CONTROLLING WATER USE EFFICIENCY WITH IRRIGATION AUTOMATION: CASES FROM DRIP AND CENTER PIVOT IRRIGATION OF CORN AND SOYBEAN

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ABSTRACT

A center pivot was completely automated using the temperature-time-threshold (TTT) method of irrigation scheduling. Methods are described that were used to automatically collect and analyze canopy temperature data and control the moving irrigation system based on the data analysis. Automatic irrigation treatments were compared with manually scheduled irrigation treatments under the same center pivot during the growing seasons of 2004 and 2005. Manual irrigations were scheduled on a weekly basis using the neutron probe to determine the profile water content and the amount of water needed to replenish the profile to field capacity. In both years there was no significant difference between manual and automatic treatments in soybean water use efficiency or irrigation water use efficiency. Using drip irrigation in an earlier study, the automated irrigation method resulted in soybean and corn yields and water use efficiencies that were also not significantly different from those obtained with manual scheduling. However with corn, the automated system responded to crop stress better, prevented yield decline in a droughty year, and showed that water use efficiency could be controlled by varying the system parameters. The automatic irrigation system has the potential to simplify management while maintaining the yields of intensely managed irrigation.

INTRODUCTION

An automated irrigation scheduling and control system that responds to stress indicators from the crop itself has the potential to decrease irrigation management and labor requirements and to increase yields per unit of irrigation water (Evett et al., 2000). Burke (1993) and Burke and Oliver (1993) showed that plant enzymes operate most efficiently in a narrow temperature range termed the thermal kinetic window. Wanjura et al. (1992, 1995) demonstrated that the midpoint of this window, called a canopy temperature threshold, could be used as a criterion for simplifying and automating irrigation scheduling. Upchurch et al. (1996) received U.S. patent no. 5,539,637 for an irrigation management system based on this optimal leaf temperature for enzyme activity and a climate-dependant time threshold. This was termed the temperature-time-threshold (TTT) method of irrigation scheduling. With this method, for every minute that the canopy temperature exceeds the threshold temperature one minute is added to a daily total (Fig. 1, left). If this daily total exceeds the time threshold at the end of the day, then an irrigation of a fixed depth is scheduled. Since humidity can limit evaporative cooling, minutes are not accrued if the wet bulb temperature is greater than the threshold temperature minus two degrees Celsius. We showed that automatic drip irrigation of corn and soybean using the TTT method was more responsive to plant stress and showed the potential to out-yield manual irrigation scheduling based on a 100% replenishment of crop water use as determined by neutron probe soil water content determinations (Evett et al., 1996, 2000).

Later, we showed (Peters and Evett, 2004a) that, to acceptable accuracy for irrigation scheduling, canopy temperatures at other times of day and in other parts of a field, which may be under different stresses, could be modeled relative to a reference diurnal temperature curve using only a one-time-of-day temperature measurement (Fig. 1, right) and the scaling equation:

$$T_{rmt} = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \qquad [1]$$

where T_{rmt} is the calculated canopy temperature at the remote location, T_e is the early morning (pre-dawn) temperature, T_{ref} is the canopy temperature from the reference location at the same time interval as T_{rmt}, $T_{rmt,t}$ is the one-time-of-day canopy temperature measurement at the remote location at any daylight time t, and $T_{ref,t}$ is the measured reference temperature from the time that the remote temperature measurement was taken (t). We applied this method to center pivot irrigation where canopy temperatures were sensed at one time of day from the moving center pivot lateral (Peters and Evett, 2004b,c) and demonstrated that soybean yield and water use efficiency values were not significantly different from those achieved using the best scientific irrigation scheduling method, which was based on soil water balance and time consuming and expensive weekly measurements with a neutron probe.

