Irrigation Strategies For Optimizing Yield and Water Use Efficiency

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Abstract

Subsurface drip irrigation (SDI) can apply precise quantities of water uniformly along the row and enhance the efficiency of water use. The Biologically Identified Optimal Temperature Interactive Console (BIOTIC) irrigation timing protocol was used to control irrigation timing using two strategies for establishing different water levels in a cotton SDI study in 2002. Daily irrigation decisions for treatments in both strategies were determined by the different time threshold (TT) values required to generate irrigation signals. The TT were specific accumulations of stress time which were periods when canopy temperature exceeded 28°C during the daytime. One strategy maintained different constant rates of irrigation (CTT) and a second strategy varied irrigation (VTT) during four growth stages in proportion to each stage's yield sensitivity to water stress. The purpose of the study was to compare the yield and water use efficiency (WUE) of the two irrigation strategies. Three water levels were established with each strategy. Cumulative irrigations in the CTT strategy were 398, 313, and 201 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively. The VTT strategy had cumulative irrigations of 152, 262, and 318 mm for the LW, MW, and HW treatments. Lint yield increased with irrigation and total water for both irrigation strategies in a positive curvilinear manner. The 5.5 hr TT treatment in the CTT strategy and the MW treatment in the VTT strategy produced the best combination of high yield and high WUE. Irrigation and total water WUE values from both irrigation strategies had a common negative linear relationship with applied water, except for the 7.5 hr TT treatment which had lower WUE values. The performance of the CTT or VTT strategies in scheduling irrigation was inconsistent across water levels based on the criteria of yield and irrigation WUE.

Introduction

Crop yield and water use efficiency are factors which usually change in opposite directions to water application. Since these factors do not maximize at the same levels of water input a choice is made on which factor receives priority. If water supply is ample yield is emphasized as long as its incremental increase from additional water remains positive. Frequently water supply is limited and irrigation level is determined by the availability of water. Irrigated area in the U.S. in 1996 was around 20 Mha and annual applications were 500 mm, ERS (1997). Irrigated area had remained constant in recent years, but irrigation application declined from 650 mm in earlier years.

Lamm, et al., 1994 irrigated corn in level basins at 0.75, 1.0, and 1.25 times ET using daily deficits of 0, 1, and 2 mm/day after tasseling. Irrigations were applied when soil water depletion was approximately 65 mm. Yields were related linearly to irrigation and water use with a reduction in irrigation or water use reflected by yield reductions. Water use efficiencies (WUE) were similar whether planned soil water depletion was used or not. The influence of low energy precision application (LEPA) sprinkler irrigation and subsurface drip irrigation (SDI) systems on WUE of cotton was studied by Bordovsky and Lyle (1998) with application rates of 2.5, 5.0, and 7.6 mm/day. Cotton yields and water use efficiencies were significantly higher for SDI than LEPA. A three

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year SDI study with cotton examined the effect of different irrigation levels, row spacing, and planting patterns on WUE, Enciso-Medina, et al., (2002). The average WUE of the ultra-narrow row spacing (0.25 m or 0.26 m) for the three years was 12 % and 21% higher than the 0.76 and 1.02 m spacings, respectively.

The use of SDI is increasing on the southern high plains due to the diminishing supply of water from the Ogallala aquifer which is the primary water supply. The advantage of SDI over other irrigation methods is the reduction of water loss from evaporation. A disadvantage is the high initial cost to purchase the equipment and install the system. SDI can be used with a wide range of water supplies and the quantities applied can be precisely controlled. The capability of SDI to apply precise quantities of irrigation with a wide spectrum of application frequencies may make it possible to produce high yields with improvements in water use efficiency. The trade-offs between amount of irrigation and the efficiency of its use by crops in producing the yield component of total biomass need further study. We have investigated the BIOTIC methodology for timing irrigation and identified operational parameters that produce high yield without applying excessive irrigation (Upchurch , et al., 1996; Wanjura, et al., 1992; Wanjura, et al., 1995).

