. 1992, 1995). Wanjura et al. (2004) and Evett et al. (1996) demonstrated that varying either the time or temperature of the dual threshold algorithm could be used to control irrigation at different treatment levels and crop WUE. The TTT method was initially used to manage cotton, corn, and soybean with subsurface drip irrigation. This method has also been used for irrigation scheduling of soybean (Peters and Evett 2008), cotton (O'Shaughnessy and Evett 2010) and sorghum (O'Shaughnessy et al. 2012a) under sprinkler irrigation. At high irrigation treatment levels [those meeting full evapotranspiration (ET) or nearly full ET requirements], yield and WUE results have been similar or better for the TTT method as compared with a manual method of irrigation scheduling using soil water readings with a neutron probe.

Another plant feedback method, the CWSI-TT, also contains two thresholds. The first is a crop water stress index threshold that varies between the values of 0 and 1, where 0 represents a non-stressed plant and 1 represents a fully stressed plant. The second threshold is a time threshold, whereby time is accumulated when the pre-established CWSI threshold is exceeded. O'Shaughnessy et al. (2012b) used this algorithm with a CWSI threshold of 0.45 and time threshold of 420 min for automatic irrigation scheduling of two hybrids of grain sorghum. For a long season sorghum hybrid, the CWSI-TT scheduling method resulted in similar or better grain yields, ET, and crop water use efficiency (WUE) than irrigation based on neutron probe readings.

The iCWSI (Eq. 1) was used by O'Shaughnessy et al. (2015) for site-specific irrigation scheduling of cotton. The algorithm required a single threshold for triggering irrigations, but the CWSI was calculated over daylight hours at 1-min time steps and was based on the theoretical CWSI developed by Jackson et al. (1981, 1988):

$$\mathrm{iCWSI_r} = \sum_{i=1}^{N} \left[\frac{(T'_\mathrm{c} - T_\mathrm{a}) - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}}{(T_\mathrm{c} - T_\mathrm{a})_\mathrm{ul} - (T_\mathrm{c} - T_\mathrm{a})_\mathrm{ll}} \right] \quad (1)$$

where $\mathrm{iCWSI_r}$ is the integrated CWSI calculated for a remote location r, i is the ith time step, N is the total number of time steps during daylight hours (9:00 a.m. to 7:00 p.m., using 1-min intervals), T'_c is the scaled crop canopy temperature (explained later) at remote location r at the ith time step, T_a is air temperature, and $(T_\mathrm{c}-T_\mathrm{a})_\mathrm{ll}$ represents the estimated difference between a well-watered canopy and air, while $(T_\mathrm{c}-T_\mathrm{a})_\mathrm{ul}$ represents the temperature difference between a non-transpiring canopy and air. More detail is provides in "Materials and methods".

The iCWSI algorithm used by O'Shaughnessy et al. (2015) summed the CWSI values calculated at discrete intervals inclusive of 9:00 a.m. to 7:00 p.m., and maintained a constant threshold throughout the growing season for triggering irrigations. As with the other plant feedback methods of irrigation scheduling described above, when an irrigation signal was received, water was applied in the amount of peak daily water use multiplied by the number of days required for the center pivot to complete an irrigation cycle. This method produced cotton lint yields and WUE that were similar to those from manually scheduled irrigations using weekly neutron probe readings in the highest irrigation treatment plots (75 and 50% of full ET demand). Osroosh et al. (2015, 2016) also used a theoretically based CWSI calculated continuously over daylight hours to schedule irrigation for apple trees. Rather than using a cumulative threshold their algorithm incorporated a dynamic CWSI threshold that was determined daily.

While the theoretical CWSI has been used to characterize the level of water stress in corn (Yazar et al. 1999; Irmak et al. 2000; Taghvaeian et al. 2012; DeJonge et al. 2015), there are limited studies that have been used to integrate CWSI-based irrigation scheduling for site-specific irrigation management with a sprinkler irrigation system. For corn production to remain sustainable in water limited regions, farmers must turn to alternative methods of irrigation scheduling to improve crop WUE. The objectives of this study were to: (1) determine if a theoretically based integrated CWSI (iCWSI) calculated over daylight hours could be used as a threshold for site-specific irrigation scheduling of corn in a semi-arid region, (2) investigate whether a plant feedback system can be used for irrigation management of corn over a large-sized field, where canopy temperature measurements are made infrequently, and (3) develop iCWSI thresholds for the different irrigation treatment levels for future work related to site-specific variable rate irrigation scheduling.

Materials and methods

Experimental site

The 2-year study was conducted at the USDA-ARS Conservation and Production Research Laboratory (CPRL), Bushland, Tex. (35°10′N, 102°05′W, 1169 m above mean sea level) under a six-span center pivot system outfitted with the hardware of a commercial variable rate irrigation system (Valmont Industries,[1] Valley, Nebr.). The soil type was Pullman clay loam, a fine, mixed, superactive, thermic, Torrertic Paleustoll (Soil Survey Staff 2004) with field capacity of 0.33 $m^3\ m^{-3}$ and wilting point of 0.19 $m^3\ m^{-3}$. Mean annual rainfall for this semi-arid climate is 470 mm, with a mean rainfall amount of 280 mm occurring during the summer cropping season (May–September) (O'Shaughnessy et al. 2014). Each season, only half of the center pivot field (20.4 ha), was managed, with the southwest side cropped in growing season 2013 and the northeast side cropped in 2014. Fallowing of the uncropped half of the field was done to allow soil water contents to become less spatially variable after a VRI experiment was conducted.

Hybrid and agronomic information

Two short season corn hybrids, a drought tolerant (DT) variety, Pioneer® Optimum® AQUAmax™ P0876HR (see footnote 1), and a conventional (CONV) variety, Pioneer® 33Y75 were planted on the same day in each year (DOY 134, May 14, 2013 and DOY 135, May 15, 2014) in concentric rows spaced 0.76 m apart, at a planting rate of 76,600 seeds ha^{-1}. Days to maturity as listed by Dupont Pioneer for the DT and CON hybrids were 108 and 115 days, respectively. Ratings of drought tolerance, stalk strength, and plant height are described in Mounce et al. (2016).

Agronomic practices were the same across irrigation treatment methods and irrigation levels, and the field was managed with conventional-till practices. Furrows were diked to reduce runoff and run-on between treatment plots. Fertilizer was applied at the rates of 272 and 252 kg N ha^{-1} in 2013 and 2014, respectively, after analysis of composite soil samples taken prior to planting. Herbicides, G-max lite (dimethenamid-P and atrazine) and Bicep II Magnum (atrazine and *S*-metolachlor) were applied for weed control in 2013 and 2014, respectively, after planting.

Irrigation treatments and scheduling

The experimental design was arranged in a strip-split plot design with the hybrids as main plots and the irrigation treatments and methods as subplots. The plots were organized in a randomized complete block design (RCBD) in 2013 and a Latin Square design in 2014 (Fig. 2). Plots were replicated five times in 2013 and six times in 2014. Neutron probe access tubes were placed near the center in each plot to a depth of 2.4 m. For each of the two corn hybrids, three irrigation treatments were applied, i.e., 100, 75, and 50% (I_{100}, I_{75}, and I_{50}) replenishment of soil water depletion to field capacity in the top 1.5 m of soil. To investigate if a theoretical iCWSI calculated over daylight hours could be used to manage site-specific irrigation scheduling of corn, crop responses in plant feedback-control plots were compared with crop responses in manual-control irrigation treatment plots for both the DT and CONV hybrids.

The manual irrigation-scheduling method was designated by "*M*" and the plant feedback method was designated with "*C*" for the iCWSI (Fig. 1). Manual irrigation amounts were based on the mean of weekly neutron probe (NP) [model 503DR1.5, Instrotek (Campbell Pacific Nuclear), Concord, Calif.] readings from the M_{100} treatment plots. Irrigation amounts applied to the M_{75} and M_{50} treatment plots were 75 and 50% of the amount applied to the M_{100} plots. Rainfall that occurred before an irrigation event was subtracted from the total irrigation required.