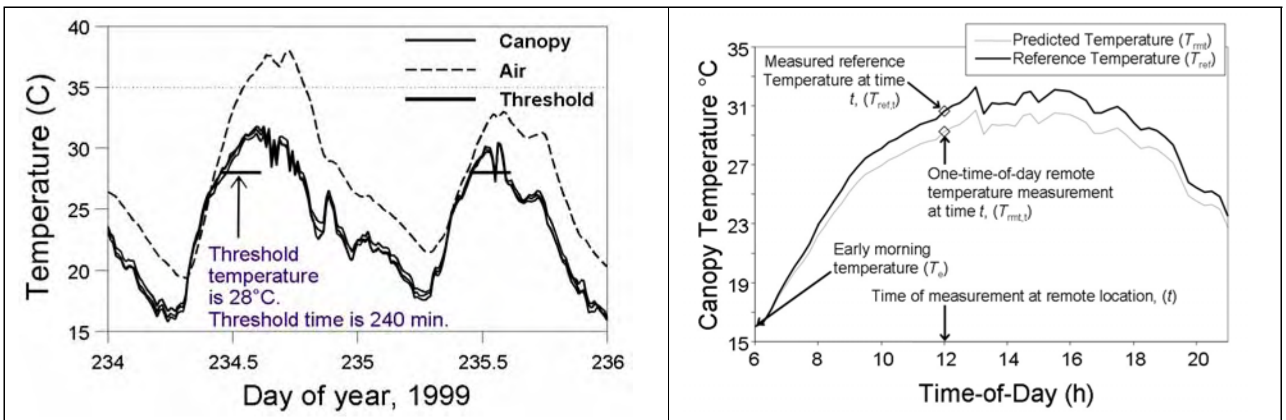

Figure 1. (**Left**) Canopy temperatures of three replicate plots on corn in 1999 (Evett et al., 2000) compared with air temperature. Also shown are horizontal bars drawn at the threshold temperature of 28°C and over the length of the threshold time (240-min). Because the canopy was above the threshold temperature for more than the threshold time on day 234, irrigation occurred in the evening of that day, but not in the evening of day 235. (**Right**) Diagram of the terms used in the scaled method (Equation 1). Time t might be any daylight time at which a canopy temperature ($T_{rmt,t}$) was measured at a remote location in the field. A contemporaneous temperature ($T_{ref,t}$) from the reference temperature data is then used in equation 1 along with the common pre-dawn minimum temperature (T_e) and each value in the reference temperature data (T_{ref}) to predict corresponding temperatures at the remote location for daylight hours (T_{rmt}).

For site specific irrigation to be practical on a large scale, there is a need to develop inexpensive, real-time sensing of the soil and/or plant status integrated with communications networks and control and decision support systems (e.g. Evans et al., 2000). The need for proper decision-support systems for implementing precision decisions was reiterated by McBratney et al. (2005) who stated that there was insufficient recognition of temporal variation as well as spatial variation. We developed a real-time canopy temperature monitoring system integrated with a decision support system to apply the TTT method to center pivot irrigation control and automation (Peters and Evett, 2005a,b). The system used wireless data transmission between dataloggers and the base station computer, which served as a supervisory control and data acquisition (SCADA) system hub, and which transmitted control signals to the center pivot control panel by radio.

The purpose of this paper is to present results from TTT automated center pivot irrigation of soybean and compare them with results from previous studies of the TTT system using drip irrigation.

