Irrigation Scheduling Based on Crop Canopy Temperature for Humid Environments

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Abstract. *The use of infrared thermometers (IR) to measure canopy temperatures for irrigation scheduling has been successfully applied in arid environments. Functionality of this technique in humid areas has been limited due to the presence of low vapor pressure deficits (VPD) and intermittent cloud cover. This study evaluated an alternate scheduling method for humid environments based on comparing measured canopy temperature with calculated canopy temperature of a well-watered crop. Irrigation was applied when the measured canopy temperature was greater than the predicted canopy temperature for more than three consecutive hours on two consecutive days. This method was evaluated against well-watered, semi-stressed, and dryland treatments of corn, soybean, and cotton on the basis of yield, irrigation amount, and irrigation water use efficiency (IWUE). Canopy temperature was underpredicted when the VPD was greater than 2 kPa. Limiting data to conditions when the solar radiation was greater than 200 W m^{-2} and the Richardson number was less than 0.2 resulted in very good prediction of canopy temperatures for cotton and soybean, particularly in the later growing period, but corn temperatures were consistently underpredicted. Although soybean and cotton yields were not significantly different across treatments, IWUE was improved for corn and cotton by use of this technique. Corn yield was greater for the well-watered crop, but the IR method resulted in 85% of the maximum yield while requiring less than 50% of the irrigation water. Results from this study suggest that the threshold temperature may be up to 1°C greater for corn and soybean and up to 0.5°C greater for cotton for humid compared to arid environments. This method shows potential as a tool for irrigation scheduling in humid environments. Further work is suggested to determine if conditions of excessive cloud cover and high VPD can be better accommodated, and to refine the threshold temperatures for corn, soybean, and cotton for humid environments.*

Keywords. *Infrared thermometer, Vapor pressure deficit, Water use efficiency.*

Irrigated acreage in the U.S. has continued to expand, especially in humid regions where irrigation is often used to supplement rainfall during the growing season (Frank, 2001). As in arid regions, water inputs can be reduced through proper irrigation scheduling to achieve improved irrigation water use efficiency (IWUE). This has become more important in recent years as energy costs for pumping have increased. Numerous irrigation scheduling methods are available, varying in complexity and functionality (Thompson et al., 2002). These include evaporation pans, soil-based methods using tensiometers or gypsum blocks, weighing lysimeters, evapotranspiration (ET) models, or by indirectly relating crop water status to canopy temperature. The chosen method is often dictated by ease of use, available data, and the required degree of accuracy.

Canopy temperature measurement with infrared thermometers has been an effective tool for irrigation scheduling in semi-arid and arid conditions (Evett et al., 2000). Canopy temperature can be an indicator of plant water status because a non-stressed plant transpires, cooling its environment. Stomatal closure on a water-stressed plant will suppress transpiration, raising its temperature (Jackson, 1982). Wiegand and Namken (1966) first used canopy temperature to determine plant water stress. However, irrigation scheduling using this concept was impractical until hand-held infrared thermometers became commercially available (Gardner et al., 1992).

One of the first approaches for irrigation scheduling based on canopy temperatures used stress degree days (SDD) (Jackson et al., 1977). In this method, the only measurements needed are the canopy and air temperatures, and the only calculation is the difference between the canopy and air temperatures ($T_c - T_a$). The SDD was described by Jackson et al. (1977) as:

$$\mathrm{SDD} = \sum_{n=i}^{N} (T_c - T_a)_n \qquad (1)$$

which is the sum of the difference in canopy and air temperatures over $n = 1$ to N days. This method requires one measurement a day, taken between 1 to 2 h after solar noon.

A shortcoming of the SDD method is that it ignored additional environmental factors influencing plant stress and water status, including vapor pressure deficit (VPD), wind speed, and net solar radiation. To adjust for these factors, Idso

Submitted for review in December 2010 as manuscript number SW 8985; approved for publication by the Soil & Water Division of ASABE in October 2011.

