Estimating Cotton Water Stress for Production Management

D.F. Wanjura and D.R. Upchurch
USDA-ARS, Cropping Systems Res. Lab., Route 3, Box 215, Lubbock, TX 79401, USA.

ABSTRACT

Crop water stress evaluation is essential for accurate irrigation scheduling. Cotton was grown in 1997 using four irrigation levels where canopy temperatures (TC) were continuously measured with infrared thermometers. Water level treatments were rainfall (WL1)-, 1/3 ET (WL2), 2/3 ET (WL3), and 1.0 ET (WL4). This report compares the accuracy of different stress indices for describing crop water stress. The first method for estimating water stress was the daily summation of stress time (ST) when TC exceeded 28°C. The second method was the Crop Water Stress Index (CWSI) that included a theoretical procedure, CWSI-T, and the empirical method, CWSI-E. ST was compared for three daily periods- Midday, Daytime and Entire Day defined by threshold levels of net irradiance and air temperature. Cotton ST for the Daytime and Entire Day increased as the amount of water applied declined and was significantly different among all water levels. The CWSI-T and CWSI-E values also declined as the quantity of water applied increased. CWSI-E was more accurate than CWSI-T because its stress values for the well-watered treatment WL4 were zero and values for all water levels were within the theoretical range of 0 to 1.0. CWSI and ST were linearly related with yield.

Introduction

Cotton is irrigated to control plant water stress level in order to optimize yield. Cotton is a drought tolerant crop but readily responds to irrigation. While irrigation is essential in arid environments and used in semi-arid environments when available, there are usually periods in humid climates when supplemental irrigation will increase yield. Irrigation scheduling that supplies correct quantities of water results in efficient water use and economical yield.

The earliest detectable external symptom of crop water stress occurs during the daytime period of high energy influx as higher plant canopy temperature compared to a well-watered crop canopy. Research has focused on the measurement and interpretation of canopy temperature (TC) for application in developing management tools for cotton production (Burke *et al.*, 1990; Wanjura *et al.*, 1992; Wanjura and Upchurch, 1997). Mahan *et al.* (1990) identified thermal kinetic windows for several crops where plant physiological processes occur at maximum efficiency. The concept of an optimum crop temperature is used in an irrigation scheduling method that accumulates time above a threshold temperature (Wanjura *et al.*, 1992).

The objective of this report is to compare different procedures for quantifying crop water stress that use canopy temperature.

Procedure

Crop Water Stress Analysis. Daily stress time (ST) was the first indicator. This is the accumulation of time when cotton TC > 28°C and calculated as: $ST = \sum(t_i)$; where t_i is a time period when TC > 28°C. The other method for characterizing water stress was the Crop Water Stress Index (CWSI). CWSI considers the whole environment surrounding the plant so its values should be comparable across locations. The CWSI is scaled between 0 and 1.0, where 0 is completely non-water-stressed and 1.0 is completely water stressed because no water is available for transpiration. Daily periods for calculating CWSI were limited to those when energy flux was high enough to impose a limitation on crop transpiration if soil water content was low. These conditions were net irradiance (Rn) ≥ 200 W m^{-2}, air temperature(Ta) ≥ 28°C, vapour pressure deficit ≥ 2.0 kPa, and windspeed ≥ 1.5 ms^{-1}. CWSI analysis only included days of the growing season when LAI in the irrigated treatments was above 1.0.

The empirical CWSI method is based on defining baselines that represent a completely non-water-stressed and a completely water-stressed canopy (Fig. 1). The completely non-water-stressed reference level of CWSI (0.0) is the sloping straight line. The completely water-stressed reference of CWSI (1.0) is the horizontal line calculated with a procedure described in Idso *et al.* (1981). The two baselines can also be defined from the theoretical method of Jackson *et al.* (1982). The sloping line of Fig. 1 is usually computed by regression between (Tc - Ta) and VPD. CWSI is represented in Fig. 1 as the vertical distance from the measured point to the sloping line (c - b) divided by the total vertical distance (c - a) between the two lines passing through the same point.