MATERIALS AND METHODS

Experiments were conducted under a three-tower, 127-m long research center pivot located at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas (35° 11' N, 102° 06' W, 1170 m elev. above MSL). Soybeans were grown in 2004 and 2005 on a Pullman fine, mixed, superactive, thermic Torrertic Paleustoll. Experimental treatments were applied to alternative halves of the field each year to allow the other half's soil water content differences from the previous year's experiment to be minimized by growing a wheat cover crop. Crops were planted in concentric circles out from the center point (Fig. 2). Radially, four different water amount treatments were randomized within two blocks (100%, 66% and 33% of projected irrigation needs, and a dry-land, or no-irrigation treatment). Each drop was pressure regulated to 6 psi. Irrigation rate was controlled radially by nozzle sizing and, in the direction of travel, by lateral speed. Drops were spaced every other furrow (1.52 m) and fitted with low energy precision application (LEPA) drag socks. Furrows were dammed/diked to limit runon and runoff. Along the arc of the irrigated half circle there were, alternately, three blocks each of the automatically controlled (via the TTT method) treatments, and the manually scheduled treatments, which were irrigated to replace soil water deficiency as determined by neutron probe (NP). The combination of radial and arc-wise blocking effectively controlled for differences in soil properties underneath the pivot. Typically, statistical analysis shows no block effect, resulting in six replications of each treatment (irrigation amount and method). Irrigation amounts for the automatic and manual scheduling methods could be different. Irrigation frequency for either method could be up to three times per week. Two additional crop rows were planted around the outside and inside edges of the pivot to reduce border effects. Agronomic practices common in the region for high yields were applied.

The pivot movement and positioning were controlled remotely by a computer located in an off-site building, communicating through two different 900-MHz radios (Fig. 2). One radio was used by the center pivot remote control system to communicate with the pivot through a second radio mounted at the pivot center point, thus allowing system status checks and control. The second system consisted of a Campbell Scientific[1] RF400 radio that communicated to similar radios connected to dataloggers mounted on the pivot and in the field.

One center-pivot-mounted datalogger collected data from 16 infrared thermocouple thermometers (IRTC) that were attached to the trusses of the pivot on the leading side of the

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

pivot (Fig. 2). The pivot was allowed to irrigate in only one direction so that the sensors would not view wet canopy. The IRTCs were oriented so that they pointed parallel to the center pivot lateral (perpendicular to crop rows) towards a spot in the middle of each concentric irrigation treatment plot. In order to minimize sensor angle related effects, two IRTCs were aimed at approximately the same spot from either side of each plot, and the average of these two readings for each plot was used (Wanjura et al., 1995). The IRTCS were connected to a multiplexer (Campbell Scientific AM25T) at the second tower, which in turn was connected to a datalogger placed at the third and last tower. The IRTCs were sensed for canopy temperature on 10-s intervals; and the one minute averages were recorded. A second datalogger and radio provided interface to a GPS unit mounted on the last tower.

Sixteen IRTCs were mounted in stationary locations in the field and connected to a separate datalogger (Fig. 2). Each IRTC was mounted in the nadir position over the crop row close enough to the canopy that soil was not included in the field-of-view. These IRTCs were adjusted up with the changing height of the canopy. One IRTC was mounted in each irrigation level of both the automatic and manual treatments. These IRTCs were similarly connected through a multiplexer (Campbell Scientific AM25T) to a datalogger that recorded the five-minute averages of each of the IRTC readings collected on 10-s intervals.

Each IRTC was calibrated using a black body (Omega Black Point, model BB701) before the season began. Using the calibration, each IRTC was individually corrected by the data analysis software running on the control computer. The IRTCs in stationary positions in the field were Exergen model IRt/c.2-T-80 with a 2:1 field of view, which are relatively insensitive to sensor body temperature. In 2004, IRTCs on the center pivot lateral were narrow field of view (10:1) (Exergen model IRt/c.JR-10). In 2005, these were replaced with type T IRTCs (IRt/c.2-T-80).

