A FULLY AUTOMATED CENTER PIVOT USING CROP CANOPY TEMPERATURE; PRELIMINARY RESULTS

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ABSTRACT

It has been shown that the temperature-time threshold (TTT) method of automatic irrigation scheduling is a viable alternative to traditional soil water based irrigation scheduling in the Southern High Plains. This method was used to fully automate a center pivot in the panhandle of Texas. An array of 16 IRTCs were mounted on the pivot and connected to a datalogger also mounted on the pivot. A separate array of IRTCs were located in stationary positions in the field and connected to a separate datalogger. Two different spread spectrum (900 MHz) radios were connected to a desktop computer located nearby that queried both dataloggers, got pivot status information, and sent commands to the center pivot control panel. Using scheduled data collection intervals, this computer was able to collect the data, analyze it, determine need for an irrigation event, and issue control commands to completely automate the center pivot. The field under the pivot was divided into pie slices with every other pie slice an automatic treatment. The pie slices in between served as the control and these were scheduled manually to refill the soil water content to field capacity on a weekly basis using neutron probe soil moisture measurements. The preliminary results from this experiment are presented and the statistics showing the differences between the two methods are given.

INTRODUCTION

An automated irrigation scheduling and control system that responds to stress indicators from the crop itself has the potential to lower crop 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 use of this window as 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

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scheduling. With this method, for every minute that the canopy temperature exceeds the threshold temperature one minute is added to the daily total. 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. Evett et al. (1996, 2000) demonstrated in seven years of drip irrigated plots on corn, cotton and soybeans near Bushland, Texas that automatic irrigation 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 measurements.

The objectives of this study were to: (1) apply the TTT method of irrigation scheduling to a center pivot irrigation system with an array of infrared thermocouples mounted on the center pivot itself; (2) configure the center pivot to be automatically controlled according to the plant water needs as determined from the TTT method of irrigation scheduling; (3) compare the automatic irrigation scheduling to manual irrigation scheduling based on neutron probe soil water content measurements in the same field.

Diurnal Canopy Temperature Determination

Infrared radiation sensors mounted on self-propelled center pivots or linear move irrigation systems can provide only one-time-of-day canopy temperature measurements at each field location; and these measurements occur at uncertain times of day. The application of the TTT system of irrigation scheduling to specific locations under a center pivot or linear move irrigation system requires a method of determining diurnal canopy temperature dynamics at each location from these one-time-of-day canopy temperature measurements.

Peters and Evett (2004a,b) found that the most direct and simple way to determine how changing environmental conditions over a day affect canopy temperature dynamics is to measure canopy temperature in one stationary reference location. Canopy temperatures in other parts of a field, which may be under different stresses, may be modeled relative to this reference using one-time-of-day temperature measurements from those locations. If pre-dawn canopy temperatures throughout the field (T_e; *e* for early) are assumed to be the same then:

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

where T_{rmt} (°C) is the calculated canopy temperature at the remote location; T_{ref} (°C) is the canopy temperature from the reference location at the same time interval as T_{rmt} (°C); $T_{rmt,t}$ (°C) is the one-time-of-day canopy temperature measurement at the remote location at any daylight time *t*; and $T_{ref,t}$ (°C) is the measured reference temperature from the time, *t*, that the remote temperature measurement was taken.

MATERIALS AND METHODS

The experimental site was 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). Data were collected during 2004 on soybeans grown on a Pullman fine, mixed, superactive, thermic Torrertic Paleustoll. Only half of the field was used. Soybeans were planted in concentric circles out from the center point (fig. 2). Four different water level treatments were applied radially out from the center point (100%, 66% and 33% of projected irrigation needs, and a dry-land, or no irrigation treatment). The irrigation level was controlled by pressure regulators and nozzle sizes as appropriate. Drops were spaced every other row (1.52 m) and irrigated with low energy precision application (LEPA) drag socks. The furrows were dammed/diked to limit water movement in the furrows. Radially, two replications of each of the irrigation level treatments were applied in a randomized block pattern with the second tower wheel track serving as the block separation line. Along the arc of the irrigated half circle there were three replications each of an automatically controlled (via the TTT method) treatment, and a treatment that was manually scheduled (using soil water deficiency as determined by neutron probe soil moisture content readings). These treatments were applied alternatively to “pie slices” in order to block for any differences in soil types underneath the pivot. The two radial and three arc-wise replications created a total of six replicate

