Pp. 401-408 *In* Proceedings of the 4th Decennial National Irrigation Sym., Nov. 14-16, 2000, Phoenix, AZ.

AUTOMATIC DRIP IRRIGATION OF CORN AND SOYBEAN

S.R. Evett, T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura*

ABSTRACT

Irrigation scheduling goals may include maximizing yield and maximizing water use efficiency - two goals that usually conflict. Which goal is chosen depends on many factors. But, clearly, an automatic irrigation system that allowed either goal to be chosen would be a useful farming tool. We tested a system that uses species-specific threshold temperatures and region-specific threshold times, compared with daily canopy temperature time above the threshold, to automatically schedule and apply irrigations. Corn (*Zea mays* L., hybrid Pioneer 3162) was grown in 1997 and 1999; and soybean (*Glycine Max* (L.), var. Pioneer 9481) was grown in 1996 and 1998, all with surface and subsurface drip irrigation. Four automatic treatments were implemented each season. The default threshold temperatures are 27°C and 28°C for soybean and corn, respectively, as determined from the peak photosynthetic enzyme activity measured as a function of temperature. We applied treatments using the default threshold temperatures and thresholds 2°C higher; and for each threshold we used two threshold times. The times were the daily mean time that well-watered crops of each species were above the threshold temperatures during the irrigation season in previous studies. If canopy temperature, measured every minute with an infrared thermometer, was above the threshold temperature for more than the threshold time in any day, then an irrigation equal to peak consumptive use (10 mm) was applied that night. Each year, the four automatic treatments were compared with a manual weekly irrigation regime that was 100% replenishment of water to field capacity as measured by neutron probe. Treatments of 67% and 33% of the 100% amount were also applied manually to provide data for curves of yield vs. water use. Treatments were triply replicated. Most or all of the automatic treatments out yielded the 100% treatment in each year. Corn yields were 0.94 to 1.21 kg m^{-2} for automatic treatments and 0.65 to 1.15 kg m^{-2} for the 100% treatment. Soybean yields were 0.35 to 0.43 kg m^{-2} for automatic treatments and 0.36 to 0.40 kg m^{-2} for the 100% treatment. In general, increasing threshold temperature or time shifted treatments away from maximum yields and closer to maximum water use efficiencies. In mid-season, the mean corn canopy temperature for the 28 and 30°C treatments (three replicates) was separated by about 2°C through most of the daylight hours. As with corn yield, total water use (mm) and water use efficiency, WUE (kg m^{-3}), were stable over the 1997 and 1999 years for the automatic irrigation treatments (means of 752 mm and 1.48 kg m^{-3}, respectively). Water use and WUE varied widely over the two years for the manual treatments (569 and 756 mm, and 0.65 and 1.52 kg m^{-3} for 1997 and 1999, respectively, for the 100% treatment). For soybean, yields and WUE were not more stable for all automatic treatments. It appears that manipulation of temperature and time thresholds will allow a choice between maximum yields and maximum water use efficiencies to be achieved for corn, but not for soybean.
Keywords. Microirrigation, Drip, Canopy Temperature, Yield, Water Use Efficiency

INTRODUCTION

A reliable automated, real-time irrigation scheduling and control system would have obvious advantages that include lower labor costs and lower plant stress levels, and that could include lower water use or higher water use efficiency. Recently Burke (1993) and Burke and Oliver (1993) showed that plant enzymes operate most productively in a narrow temperature range called the thermal kinetic window. Wanjura et al. (1992 and 1993) described systems for using a threshold canopy temperature, based on the

*S.R. Evett, Soil Scientist; T.A. Howell, Research Leader and Agricultural Engineer; and A.D. Schneider, Agricultural Engineer, Water Management Research Unit, USDA-ARS, Bushland, TX; D.R. Upchurch, Laboratory Director and Soil Scientist; and D.F. Wanjura, Agricultural Engineer, USDA-ARS, Lubbock, TX

thermal kinetic window, as an index for automatic control of irrigation on a near real-time basis. A temperature-time threshold concept was introduced by Wanjura et al. (1995a,b) to see if irrigation intervals could be extended to once a day or longer. The studies, conducted with cotton (*Gossypium hirsutum*, L.), were not replicated but did prove the workability of an automated system and appeared to confirm that the 28°C threshold for cotton resulted in the largest yields. Upchurch et al. (1996) received patent no. 08/261,510 for an irrigation management system based on optimal leaf temperature for enzyme activity. For drip-irrigated field corn, Howell et al. (1997) showed no significant difference in yield between once-a-day and once-a-week irrigation treatments that replenished soil water to field capacity.