$$CWSI = \frac{(c - b)}{(c - a)} \quad (1)$$

An alternative empirical method for calculating CWSI requires a reference plot of well-watered cotton. The method of Idso *et al.* (1981) is applied to calculate the maximum canopy temperature (TCmax) for zero transpiration at VPD = 0 or the theoretical method, Jackson *et al.* (1982) is solved for the same condition. TC for the non-water-stressed plot (TCmin) is measured in addition to canopy temperatures in other treatments (TCi). Then Equation 2 calculates

$$CWSI - E = \frac{(TCi - TCmin)}{(TCmax - TCmin)} \quad (2)$$

The theoretical method of Jackson *et al.* (1982) is used to compute the stress index designated as CWSI-T.

Field Study. Cotton cultivar Paymaster HS 26 was grown under four soil water regimes at Lubbock, TX in 1997. Water level treatments were rainfall (WL1), 1/3 ET (WL2), 2/3 ET (WL3), and 1.0 ET (WL4). An average ET value of 7 mm d^{-1} represented the 1.0 ET water level for cotton. Subsurface drip irrigation with laterals at 1.0 m was applied at 3-day intervals unless at least 14 mm of rain fell between irrigations. Water level treatments were in randomized blocks with four times replications. Plot size was 12 rows wide by 12 m long.

The trials were planting on May 15 1997 with a row spacing of 1.0 m. Fertilization was 90-kg N ha^{-1} injected into beds on April 21. Prowl was applied before planting with pre-emergence Caporal. The soil type was Olton series (fine, mixed, thermic Aridic Paleustolls). Hand-harvested subplots of each plot. 1 m by four rows were used to assess yields.

An automated weather station sampled and stored 15-min averages of windspeed and direction, dry bulb and wet bulb air temperature, and Rn all at 2 m above the ground. An automated rain gauge measured rainfall and infrared thermometers the temperature of the top surface of plant canopies.

Results and Discussion

Irrigation commenced on June 30 at first square and was terminated on September 15. Twenty irrigations of 21 mm each were applied. Total water applied as rainfall and irrigation was 192, 356, 462, and 596 mm to water levels WL1, WL2, WL3, and WL4, respectively (Table 1).

Stress Time. The period in the analysis for all water stress indicators was day-of-year (DOY) 200-258 (July 19 through September 15). Table 2 shows average ST for the four water levels in for the daily periods Midday (Rn > 200 Wm-2 and Ta > 28 °C), Daytime (Rn > 10 Wm-2 and Ta > 24 °C), and for the Entire day (24-hours). Midday ST were smaller than either Daytime or Entire day ST, demonstrating that cotton TC remained above its crop specific optimum when Rn was below 200 Wm-2 and Ta was below 28°C. ST values for Daytime and Entire Day periods were similar, indicating that TC rarely remained above 28°C after sunset or during early morning after sunrise. All water levels had significantly different ST values during Daytime and the Entire Day and were inversely related to the amount of water applied.

Crop Water Stress Index. Seasonal CWSI-T values declined as the quantity of water was increased, i.e., 0.42, 0.22, -0.15, -0.41, respectively for WL1, WL2, WL3, and WL4.Negative CWSI-T values for WL3 and WL4 indicate low water stress. The CWSI-T values did not conform to the theoretical range of 0 to 1.0. This discrepancy is likely due to errors in the calculated values of ra, canopy resistance, rc, and the value for canopy resistance of non-water stressed cotton, rcp, chosen as 20 sm-1.

In the CWSI-E method TCmax was calculated and the measured TC of water level WL4 represented TCmin. The CWSI-E method forced values for water level WL4 to be zero. CWSI-E also decreased as the amount of water applied in the four water level treatments increased, i.e., 0.54, 0.40, 0.16, and 0.0, for WL1, WL2, WL3, and WL4, respectively.

Midday Hourly CWSI. The variation in CWSI during the Midday period was examined by calculating 15-min average values at hourly intervals (Fig. 2). Time periods before 1200 h on most days were deleted by the limitation of Ta > 28°C. The variation in CWSI was generally less than 0.2 units with maximum values at 1400 h or 1500 h. The range of CWSI-T values at WL4 was greater than CWSI-E because the latter method gives all zero values. These CWSI estimates agree with the recommendation that single time of day measurements of CWSI should not begin before about solar noon (Gardner *et al.*, 1992).