As discussed previously, irrigation scheduling for the plant feedback system was based on the theoretical crop water stress index (CWSI) (Jackson et al. 1981, 1988) calculated at a 1-min time step and summed over daylight hours.

The 'lower limit' of the difference between crop canopy and air temperatures occurring for a well-watered crop during the *i*th time interval was determined using Eq. 2:

$$(T_c' - T_a)_{ll} = \frac{r_a R_n}{\rho C_p} \times \frac{\gamma}{\gamma + \Delta} - \frac{e_s - e_a}{\gamma + \Delta} \quad (2)$$

while the upper limit of the same difference occurring during the same *i*th interval for a severely stressed crop is shown in Eq. 3:

$$(T_c' - T_a)_{ul} = \frac{r_a R_n}{\rho C_p} \quad (3)$$

where r_a is the aerodynamic resistance, R_n is the net radiation (estimated as in Allen et al. 1998), ρ is the density of the air and C_p is the specific heat capacity of dry air, γ is the psychometric constant, Δ is the derivative with respect to temperature of the saturated vapor pressure–temperature relationship and can be estimated using Eq. 4 (Jackson et al. 1988):

$$\Delta = 45.03 + 3.014T + 0.05345T^2 + 0.00224T^3 \quad (4)$$

and T is the mean of T_c' and T_a.

[1] The mention of trade names, commercial products or companies in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

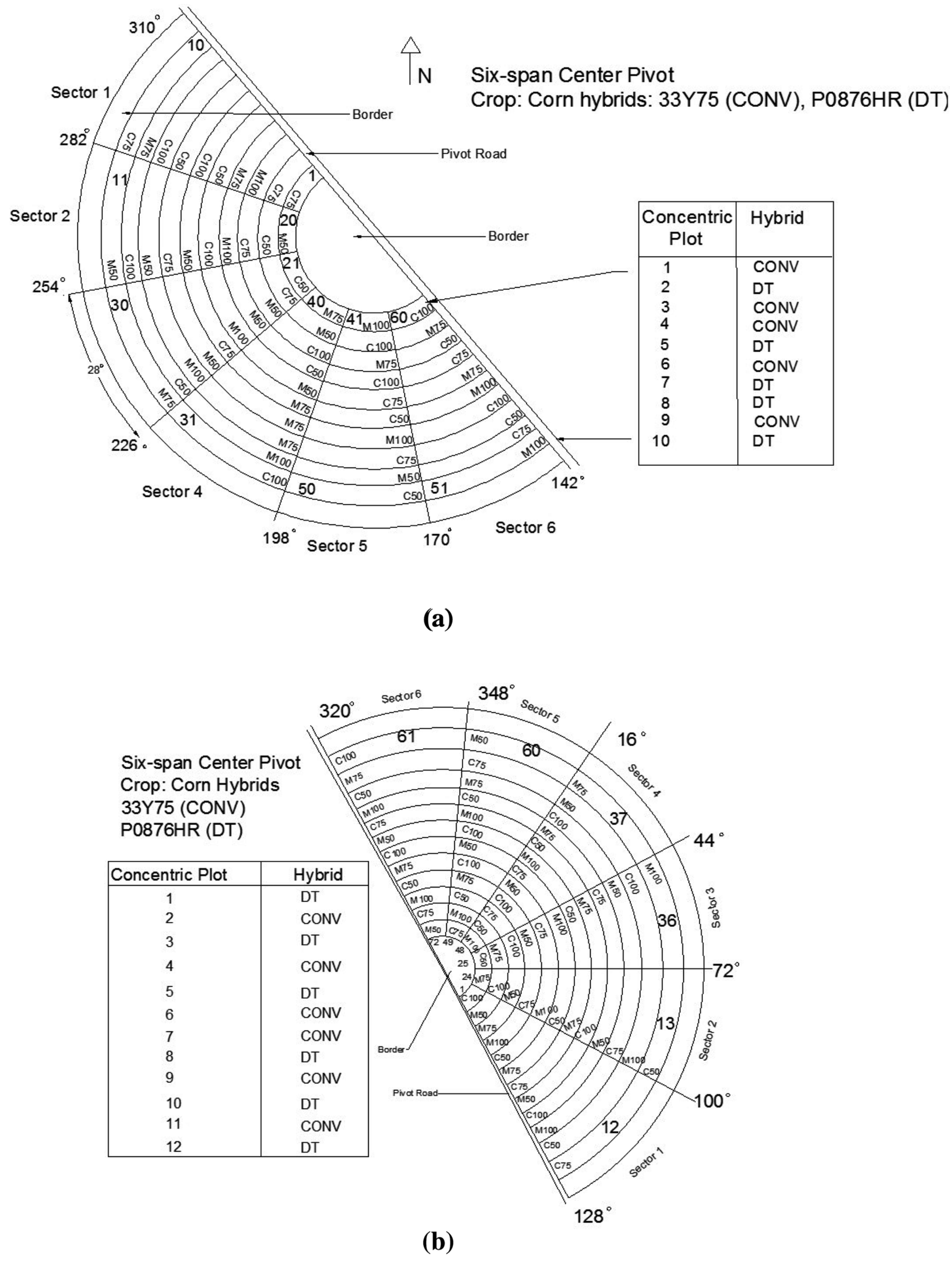


Fig. 1 Plot plans for corn hybrids P0876HR (DT) and 33Y75 (CONV) during growing seasons 2013 (**a**) and 2014 (**b**) at Bushland, Texas under a variable rate irrigation center pivot system. Main treatments were two irrigation methods (M-manual and C-iCWSI) and three irrigation treatment levels (I_{100}, I_{75}, and I_{50})

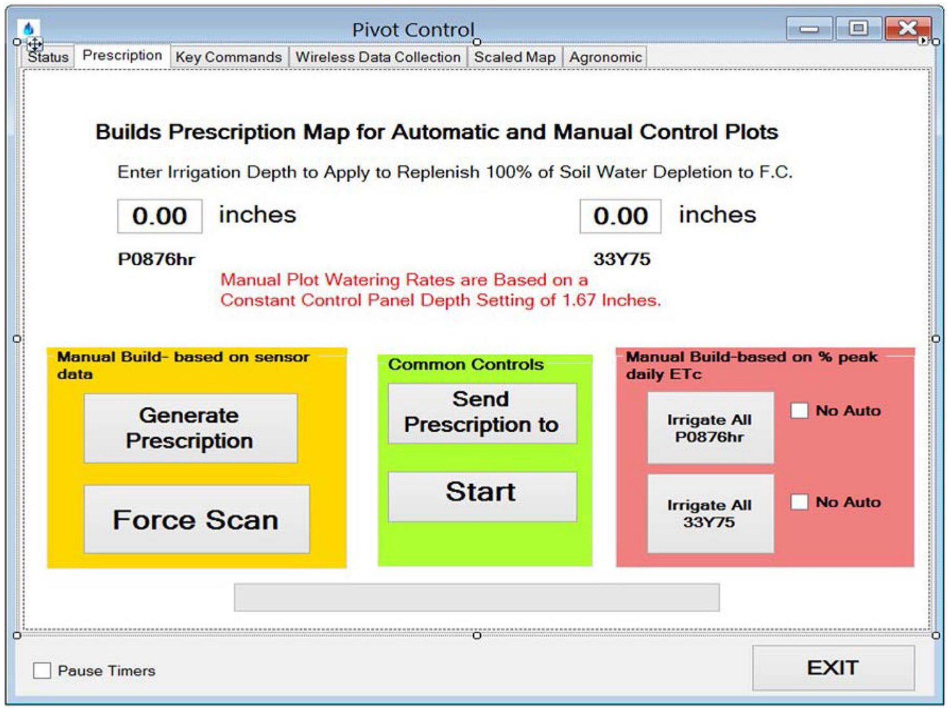


Fig. 2 Graphical user interface used to simplify prescription map building and irrigation control using two different irrigation methods (manual and plant feedback), two corn hybrids P0876HR (DT) and 33Y75 (CONV), and three watering rates

The iCWSI$_r$ was determined for each remote location, *r* (area in the field where a temperature measurement was taken from the IRTs located on the moving pivot lateral) by scaling the one-time-of-day remote canopy temperature measurements to a daytime temperature curve (Peters and Evett 2004) (Eq. 5) using a reference temperature curve:

$$T_c' = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \tag{5}$$

where T_c' is the scaled temperature, T_e is the predawn canopy temperature measured directly with a stationary IRT, T_{ref} is the reference canopy temperature at the same time interval as T_s, $T_{rmt,t}$ is the one-time-of-day canopy temperature measurement at the remote location at time *t*, and $T_{ref,t}$ is the measured reference temperature for the time *t* that the remote measurement was taken.