In a precursor to the study reported here, we used 28 and 30°C thresholds and 15-min and 3-d decision intervals to automatically drip irrigate corn in 1995 (Evett et al., 1996). We found that the automatic method was more responsive to plant stress and produced yields equal to or greater than those from treatments irrigated to replenish soil water to field capacity weekly. We also concluded that a 15-min decision interval was too frequent and a 3-d interval probably too infrequent for best production and water use. Thus, in the present study we used a decision interval of one day. Our objectives were to test the temperature-time threshold method for corn and soybean production under surface and subsurface drip irrigation in a replicated experiment using two threshold temperatures and two threshold times, and to compare yields and water use efficiencies (WUE) with those obtained using weekly replenishment of soil water to field capacity.

METHODS AND MATERIALS

The study area consisted of 21 plots on a Pullman clay loam, fine, mixed, thermic Torrertic Paleustoll at Bushland, TX. Each 10.7 by 27.4-m plot contained 12 rows with 0.76-m row spacing. Half of each plot was surface irrigated with three drip lines (model T25-0.6-18, Netafim Irrigation Inc., Fresno, CA[**]) in every other interrow (1.52-m line spacing). The other half plot was irrigated with drip lines buried at 0.3-m depth in every other interrow. The pressure compensating emitters were spaced at 0.45-m intervals along the tubing and were rated at 2.7 L/h at the 69 kPa design pressure. Flow to each plot submain was controlled at 908 L/h by a Dole Flow Control valve (Eaton Corp., Carol Stream, IL). Weekly, flow to each IRT plot was recorded from totalizing flow meters (Master Meter 1 inch). Phosphoric acid was injected at 5.3 mg/L as a P source and to prevent root plugging.

Soil water content was measured weekly by neutron scattering at depths of 0.1 through 2.3 m with 0.2-m increments (model 503DR moisture meter, Campbell Pacific Nuclear Int., Inc., Martinez, CA)(one access tube per plot, 32 s counts at each depth). The gage was previously field calibrated for the A, B and calcic B horizons with coefficients of determination of 0.90, 0.96, and 0.97, respectively, and RMSE < 0.01 m^3 m^{-3} for all horizons, using methods described by Evett and Steiner (1995). The change in stored soil water to 2.4-m depth was calculated between the first measurement date and harvest. Seasonal crop water use was calculated as the sum of irrigation, rainfall, and decrease in stored soil moisture. Plots were leveled and bermed to prevent runoff and runon.

Seven irrigation treatments were randomized in a split plot (surface and subsurface drip) design with three replications. Treatments were randomized each year. Four of the treatments were implemented with two threshold canopy temperatures, each of which was implemented with two threshold times to create four automatic irrigation treatments. One of the other three treatments, designated 100%, consisted of weekly irrigations to replace 100% of crop water use as measured by neutron scattering (average of three replicates). Crop water use was calculated as the difference between soil water storage in the top 1.5 m of

---

[**]The mention of trade or manufacturer names is for information only and does not imply an endorsement, recommendation or exclusion by USDA-Agricultural Research Service.

soil and field capacity in that layer (0.333 m^3 m^{-3} average water content). Two other treatments, designated 67% and 33%, were irrigated weekly to provide 67% and 33% of the amount provided to the 100% treatment.

The threshold temperatures were determined by the ARS Plant Stress and Water Conservation Laboratory, Lubbock, TX, on the basis of temperature kinetics of soybean and corn photosynthetic enzymes. The 28°C threshold is the center of the thermal kinetic window for corn (Burke, 1996) and represents peak photosynthetic enzyme activity. It should be the optimum. The optimum temperature threshold for soybean was determined to be 27°C. For corn, a 30°C threshold treatment was established to see if a 2°C increase would substantially change water use, WUE, and yields. For soybean, a 29°C threshold was used.