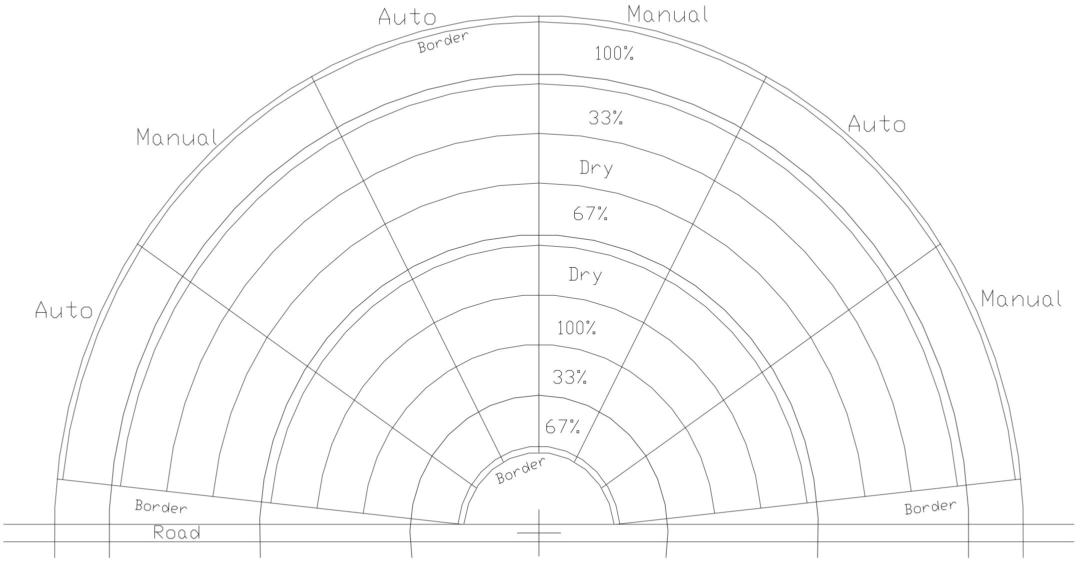

Figure 2. Automatic center pivot irrigation experiment plot plan

plots for each treatment. Two additional rows of soybeans were planted around the outside and inside edges of the pivot to help minimize 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 a nearby building, which communicated through two different 900-MHz radios (fig. 3). One radio was part of a center pivot remote control system ("Base Station") produced by Valmont Industries[3]. This radio communicated with the pivot through a second radio mounted at the pivot center point, thus allowing status checks and control commands to be sent and received at the pivot control panel. The second system consisted of a Campbell Scientific RF400 radio that communicated to similar radios connected to a datalogger mounted on the pivot and a separate datalogger in the field.

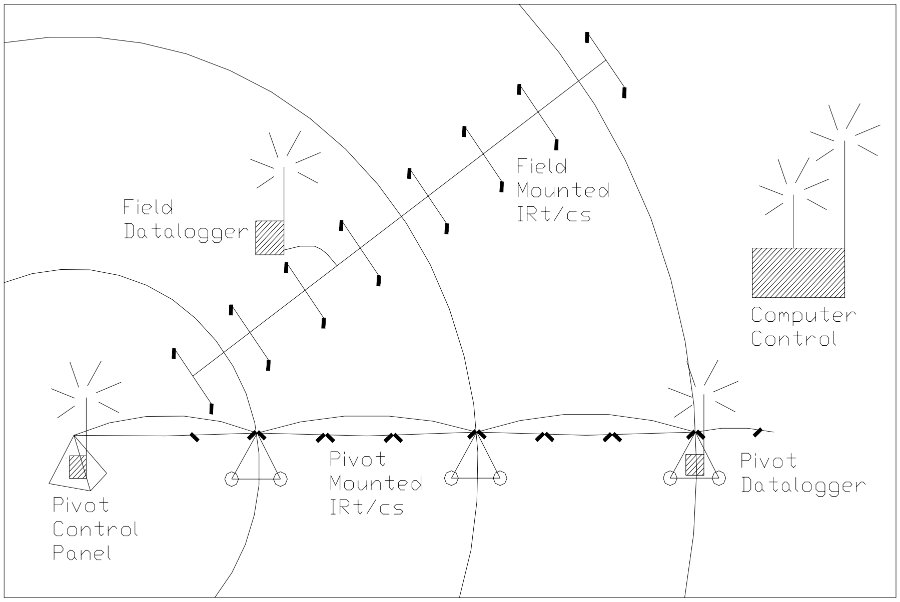

Figure 3. Automatic center pivot control set-up.