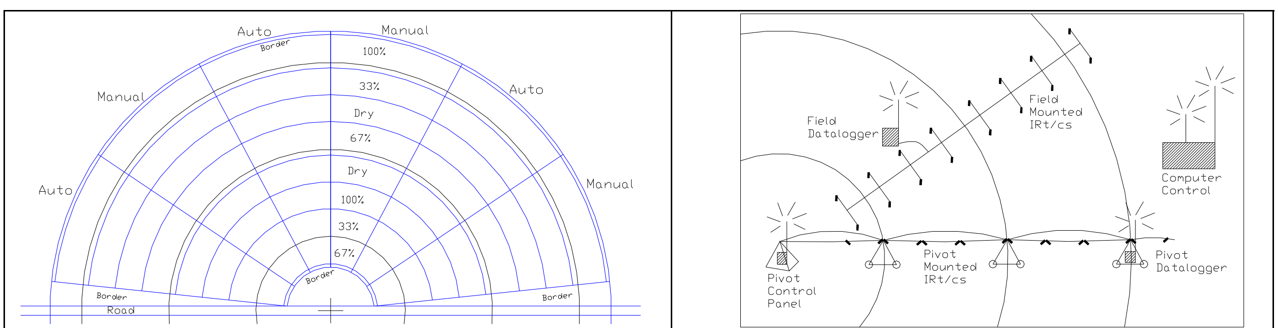

Figure 2. (Left) Automated center pivot irrigation experiment plot plan divided into six “pie slices” labeled Auto for automatically irrigated and Manual for manually irrigated. Irrigation amounts were 100% of the amount determined by each of the two irrigation scheduling methods used in the arcs labeled 100%. In the arcs labeled 67% and 33%, the irrigation amounts were 67% and 33% of the amount applied in 100% arcs. (Right) Automatic center pivot control diagram showing locations of radio antennas, dataloggers and sensors.

During an automatic irrigation event, the pivot stopped at the edge of each arc-wise block (pie slice), paused 10 minutes to drain, and then ran dry over the manual irrigation treatment. It then pressured up again for the next automatic irrigation treatment and continued on in this fashion until all of the automatic irrigation segments were irrigated. An application depth of 20 mm was applied at each automatic irrigation event. This was equivalent to the maximum, two-day crop water use rate for the region. After irrigating the last automatic plot, the pivot continued on around dry to its starting point. During a manual irrigation event, the pivot performed similarly except it irrigated only the manual irrigation blocks at manually set application depths based on that for the 100% treatment, which was based on the soil water deficit as determined by weekly NP readings in 100% treatment plots. In order to both manually and automatically control the same pivot, automatic irrigations were only allowed on even days of the year, and manual irrigations were only allowed on odd days of the year.

The off-site control computer was programmed to call the pivot-mounted datalogger and the pivot control panel every minute to retrieve data and status reports. Software written in Visual Basic reviewed the status reports every minute to determine whether the pivot had crossed a plot boundary. If it had, new instructions were sent to the pivot depending on its location and the subprogram (automatic or manual) that was running at the time. The control computer was linked via wireless Ethernet to a computer in the laboratory through which manual irrigation settings were entered, and system status was checked. Center pivot lateral position was obtained by a combination of pivot control panel resolver angle reports and a GPS system mounted on the pivot end tower (Peters and Evett, 2005a,b).

The field datalogger was polled only once a day soon after midnight. At this time the previous day's data were analyzed to determine the next day's strategy. If the pivot did not move during the previous day, the temperature curve collected by the pivot-mounted IRTCs was used to determine whether irrigation was required. If the pivot *did* move during the previous day then a subroutine was called that scaled one time-of-day temperature measurements and made decisions based on the results. The two canopy temperature measurements from the field-mounted IRTCs in the 100%, automatic treatments were averaged and used as the reference curve for scaling the one time-of-day measurement into a diurnal curve (Eq. 1).

To establish the crop stand, the plots were uniformly irrigated using standard scheduling methods until the crop had grown such that the soil between the rows was not visible when viewed at a 45° angle from the pivot IRTCs. At the end of the season the dry yield was determined by harvesting a 3.48-m^2 sample near the center of each plot. The total dry biomass was measured, as well as the dry grain yield and average seed weight. Total water use was determined by soil water balance (e.g. Evett, 2002). Water use efficiency (*WUE*) and irrigation water use efficiency (*IWUE*) were calculated per Burt et al. (1997) and Howell (2002).