For corn, the time threshold was determined to be 240 min for a 28°C threshold temperature using the crop energy balance method proposed by Wanjura et al. (1995b) with weather data from Bushland. The aim of this method is to calculate, over the irrigation season, the average time period over a day for which the canopy temperature of a well-watered crop, with a particular canopy resistance, exceeds the threshold temperature. For a 30°C threshold temperature, the time threshold was 160 min. To study the effects of using a shorter or longer threshold time, the threshold time for 28°C was used with the 30°C threshold, and the threshold time for 30°C was used with the 28°C threshold. The resulting four treatments, collectively called the corn IRT treatments, were designated 28-240, 28-160, 30-160, and 30-240. For soybeans grown under sprinkler irrigation at Bushland in 1995, the threshold times were 256 min and 171 min for threshold temperatures of 27 and 29°C, respectively. The four soybean IRT treatments were designated 27-256, 27-171, 29-171, and 29-256.

For irrigation system control, the time threshold is compared to a daily accumulation of measured time that the canopy is above the threshold temperature. During our experiment, the canopy temperature was measured every second and the mean calculated every minute. If the mean temperature was above the threshold temperature, and if the relative humidity (RH) was below a limiting RH, then one minute was added to the sum of time for which canopy temperature exceeded the threshold. The limiting RH was that equivalent to a wet bulb temperature of 2°C below the threshold temperature. This limitation is introduced to avoid counting times when the canopy cannot physically cool below the threshold temperature due to high humidity. Irrigations are applied on any day when the time threshold is exceeded. The irrigation amount is set equal to the crop's peak daily ET. For both soybean and corn at Bushland, this was chosen as 10 mm from historical data. The 28-240 and 30-160 corn treatments and the 27-256 and 29-171 soybean treatments can be called the theory-based treatments because they used time thresholds that were determined for their respective temperature thresholds. For each species, the other two IRT treatments, 28-160 and 30-240 for corn and 27-171 and 29-256 for soybean, were used to explore whether lowering or raising, respectively, the time threshold for a given temperature threshold would cause changes in irrigation amount, yield, and/or water use efficiency.

Canopy temperature was measured with thermocouple infrared thermometers (IRT) (model IRt/c.2-T-80, Exergen Corp., Newton, MA) digitized with a data logger (model 21x, Campbell Sci. Inc., Logan, UT) that also served to control flow to the 12 plots irrigated by canopy temperature control. There was one IRT per plot, mounted on an adjustable mast one third of the distance from the south end of the plot, and adjusted to point down 45° from the horizontal and to point across the rows at 45° from north. Flow to each IRT plot was turned on and off by a solenoid valve actuated by the data logger via a control module (Campbell Sci. Inc. model SDM-CD16AC, Logan UT).

Corn (*Zea mays* L., hybrid Pioneer 3162) was planted in 1997 after 186 kg N ha^{-1} was applied, and in 1999 after 230 kg N ha^{-1}. Atrazine was applied at 2.24 kg ha^{-1} in 1997 and1999. For corn, liquid urea was injected into the irrigation water at 75 mg L^{-1}. Soybean (*Glycine Max* (L.), var. Pioneer 9481, late maturity group 4) was planted in 1996 and 1998, after Treflan was applied and incorporated. Analysis of variance of the results and Student-Newman-Keuls multiple range tests on the means were done using the SAS (SAS Institute, Inc., Cary, NC) and COSTAT statistical analysis packages (COHORT, Inc., Minneapolis, MN).

RESULTS

Corn

In 1999, growing season rainfall was 134 mm greater than that in 1997 (Table 1). Total water use by the IRT treatments was similar in both years. But, for the manually irrigated treatments, water use in 1999 was about 175 mm more than in 1997. A small amount of the extra water use was from greater soil water depletion. However, the major difference in water use between years was probably due to crop response to plentiful rainfall and a mild microclimate in 1999, whereas in 1997 the microclimate was harsh and the weekly irrigation regime was not frequent enough to prevent crop stress that diminished plant development and yields significantly.

Table 1. Irrigation, soil water used, and total water use[a].