The center-pivot-mounted datalogger collected data from 16 infrared thermocouple thermometers (IRTC) that were attached to the trusses of the pivot (fig. 3). They were mounted on the leading side of the pivot and the pivot was only allowed to irrigate in one direction so that the sensors would not view wet canopy. The IRTCs were oriented so that they pointed parallel to the center pivot arm (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

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[3] 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

IRTCs were aimed at approximately the same spot from either side of each plot. The average of these two readings for each plot was used. Wanjura et. al. (1995) reported that canopy temperatures differed less than 0.5° C when measured by either one sensor in the nadir position, or two sensors pointed at the row from opposite directions. The IRTCS were connected to a multiplexer (Campbell Scientific AM25T) at the second tower, which in turn was connected to a datalogger (Campbell Scientific CR10X) placed at the third and last tower. The IRTCs were sensed for canopy temperature on 10 second intervals; and the one minute averages were logged.

Sixteen IRTCs (Exergen model IRt/c.2-T-80) were mounted in stationary locations in the field and connected to a separate datalogger (fig. 3). Each IRTC was mounted in the nadir position over the crop row close enough to the canopy so 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) and to a datalogger (Campbell Scientific CR21X). The datalogger logged the five minute averages of each of the IRTC readings collected on 10 second intervals.

Each IRTC was separately calibrated using a black body (Omega Black Point, model BB701) before the season began. A second order polynomial was fitted to the results of the calibration and each IRTC was individually corrected by the data analysis software running on the control computer in the nearby building.

During an automatic irrigation event the pivot stopped at the edge of the treatment, paused 10 minutes to drain, and then ran dry over the manual irrigation treatment. It would then pressure 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 evapotranspiration rate for the region during the hot, windy summer months. 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 would irrigate only the manual irrigation treatments at a manually set application depth required to replenish soil water content to field capacity (0.33 $m^3\ m^{-3}$), thus preventing crop stress for the 100% treatments. The soil water deficit was determined by weekly neutron probe readings in the 100% manual irrigation treatments. The neutron probe was field calibrated as in Evett and Steiner (1995) and was read at 20-cm depth increments. A depth control stand (Evett et al., 2003) was used to improve accuracy in the near-surface (10-cm depth) reading. In order to both manually and automatically control the same pivot, automatic irrigations were only allowed on even days of year, and manual irrigations were only allowed on odd days of year.

The central control computer was programmed to call the pivot-mounted datalogger and the pivot control panel every minute to retrieve status reports. Software was written in Visual Basic that 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 program (automatic or manual) that was running at the time. In this way the complex motion of the center pivot was controlled.

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 together and used as the reference curve for scaling the one time-of-day measurement into a diurnal curve (equation 1).

To establish the plots, the plots were uniformly irrigated until 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 yield, Y (kg m^{-2}), and average bean weight. The total water use, W_U (m), was determined by subtracting the soil profile water content (m) determined at the first measurement date from the water content determined after harvest, and adding the total amount of irrigation, I (m), and rainfall (m) for that time period. Water use efficiency (*WUE*) was calculated as:

$$WUE = \frac{Y}{W_U} \qquad [2]$$

and irrigation water use efficiency (*IWUE*) was calculated as:

$$IWUE = \frac{Y - Y_D}{I} \qquad [3]$$

where Y_D was mean yield (kg m^{-2}) in the dryland plots. Both WUE and IWUE are given in units of kg/m^3.

RESULTS AND DISCUSSION

Exergen IRTCs have a capacitor built into the sensor to help to minimize the effects of ambient electromagnetic noise on the sensor's readings. This capacitance interacts with the Campbell Scientific CR10X datalogger to give readings that are slightly incorrect. The pivot-mounted IRTCs were wired into a CR10X. This is not an issue with the Campbell Scientific CR21X that was used for the stationary field measurements. It was discovered that the pivot-mounted, narrow field-of-view sensors were particularly sensitive to the sensor body temperature and gave errant readings when the sensor bodies were at elevated or cooler temperatures. Because the sensors were calibrated independently in the laboratory before mounting them on the pivot, and because the readings were reasonable, this error was not caught until after the season was effectively over. This resulted in pivot IRTC temperatures that were highly variable and that gave answers that were generally three to five degrees Celsius low.