The data were analyzed using SAS (SAS Institute, Inc., Cary, NC) with a procedure for mixed models (Proc Mixed) with the Tukey-Kramer method for adjusting for multiplicity and are given in Tables 1 and 2.

RESULTS AND DISCUSSION

The model IRt/c.JR-10 IRTCs used in 2004 on the center pivot lateral were very sensitive to the sensor body temperature. Type T IRTCs used at stationary locations in the field had previously been shown to be relatively insensitive to sensor body temperature. It was assumed that this would be true for the model IRt/c.JR-10 sensors as well. Thus, all sensors were calibrated independently in the laboratory under practically isothermal conditions; and the errors due to differences between canopy temperature and sensor body temperature were not noticed until after the season was effectively over. This resulted in canopy temperature measurements from the pivot-mounted IRTCs that were three to five degrees Celsius lower than actual. Efforts to calibrate the model IRt/c.JR-10 sensors with sensor body temperature included in the calibration showed that the response was hysteretic so that no dependable calibration could be established. Although the manufacturer replaced these sensors at virtually no cost, the TTT irrigation control in 2004 was based on canopy temperature values that were cooler than actual, resulting in deficit irrigation of even the 100% TTT plots.

The 2004 pivot IRTC measured temperatures were compared to the field IRTC data from times when the pivot was located in approximately the same location. It was found that the pivot mounted IRTCs varied linearly with the more correct field IRTCs. Regression was used to obtain the equation:

$$T_{corrected} = 0.7641 \cdot T_{pivot} + 9.1713 \qquad [2]$$

This equation was used to obtain corrected ($T_{corrected}$) canopy temperatures using the pivot temperatures (T_{pivot}) ($r^2 = 0.9731$).

To evaluate the effect that the errors had on the irrigation experiment, the corrected temperatures were analyzed to find what the irrigation decisions would have been if the temperatures had been correct. The results showed that, in five different instances throughout the irrigation season, automatic irrigations should have occurred but didn't due to the lower than actual reported temperatures. The temperature threshold was effectively set at 30 ˚C instead of the 27 ˚C for soybeans that is specified by theory. When tested, there was no difference in the irrigation decisions made by the uncorrected data with a 27°C temperature threshold and the corrected temperatures with a 30°C temperature threshold. A different IRTC was used in 2005 as described above and the problem was corrected for the 2005 season.

In 2004 the manual irrigation treatment yielded significantly more than the automatic irrigation treatment ($Pr > |t| = 0.035$) with an average difference of 0.025 kg/m^2 (Table 1). We believe that this was mainly due to the sensor inaccuracy, which was equivalent to the temperature threshold being set three degrees Celsius greater than it should have been. Although not significantly different, the manual treatments also showed numerically larger WUE and IWUE. For this first season there were no significant differences between the automatic and the manual treatments for any variable (yield, bean mass, etc.) within an irrigation level, with the exception of yield at the 67% irrigation level.

In 2005, with the IRTC issue corrected, the automatic treatment yielded more than the manual irrigation treatment (Table 2). Although the difference was not significant, differences in the treatments could be seen in the field. Because the automatic system makes irrigation management easier, a non-significant difference is viewed as a positive result. In fact, yields from the manual and automatic treatments were not significantly different from each other at any of the irrigation levels in 2005. The automatic treatment resulted in slightly smaller, though not significantly different, total water and irrigation water use efficiencies.