The objective of this paper is to describe the results from a one year field study where BIOTIC was utilized to vary seasonal irrigation using two strategies for timing irrigation application. One strategy maintained a constant crop water stress during the irrigation season and the other strategy varied irrigation frequency in proportion to the sensitivity of yield to water stress during different growth stages.

Materials and Methods

Two studies were conducted in adjacent blocks in the field of the Plant Stress and Water Conservation Laboratory at Lubbock, TX. The cotton variety Paymaster 2326 BGRR was planted on 13 May 2002 (DOY 133) in north-south rows having a spacing of 1 m. Most seedlings emerged by 20 May and the final seedling population averaged 50,500 plants/acre. One study examined the strategy of using constant time thresholds, (CTT) of 2.5, 5.5, and 7.5 hrs of canopy temperature above 28°C and the other study included three water levels designated as LW, MW, and HW, which utilized a strategy of variable time thresholds (VTT) that were changed during five growth stages. Both studies were watered with subsurface drip irrigation. The CTT study had laterals located under each bed and the VTT study had laterals under alternate furrows. Two 13 mm irrigations were applied through the subsurface drip irrigation system on 14 May and 16 May to ensure adequate moisture for germination.

The drip lateral diameter was 0.875 in ID with 0.23 gph emitters having a 24 in spacing. Each irrigation zone included 8 rows 542 feet long and was individually metered. An Elgal-Agro Controller Ver. 109 (Eldar-Shany, Yad Mordechai, 79145, Israel) was activated by a 5 mv signal from a Campbell Scientific CR 7 data logger that computed stress time values and generated irrigation signals from canopy temperature measured by infrared thermocouples located within plots.

The time-threshold (TT) is an integral part of the BIOTIC protocol for timing irrigation applications. Different TT values apply varying irrigation amounts which cause different soil water levels. The three irrigation treatments in the CTT study were controlled by TT of 2.5, 5.5, and 7.5 hr, which were selected to apply excessive, optimum, and deficient amounts of water. Canopy temperature > 28 °C, air temperature > 28 °C, and net radiation > 200 Wm^{-2} were required for a time interval to be added to the stress time accumulation for determining the occurrence of an irrigation signal. Irrigation signals were dependent on the amount of time above a canopy temperature of 28 °C (referred to as stress time) exceeding the TT for each irrigation treatment.

Irrigation decisions were made daily and a 5 mm irrigation was applied in response to an irrigation signal, which could be over-ridden by recent sufficient amounts of rain. The target amount of water application was 5 mm from either rain or irrigation. Rain events > 5 mm were accumulated and prevented irrigation until their accumulation was reduced to zero at the rate of 5 mm day^{-1}. When the daily accumulation of ST for an irrigation treatment failed to exceed the required TT, only 5 mm was applied after the next irrigation signal regardless, of the number of days between irrigation signals.

Both experiments were randomized complete block designs with four replications in the CTT study and three replications in the VTT study. The studies were sprayed with Ginstar on DOY 270 (27 September) to drop the leaves. Each plot was stripper harvested on DOY 316 to provide an estimate of lint yield.
In addition to monitoring canopy temperature in both studies, air temperature, relative humidity, net radiation, and windspeed were measured at a 2 m height and saved as 15 min averages.

Microclimate measurements and crop development data were collected only in the CTT study. Plant heights were measured weekly beginning on DOY 164 and bi-weekly biomass sampling started on DOY 171.

Results and Discussion

After planting, automated irrigation in each of the studies was delayed until cotton plant canopies had reached sufficient size to measure canopy temperature with infrared thermocouples without viewing the soil below the plants. Early season rain of 115 mm between DOY 155 and DOY 162 provided sufficient moisture for seedlings growth without irrigation, Fig. 1.

Automated irrigation began on DOY 170 in the CTT study and DOY 177 in the VTT study. Plants in both studies had reached the squaring growth stage when irrigation was started. The irrigation signal TT values remained constant for the entire irrigation period for each treatment in the CTT study. The TT values used for the VTT study are given in Table 1 for each growth stage. Lower TT values result in more irrigation during the season because the probability of accumulating sufficient stress time to trigger an irrigation signal is higher for each day.