Water Stress and Yield. CWSI-T for cotton showed a negative linear response to water level, Fig. 3.The relationship of CWSI-E with water level is also negatively linear but with a smaller slope. WL1 yield for cotton was 24 % of WL4 yield and WL1 average CWSI ranged from 0.42 to 0.54 depending on which method was used for computation. Water level had a positive linear effect on yield (Fig. 3).

Both ST and CWSI were linearly correlated with lint yield, Fig. 4.The coefficient of determination for ST and lint yield was 0.80 for the Midday period and 0.98 for the Daytime and Entire Day periods. The slope of the yield line for the Midday period, which is steeper than for Daytime and Entire Day periods, would require more accuracy in measuring ST. The reduced level of correlation during the Midday period agrees with the degree of statistical separation of ST in Table 2 among water levels. Lint yield declined as CWSI increased for each method used to estimate CWSI. Linear coefficients of determination were 0.96 for both CWSI methods.

Conclusions

Daily stress times (ST) computed for Daytime and Entire Day periods increased as applied water declined and differed significantly among water levels. The most accurate values of CWSI were computed with the empirical method CWSI-E. ST and CWSI values were linearly related to yield. The CWSI method of characterizing water stress is potentially accurate for across environment comparisons but it is more difficult to use than ST because of additional environmental factors that must be measured or computed. ST was a sensitive indicator of water stress but its consistency among years and locations requires further evaluation.

References

Burke, J.J., J.L. Hatfield and D.F. Wanjura. (1990): A thermal stress index for cotton. Agron. J. 82:526-530.

Gardner, B.R., D.C. Nielsen and C.C. Shock. (1992): Infrared thermometry and the crop water stress index. II. Sampling procedure and interpretation. J. Prod. Agric. 5:466-475.

Idso, S.B., R.D. Jackson, P.J. Pinter, Jr., R.J. Reginato and J.L. Hatfield. (1981): Normalizing the stress-degree day parameter for environmental variability. Agric. Meteor. 24:45-55.

Idso, S.B. (1982): Non-water-stressed baselines: A key to measuring and interpreting plant water stress. Agric. Meteor. 27:59-70.

Jackson, R.D., S.B. Idso, R.J. Reginato and P.J. Pinter Jr. (1981): Canopy temperature as a crop water stress indicator. Water Resources Res. 17:1133-1138.

Mahan, J.R., J.J. Burke and K.A. Orzech. (1990): Thermal dependence of the apparent K_m of glutathione reductase from three plant species. Plant Physiol. 93:822-824.

Wanjura, D.F. and D.R. Upchurch. (1997): Accounting for humidity in canopy-temperature-controlled irrigation scheduling. Agric. Water Mgt. 34:217-231.

Wanjura, D.F., D.R. Upchurch and J.R. Mahan. (1992): Automated irrigation based on threshold canopy temperature. Trans. ASAE 35:1411-1417.

Table 1. Irrigation and agronomic summary for cotton field study, 1997.

Water Level	Total Water Applied, cm	Population plants ha^{-1}	Yield[1/] kg lint ha^{-1}
WL1	19.2	112,200	365 d[1]
WL2	35.6	120,300	855 c
WL3	46.2	124,800	1251 b
WL4	59.6	119,300	1510 a

1/ Yields for the same crop followed by a common letter are statistically equal at the 0.05 level of probability according to Duncan's Multiple Range test.

Table 2. Average daily time above 28 °C (ST) during three daily time intervals for cotton grown under four water levels, 1997.

Water Level	Time above 28°C, hours / day		
	Midday	Daytime	Entire Day
WL 1	5.54 a [1]	8.51 a	8.61 a
WL 2	5.51 a	7.79 b	7.82 b
WL 3	5.24 b	6.57 c	6.57 c
WL 4	4.86 c	5.92 d	5.93 d

1/ ST values for the same time period followed by a common letter are statistically equal at the 0.01 level of probability according to Duncan's New Multiple Range Test.

