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Canopy Temperature Based Automatic Irrigation Control

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ABSTRACT

Automatic irrigation control on the basis of a threshold canopy temperature has been shown feasible for cotton but has not been evaluated for corn. Triplicate drip irrigation plots were established on Pullman clay loam for seven irrigation treatments including weekly 100% replacement of water use, 67% of the 100% treatment, a dryland treatment, and four automatic irrigation treatments: a 28°C threshold applied to two decision intervals (15 min and 3 days), and a 30°C threshold applied to the two decision intervals. Corn yield for the 28°C, 15-min interval was significantly higher at 1.20 kg m^{-2} than for the 100% replacement but irrigation was also significantly higher (906 mm vs. 589 mm) causing deep drainage losses. For the 15-min, 30°C and 3-day, 28°C treatments irrigation was significantly lower than for 15-min, 28°C (625 and 585 mm, respectively) but yields were not significantly lower (1.20 and 1.06 kg m^{-2}, respectively) and were statistically equivalent to that for the 100% treatment. Water use efficiency was significantly lower for the 15-min, 28°C treatment, at 1.23 kg m^{-3}, than for the 15-min, 30°C, 3-day, 28°C and 100% treatments (mean of 1.36 kg m^{-3}). Automatic irrigation using threshold canopy temperature was more responsive to plant stress and showed the potential to outyield manual irrigation based on 100% replenishment of crop water use.

Keywords: Corn, Drip, Microirrigation, Real-time, Scheduling, Yield

INTRODUCTION

Irrigation scheduling and irrigation system control are interdependent processes that traditionally have been rather loosely coupled, most often requiring human intervention to initiate and quide the irrigation as well as oversee the scheduling process. A reliable automated, real time irrigation scheduling and control system has obvious advantages that include lower labor costs, lower plant stress levels, and lower water use. 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 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. (1995) received patent no. 08/261,510 for an irrigation management system based on optimal leaf temperature for enzyme activity. Our objective was to test this method for corn production under surface and subsurface drip irrigation in a replicated experiment using two threshold temperatures and two irrigation decision intervals.

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METHODS AND MATERIALS

The study area consisted of 21 plots on the Pullman clay loam, fine, mixed, thermic Torrertic Paleustoll at Bushland, TX. Each 10.7 by 27.4-m plot was planted to 12 rows of corn with 0.76-m row spacing. Half of each plot was surface irrigated with three drip lines (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. 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). Liquid urea was applied pre-plant at 202 kg/ha and urea was injected into the irrigation water at 75 mg L^{-1} from June 21 to August 7. Phosphoric acid was injected at 5.3 mg L^{-1} over the same interval 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 using a Campbell Pacific Nuclear, Inc. model 503DR moisture gage (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, using methods described by Evett and Steiner (1995).

Seven irrigation treatments were randomized in a split plot (surface and subsurface drip) design with three replications. Four of the treatments were implemented with two threshold canopy temperatures, 28° and 30°C; and two irrigation decision intervals, 15 min and three days. The 28°C threshold is the center of the thermal kinetic window for corn (Burke, 1996) and should be the optimum. The 30°C threshold was established to see if a 2°C increase would substantially decrease water use and yields. These four treatments, collectively called the IRT treatments, were designated 15min-28, 15min-30, 3day-28, and 3day-30 (Table 1). One treatment received only pre-plant irrigation and was designated Dryland. One of the remaining two treatments, designated 100%, consisted of weekly irrigations to replace 100% of crop water use as measured by neutron scattering to maintain a control level of 0.333 m^3 m^{-3} average water content in the top 1.5 m of soil. The final treatment, designated 67%, was irrigated weekly to provide 67% of the amount provided to the 100% treatment. The 67% and 100% treatments were identical to those used by Howell et al. (1994) on the same drip system except that they used Pioneer 3245. All plots were bermed to prevent runoff and runon.

The time threshold was determined to be 4 hours 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 number of hours in a day for which the canopy temperature of a well-watered crop, with a particular canopy resistance, exceeds the threshold temperature. 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.

[**]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.

Table 1. Treatments, and criteria and decision intervals for irrigation.