Water Application

Irrigation after crop emergence was initiated on DOY 170 in the CTT and on DOY 177 in the VTT studies, Fig. 1. Cumulative irrigation was 398, 313, and 201 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively, in the CTT study. In the VTT study total irrigation was 152, 262, and 318 mm for the LW, MW, and HW treatments. Differences in irrigation application rate began on DOY 193 among treatments in both studies. The rate of irrigation application was different and constant for each treatment in both studies for most of the irrigation period following DOY 193. Cumulative irrigation was nearly equal between the MW and HW water levels in the VTT study through DOY 220.

Total rain during the growing season was 177 mm with 83% received by DOY 192. Total water applications in the CTT study were 577, 492, and 380 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively, Fig. 2. In the VTT study total water amounts were 490, 434, and 324 mm, respectively, for the HW, MW, and LW water levels.

The 5.5 hr TT and HW treatments received the same amount of irrigation and total water application. Irrigation signals were determined by a constant TT value in the 5.5 hr TT treatment and a combination of 3.0 hr TT and 5.0 hr TT in the HW treatment. The 5.5 hr TT treatment also started irrigating on DOY 170 compared with DOY 177 for the HW treatment.

Yield and Water Use Efficiency

The highest lint yield in the CTT study was 1588 kg ha^{-1} from the 2.5 hr TT treatment, but it was not statistically different from the 1555 kg ha^{-1} yield for the 5.5 hr TT treatment, Table 2. The 1018 kg lint ha^{-1} from the 7.5 hr TT was lower than from the other treatments. As a comparison the dryland yield was 307 kg lint ha^{-1}. In the variable time threshold study the lint yields of 1476 kg ha^{-1} and 1453 kg ha^{-1} for the HW and MW treatments, respectively, were similar and different from the LW yield of 1110 kg ha^{-1}.

The relationship of irrigation and total water applied during the season with lint yield and water use efficiency are compared in Fig. 3. Irrigation WUE values from both studies fit a common negative linear relationship with amount of irrigation, except for the 7.5 hr TT treatment. Total water WUE values show a similar relationship with water applied, including the anomaly of the 7.5 hr TT. The WUE values based on total water are lower than those based only on irrigation since rain is included in total water. Rain in proportion to irrigation ranged from 31% for the 2.5 hr TT treatment to 114% for the LW treatment.

Water use efficiency based on either irrigation or total water was negatively related with lint yield in both studies, Fig. 4. The trend lines do not include the 7.5 hr TT treatment since its response deviates from the pattern of the other treatments. The slope of the lint yield-WUE relationship is greater for irrigation than total water, primarily due to the large decrease from irrigation WUE to total water WUE in the LW treatment.

The most water limited treatments, 7.5 hr TT in the CTT strategy and the LW treatment in the VTT strategy, had contrasting responses to quantity of water application. The LW treatment received about 5 cm less irrigation than the 7.5 hr TT treatment but its yield was about 100 kg lint/ha higher, Table 2. The irrigation WUE for the LW treatment was 73 kg lint ha^{-1} cm^{-1} compared to 51 kg lint ha^{-1} cm^{-1} for the 7.5 hr TT treatment. One explanation for the different yield responses to limited water may be in the variation of irrigation applied over time. The 7.5 hr TT treatment received irrigations throughout the season that maintained a relatively constant level of moderately high water stress. The LW treatment received ample irrigation during the squaring growth stage, followed by limited irrigation during boll setting, followed by no irrigation during boll maturation, Table 1.Thus the LW treatment had low water stress up to first bloom, moderate water stress during boll setting, followed by relatively high water stress during crop boll maturation.