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et al. (1981) proposed the crop water stress index (CWSI). They found a linear relationship for a given crop water status by plotting the difference between canopy and air temperature versus VPD, with the upper limit being the non-transpiring baseline and the lower limit being the well-watered (non water-stressed) baseline. The well-watered baseline had a negative slope, meaning that at high VPD the air temperature was much greater than the canopy temperature. For a non-transpiring crop, there was no change in the difference between canopy and air temperature with changing VPD, but the entire line shifted up with an increase in air temperature. The CWSI is calculated as:

$$\mathrm{CWSI} = \frac{T_c - T_{\max}}{T_{\min} - T_{\max}} \tag{2}$$

where

$T_{\max}$ = point on the non-transpiring line (°C)

$T_{\min}$ = point on the well-watered baseline, calculated at the same VPD as T_c (°C).

This relationship was linear for corn, cotton, and soybean, but the slopes and intercepts of the well-watered baseline differed among crops.

Development of the well-watered baseline has limited this procedure. Idso (1982) developed well-watered baselines from previous years' data, giving correlation coefficients for different crops between 0.86 and 0.998. However, the baseline needed to be developed for each specific site and crop. Jackson et al. (1981) developed a theoretical baseline, eliminating the need for well-watered crop data. The equation for this theoretical baseline can be written as:

$$T_c - T_a = \frac{r_a(R_n - G)}{\rho c_p} \cdot \frac{\gamma(1 + r_c/r_a)}{(\Delta + \gamma(1 + r_c/r_a))} - \frac{e_a^* - e_a}{(\Delta + \gamma(1 + r_c/r_a))} \tag{3}$$

where

T_c = canopy temperature (°C)

T_a = ambient air temperature (°C)

γ = psychrometric constant (Pa °C^{-1})

Δ = slope of the saturation vapor pressure vs. temperature curve (Pa °C^{-1}) calculated at $(T_c + T_a)/2$

r_a = aerodynamic resistance to heat flow between the surface and the reference height (s m^{-1})

r_c = canopy resistance to vapor transport (s m^{-1})

ρ = air density (kg m^{-3})

c_p = specific heat at constant pressure (J kg^{-1} °C^{-1})

R_n = net radiation (W m^{-2})

G = soil heat flux (W m^{-2})

$e_a{}^*$ = saturated vapor pressure at air temperature (Pa)

e_a = actual vapor pressure of the air (Pa).

The non-transpiring baseline can also be calculated using equation 3 by assuming that r_c approaches infinity for a non-transpiring crop. Equation 3 then becomes:

$$T_c - T_a = \frac{r_a(R_n - G)}{\rho c_p} \tag{4}$$

A problem with previous methods based on the CWSI is that at low vapor pressure deficits the non-transpiring and well-watered baselines are too close together to accurately determine CWSI, a problem that is exacerbated by any deviation between the calculated baseline and the actual behavior of a well-watered crop under the particular field conditions. Therefore, the method has not been recommended for use in humid environments (Jones et al., 1997). To correct for this limitation, alternate methods to determine the well-watered baseline have been proposed. Gardner et al. (1992) used the canopy temperature of a well-watered plot to calculate this specific baseline; however, this requires a separate irrigation treatment, which may not be practical.

Alves et al. (2000) assumed that a well-watered canopy surface temperature equaled the wet-bulb temperature, simplifying the calculation of the well-watered baseline and eliminating r_c. By calculating the difference in actual vapor pressure of the air at the surface and at the reference height of the temperature probe, the well-watered baseline was defined as:

$$T_c - T_w = \frac{\gamma}{\Delta + \gamma} \frac{r_a}{\rho c_p}(R_n - G) \tag{5}$$

where

T_c = canopy temperature at the surface

T_w = wet bulb temperature at the reference height.