Yields were in the range reported by Evett et al. (2000) for three years of automatically drip irrigated soybean, and by Eck et al. (1987) for three years of fully furrow irrigated soybean. Water use efficiencies were larger than those reported by Evett et al. (2000), which ranged from 0.25 to 0.51 kg m^{-3} for drip irrigated soybean at the same location. They were also larger than values ranging from 0.05 to 0.61 kg m^{-3} reported by Eck et al. (1987). Contrary to results of Evett et al. (2000) and Eck et al. (1987), water use efficiency in 2005 was increased by deficit irrigation, though not in 2004. Results of Evett et al. (2000) showed that water use efficiency of soybean is relatively insensitive to irrigation level (Figure 3, right). By contrast, water use efficiency of grain corn is very sensitive to irrigation level; and it was shown by Evett et al. (2001) that water use efficiency could be controlled using the TTT irrigation automation system with drip irrigation (Figure 3, left). Future studies will elucidate whether corn WUE can also be controlled with the automated center pivot system. Differences in water use across years are partially due to weather differences.

Table 1. Results from 2004 by treatment (automatic vs. manual), irrigation level (100%, 66%, 33%, and dry), and the cross between the two. Numbers in a column followed by the same letter are not significantly different at the 0.05 probability level.

		Dry Yield (kg m^{-2})	Total Water Use (mm)	Water Use Efficiency (kg m^{-3})	Irrigation Water Use Efficiency (kg m^{-3})
Method	Manual	0.295 a	455 a	0.63 a	0.96 a
	Auto	0.270 b	435 b	0.60 a	0.91 a
Irrigation Level	100%	0.400 a	600 a	0.67 a	0.78 c
	67%	0.345 b	502 b	0.69 a	0.93 b
	33%	0.256 c	392 c	0.65 a	1.10 a
	Dry	0.130 d	285 d	0.46 b	
Treatment by Irrigation Level	Manual 100%	0.411 a	620 a	0.66 ab	0.76 c
	Auto 100%	0.389 a	580 b	0.67 ab	0.81 c
	Manual 67%	0.374 a	517 c	0.72 a	0.98 abc
	Auto 67%	0.317 b	488 d	0.65 ab	0.87 bc
	Manual 33%	0.271 c	396 e	0.68 ab	1.15 a
	Auto 33%	0.240 c	387 e	0.62 b	1.05 ab
	Manual Dry	0.125 d	285 f	0.44 c	
	Auto Dry	0.134 d	285 f	0.47 c	

Table 2. Results from 2005 by treatment (automatic vs. manual), irrigation level (100%, 66%, 33%, and dry), and the cross between the two. Numbers in a column followed by the same letter are not significantly different at the 0.05 probability level.

		Dry Yield (kg/m^2)	Total Water Use (mm)	Water Use Efficiency (kg/m^3)	Irrigation Water Use Efficiency (kg/m^3)
Method	Manual	0.272 a	218 b	1.30 a	0.77 a
	Auto	0.289 a	254 a	1.18 a	0.73 a
Irrigation Level	100%	0.383 a	351 a	1.10 a	0.77 a
	67%	0.321 b	273 b	1.18 a	0.80 a
	33%	0.239 c	193 c	1.25 a	0.69 a
	Dry	0.178 d	127 d	1.43 a	
Treatment by Irrigation Level	Manual 100%	0.374 a	323 b	1.16 b	0.84 a
	Auto 100%	0.391 a	379 a	1.03 b	0.71 a
	Manual 67%	0.307 b	254 c	1.21 b	0.82 a
	Auto 67%	0.335 b	292 b	1.15 b	0.78 a
	Manual 33%	0.229 c	180 d	1.28 ab	0.66 a
	Auto 33%	0.249 c	207 d	1.21 ab	0.72 a
	Manual Dry	0.177 d	116 e	1.54 a	
	Auto Dry	0.180 d	137 e	1.33 ab	