Treatment	Decision Criteria	Decision Interval
15min-28	Above 28°C mean canopy temperature during interval	15 minutes
15min-30	Above 30°C mean canopy temperature during interval	15 minutes
3day-28	More than 240 minutes above 28°C on 3rd day after irrigation	3 days
3day-30	More than 240 minutes above 30°C on 3rd day after irrigation	3 days
100%	Irrigate to bring profile water content up to 500 mm in top 1.5 m	weekly
67%	Apply 67% of the irrigation for the 100% treatment	weekly
Dryland	None, no irrigation	none

In the simplest case 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 corn at Bushland this was chosen as 10 mm from historical data. However, if irrigation system limitations require that irrigation can only be done every few days then the irrigation amount may be set to the peak ET multiplied by the number of days between irrigations. For our 3 day treatment the irrigation amount was set to three times the peak ET or 30 mm. The irrigation decision was made as follows. After an irrigation the system waited three days before irrigating again. This delay allowed the irrigation amount to be used if peak ET was occurring and avoided over-irrigating and possibly causing runoff or deep percolation losses. On the third day the system checked to see if the time threshold was exceeded and if so then another irrigation of 30 mm was applied. If not then the system checked the next day and each succeeding day until the threshold time was surpassed, triggering an irrigation. The counter for the threshold time was re-set to zero at midnight each day. The 15 minute IRT treatments were instituted without a time threshold per se. If the average temperature over a 15 minute interval exceeded the threshold temperature an irrigation was applied. The amount of the irrigation was calculated by dividing the peak ET by the number of 15 minute intervals in the time threshold. Since the time threshold was 4 hours and there are sixteen 15 minute periods in that time, the irrigation amount for the 15 minute treatments was 10/16 = 0.625 mm.

Canopy temperature was measured with thermocouple infrared thermometers (IRT) (Exergen Corp. model IRt/c.2-T-80, Newton, MA) digitized with a data logger (Campbell Sci. Inc. model 21x, 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. Measurements were made every second and mean values were stored every minute. 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). Flow to each IRT plot was measured redundantly using both a manual and an electronic flow meter (Data Industrial model 4002000022, Mattapoisett MA; or George Fischer Signet model 2530, Tustin, CA). An outboard pulse counter (Campbell Sci. Inc. model SDM-SW8A, Logan UT) was used to count electronic pulses from eight of the 12 meters - the other four were read directly by the data logger.

Liquid urea was injected before planting at 20.2 g m^{-2}. Due to the cool, wet spring no pre-plant irrigation was required. Corn (*Zea mays* L., hybrid Pioneer 3261) was planted on April 28, 1995, with Counter 20CR applied to control root worms (1.46 kg/ha terbufos), and had fully emerged by May 15. Neutron probe access tubes were installed and first read on May 9. A 76-mm irrigation was applied to all except Dryland plots on May 19 because the automatic system was not fully installed. Spring weather was unusually cool and June was particularly cool with mean maximum temperature 2°C cooler than the 20 year mean and mean minimum temperature 3°C cooler than the 20 year mean (Table 2). May brought almost twice the 20 year mean rainfall but June brought about 38 mm less than normal. The cool temperatures in May and June delayed plant growth and probably reduced yield potential. Although rain in July was a little above normal about 78% of this came in one rain on July 1 that caused runoff and runon from an upslope fallow field for some plots despite the berms. August rainfall was below normal and 95% of August rain came in one 51-mm rain on August 14 that again caused runon and runoff. Most of July and August was unusually dry and windy, especially during silking, further reducing yield potential. Electronic flow meters were installed on June 30 and the data logger was programmed and allowed to control irrigation. Analysis of variance of the results and Student-Newman-Keuls multiple range tests on the means were done using the COSTAT statistical analysis package (COHORT, Inc., Minneapolis, MN).

Table 2. Monthly weather means and historical means.

	Mean Precipitation (mm)				Mean Max. Air Temp. (°C)				Mean Min. Air Temp. (°C)			
	1993	1994	1995	20 year	1993	1994	1995	20 year	1993	1994	1995	20 year
April	14	41	55	24	21.1	20.9	20.3	21.1	2.3	2.8	1.8	3.9
May	56	56	115	66	24.7	24.3	23.3	24.8	9.1	10.1	8.3	9.3
June	65	51	39	77	30.3	34.3	28.3	30.1	14.5	16.1	13.1	14.8
July	100	128	82	64	32.6	32.3	32.4	32.3	18.2	16.7	16.0	16.9
Aug.	50	74	54	75	31.2	31.6	32.4	31.1	16.1	15.7	16.7	16.3
Sept.	14	44	73	59	31.9	28.2	26.4	27.3	9.8	11.6	12.1	11.8
Oct.	23	44	19	32	20.8	22.2	23.2	21.7	3.2	5.7	3.7	5.0