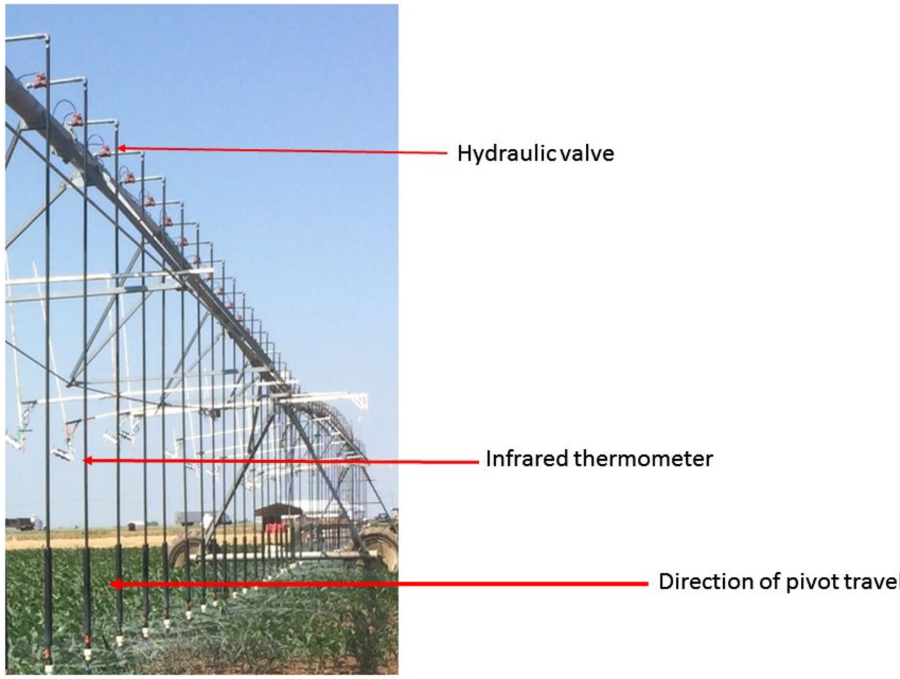
The reference temperature curve was recorded as 1-min averages of the measurements from the stationary IRTs located in well-watered areas of the field. Remote temperature measurements recorded every 2° (approximately 24) were averaged, and scaled against the reference temperature curve to provide an estimate of diurnal canopy temperature for each remote location. Canopy temperature data were collected continuously, and data were managed at midnight at the embedded computer. The iCWSI was calculated separately for each hybrid and only from the C_{100} treatment plots that the VRI system traveled over during daylight hours; such plots are herein referred to as "contributing" plots.

A grand mean iCWSI was calculated from each contributing C_{100} treatment plot for each hybrid using a weighted average based on the area of the plot. If the grand mean for each hybrid was greater than the established threshold of 100 (dimensionless), an irrigation was triggered, resulting in an application depth of 35 mm (peak daily water use × 3.5-day irrigation frequency) for each C_{100} treatment plot, 26 mm for each C_{75} treatment plot, and 18 mm for each C_{50} treatment plot. The threshold of 100 was established using canopy temperature measurements over corn from a prior experiment at Bushland, Texas (Evett et al. 1996). Controlled irrigation amounts at the I_{75} and I_{50} levels were used to help investigate thresholds at these deficit levels.

Software developed by ARS scientists at Bushland was used to manage sensor data, build a prescription map based on manual input and plant feedback information, and control the VRI hardware. The graphical user interface (GUI) of this software, written in the visual basic programming language using the Visual Studio 2010 (version 10.0.4) software development environment, is displayed in Fig. 2.

Irrigation amounts to replenish 100% soil water depletion to field capacity for manually controlled plots were entered for each hybrid using the GUI (Fig. 2). Irrigation amounts for the M_{75} and M_{50} treatment plots (75 and 50% of the entered amounts) were calculated in the background by the software. The "Generate Prescription" button (Fig. 2) produced a prescription map based on the data entered for manual-control treatment plots (user input) and the grand mean iCWSI values calculated for the C_{100} treatment plots × hybrid (software generated).

Fig. 3 Variable rate irrigation center pivot system with in-canopy drops for low elevation spray application. A hydraulic valve is on each drop (spaced 1.5 m apart). Wireless infrared canopy temperature sensors (IRTs) are mounted on masts forward of the spray. The sprinkler is moving towards the *left*



When an irrigation signal was triggered for either of the plant feedback by hybrid control plots, the fixed application depths for the C_{100}, $C_{75,}$ and C_{50} treatment plots were applied to the respective designated plots. If the established threshold of 100 was not exceeded, then water was withheld from plant feedback treatment plots for that hybrid. The buttons on the lower right-hand side of the interface were used to apply irrigation treatments prior to full canopy cover. The "Force Scan" button was used to move the VRI system around the field, while the water was off, to collect canopy temperature measurements, weather data, and information from the Pro2 Panel. This action provided the means to build an initial prescription map and acquire additional data (canopy temperature measurements and calculated iCWSI values) throughout the irrigation season. The "Send Prescription" and "Start" buttons consolidated and simplified efforts. Once the canopy cover was nearly full, the VRI system was operated every 3.5 days, unless the rain gauge recorded greater than 20 mm of precipitation the previous day.

Neutron probe (NP) readings were taken every 30 days in the I_{75} and I_{50} irrigation treatment plots for both methods. The NP was calibrated to an accuracy of better than 0.01 m^3 m^{-3}, resulting in separate calibrations for three distinct soil layers Ap, Bt, and Btca, using methods described by Evett (2008), where Ap is the mineral horizon that has been plowed or disturbed; Bt is the subsurface horizon characterized by an alluvial accumulation of silicate clay; and Btca is the subsurface horizon characterized by $CaCO_3$ accumulation. To ensure accuracy of the 0.10-m depth readings (Evett 2003), a depth control stand was used, and deeper readings were taken at 0.20-m depth increments to 2.30 m.

Irrigation and sensor systems

The six-span commercial variable rate irrigation (VRI) center pivot was outfitted with 25 sprinkler zones. Each zone contained six drops spaced 1.5 m apart. A hydraulic valve was installed on each sprinkler to control water flow, and each set of drop valves within a sprinkler zone was controlled hydraulically using an electronic solenoid valve situated in a VRI control tower box located on the nearby center pivot support tower. Other main VRI hardware components consisted of a power line signal carrier, and a continuously powered global positioning system (GPS) receiver located at the end tower.