Use of this equation requires that the crop be well-watered and fully transpiring. Equation 5 can also be derived by calculating the wet-bulb temperature of the surface using the difference in actual vapor pressure between the surface height and the reference height, and applying the concept of latent and sensible heat flux. Assuming the canopy resistance is much smaller than the aerodynamic resistance, and applying the saturation vapor pressure curve for T_w (Monteith and Unsworth, 1990), Alves and Pereira (2000) showed that equation 5 was a good estimator of canopy temperature in iceberg lettuce. However, little research has been conducted to validate this in other crops or non-Mediterranean climates.

An alternate irrigation scheduling approach based on canopy temperature in arid or semi-arid regions is the use of a temperature-time threshold. Conceptually, the temperature threshold is the limiting crop temperature and the time threshold is based on how long the crop can be above that temperature without being stressed. For corn, cotton, and soybean, temperature thresholds were based on the optimum canopy temperatures for peak photosynthetic enzyme activity, which were found to be 28°C, 28°C, and 27°C, respectively (Wanjura and Upchurch, 2000; Evett et al., 2000). Wanjura et al. (1995a) tested several different time thresholds between 2 and 8 h in cotton. In two years of tests, they found that a time threshold of 4 to 6 h gave the same yields as the shorter time thresholds, but with less water applied (Wanjura et al., 1990). This method worked well in arid environments, resulting in higher yields and water use efficiencies (Evett et al., 2000).

In humid environments, canopy temperature may exceed the threshold without crop stress due to the limiting relative humidity defined as "the minimum level of relative humidity of the air surrounding the canopy that increases canopy temperature by limiting transpiration" (Wanjura and Upchurch, 1997). To overcome this problem, Wanjura and Upchurch (1997) proposed that if relative humidity was above the limiting value, the time represented by those data was not added to the daily total. In humid environments, Wanjura et al. (1995b) found that the optimum temperature difference between the threshold and maximum wet-bulb temperature was

2°C to 4°C. They also proposed increasing the time threshold to compensate for the time that the plant is above its optimum canopy temperature, but not truly water-stressed. However, excluding these data points could eliminate days of high humidity from the time-temperature threshold calculation even though actual water stress was present.

Sadler et al. (2002) showed that infrared thermometers could be used to measure water stress at different locations within a field. They showed that the canopy temperature could be a useful tool to address in-field variability with sandy soils. Peters and Evett (2008) demonstrated that it was possible to completely automate a center pivot using the temperature-time-threshold method of irrigation scheduling for arid regions.

In general, irrigation scheduling based on canopy temperature has not been as effective in humid areas due to increased cloud cover and low VPD (high humidity). Cloud cover reduces the accuracy of energy balance equations that are based on the assumption of clear-sky conditions. Low VPD result in decreased differences between the canopy and air temperatures, making it more difficult to identify water stress conditions. Although past research has attempted to address this issue, results have not been completely successful and additional work is warranted.

The objective of this research was to develop and test an improved irrigation scheduling method based on canopy temperature that would work well in a humid environment. Specifically, irrigations were scheduled by comparing measured canopy temperature with calculated canopy temperature of a well-watered crop. Irrigation was applied when the measured canopy temperature was greater than the predicted (calculated) canopy temperature for more than three consecutive hours on two consecutive days. The method was evaluated against well-watered, semi-stressed, and dryland treatments of corn, soybean, and cotton on the basis of yield, irrigation amount, and IWUE.

Materials and Methods

The irrigation scheduling study was conducted on small plots during the 2002 and 2003 growing seasons at the Lee and Rhodes research farms, respectively, of the University of Missouri, Delta Center, Portageville, Missouri. An irrigation scheduling treatment based on crop canopy temperature measurement was compared to well-watered, semi-stressed, and dryland treatments.