RESULTS

The initial ANOVA for the randomized split plot design showed that, while irrigation treatments were significant, the drip tube depth, either on the surface or at 0.3 m, had no significant effect on any of the six variables examined in Table 3. Therefore, further data analysis was done as a randomized design without the split plot factor. The 15-minute decision interval resulted in more water being applied for both the 28° (906 mm) and 30°C (625 mm) thresholds than did the three-day interval for the equivalent thresholds (585 mm and 535 mm for 28° and 30°C, respectively) (Table 3). For the same decision interval (15-min or 3-day) the 28°C treatments both applied significantly more water than the 30°C treatments. Water applied to the 100% replacement treatment was very close to that applied to the 3day-28 treatment, while the 67% treatment received significantly less water than all others except Dryland.

Due to the cool spring that limited evapotranspriation and irrigation, the above normal rain in May, and the equal irrigation applied on May 19, soil water in the upper 1.5 m of the profile remained about equivalent for all treatments through July 17 after which profile water began to diverge by treatment (Fig. 1). The 28°C treatments kept the profile wetter in the last month, apparently being more responsive to plant stress. All IRT controlled treatments tended to keep the profile wetter during the last five weeks than did the 100% replacement treatment. From May 9 to Sept. 11 profile water content through 2.5 m depth increased for three of the IRT treatments with the 15min-28 treatment resulting in significantly greater water content increase (Table 3). Change in storage for the 3day-30 treatment was negative and significantly lower during this period than that for the other IRT treatments and the 100% treatment. The 100% treatment added about the same amount as the 3day-28 treatment. All treatments including Dryland added water to the profile in the 1.5 to 2.5 m depth. The fact that even the Dryland treatment added water in the 1.5 to 2.5 m depth range indicates that the large rain of July 1 and 2 (65 mm) caused macropore flow resulting in deep water movement. Subtracting the average 5 mm increase in the 1.5 to 2.5 m depth range for the Dryland treatment from the increase in this depth range for all other treatments shows that irrigation alone added more than twice as much on the 15min-28 treatment as on any other treatment, resulting in this treatment attaining water contents exceeding the drained upper limit of about 500 mm (Fig. 2) and certainly causing loss of water to deep drainage.

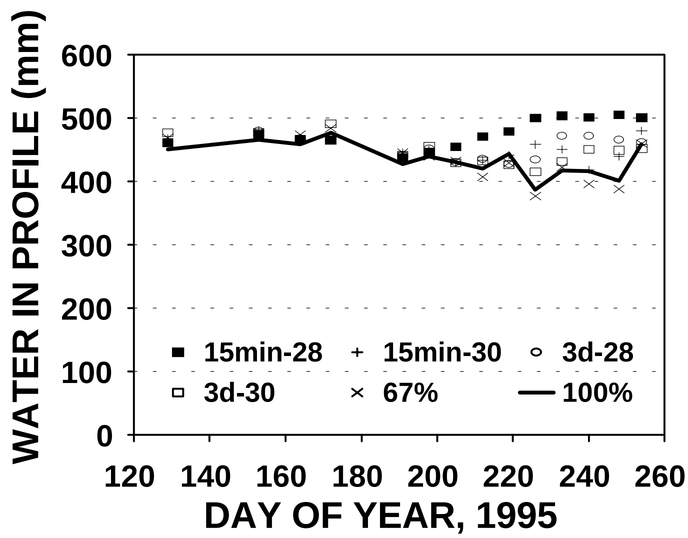

Figure 1. Water Content of the surface to 1.5 m deep soil profile over the 1995 season.

Table 3. Yield, Water Use, and Water Use Efficiency Results.

Treatment	Grain Yield† kg m^{-2}	Irrigation mm	Water Use‡ mm	WUE§ kg m^{-3}	Irrigation WUE kg m^{-3}	Change in Storage‖ mm
15min-28	1.198 a#	906 a	1067 a	1.125 b	1.330 b	80 a
15min-30	1.103 ab	625 b	805 b	1.368 a	1.765 a	33 b
3day-28	1.064 abc	585 b	768 b	1.384 a	1.816 a	19 bc
3day-30	0.933 c	535 c	724 c	1.286 a	1.740 a	-12 d
100%	1.029 bc	589 b	776 b	1.326 a	1.748 a	22 bc
67%	0.757 d	427 d	620 d	1.221 ab	1.775 a	-1 cd
Dryland	0 e	0 e	196 e	0 c	-	-75 e

† Oven dried grain.
‡ Sum of irrigation, precipitation and change in storage, assuming no runoff or deep percolation.
§ Ratio of dry grain mass to water mass per unit area.
‖ Change in profile water content from the surface to 2.5 m depth over the period May 9 to Sept. 11, 1995.
Numbers in columns not followed by the same letter are significantly different at the 0.05 level.