Among the treatments receiving high levels of irrigation the 5.5 hr TT treatment had a yield of 1555 kg lint/ha and the HW treatment produced 1476 kg lint/ha. However, the 5.5 hr TT had an irrigation WUE of 50 kg lint ha^{-1} cm^{-1} compared to 46 kg lint ha^{-1} cm^{-1} for the HW treatment. These treatments did not agree with the general trend of decreasing irrigation WUE as yield increases.

In the CTT strategy the 5.5 hr TT treatment produced 98% of the highest yield (2.5 hr TT treatment) with an irrigation WUE that was 98% of the highest irrigation WUE (7.5 hr TT treatment). In the VTT strategy the MW treatment produced 98% of the highest yield (HW) with an irrigation WUE that was 76% of the highest value (LW treatment).

Comparing between the two strategies the 5.5 hr TT treatment and the HW treatment at the high irrigation level received the same amount of irrigation, there were no differences in irrigation WUE, but lint yield of the 5.5 hr TT treatment was higher than the HW treatment yield. The 7.5 hr TT and LW treatments received the least amount of irrigation within their respective studies. Irrigation was higher in the 7.5 hr TT treatment than in the LW treatment with, yield and irrigation WUE being higher in LW treatment than for the 7.5 hr TT treatment. Thus the performance of the CTT or VTT strategies to scheduling irrigation were inconsistent across water levels based on the criteria of yield and irrigation WUE. It is important to emphasize that these are first year results of a planned multi-year study.

Conclusions

Cumulative irrigations in the CTT study were 398, 313, and 201 mm for the 2.5 hr TT, 5.5 hr TT, and 7.5 hr TT treatments, respectively. The VTT study cumulative irrigations were 318, 262, and 152 mm for the HW, MW, and LW treatments. Water use efficiency based on irrigation or total water from both studies fit a common negative linear relationship with amount of irrigation, except for the 7.5 hr TT treatment. The most water limited treatments, 7.5 hr TT in the CTT study and the LW treatment in the VTT study, had contrasting yield (1018 kg lint/ha versus 1110 kg lint/ha) and irrigation WUE (51 kg lint ha^{-1} cm^{-1} versus 73 kg lint ha^{-1} cm^{-1}) responses to quantity of irrigation applied (201 mm versus 152 mm). Among the high irrigation treatments the 5.5 hr TT treatment had a yield of 1555 kg lint/ha and the HW treatment produced 1476 kg lint/ha. However, the 5.5 hr TT treatment had an irrigation WUE of 50 kg lint ha^{-1} cm^{-1} compared with 46 kg lint ha^{-1} cm^{-1} for the HW treatment. The performance of the CTT or VTT strategies to scheduling irrigation was inconsistent across water levels based on the criteria of yield and irrigation WUE.

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Table 1 Time thresholds used to control irrigation during five growth stages in the three water levels of the variable time threshold study, 2002

Growth Stage ID	Growth Stage Description	Crop Water Level LW	MW	HW
		- - - Time Threshold, hours - - -		
GS 1	Emergence to First Square [1]	NI	NI	NI
GS 2	First Square to First Bloom DOY 177 – DOY 190 [2]	3	3	3
GS 3	First Bloom plus 2 weeks DOY 191- DOY 204	7	5	3
GS 4	Peak Bloom plus 3 weeks DOY 205 – DOY 233	7	5	3
GS 5	Boll Maturity (80 % open bolls) DOY 234 [3]	NI	7	5

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[1] Rain between DOY155 - DOY162 was 115 mm when seedling leaf area was too small to measure canopy temperature without also viewing some bare soil.

[2] Automated irrigation was delayed beyond first square because infrared thermometers were viewing some bare soil through the canopy on DOY 171 and 113 mm of rain fell between DOY155 - DOY162, which allocated 5 mm of rain per day for seedling use.

[3] Final irrigations were applied on DOY 231, DOY 250, and DOY 255 to the LW, MW, and HW crop soil water levels, respectively.