Figure 1. Empirical method for calculating the crop water stress index CWSI = (c-b)/(c-a).

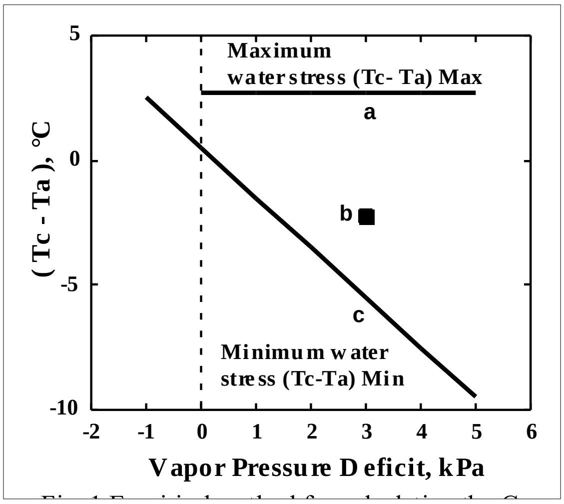

Figure 2. Hourly CWSI – T and CWSI – E values for cotton averaged for the period DOY 200 – 258, 1997.

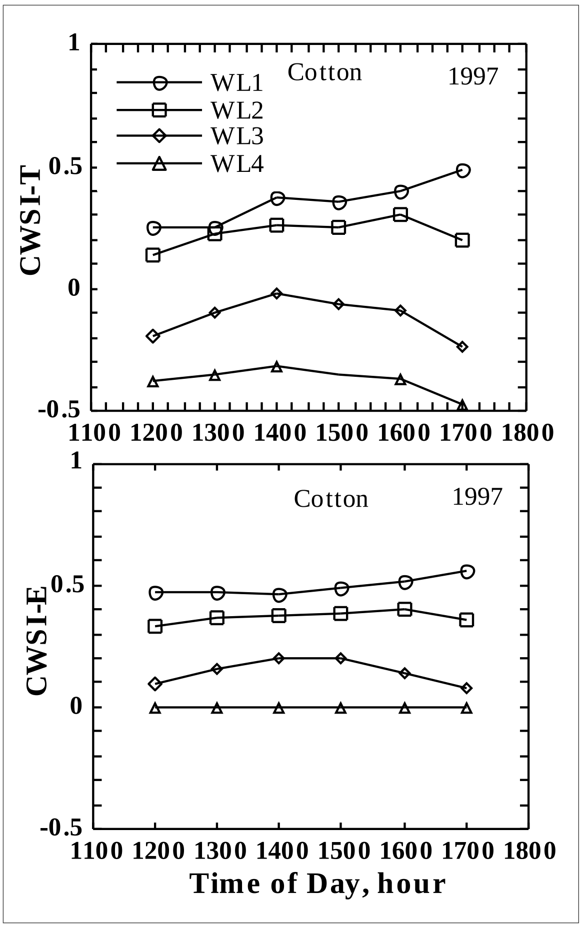

Figure 3. Relationship of water level with crop water stress index and lint yield, 1997.

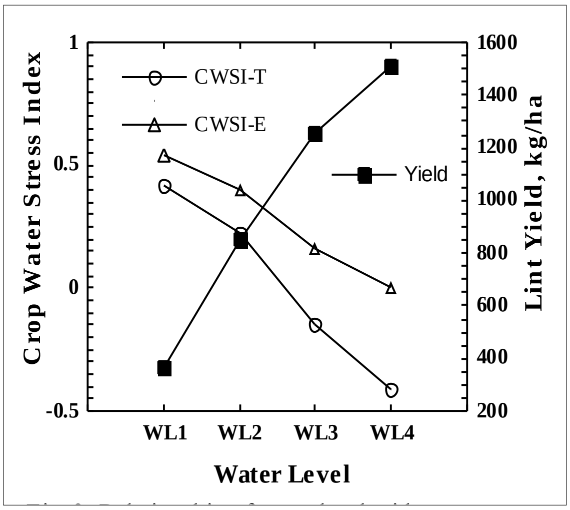

Figure 4. Relationship of ST for three daily periods and the CWSI with cotton yield, 1997.