Due to rainfall, water use amounts were greater than irrigation amounts, but statistical differences between treatments were similar to those for irrigation amounts. Yields increased with amount of water applied in a curvilinear fashion (Fig. 2 and Table 3). The 15min-28 treatment yielded the most (significantly more than 3day-30, 100% and 67% treatments) but at the expense of 281 mm more water applied than for the next closest treatment, 15min-30. Yields were lower than previous years on the same plots but with a different hybrid (Pioneer 3245) (Table 2). The grain yield for the 100% treatment was 0.191 and 0.175 kg m^{-2} lower than yields for the same treatment in 1993 and 1994, respectively (Howell et al., 1994). For the 67% treatment, yield was lower by 0.332 and 0.400 kg m^{-2} than yields for the same treatment in 1993 and 1994, respectively. These lower yields in 1995 were probably due to the slow crop development due to a late spring and the hot, windy conditions during silking and grain fill. Water use efficiency (WUE) was significantly lower for the 15min-28 treatment than for all but the 67% and Dryland treatments. There was no significant difference in WUE between the 100% and the other three IRT treatments although the 3day-28 treatment gave the highest WUE at 1.38 kg m^{-3}. At 1.33 kg m^{-3} the WUE for 100% was lower than the values of 1.39 and 1.40 kg m^{-3} measured in 1993 and 1994 for this treatment. At 1.22 kg m^{-3} the WUE for the 67% treatment was lower than the 1.49 and 1.50 kg m^{-3} values recorded in 1993 and 1994, respectively. Irrigation WUE was significantly lower for the 15min-28 treatment than for all other irrigated treatments which were statistically identical.

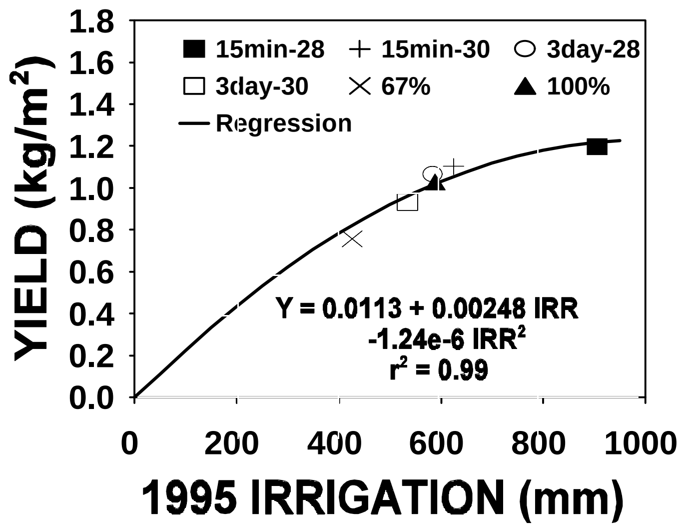

Figure 2. The yield (Y) vs. irrigation (IRR) relationship for corn grown in 1995.

CONCLUSION

The 15 minute time threshold resulted in over-irrigation and loss of water to deep drainage (15min-28 treatment) unless the temperature threshold was above the optimum (15min-30 treatment) established by studies of the thermal kinetic window. However, yields were 9% higher for the 15min-28 than for the 15min-30 treatment. Three temperature-time threshold methods all worked as well or better than the 100% replacement treatment from a yield point of view, and only the 15min-28 treatment applied significantly more water than the 100% treatment. On this basis we can conclude that the temperature-time threshold method can be successfully applied to drip irrigation of corn. Field observations indicated that the three day decision interval, even with a 28°C temperature threshold, often resulted in visibly stressed corn in July and August. Stress was particularly noticeable during silking. This is reflected in the lower yields for 3day-28 and 3day-30. A one day decision interval with a 28°C threshold temperature may prove better than any of the treatments applied in this study and will be evaluated in future studies using a corn-soybean rotation.

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