Table 2 Yield, water application, and water use efficiency for time-threshold irrigation and water use efficiency studies, 2002

Time Threshold Treatments	Lint yield, kg ha $^{-1}$	Total Irrigation cm	Total Water cm	Water Use Efficiency Irrigation, kg lint ha $^{-1}$ cm $^{-1}$	Total Water,
		Constant Time Threshold Study			
2.5 hr	1588 a [1]	39.8	57.7	39.9	27.5
5.5 hr	1555 a	31.3	49.2	49.7	31.6
7.5 hr	1018 b	20.1	38.0	50.6	26.8
		Variable Time Threshold Study			
LW	1110 b	15.2	32.4	73.0	34.3
MW	1453 a	26.2	43.4	55.5	33.5
HW	1476 a	31.8	49.0	46.4	30.1
Dryland	307	- - -	17.7	- - -	17.3

[1] Lint yields followed by a common letter are statistically similar at the 0.01 probability level according to Duncan's Multiple Range Test.

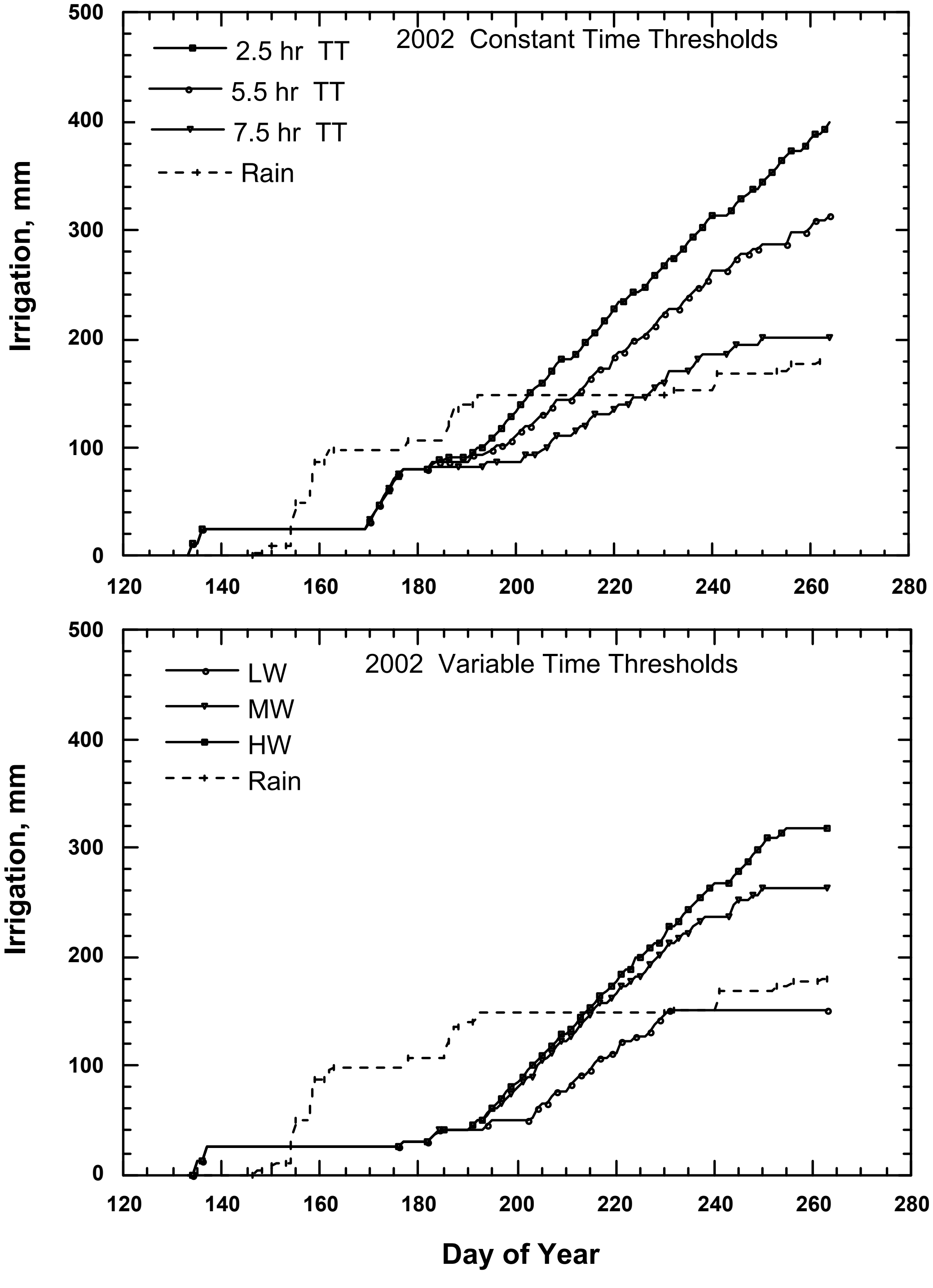

Fig. 1 Cumulative irrigation for constant and variable time threshold studies, 2002