Treatment	Irrigation (mm)		Soil Water Used (mm)		Total Water Use (mm)	
Corn	1997	1999	1997	1999	1997	1999
28-240[b]	639 a[c]	387 a	15 c	96 ab	843 a	806 a
28-160	595 a	389 a	5 c	96 ab	789 b	808 a
30-160	534 b	293 c	28 c	118 ab	751 b	735 b
30-240	443 c	222 d	29 c	79 b	661 c	624 d
100%	337 d	336 b	42 bc	97 ab	569 d	756 b
67%	224 e	224 d	81 ab	118 ab	494 e	666 c
33%	108 f	115 e	116 a	139 a	412 f	577 e
Soybean	1996	1998	1996	1998	1996	1998
27-256	770 bc	715 a	-14 ab	66 ab	1167 bc	866 b
27-171	968 ab	734 a	-43 a	90 abc	1335 ab	910 a
29-171	1044 a	648 b	-21 ab	95 abc	1433 a	828 bc
29-256	805 bc	610 c	29 dc	101 bcd	1245 abc	797 c
100%	671 dc	570 d	10 bc	63 a	1092 dc	718 d
67%	586 dc	477 e	28 dc	124 dc	1024 dc	686 d
33%	450 d	371 f	50 d	133 d	910 d	589 e

[a] For corn, rainfall during the irrigation season was 189 mm in 1997, and 323 mm in 1999. For soybean, rainfall during the irrigation season was 411 mm in 1996, and 85 mm in 1998. Total water use was the sum of irrigation, rainfall, and change in stored soil water to 2.4-m depth.

[b] Hyphenated treatment names include the threshold temperature (°C) as the first number, and the threshold time (min) as the second number. Treatment names with percent signs are based on weekly replenishment of soil water in the top 1.5 m of the profile to field capacity.

[c] Numbers in a column followed by the same letter are not significantly different at the 0.05 probability level.

The very different weather in 1997 and 1999 provided contrasts in the way in which the IRT treatments applied irrigations. In the more stressful 1997, the IRT treatments applied significantly more water than did any manual treatment. And, yields for the IRT treatments were significantly greater than for any manual treatment. Also, the 28°C treatments applied significantly more water than did the 30°C treatments. In 1999, the 28°C IRT treatments and the 100% treatment applied significantly more water than any other treatment. As in 1997, the 30°C treatments applied significantly less water than did the 28°C treatments. However, total water use was nearly the same for IRT treatments in 1997 and 1999, while the manual treatments used from 165 to 187-mm more water in 1999 than in 1997. The difference was in irrigation applications. The manual method applied nearly the same amount of water in both years, whereas the IRT method applied from 152 to 241 mm less water in 1999 than in 1997.

The two years also provided contrasts in yield and water use efficiency across treatments. Yields for the IRT treatments were fairly stable across years, whereas yields for the manual treatments increased greatly for the milder 1999 season (Table 2). In 1997, yields for IRT treatments were significantly greater than for manual treatments. And, yields for the theory-based IRT treatments 28-240 and 30-160 were significantly higher than those that explored variations from theory, 28-160 and 30-240. This shows that yields were adversely impacted by both lowering and increasing the time threshold from that determined to be appropriate for a given temperature threshold. For the 30°C treatments, increasing the time threshold decreased both the applied irrigation depth and the yield significantly.

Table 2. Yields, irrigation water use efficiency (IWUE), and total water use efficiency (WUE).

Corn	Dry Yield (kg/m^2)		IWUE (kg/m^3)		WUE (kg/m^3)	
Treatment	1997	1999	1997	1999	1997	1999
28-240[a]	1.18 a[b]	1.20 ab	1.84 abc	3.11 d	1.40 abc	1.49 a
28-160	1.04 b	1.21 a	1.77 bc	3.13 d	1.32 bc	1.50 a
30-160	1.19 a	1.07 bc	2.23 a	3.69 c	1.59 a	1.46 a
30-240	0.94 b	1.00 c	2.12 ab	4.54 b	1.42 ab	1.62 a
100%	0.65 c	1.15 ab	1.96 ab	3.42 dc	1.16 c	1.52 a
67%	0.32 d	1.00 c	1.43 c	4.47 b	0.65 d	1.50 a
33%	0.02 e	0.70 d	0.23 d	6.10 a	0.06 e	1.21 b
Soybean	1996	1998	1996	1998	1996	1998
27-256†	0.407 ab‡	0.403 a	0.554 ab	0.565 ab	0.354 a	0.466 ab
27-171	0.402 ab	0.410 a	0.416 b	0.559 b	0.302 a	0.451 b
29-171	0.432 a	0.392 ab	0.421 b	0.604 ab	0.305 a	0.474 ab
29-256	0.423 a	0.348 c	0.528 ab	0.571 ab	0.341 a	0.437 b
100%	0.401 ab	0.364 ab	0.600 ab	0.639 a	0.368 a	0.509 a
67%	0.368 bc	0.289 d	0.647 a	0.605 ab	0.363 a	0.421 b
33%	0.328 c	0.216 e	0.738 a	0.583 ab	0.362 a	0.367 c