Temperature-Based Scheduling Method

The canopy temperature (IR) treatment was irrigated with 2.5 cm of water when the measured canopy temperature was greater than the calculated canopy temperature of the well-watered treatment using equation 5 for more than three consecutive hours on each of two consecutive days. Selection of this method was based on preliminary analysis of canopy temperatures taken during the 2001 growing season for dryland and well-watered cotton and soybean. The three-consecutive-hour time parameter was similar to that proposed by Wanjura et al. (1995b), and the two-consecutive-day parameter was used to increase the confidence that elevated canopy temperatures were due to plant water stress and not high relative humidity. The slope of the saturated vapor pressure vs. temperature curve was determined as $(T_a + T_w)/2$. Net radiation was estimated to be 75% of the total incoming solar radiation (Fritschen, 1967), and soil heat flux was estimated to be 10% of R_n (Clothier et al., 1986).

Aerodynamic resistance was based on wind speed and crop height using the following equation (Jensen et al., 1990):

$$r_a = \frac{\ln[(z_w - d)/z_{om}]\ln[(z_p - d)/z_{ov}]}{k^2 u_z} \qquad (6)$$

where

z_w = height of wind speed measurement (m)
z_p = height of humidity and temperature measurements (m)
d = displacement height (m; $d = 2/3h_c$)
h_c = crop height (m)
z_{om} = roughness length for momentum transfer (m; $z_{om} = 0.123h_c$)
z_{ov} = roughness length for vapor transfer (m; $z_{ov} = 0.1z_{om}$)
k = von Karman's constant (0.41)
u_z = wind speed at height z_w (m s^{-1}).

To satisfy assumptions made in the energy balance model, periods of extreme cloud cover (average net radiation during a 15 min interval below 200 W m^{-2}) and atmospheric instability (absolute value of the Richardson number (Ri) greater than 0.2; Alves and Pereira, 2000) were not included in the consecutive time clock. This automatically removed nighttime, early morning, and sunset values. The Richardson number was approximated using the following equation, assuming the displacement height was less than 2 m (Verma and Barfield, 1979):

$$Ri \cong \frac{g}{T}\frac{(T_s - T_a)(z_w - d)}{{u_z}^2} \qquad (7)$$

where

g = acceleration due to gravity (m s^{-2})
T = mean of T_a and T_s temperature (K)
T_s = surface temperature (K)
T_a = ambient air temperature (K).

Data Collection

Infrared thermometers (model IRTS-S, Apogee Instruments; Logan, Utah) were used to measure crop canopy temperatures. Infrared thermometers quantify the surface temperature of an object by measuring the energy transmitted in the 8 to 14 micron range (Bugbee et al., 1998). The infrared thermometers (IRT) used in this study had a 1:1 field of view and a manufacturer's stated accuracy of ±0.1°C when the measured temperature was equal to the temperature of the sensor; otherwise, the accuracy was ±1.0°C. A cylindrical white PVC shield was added to the sensor to limit solar heating of the IRT body and improve accuracy. Sensors were calibrated by measuring the temperature of a water bath since the emissivity of water and a plant leaf are approximately the same (~0.96) (Bugbee et al., 1998). The accuracy of the IRT sensors was ±0.5°C in the temperature range encountered in this study (maximum difference between air and canopy temperature of ±7°C). An IRT was placed in each plot at a 35° angle below the horizontal and a 45° angle from the crop row direction with the sensor facing southeast (Wanjura et al., 1992; Wanjura and Upchurch, 2000; Sadler et al., 2002). This permitted a complete view of the crop canopy with minimal soil background, and ensured that the IRT did not shade the canopy in its field of view. The IRT height was periodically adjusted to approximately 15 cm above the canopy throughout the growing season to compensate for crop growth.

The IRT output was sampled every minute, and 15 min averages were recorded using a datalogger (CR10X, Campbell Scientific, Inc., Logan, Utah). The datalogger also recorded 15 min averages for mean ambient air temperature and vapor pressure (HMP45C, Campbell Scientific, 2 m height), wind speed (03101 anemometer, Campbell Scientific, 3 m height), and solar radiation (LI200X pyranometer, Campbell Scientific, 3 m height). Canopy temperatures were not measured until crop foliage was sufficient to completely fill the field of view of the IRT sensors.