Each drop hose was approximately 0.47 m above the ground and outfitted with a low drift nozzle (LDN) sprinkler package (Senninger, Clermont, Fla), providing low elevation spray application (LESA) (Fig. 3). Nozzles were selected to provide a uniform application along the lateral pipeline, and the "on/off" pulsing of the hydraulic valves controlled watering rates for each sprinkler zone. For this study, the VRI system was operated at a set speed of 19.6 m h^{-1} (maximum application of 42 mm) with a duty cycle (period of "On" and "Off" time) of 300 s. It took the VRI system approximately 36 h to complete an irrigation over the cropped half of the field and walk dry over the fallowed half to the start location. The VRI system was started at the same location during each growing season (308° and 128° in 2013 and 2014, respectively, Fig. 2) but at different times of a 24-h period. Staggering the start time and establishing a slower speed were intentional to help investigate the objective of irrigating corn over a large-sized field, where some areas of the field would only be viewed by IRTs every 5–6 days.

A wireless network of infrared thermometers (IRTs) as described in O'Shaughnessy et al. (2013) was integrated with the VRI sprinkler system. The IRTs were mounted on masts extending 4 m in front of the center pivot pipeline forward of the drops when the system moved in the reverse direction. Each IRT was located at the border of a management zone (MZ), totaling 20 IRTs on the pivot lateral in 2013, and 24 IRTs in 2014. Each MZ was comprised of two sprinkler banks (18.2 m wide) in 2013 and one sprinkler bank in 2014 (9.1 m wide). Plots were narrowed in 2014 because of limited seed for the DT hybrid, as discussed in Mounce et al. (2016). Each IRT was turned inwards towards the center of the MZ (azimuthal angle of 45°) and looking downwards at the canopy at an oblique angle relative to nadir. Temperature measurements from the paired sensors for each MZ were averaged to average out sun angle effects. Two wireless IRTs were located in the well-watered inner borders of the cornfield; the borders were irrigated each time and there was an irrigation event to a depth of 26 mm. All IRTs were calibrated against a commercial blackbody (model CES100, Electro Optical Industries, Inc., Santa Barbara, Calif.) in a controlled temperature chamber (Environmental Growth Chambers, Chagrinfalls, Ohio) using the calibration procedure, as described in O'Shaughnessy et al. (2011).

Microclimatological data with sensors from Campbell Scientific (Logan, Utah)-measuring air temperature and relative humidity (model HC2S3), solar irradiance (CS300), precipitation (TE525), wind direction, and wind speed (Wind Sentry 03101) were read every 5 s, averaged every minute, and collected with a CR1000 datalogger, located near the cropped field. The data were then polled by the embedded computer using telemetry in the 900-MHz bandwidth. A serial connection between the embedded computer and the Pro2 Panel of the center pivot system allowed both collections of data pertinent to the center pivot operation and its GPS location and control of the center pivot.

Plant and yield measurements

Plant stand counts were taken on day of year (DOY) 156 (June 5, 2013) and DOY 149 (May 29, 2014). During the vegetative stages of the corn, plant height and width measurements were performed bi-weekly from three representative plants near the center of each plot. Plant mappings during the reproductive stage consisted of assessing the growth stage and number of ears per plant from three representative plants in each plot.

Samples for total above ground biomass were taken from a 1.5 m^2 area near the NP within each treatment plot, and grain samples were taken from a 10 m^2 area near the NP from each treatment plot when grain moisture was approximately 18%. Samples were dried in an oven at 60 °C until less than 10 g of moisture were lost over a 24-h period. Dried samples were threshed, and the grain was cleaned and weighed. Three 500-kernel subsamples were obtained from each plot, and dried again for 24 h to achieve dry weight.

Evapotranspiration and WUE calculations

Evapotranspiration (ET) was calculated for the growing season using the soil water balance equation:

$$\mathrm{ET} = P + I + F - \Delta S - R \tag{6}$$

where P is the precipitation (mm), I is the irrigation water applied (mm), F is the flux across the lower boundary of the control volume (taken as positive when entering the control volume), ΔS is the change in soil water stored in the profile (surface to 2.4-m depth, determined by NP), and R is the runoff, all in units of mm. Furrow diking was assumed to reduce runoff to negligible values, and water contents at 2.10- and 2.30-m depths were small enough that hydraulic conductivity was very small, which assured that deep soil water flux was negligible. Flux across the lower boundary was assumed to be zero.

Given negligible values of R and F, we calculated WUE as defined by Howell (2001):

$$\mathrm{WUE} = \frac{\text{Yield (economic yield)}}{(P + I + \Delta S)} \tag{7}$$

where P is precipitation, I is irrigation applied, and ΔS is soil water used within the root zone during the growing season. We took dry grain yield as the economic yield and calculated harvest index (HI), the allocation of photosynthesis between the vegetative and grain portion of a plant, as defined by (Sinclair 1998)

$$\mathrm{HI} = \frac{\text{Grain Yield}}{\text{Total Above Ground Biomass}} \tag{8}$$

where the grain yield is the dry yield and the total above ground biomass was the dry value. Harvest index is a factor in evaluating criteria of corn growth and yield (DeLoughery and Crookston 1979; Echarte and Andrade 2003), trait improvements (Hall and Richards 2013), and reproduction efficiency (Unkovich et al. 2010).

Growing degree days (GDD) were calculated beginning on the day after planting as

Table 1 Total and mean maximum (max) and minimum (min) climatic conditions for 2013 and 2014 growing seasons

Month	Min daily temperature (°C)	Max daily temperature (°C)	Total monthly GDD	Min RH (%)	Max RH (%)	Total precipitation (mm)	Max daily SI (MJ m^{-2} d^{-1})	ET_o (mm d^{-1})
Growing season 2013								
May	9.5	27.7	284	16	77	35	25	7
June	17.4	32.7	397	23	82	91	27	8
July	17.8	30.6	406	33	83	84	24	6
August	17.5	32.2	418	31	86	41	24	6
September	14.6	29.5	348	29	82	21	19	5
October	4.0	22.7	195	22	78	3	16	4
Growing season 2014								
May	9.6	26.9	273	19	63	115	25	7
June	16.2	30.6	369	30	88	139	26	7
July	17.8	30.1	405	38	87	125	24	6
August	17.1	32.8	419	28	85	32	22	6
September	14.6	26.1	305	52	94	104	16	3
October	8.1	23.9	221	32	87	33	15	3

GDD growing degree days, *SI* solar irradiance, ET_o reference evapotranspiration measured over grass fetch at Bushland, Texas

$$\text{GDD}\ (^\circ\text{C}) = ((\text{Daily max temp}\ ^\circ\text{C} + \text{Daily min temp}\ ^\circ\text{C})/2) - 10\ ^\circ\text{C} \quad (9)$$

where if daily max temp >30 °C, then daily max temp is set to 30 °C, and if daily max (or min) temp <10 °C, then daily max (or min) temp is set to 10 °C; and where daily max temp and daily min temp are the maximum and minimum air temperatures, respectively.

Statistical methods

Crop responses of dry grain and biomass yield, ET, WUE, and yield components were analyzed for differences across treatments using the general linear model (GLM) procedures of PROC GLM (SAS, 9.3 SAS Institute Inc., Cary, NC). The mixed model PROC MIXED procedure (Littell et al. 2006) was used to determine the significance of the main effects of irrigation methods (manual and plant control feedback) and irrigation treatment levels on crop response within each year. Concentric plots were treated as random effects in 2013 to address variability among the same hybrid and between sensors, while in 2014, concentric plots and sectors (pie-shaped sections of the field) were treated as random effects. The least significant difference was assessed for pairwise mean comparisons, while multiple mean comparisons were performed using the Tukey–Kramer method for α set at the 0.05 significance level. One-sample t tests were performed on the C_{100} treatment plots for each category of crop response to determine if there was a significant difference between any one measured value and the sample mean.

Results

Climatic conditions

Compared with 2014, the 2013 growing season was drier, with precipitation from May through October totaling 273 mm or approximately 50% of the amount received during the same period in 2014 (548 mm). Two hailstorms occurred in the 2013 growing season; however, both hybrids overcame the damage from hailstones and high winds. Maximum and minimum air temperatures were greater in 2013. Cumulative growing degree days (AGDD, based on Eq. 9) were 3% greater in 2013 at 2048 °C compared with 1992 °C in 2014. Average monthly short crop (grass) reference evapotranspiration (ET_o) was calculated using standardized methods (ASCE 2005). The weather was warmer and drier in 2013 (Table 1).