[a]Hyphenated treatment names include the threshold temperature (°C) as the first number, and the threshold time (min) as the second number. Treatment names with percent signs are based on weekly replenishment of soil water in the top 1.5 m of the profile to field capacity.

[b]Numbers in a column followed by the same letter are not significantly different at the 0.05 probability level.

In 1999, yields for the 28°C IRT treatments were significantly higher than those for the 30°C treatments, but were not significantly different from the 100% manual treatment (Table 2). Yields for the 30°C IRT treatments were not significantly different from those for the 67% and 33% manual treatments. In 1997, the WUE for the 28°C treatments was not significantly different from that for the 100% treatment. However, total WUE values for the 30°C IRT treatments were significantly higher than those for the manual treatments. This was due to a combination of less irrigation applied than for the 28°C treatments and larger yields achieved than for manual treatments. In 1999, only the 33% treatment resulted in a WUE that was significantly lower than the others. But, the IRT treatments used, on average, 205 mm less irrigation water in 1999 than in 1997, whereas the manual treatments used almost identical amounts of irrigation water in both years. Except for the 30-160 treatment, WUE values were higher in 1999 than in 1997. But, for the manual treatments, WUE values increased much more from 1997 to 1999 than for the IRT treatments. Overall, WUE values were significantly correlated with total water use (Fig. 1). Increasing the threshold temperature or time from the theoretical values will often increase water use efficiency while reducing yield and irrigation depth. With the 1-day decision interval used in 1996-1998, the IRT treatments resulted in generally higher WUE values than for either the 3-d or 15-min decision intervals used with IRT treatments in 1995 (Fig. 1).