2002 Field Experiment

The four treatments in 2002 included well-watered (100%), semi-stressed (50%), dryland, and the IR treatment described above. The well-watered treatment was irrigated twice a week by replacing the predicted ET based on the Penman-Monteith equation (Jensen et al., 1990) minus the effective rainfall over the preceding time interval. The K_c values were determined using regression equations, based on 30 years of weather data, as a function of daily heat units (MU Extension, 2011). The semi-stressed treatment was irrigated on the same day as the well-watered treatment but with half as much water. The dryland treatment was not irrigated.

The 2002 experiment included cotton and soybean. Three replications for each of the four treatments resulted in a total of 24 plots, which were watered with impact sprinklers installed in the corners of each plot. Crops were planted in 0.76 m rows in 7.6 m × 9.1 m plots on Tiptonville silty clay loam in southeast Missouri. Cotton (PM 1218 RR) was planted on day of year (DOY) 154 with emergence on DOY 159. Soybean (DPL 5960, a group V determinate variety) was planted on DOY 128 with emergence on DOY 132. Soybean growth stage was R1 on DOY 199 and R6 on DOY 260.

2003 Field Experiment

Revisions were made in 2003 to help better evaluate the effectiveness of using canopy temperature for scheduling. Crops were moved from a Tiptonville silty clay loam to a nearby field of Malden fine sand to decrease the soil water-holding capacity and increase potential water stress. The semi-stressed treatment (50%) was irrigated once a week but with half the calculated ET minus the effective rainfall for that time period rather than half the irrigation depth of the well-watered treatment, providing the potential to make better use of rainfall. Corn was added as a third crop since it is more prone to water-stress timing than either cotton or soybean. Thus, there were three crops with four treatments. Three replications for each treatment resulted in a total of 36 plots. Plots were watered using 12 mm dripline, with inline pressure-compensating emitters, laid in each row. Emitter spacing was 30.5 cm with a flow rate of 1.51 L h^{-1}. The irrigation system was changed to a drip system to eliminate potential wind drift between plots.

Crops were planted in 0.76 m rows in 7.6 m × 12.2 m plots. Corn (DKC 64-11 RR) was planted on DOY 101 with an emergence date of DOY 108. Corn reached the VT stage on DOY 176 and R6 on DOY 220. Cotton (PM 1218 RR) was planted on DOY 118 with an emergence date of DOY 124. Soybean (Morsoy 4480, a group IV indeterminate variety) was planted on DOY 133 with an emergence date of DOY 139. Soybean reached growth stage R1 on DOY 185 and R6 on DOY 241.

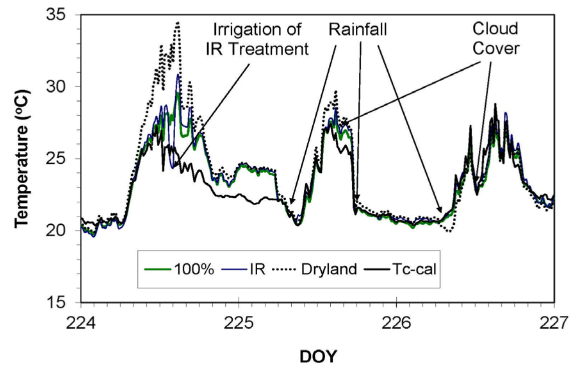

Figure 1. Diurnal cotton canopy temperature pattern for well-watered (100%), IR, dryland, and calculated T_c for DOY 224-227, 2002, at the Lee farm.