The pivot IRTC measured temperatures were compared to the field IRTC data from times when the pivot was located in approximately the same location (Figure 4). It was found that the pivot mounted IRTCs varied linearly with the more correct field IRTCs. Regression was used to obtain the equation:

$$T_{corrected} = 0.7641 \cdot T_{pivot} + 9.1713 \qquad [4]$$

This equation can be used to obtain a corrected ($T_{corrected}$) canopy temperature using the pivot temperatures (T_{pivot}) (both in ˚C) with an r^2 value of 0.9731.

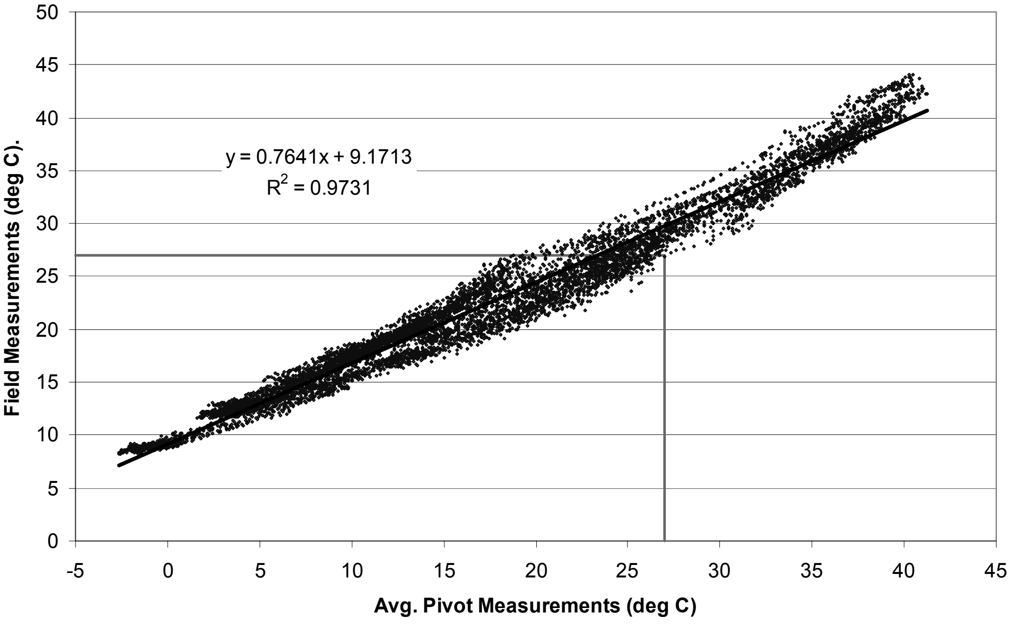

Figure 4. Regression of measured canopy temperatures on the pivot with those measured in stationary location near where the pivot was located.

To evaluate the effect that this error had on the irrigation experiment, the corrected temperatures were run back through a specifically written computer program. The irrigation decisions of what should have happened if the sensors were reading correctly were compared against what was actually done. The results showed that in five different instances throughout the season automatic irrigations should have run but didn't because the temperatures were reported low. 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 at 27 ˚C temperature threshold and the corrected temperatures with a 30 ˚C temperature threshold.

The yield data from 2004 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 (Table 1). 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 issue, 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. 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.