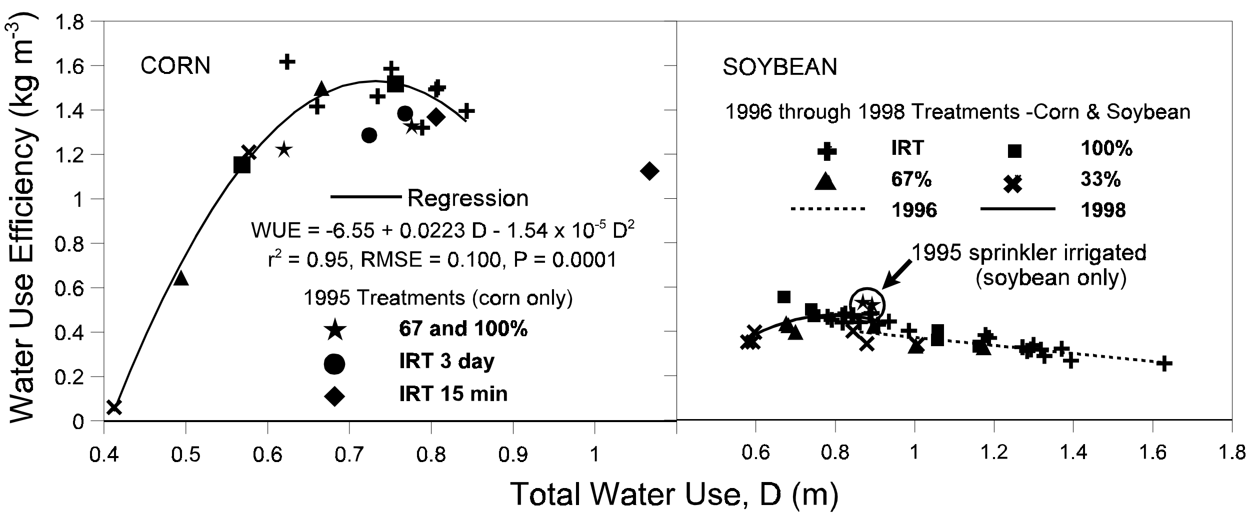

Fig. 1. Corn (left) and soybean (right) water use efficiencies, WUE (kg m^{-3}), for IRT and manual irrigation treatments under drip irrigation. For corn, WUE was significantly correlated with total water use (P = 0.0001 for the regression and all coefficients). For soybean in 1996, WUE was negatively and significantly correlated with water use (dashed line), as it was for the larger water use amounts in 1998. Results for drip-irrigated corn and sprinkler-irrigated soybean in 1995 are shown for comparison.

These results show that the IRT method is particularly adept at responding to corn water use needs, and results in stable and high production and water use efficiency across years that vary widely in weather conditions. In both years, mean canopy temperatures during August for the IRT treatments give an indication of the degree of control over plant stress that is achieved. In 1997, the theory-based IRT treatments (28-240 and 30-160) differed by about 2°C in midday (data not shown). The more stressful 30-240 treatment was up to 5°C warmer than the less stressful 28-160 treatment. In the mild weather of 1999, the 30-160 treatment was only about 1°C warmer than the 28-240 treatment during some midday periods. As would be expected, the temperature difference between 30-240 and 28-160 treatments was larger than that between 30-160 and 28-240 treatments, reinforcing the 1997 results.

<u>Soybean</u>

Even though growing season rainfall was unusually large (411 mm), both IRT and manual methods applied more irrigation water in 1996 than in 1998 (Table 1). For three of the IRT treatments, this resulted in actually increasing soil water storage over the season. The increased irrigation was due to very dry conditions before and after planting (5 mm total rainfall from 1 Jan. to 30 May, 1996) that caused deep soil cracking. In order to germinate seed, an average of 295 mm of irrigation was applied pre- and post-plant through day 132 (12 May). Despite what appears to be excessive irrigation, all IRT treatments in 1996 yielded more (0.402 to 0.432 kg m^{-2}) than manual ones (0.328 to 0.401 kg m^{-2}) (not significantly different for the 100% treatment) (Table 2). In 1998, three IRT treatments yielded more (0.392 to 0.410 kg m^{-2}) than manual ones (0.216 to 0.364 kg m^{-2}). But, the non-theory based 29-256 IRT treatment yielded significantly less (0.348 kg m^{-2}) than the 100% treatment. Yield stability across the 1996 and 1998 seasons was higher for the 27°C IRT treatments than it was for the 100% treatment. Both of the 29°C IRT treatments showed less stability.

Unlike for corn, increased yields did not result in increased water use efficiency (Fig. 1 and Table 2). In fact, in 1996, WUE was negatively and significantly correlated with total water use; and the 67% and 33% manual treatments exhibited significantly higher irrigation WUE. The combination of a very dry spring that caused substantial irrigation applications to germinate the crop, with a crop season that was above-average in rainfall, resulted in a soil profile that was overfull of water in 1996 (data not shown). The fact that the 100% treatment applied less water may illustrate a tendency for the IRT treatments to over-irrigate during a wet season if the profile becomes wet enough to cause plant stress. The 1998 growing season was unusually hot and dry, with only 85 mm of growing season rainfall. In 1998, only the 27-171 IRT treatment had significantly lower irrigation WUE. In both years, yields for the IRT treatments were comparable with those for a 1995 sprinkler irrigated crop in a nearby field (except for the low-yielding 29-256 treatment in 1998). The 27-256 and 27-171 IRT treatments had stable yields across years. But, the other IRT treatments and all the manual treatments exhibited decreased yields in 1998. The great differences in weather between years illustrate the need for multi-year studies of the IRT automatic irrigation system.

Eck et al. (1987) reported lower yields (0.272, 0.371, and 0.362 kg m^{-2}) for three years of unstressed border irrigated soybeans (Douglas, maturity group IV) at Bushland, indicating that drip irrigation provides higher yields. Water use efficiencies (0.40, 0.45, and 0.50 kg m^{-3}) reported by Eck et al. (1987) were in the same range as those reported in this study. Applying water stress did not increase WUE in the Eck et al. (1987) study, supporting the rather flat WUE vs. total water use relationship observed in this study.