Irrigation amounts

Due to the lack of spring precipitation and a dry seedbed, irrigation amounts applied prior to planting in April 2013 totaled 144 mm. During the 2013 irrigation season, a computer coding error caused the cumulative irrigation applied to one plot in each of the two hybrid treatment plots at the I_{50} level to be much greater than the amount applied to the other four plots. Therefore, only four replications of each hybrid at the I_{50} treatment plots were used to compute crop response (plots excluded were 5, 11, 29, and 49, Fig. 2a).

Table 2 Yield, crop water use (ET), grain water use efficiency (WUE), kernel mass, kernels per ear, biomass and harvest index between years (overall mean), and significance levels for interactions between year, hybrid, irrigation-scheduling method, and irrigation-level treatment

	Yield (kg m^{-2})	ET (mm)	Grain WUE (kg m^{-3})	Kernel mass (mg)	Kernels/ear	Biomass (kg m^{-2})	Harvest index
2013	1.00b	617.5b	1.61b	371a	458b	1.84b	0.54a
2014	1.35a	646.0a	2.10a	294b	530a	2.6a	0.53a
Year × hybrid	NS	NS	NS	NS	NS	NS	NS
Year × irrigation method	NS	S	NS	NS	NS	NS	NS
Year × irrigation level	NS	NS	S	S	S	NS	NS

Overall mean values in each column followed by a different letter are significantly different at $p < 0.05$

NS not significant at the $p = 0.05$ probability level

S significant at the $p = 0.05$ probability level

In 2014, the electronic relay controlling the first sprinkler zone failed approximately 45 days after planting, and was replaced when shorter plant heights were observed. Irrigation amounts to plots 1, 20, 21, 40, 41, and 60 reduced and not included in the evaluation of crop response. Mean cumulative irrigation amounts compared between the manual and plant feedback irrigation-scheduling methods across the same irrigation treatment levels (e.g., M100 and C100; M75 and C75; and M50 and C50) were within 20 mm for the DT hybrid and 24 mm for the CON hybrid. Irrigations for the DT hybrid were terminated after DOY 244 as it neared physiological maturity. The last irrigation to the CON hybrid plots (35 mm to replenish 100% soil water depletion to field capacity) was applied on DOY 248, while the crop was still in the R5 (dent) stage.

In 2014, irrigations totaling 127 mm were applied prior to planting. Total seasonal irrigation amounts across the same irrigation treatment level varied as much as 34% between irrigation-scheduling methods within the DT hybrid and as much as 20% between methods for the CON hybrids. In both cases, more water was applied to the plant feedback-control plots. The total number of irrigations triggered for the DT plant feedback-control plots was the same as the number of irrigations scheduled for the manual-control plots. However, the irrigation events did not always occur on the same day, and irrigation amounts for the M_{100} control plots were typically 6 mm less. For the CON hybrid, there was one less irrigation event for the manual-control plots. The manual-control plots required lesser amounts of water during the vegetative stage, but when the crop reached the R3 stage, the irrigation amounts required by the manual-control plots were nearly equivalent to those applied to the plant feedback-control plots. Since freshwater is a limited resource in this region, it would be worthwhile to investigate if crop WUE for the plant feedback system could be improved by refining the plant feedback algorithm. It is possible that this could be achieved by applying a dynamic amount of water that is dependent on the growth stage of the crop. The application amount could be a product of the crop coefficient (K_c), peak daily water use and the irrigation interval. To maintain automation, K_c could be estimated as a function of growing degree days. However, further research is required to test this process, and it is important to avoid applying small irrigation amounts in this environment, since evaporative losses can easily negate the effectiveness of small irrigations (Tolk et al. 2015).

Crop water use, grain and biomass yields, and water use efficiency

Grain and biomass yields were 35 and 38% larger in 2014 compared with 2013, while ET and dry grain WUE were 5 and 30% larger in 2014. The number of kernels per ear was 15% larger and kernel mass was 26% smaller in 2014 compared with 2013. The greater yields in 2014 were due to the larger density of plants at harvest as compared with the density of plants in 2013; although the seeding rate was the same for both growing seasons, hailstorms in 2013 reduced plant density. Harvest index between years were similar (Table 2). The interaction between year and irrigation method significantly affected ET, while the effect of year and irrigation treatment level was significant for grain WUE, kernel mass, and kernels per ear.

Crop response was analyzed separately for each hybrid and year. In 2013, overall mean dry grain yield, ET, grain WUE, and the number of kernels per ear were similar between irrigation-scheduling methods (Table 3) for the DT hybrid. Kernel mass was greater for the manual-control irrigation plots. Irrigation levels significantly influenced ET, and yield components such as dry grain yield, kernel mass, kernel number per ear, and biomass. Responses to the I_{50} irrigation treatment level were significantly less compared with the I_{100} treatment level. Many other studies have shown that limiting plant available water to corn can lead to a reduction in canopy development, crop growth, grain and biomass yield (Claassen

Table 3 Drought tolerant hybrid (P0876HR) response to different irrigation methods, irrigation treatment levels, and the interaction of these effects for growing season 2013, Bushland, Texas

Hybrid/P0876HR	Irrigation water (mm)	Dry grain yield (kg m^{-2})	ET$_c$ (mm)	Grain WUE (kg m^{-3})	Kernel mass (mg)	Kernels/ear	Biomass (kg m^{-2})	HI
Irrigation method								
Manual	344	1.00a	588a	1.70a	278a	505a	1.76a	0.57a
iCWSI	332	0.95a	583a	1.63a	256b	515a	1.64a	0.55a
Irrigation treatment level								
100	418	1.14a	649a	1.76a	306a	521a	1.95a	0.59a
75	331	1.01b	582b	1.74a	278b	510a	1.68b	0.60a
50	248	0.75c	509c	1.47b	219c	500b	1.47c	0.51a
Irrigation treatment level × method								
M_{100}	424	1.17a	644ab	1.82a	316a	529a	2.06a	0.57ab
C_{100}	412	1.11ab	655a	1.70abc	296a	513a	1.84ab	0.58ab
M_{75}	334	1.05ab	585bc	1.80ab	300a	484a	1.72bc	0.61a
C_{75}	328	0.97b	579c	1.69abc	256b	537a	1.64bc	0.56ab
M_{50}	258	0.76c	520cd	1.48bc	220c	502a	1.51cd	0.54ab
C_{50}	238	0.72c	497d	1.45c	216c	497a	1.39c	0.50b

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

and Shaw 1970; Hall et al. 1982; Hugh et al. 2003; Cakir 2004; Yazar et al. 1999), and kernel number and kernel mass (Klocke et al. 2011, 2014). Analysis of mean crop response for plots in the same irrigation level compared across irrigation-scheduling methods indicated that dry grain yield, ET, grain WUE, number of kernels per ear, biomass, and HI were not significantly different (Table 3, irrigation treatment level × method). However, kernel mass for plots controlled by the plant feedback method (C_{75}) was significantly less than plots controlled by the manual irrigation method (M_{75}). Although the mean kernel mass was less, the number of kernels in the C_{75} treatment plots was numerically greater compared with the M_{75} treatment plots. It is unclear as to why this response occurred and why it was isolated within the I_{75} treatment, since irrigation amounts and crop water use were similar between methods. The response may have been associated with better timing of irrigation applications during silking and kernel set with the plant feedback method in this drier year, which could have resulted in better kernel set. Borrás et al. (2003) reported that kernel mass was negatively correlated with the number of kernels per plant, and could be due to a change in kernel growth rate. Hao et al. (2015) report dry grain yields of the same hybrid of DT corn to be in the range of 1.11–1.25 kg m^{-2} for full irrigation (meeting 100% ET); 1.05–1.09 kg m^{-2} for 75% (of full) irrigation; and 0.54–0.56 kg m^{-2} for 50% (of full) irrigation. They also reported WUE in the range of 1.66–2.20, 2.06–2.40, and 1.28–1.80 kg m^{-3} for the 100, 75, and 50% irrigation levels, respectively. It is noteworthy that there was a 20% savings of irrigation water between the C_{75} and C_{100} treatment plots, with a yield penalty of only 13%.