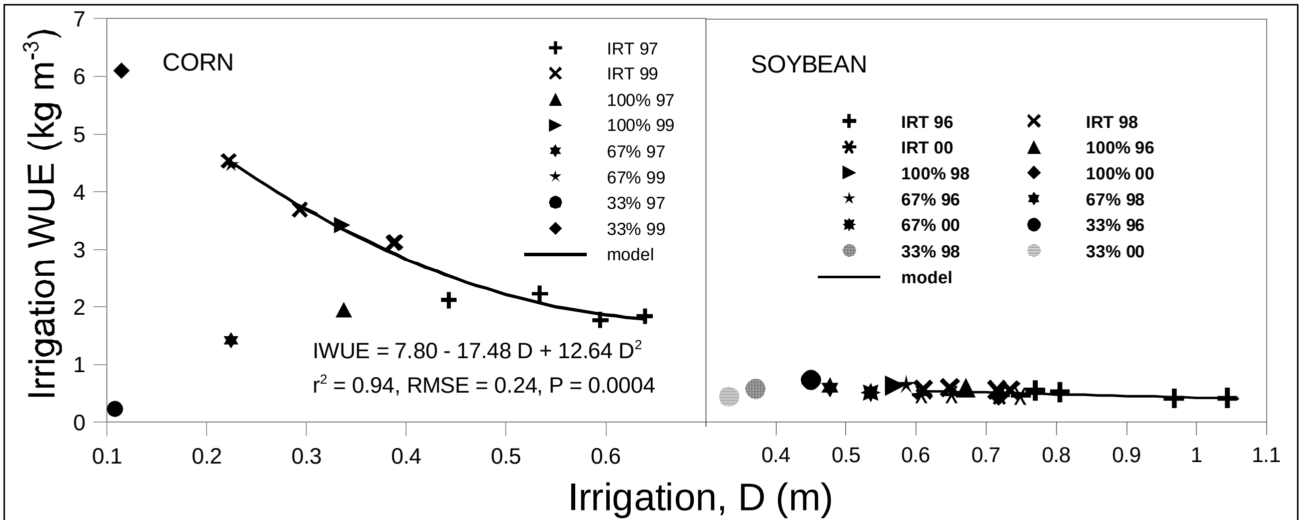

Figure 3. Corn (left) and soybean (right) irrigation water use efficiencies vs. irrigation depth (D, m) for automatic and manual drip irrigation treatments. The solid line is fitted to data from the TTT automated irrigation treatments. Years are given as two digits at the end of each label: 96 for 1996, 97 for 1997, 98 for 1998, 99 for 1999, and 00 for 2000. Labels with IRT are the TTT automation treatments. Labels with percentages are the manual irrigation treatments. This is different from the center pivot irrigation experiments, for which both manual and automated treatments were described in terms of percent of full irrigation determined for each method of scheduling.

CONCLUSIONS

Soybean yield and water use efficiency from a center pivot irrigation system configured to automatically irrigate based on crop stress signals were compared with those from manually scheduled irrigations over two growing seasons in 2004 and 2005. In 2004, incorrect canopy temperatures were recorded by the pivot-mounted infrared thermometers. This resulted in the equivalent of the threshold temperature being set at 30˚ C instead of the prescribed 27˚ C. Therefore, the automatic irrigations ran less often than they should have in 2004. Because of this, the manual treatments yielded significantly more than the automatic treatments. However, during the following season the difference between the manual and automatic irrigation treatments was not significant, with the automatic treatment yielding slightly more than the manual treatment and using slightly more water. There were no significant differences in water use efficiency in either year. It is notable that the manual irrigation scheduling used here, usually referred to as scientific irrigation scheduling, relies on use of the highly accurate neutron probe. This device is seldom used by irrigation managers due to requirements for licensing, training, and constant control of the device, which contains a radioactive sealed source and must be kept in doubly locked storage when not in use. The measurements needed for the manual irrigation scheduling took approximately four hours each week. The automatic irrigation system saves management time and decreases decision making; so a non-significant difference is viewed as a positive result. We believe that the costs and simplicity of methods presented here may become attractive to producers when available in a turn-key commercial package. This is especially true since the methods have the potential to simplify management and reduce labor costs while maintaining or increasing yields compared with intensively and scientifically managed manual irrigation scheduling.

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