Table 1. 2004 response variables for the treatment (automatic vs. manual), the 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)	Avg Bean Weight (mg/bean)	Biomass (g)	Wtr Use Efficiency (kg/m^3)	Irrig Wtr Use Efficiency (kg/m^3)	Total Water Use (mm)
Treatment	Manual	0.272 A	133 A	1222 A	1.30 A	0.77 A	218 B
	Auto	0.289 A	130 A	1306 A	1.18 A	0.73 A	254 A
Irrigation Level (%)	100%	0.383 A	148 A	1630 A	1.10 A	0.77 A	351 A
	67%	0.321 B	140 A	1380 B	1.18 A	0.80 A	273 B
	33%	0.239 C	125 B	1112 C	1.25 A	0.69 A	193 C
	Dry	0.178 D	114 B	934 D	1.43 A		127 D
Treatment * Irrigation Level	Manual 100%	0.374 A	150 A	1556 AB	1.16 B	0.84 A	323 B
	Auto 100%	0.391 A	145 A	1705 A	1.03 B	0.71 A	379 A
	Manual 67%	0.307 B	143 A	1310 CD	1.21 B	0.82 A	254 C
	Auto 67%	0.335 B	138 AB	1451 BC	1.15 B	0.78 A	292 B
	Manual 33%	0.229 C	126 BC	1064 EF	1.28 AB	0.66 A	180 D
	Auto 33%	0.249 C	124 CD	1159 DE	1.21 AB	0.72 A	207 D
	Manual Dry	0.177 D	113 D	958 F	1.54 A		116 E
	Auto Dry	0.180 D	114 CD	909 F	1.33 AB		137 E

CONCLUSION

A center pivot was configured to automatically irrigate based on crop stress signals sensed by infrared thermocouples mounted on the center pivot. These automatic treatments were compared with a manually scheduled treatment in 2004. There was an interaction of the sensors with the datalogger; and a problem with the sensor readings being highly sensitive to the sensor body temperature was found. This caused incorrect canopy temperatures to be recorded by the pivot-mounted IRTCs. 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. Because of this, the manual treatment's yields were significantly higher than the automatic treatments. There were no significant differences in water use efficiency. 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 presented have the potential to simplify management and reduce labor costs while maintaining or increasing yields compared with intensively and scientifically managed manual irrigation scheduling.

REFERENCES

Burke, J.J. 1993. Thermal kinetic windows of plant enzymes. In *Biotechnology for Aridland Plants, Proc. International Symp. IC^2 Institute.* Mabry, T.J., Nguyen, H.T., Dixon, R.A., Bonness, M.S. (eds.) The University of Texas, Austin. (pp. 73-82.)

Burke, J.J., and M.J. Oliver. 1993. Optimal thermal environments for plant metabolic processes (Cucumis sativus L.): Light-harvesting chlorophyll a/b pigment-protein complex of photosystem II and seedling establishment in cucumber. *Plant Phys.* 102(1):295-302

Evans, R.G. 2000. Controls for Precision Irrigation with Self-Propelled Systems. In *Proc. of the 4th Decennial National Irrigation Symposium*. Robert G. Evans, Brian L. Benham, and Todd P. Trooien (eds.) November 14-16, Phoenix, AZ.

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 1996. Canopy temperature based automatic irrigation control. In *Proc. International Conf. Evapotranspiration and Irrig. Scheduling*. C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.). November 3-6, 1996, San Antonio, TX. (pp. 207-213)

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 2000. Automatic drip irrigation of corn and soybean. In *Proc. of the 4th*

Decennial National Irrigation Symp. Robert G. Evans, Brian L. Benham, and Todd P. Trooien (eds.). November 14-16, Phoenix, AZ. (pp. 401-408)

Evett, S.R., and R.J. Lascano. 1993. ENWATBAL.BAS: A mechanistic evapotranspiration model written in compiled BASIC. *Agron. J.* 85(3):763-772.

Peters, R.T., and S.R. Evett. 2005. Using low-cost GPS receivers for determining field position of mechanized irrigation systems. *App. Eng. in Ag.* 21(5): 841−845

Peters, R.T., and S.R. Evett. 2004(a). Modeling diurnal canopy temperature dynamics using one time-of-day measurements and a reference temperature curve. *Agron. J.* 96:1553-1561

Peters, R.T., and S.R. Evett. 2004(b). Comparison of scaled canopy temperatures with measured results under center pivot irrigation. In: Proceedings of the 25th Annual International Irrigation Show of the Irrigation Association. Nov. 14-16, 2004. Tampa, FL. CDROM

Upchurch, D.R., Wanjura, D.F., Burke, J.J. and Mahan, J.R. 1996. Biologically-identified optimal temperature interactive console (BIOTIC) for managing irrigation. U.S. Patent No. 5539637.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1992. Automated irrigation based on threshold canopy temperature. *Trans. ASAE* 35(1):153-159.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1995. Control of irrigation scheduling using temperature-time thresholds. *Trans. ASAE* 38(2):403-409.