The results for the CONV hybrid in 2013 were similar to those for the DT hybrid in that overall mean responses were not significantly different between irrigation methods (Table 4). Similar to results for the DT hybrid, irrigation treatment levels significantly influenced dry grain yield, ET$_{c,}$ and kernel mass. Likewise, the I_{50} irrigation treatment level significantly reduced grain WUE, the number of kernels per ear, biomass, and HI. A comparison of crop responses between scheduling methods across the same irrigation treatment level showed no significant differences. Historical grain yields reported for fully irrigated conventional corn hybrids in the Texas High Plains region range between 0.77 and 1.55 kg m^{-2} and grain WUE range between 1.49 to 1.94 kg m^{-3} (Mounce et al. 2016).

In 2014, the overall mean dry grain yield, ET, and biomass were greater for the plant feedback-control plots (Table 5) in the DT hybrid. However, grain WUE and the number of kernels per ear were not significantly different between methods. Irrigation levels had a significant impact on ET and biomass for all irrigation treatments (I_{100}, $I_{75,}$ and I_{50}). Despite the additional precipitation during this growing season, the reduced amount of water applied to the I_{50} plots negatively influenced grain yield. Different from 2013, irrigation levels did not influence grain WUE. Irrigation-scheduling methods did not influence crop response when comparing results across the same irrigation treatment level. This result could be explained by the large amount of

Table 4 Conventional hybrid (33Y75) response to different irrigation methods, irrigation treatment levels, and the interaction of these effects for growing season 2013, Bushland, Texas

Hybrid/33Y75	Irrigation water (mm)	Dry grain yield (kg m^{-2})	ET$_c$ (mm)	Grain WUE (kg m^{-3})	Kernel mass (mg)	Kernels/ear	Biomass (kg m^{-2})	HI
Irrigation method								
Manual	375	0.92a	639b	1.44a	278a	501a	1.97a	0.51a
iCWSI	366	1.01a	675a	1.50a	280a	483a	2.08a	0.50a
Irrigation treatment level								
100	488	1.23a	742a	1.66a	331a	517a	2.29a	0.54a
75	412	1.00b	662b	1.51a	296b	504a	2.15a	0.50a
50	295	0.66c	568c	1.16b	209c	454b	1.64b	0.47b
Irrigation treatment level × method								
M_{100}	482	1.20a	730ab	1.64a	329a	523a	2.20a	0.57a
C_{100}	506	1.24a	754a	1.64a	333a	511a	2.39a	0.52a
M_{75}	382	0.92b	630cd	1.46ab	296a	530a	2.15a	0.49a
C_{75}	412	1.07ab	695bc	1.54a	296a	479a	2.15a	0.51a
M_{50}	283	0.64c	558d	1.15c	208b	449a	1.57b	0.48a
C_{50}	307	0.70c	578d	1.21bc	211b	459a	1.71b	0.47a

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

Table 5 Drought tolerant hybrid (P0876HR) response to different irrigation methods, irrigation treatment levels, and the interaction of these effects for growing season 2014, Bushland, Texas

Hybrid/P0876HR	Irrigation water (mm)	Dry grain yield (kg m^{-2})	ET$_c$ (mm)	Grain WUE (kg m^{-3})	Kernel mass (mg)	Kernels/ear	Biomass (kg m^{-2})	HI
Irrigation method								
Manual	261	1.32b	754b	1.75a	284b	534a	2.60a	0.53a
iCWSI	348	1.40a	845a	1.66a	302a	540a	2.44a	0.52a
Irrigation treatment level								
100	401	1.48a	888a	1.67a	315a	546a	2.77a	0.53a
75	304	1.40a	796b	1.76a	297b	541ab	2.58a	0.53a
50	209	1.20b	715c	1.68a	268b	522b	2.21b	0.51a
Irrigation treatment level × method								
M_{100}	343	1.45a	819b	1.77a	309ab	533a	2.68ab	0.54a
C_{100}	460	1.51a	956a	1.58a	322a	546a	2.86a	0.53a
M_{75}	261	1.34ab	751bc	1.78a	281bc	537a	2.53abc	0.54a
C_{75}	347	1.46ab	841b	1.74a	314ab	545a	2.63ab	0.51a
M_{50}	180	1.16c	692c	1.68a	265c	517a	2.11c	0.54a
C_{50}	238	1.23bc	740bc	1.66a	271c	528a	2.31bc	0.53a

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

precipitation received during this growing season, compared with seasonal rainfall in 2013.

Data analysis for the CON hybrid from 2014 indicates that the only difference in overall mean responses occurred in ET$_c$, whereby the mean was greater for the plant feedback-control plots (Table 6). Similarly, the I_{50} irrigation treatment level significantly reduced grain yield, kernel mass, the number of kernels per ear, and biomass. Irrigation-level treatments did not influence grain WUE or HI. Greater mean ET$_c$ was in the plant feedback-control plots at each irrigation treatment level compared across methods. Grain WUE was significantly greater for plots in the M_{50} treatment compared with the C_{50} (plant feedback-control) plots. Early in the growing season, the plant feedback system applied more irrigation water in the C_{50} treatment plots as compared with the M_{50} plots.

For both years, a one-sample t test was performed on each category of crop response for the C_{100} treatment

Table 6 Conventional hybrid (33Y75) response to different irrigation methods, irrigation treatment levels, and the interaction of these effects for growing season 2014, Bushland, Texas

Hybrid/33Y75	Irrigation water (mm)	Grain yield (kg m^{-2})	ET (mm)	Grain WUE (kg m^{-3})	Kernel mass (mg)	Kernels/ear	Biomass (kg m^{-2})	HI
Irrigation method								
Manual	309	1.39a	862b	1.61a	293a	542a	2.76a	0.51a
iCWSI	371	1.40a	918a	1.53a	294a	546a	2.68a	0.50a
Irrigation treatment level								
100	455	1.51a	999a	1.51a	308a	567a	2.86a	0.53a
75	339	1.42a	890b	1.60a	294ab	553a	2.83a	0.50a
50	227	1.25b	780c	1.60a	279b	512b	2.47b	0.49a
Irrigation treatment level × method								
M_{100}	413	1.48ab	962b	1.54b	300a	557ab	2.72ab	0.54a
C_{100}	496	1.54a	1037a	1.49b	317a	577a	3.01a	0.52a
M_{75}	308	1.38abc	863d	1.60ab	292ab	543ab	2.80ab	0.49a
C_{75}	369	1.46ab	917c	1.59b	297a	563a	2.86ab	0.51a
M_{50}	206	1.31bc	762f	1.72a	289ab	526ab	2.54b	0.50a
C_{50}	248	1.19c	800e	1.49b	268b	499b	2.41b	0.48a