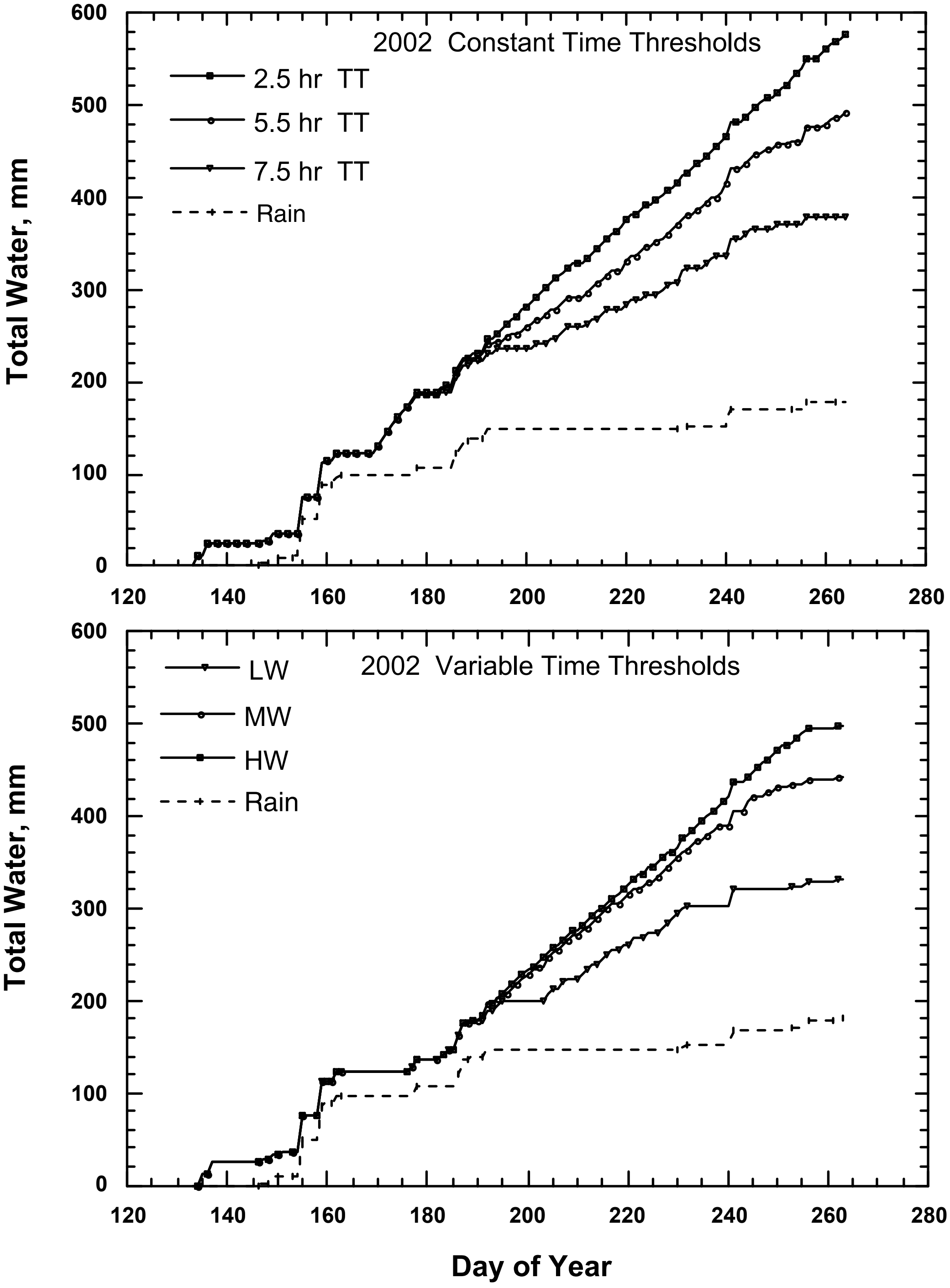

Fig. 2 Total water application for constant and variable time threshold studies, 2002.