The greater WUE that may be obtained with corn as compared with soybean is probably due largely to the differences between the two crops in photosynthetic mechanisms. Corn, a C_4 crop, is able to efficiently use higher levels of solar radiation than is the C_3 crop soybean (Loomis, 1983). The high elevation (1170 m MSL) and clear skies at our semi-arid Bushland, Texas location result in high levels of solar radiation, which clearly favor corn over soybean. One result is that some of the highest county-wide corn yields in the US are found in the Texas Panhandle. The higher WUE of corn is one reason why this water-thirsty crop is widely grown in a region of declining water supplies.

CONCLUSIONS

For corn, the canopy temperature-time threshold method of irrigation control resulted in consistently excellent yield performance and water use efficiency in two years that differed widely in weather patterns. Yields and water use efficiencies were significantly lower for the manual method compared with the IRT method in 1997. It may be that, despite the results of Howell et al. (1997) to the contrary, an irrigation interval shorter than a week is necessary for consistently good results with manual irrigation on our soil. For soybean, although IRT treatments generally out-yielded manual ones, the differences were not significant, and there was no large dependence of WUE on treatment. Still, drip irrigation of soybean did result in larger yields, but not larger WUE values, than obtained with a similar variety in a previous three-year study at Bushland. In general, increasing the threshold time and increasing the threshold temperature both resulted in smaller irrigation applications for both crops, though results are less clear for soybean. It appears that manipulation of temperature and time thresholds will allow a choice between maximum yields and maximum water use efficiencies to be achieved for corn, but not for soybean.

Application of the IRT method resulted in consistent and reliable differences in corn canopy temperature measured in the field. The IRT method shows considerable promise for corn irrigation control. Still, there are important impediments to its implementation in commercial farming operations. These include sensor reliability and cost, issues of scaling the system to larger field areas, and the fact that day-long canopy temperatures for any one field area cannot be sensed from a moving center pivot irrigation system.

REFERENCES

1. Burke, J.J. 1996. Personal communication from USDA-ARS Crop Stress Research Laboratory, Lubbock TX.

2. Burke, J.J. 1993. Thermal kinetic windows of plant enzymes. *In* Biotechnology for arid plants. pp. 73-82.

3. 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 cmplex of photosystem II and seedling establishment in cucumber. Plant Phys. 102:295-302.

4. Eck, H.V., A.C. Mathers, and J.T. Musick. 1987. Plant water stress at various growth stages and growth and yield of soybeans. Field Crops Res. 17:1-16.

5. Evett, S.R., and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type moisture gages based on field calibration. Soil Sci. Soc. Amer. J. 59:961-968.

6. Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 1996. Canopy temperature based automatic irrigation control. Pp. 207-213 *In* C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.) Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling. Nov. 3-6, 1996, San Antonio, Texas, U.S.A. 1166 pp.

7. Howell, T.A., A.D. Schneider, and S.R. Evett. 1997. Subsurface and surface microirrigation of corn - Southern High Plains. Trans. ASAE 40(3):635-641

8. Loomis, R.S. 1983. Crop manipulation for efficient use of water: An overview. Pp. 345-374 *In* H.M. Taylor, et al. (eds.) Limitations to efficient water use in crop production. Amer. Soc. Agron., Crop Sci. Soc. Amer., Soil Sci. Soc. Amer., Madison, WI.

9. Upchurch, D.R., Wanjura, D.F., Burke, J.J., and Mahan, J.R. 1996. Biologically-Identified optimal temperature interactive console (BIOTIC) for managing irrigation. United States Patent 5,539,637, July 23, 1996.

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

11. Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1993. Canopy temperature controlled irrigation scheduling. Acta Horticulturae 335:477-490.

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

13. Wanjura, D.F., D.R. Upchurch, G. Sassenrath-Cole, and W.R. DeTar. 1995b. Calculating time-thresholds for irrigation scheduling. *In* Proceedings of the 1995 Beltwide Cotton Conferences, Jan. 4-7, 1995, San Antonio, TX.