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

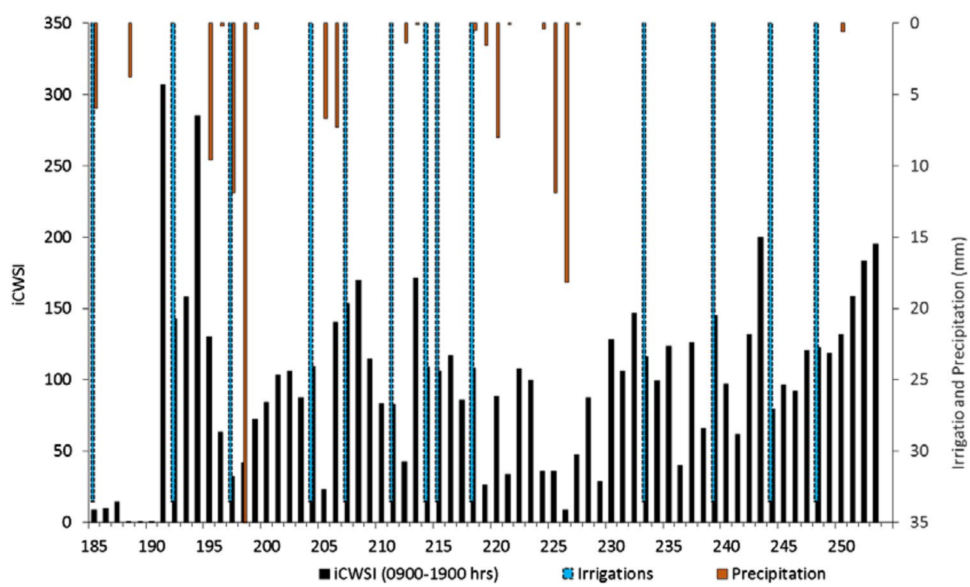


Fig. 4 Integrated crop water stress index (iCWSI) calculated daily over well-watered DT corn hybrid P0876HR during the 2013 growing season in Bushland, Texas

plots for each hybrid (data not shown). The *t* test results showed the two-tailed *P* values >0.90, indicating that the responses were not significantly different from the sample mean. These results demonstrate that irrigation triggering based on an average of the iCWSI from contributing C_{100} plots provided adequate signals for all C_{100} plots × hybrid for this study.

Integrated CWSI

The mean iCWSI in 2013 was calculated daily over the well-watered DT corn (hybrid P0876HR) in the inner border of the field using temperature measurements from the stationary IRTs. The seasonal mean daily iCWSI was 104. Early in the growing season, and then again towards the end of the irrigation season when the crop began to reach physiological maturity, the iCWSI was larger due to limited canopy cover (Fig. 4). The graph also indicates that the iCWSI was relatively small during days when precipitation was received (DOY 185, 188, 198, 205, 206, 220, 225, and 226) and after an irrigation event (DOY 192, 197, 211, 218, 233, and 244). From the period of DOY 220 through DOY 230, the average iCWSI was generally lower than at other times of the growing season. During this period, the corn was in the R3

Table 7 Day of Year (DOY), major growth stage and growing degree days (GDD) for DT hybrid during the 2013 and 2014 growing seasons at Bushland, Texas

2013			2014		
DOY	Growth stage	Growing degree days[a] (°C)	DOY	Growth stage	Growing degree days[a] (°C)
175	V-6	517	172	V-6	411
203	R-1	890	199	R-1	764
212	R-2	1015	209	R-2	907
219	R-3	1120	220	R-3	1040
233	R-4	1300	230	R-4	1176
240	R-5	1395	237	R-5	1275
255	R-6	1595	261	R-6	1538

[a] Calculated as per Eq. 9

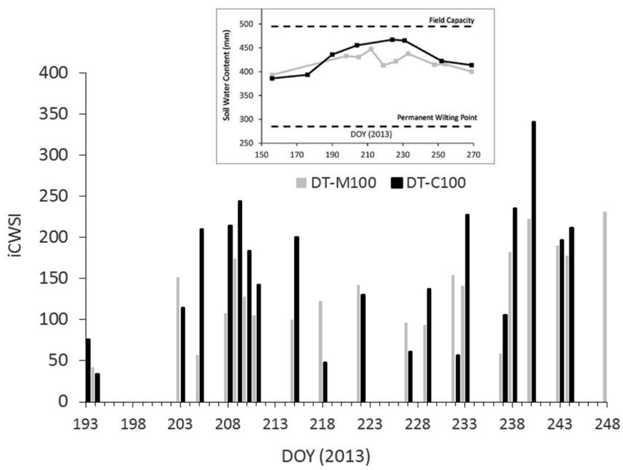


Fig. 5 Integrated crop water stress index (iCWSI) plotted for the drought tolerant (DT-P0876HR) hybrid plants in the 100% irrigation treatment plots for the irrigation methods, manual (M) and the iCWSI (C) for the different days that the VRI system traveled across the field during the 2013 irrigation season. The mean soil water content in the *top* 1.5 m for the M_{100} and C_{100} treatment plots is *inset*

(milk) stage (Table 7). At times, however, the average iCWSI did not decrease the day following an irrigation event such as on DOY 207 and 239. After DOY 254 (Sep 11 2013) the iCWSI increased due to the termination of irrigations and physiological changes in maturity and leaf senescense, similar to reports by Colaizzi et al. (2003a) and Jackson (1982).

To compare the iCWSI between irrigation methods for the I_{100} treatments in 2013, a graph was made of the discrete values, calculated only when the center pivot traveled across the field, (Fig. 5). The calculated iCWSI values for the M_{100} treatment plots (DT hybrid) were smaller compared with those for the C_{100} treatment plots during DOY 205–215 (July 24–August 3) and from DOY 233 (August 21) until DOY 241 (August 29) (data not shown). Near the end of the irrigation season, the means for both hybrids were similar. The plant feedback-control plots exhibited a smaller mean iCWSI from DOY 215 to DOY 229; during this same period, mean soil water content in the top 1.5 m was greater for the C_{100} treatment plots (Fig. 5). The inverse relationship between soil water content and the theoretical CWSI is also documented by Jackson et al. (1981) for wheat, by Colaizzi et al. (2003b) for cotton, and Ben-Gal et al. (2009) for olive orchards.

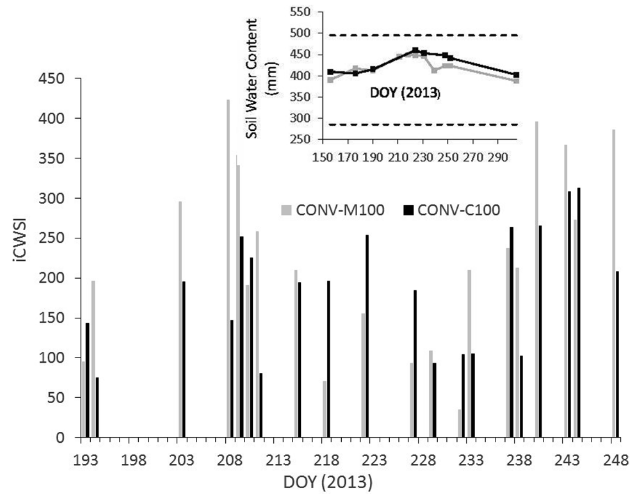


Fig. 6 Mean integrated crop water stress index (iCWSI) plotted for the CONV hybrid (33Y75) in the 100% irrigation treatment plots (I_{100}) for the irrigation methods, manual (M), and the iCWSI (C) for the different days that the VRI system traveled across the field in the 2013 irrigation season. Mean soil water content in the *top* 1.5 m for the M_{100} and C_{100} treatment plots is *inset*

For the CONV hybrid, the mean iCWSI was greater for the M_{100} control plots from DOY 193 (July 12 2013) through DOY 215 (August 3 2013), likely due to smaller irrigation amounts (typically 10 mm) applied to these treatment plots as compared with the plant feedback-control plots. However, from DOY 218 (August 6) through DOY 232 (August 20), the mean M_{100} iCWSI became smaller as compared with the mean in the C_{100} treatment plots. Mean soil water content in the top 1.5 m in the M_{100} treatment plots was similar compared with mean soil water content in the C_{100} treatment plots for these days. After DOY 232 (August 20), the greatest mean iCWSI values fluctuated between irrigation methods (Fig. 6).