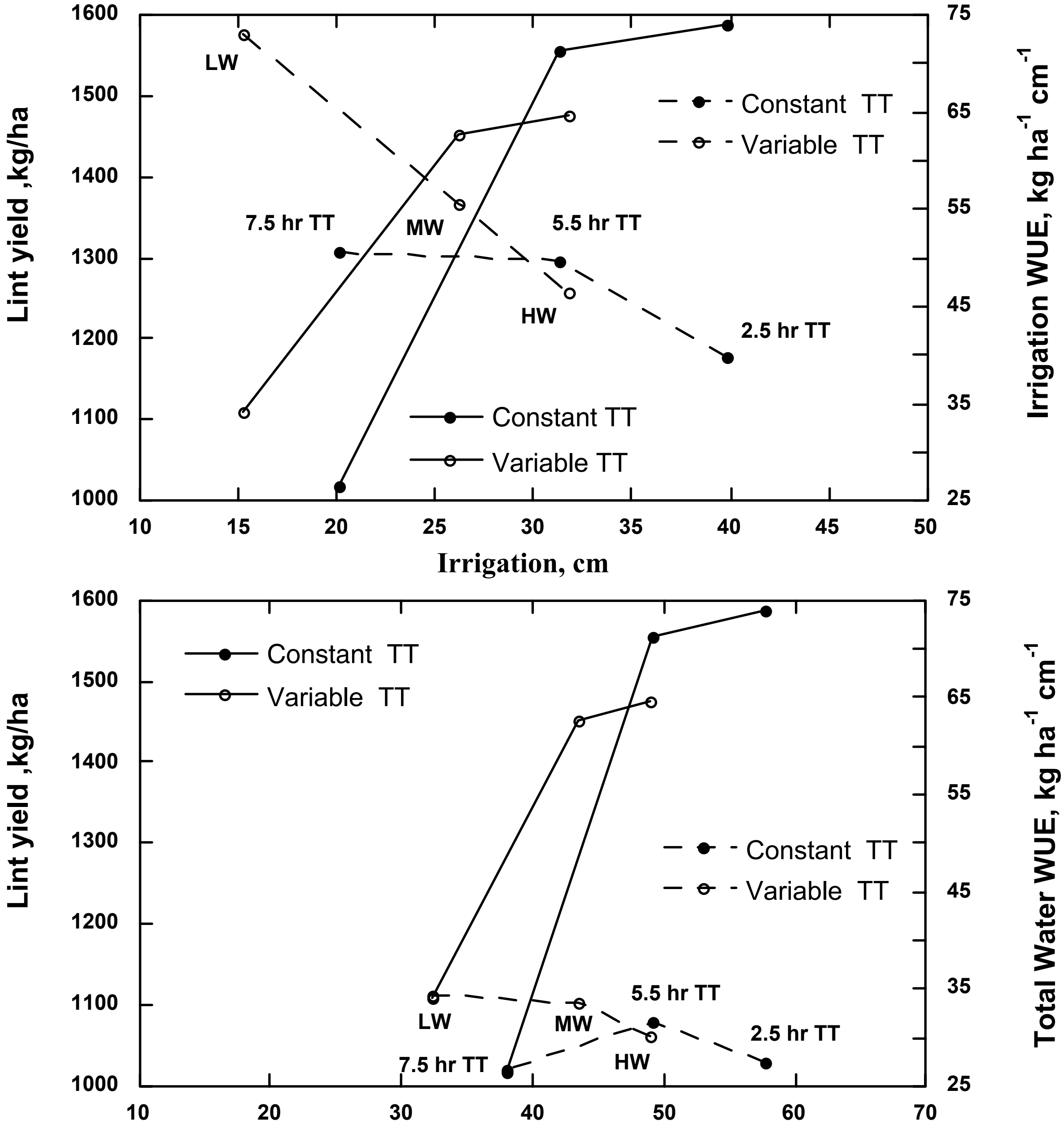

Fig. 3 Relationship of irrigation and total water with lint yield and water use efficiency for constant time threshold and variable time threshold strategies, 2002

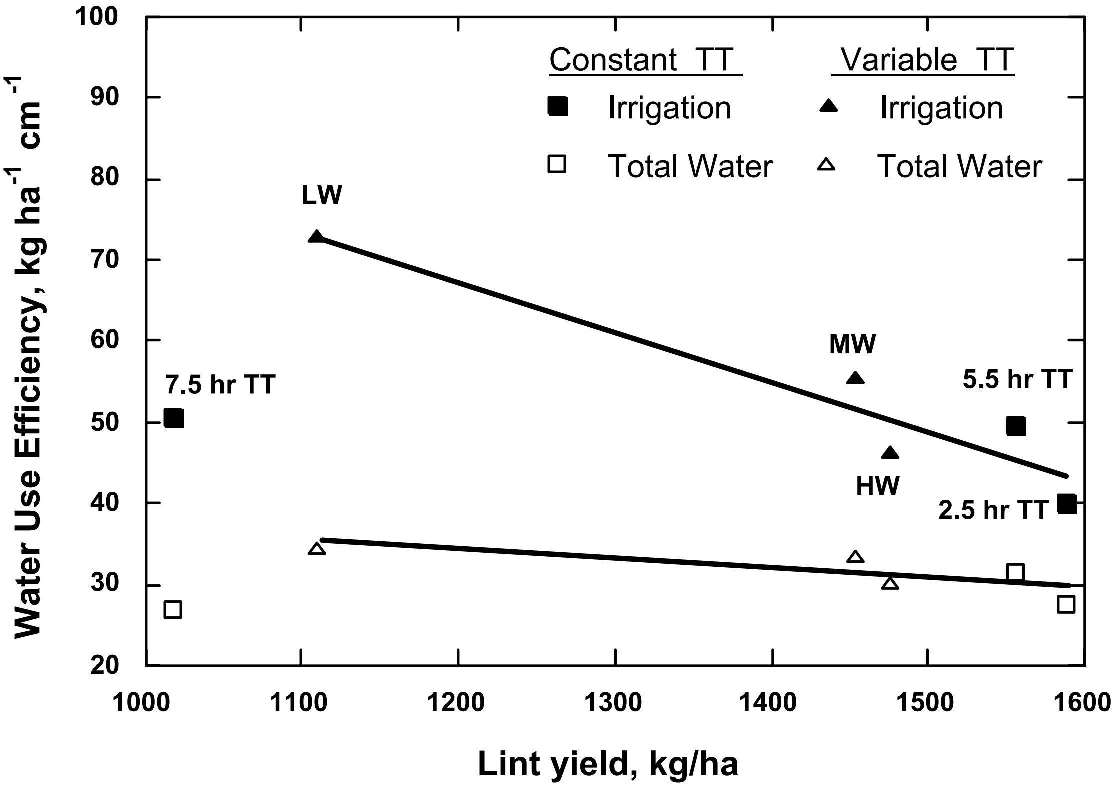

Fig. 4 Lint yield relationship with water use efficiency for constant time threshold and variable time threshold strategies, 2002.