During the wet year of 2014, the mean iCWSI in the well-watered areas of the field responded to precipitation and irrigation events until the end of the irrigation season (Fig. 7). The center pivot system irrigated less frequently than in 2013, and therefore, the number of iCWSI values calculated from the IRTs on the pivot lateral were few throughout the growing season. Rainfall stopped between DOY 213 (August 1) and DOY 231 (August 19) and was minimal after DOY 234 (August 22). Maximum daily

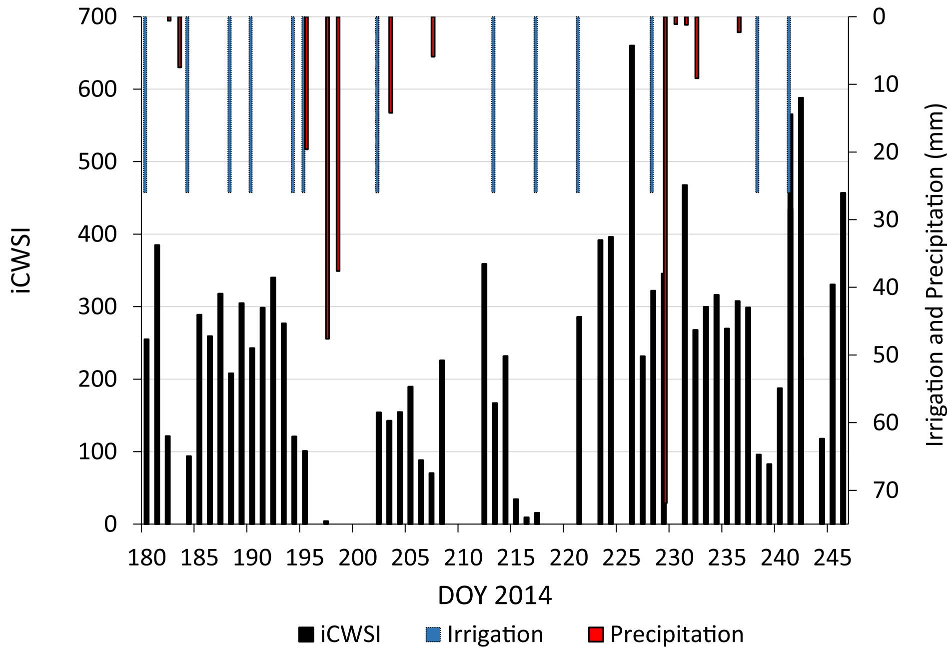


Fig. 7 Integrated crop water stress index (iCWSI) calculated daily over well-watered DT corn hybrid (P0876HR) during the 2014 growing season in Bushland, Texas

temperatures rose to 32.2 °C in August, and through the end of September, the mean maximum daily air temperature was 29.5 °C. The iCWSI steadily increased after DOY 246 (September 3).

In both hybrids, a comparison of the mean iCWSI across irrigation-scheduling methods in the I_{100} treatment plots indicated that the values were similar in early- to mid-season [DOY 172 (Jun 21) to DOY 207 (July 26)]. However, after DOY 207, the iCWSI in the manual-control plots in the DT hybrid were greater than those in the plant feedback-control plots and mean soil water content in the manual I_{100} control plots was also less until DOY 20 (September 7).

A comparison of the iCWSI within the CONV hybrid plots at the I_{100} treatment level indicated that the mean iCWSI values were similar throughout the irrigation season with the exception of DOY 225 (August 13) when the iCWSI for the M_{100} treatment plots spiked. On DOY 223 (August 11), both the manual and plant feedback-control plots received an irrigation, but the amount was 10 mm greater for the C_{100} treatment plots and mean soil water content was slightly greater from DOY 225 to DOY 250 (September 7).

For purposes of developing iCWSI thresholds for the different irrigation treatment levels for future work, a comparison was made of the mean seasonal iCWSI values between irrigation treatment levels within each hybrid. The mean iCWSI was always less in treatment plots at the I_{100} level. The greatest difference among the calculated stress index occurred between the I_{100} and I_{50} treatment plots (Table 8). The differences in the stress index between irrigation treatment levels I_{75} and I_{50} were minimal (<20) in 2013 for the CONV hybrid in the plant feedback-control plots and for both irrigation methods and hybrids in 2014. The results of minimal differences in the iCWSI between the I_{75} and I_{50} treatment levels in 2014 are not surprising due to the large amount of rainfall received during the growing season. Soil water content for all irrigation treatment levels was well above 50% maximum allowable depletion and similar for the I_{75} and I_{50} treatment plots (data not shown), indicating that plant available water was not limited during the irrigation season. Although the circumstances of mild temperatures and plentiful precipitation limited our ability to define robust

Table 8 Mean seasonal integrated crop water stress index values for the drought tolerant hybrid (P0876HR) and the conventional corn hybrid (33Y75) for the 2013 and 2014 growing seasons at Bushland, Texas

Hybrid	P0876HR		33Y75	
Irrigation level	Manual (M)	Plant feedback (C)	Manual (M)	Plant feedback (C)
Growing season 2013				
I_{100}	129	160	164	190
I_{75}	135	185	228	220
I_{50}	165	229	257	225
Growing season 2014				
I_{100}	197	179	175	166
I_{75}	209	219	189	195
I_{50}	225	228	193	211

threshold boundaries between the three irrigation levels used in this study, ranges of thresholds for a well-watered and moderately stressed corn (I_{50} treatment level) could be developed for future investigation.

In 2013 and 2014, there was nearly a difference of 15% in the seasonal mean iCWSI when comparing the mean iCWSI in the M_{100} and the C_{100} treatment plots of both hybrids during the same year. Mean iCWSIs calculated from IRTs on the center pivot pipeline were larger than those calculated from stationary IRTs in the field over-looking a well-watered crop. The differences can be attributed to soil background and sunlit and shaded canopy viewed by the IRTs on the moving pivot pipeline as the VRI system traveled across the field (Humes et al. 1994; Colaizzi et al. 2016), while the stationary IRTs were positioned over plant canopy. Linear regression analysis of the data in Table 8 showed that irrigation level explained 73% of the variance in iCWSI for the feedback-controlled treatments compared with only 24% of the variance in iCWSI for the manually controlled treatments. The linear response rate was nearly identical between manual and feedback-control methods. These results illustrate the responsiveness of the feedback method to crop stress, compared with the manual method, which relies on soil water content as a surrogate for crop stress.

Conclusions

In this 2-year study, a theoretically based iCWSI was used to control irrigation scheduling of two different corn hybrids using a wireless network of IRTs integrated with a variable rate irrigation center pivot system. Climatic conditions were very different for the 2 years, and affected crop response. When compared with crop response for the manual-control irrigation-scheduling treatment, grain and biomass yields for the plant feedback irrigation-scheduling treatment were similar, and in most cases, yield components for the plant feedback treatment were also similar. Irrigation scheduling with the plant feedback system was conducted over a large-size field, making it impossible for the IRTs to view the entire crop canopy over daylight hours. However, managing all plant feedback plots in the highest irrigation treatment level (C_{100}) by averaging the iCWSI from plots where the pivot traveled over daylight hours produced mean crop responses in all C_{100} plots that were similar to the sample mean. This management method assumed homogeneity among the C_{100} treatment plots. The mean iCWSI values fluctuated among hybrids and years, and the irrigation amounts for the treatment levels determined by the plant feedback system varied widely from the manual methods. However, the data provided a basis for establishing a range of thresholds that could be used to trigger different levels of irrigation in future work. For example, the first threshold could be: $100 < \text{iCWSI} \leq 150$ with an application depth of $0.5 \times$ peak daily water use $\times$ irrigation interval, the second threshold could be: $150 < \text{iCWSI} \leq 225$ with an application depth of $0.75 \times$ peak daily water use $\times$ irrigation interval, and a third threshold could be: iCWSI >225 with an application depth of $1.0 \times$ peak daily water use $\times$ irrigation interval. Crop response to a range of CWSI thresholds will require future investigation, but this approach is expected to improve on a binary (either irrigate or not) plant feedback method as was used here.

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