Results and Discussion

Diurnal Patterns of Canopy Temperature

An example of the diurnal temperature pattern for well-watered, IR, and dryland cotton, along with calculated T_c using equation 5 is shown in figure 1 for the period from midnight on DOY 224 through midnight DOY 227, 2002. The purpose of these data is to show the general canopy temperature response to irrigation, rainfall, and cloud cover, with detailed analyses of these responses discussed in the following sections. The IR treatment was sprinkler irrigated just after noon on DOY 224, as noted by the measured IR temperature falling below calculated T_c. The measured IR temperature again exceeded calculated T_c shortly after irrigation ended. Rainfall occurred before dawn and again in the late afternoon on DOY 225 and before dawn on DOY 226. This lowered the dryland canopy temperature to be similar to the well-watered treatment during these times. Extreme cloud cover was observed in the afternoon of DOY 225 starting at 2:00 p.m. until nightfall and for an hour around noon on DOY 226. Diurnal patterns of soybean and corn temperatures were similar to those shown for cotton in figure 1.

Calculated T_C versus Measured T_C

To evaluate the accuracy of the method, canopy temperature calculated using equation 5 was compared to the measured canopy temperature of all replicates of the well-watered treatment for two different time periods during the growing season. An attempt was made to keep the same time periods between crops and years. The first period (P1) was from DOY 186 to 210, and the second period (P2) was from DOY 211 to 235. The beginning date of the first period (DOY 186) was when all crops in both years had sufficient canopy to fill the field of view of the IRT. The exception was cotton in 2002, where sufficient canopy was not attained until DOY 192. Period 2 approximated the time when all crops were fully in the reproductive stage.

The data were evaluated for two sets of conditions, labeled dataset A and dataset B. Dataset A included restrictions on net solar radiation and Richardson number, as previously discussed. The relationship of calculated to measured cotton T_c

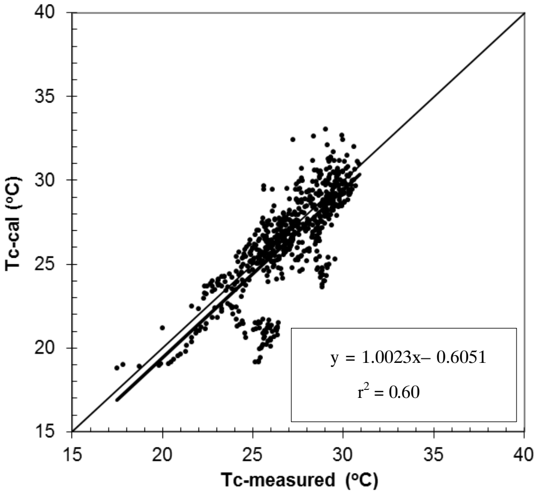

Figure 2. Comparison of measured cotton canopy temperature for well-watered treatments vs. calculated cotton canopy temperature during P2 (DOY 211-235) in the 2002 growing season at the Lee farm.

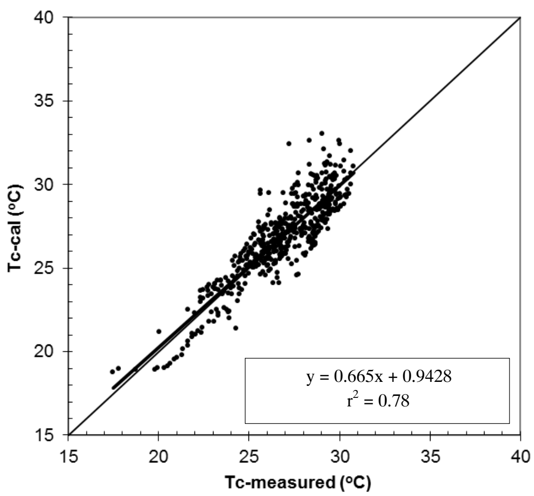

Figure 3. Comparison of measured cotton canopy temperature for well-watered treatments vs. calculated cotton canopy temperature during P2 (DOY 211-235) in the 2002 growing season (Lee farm) after removing points where VPD > 2 kPa at the Lee farm.

for P2 in 2002 is shown in figure 2. Although the relationship is good ($r^2 = 0.60$), there are two data point groups where the canopy temperature is underpredicted. This underprediction was occurring when VPD was greater than 2 kPa. A modified dataset (dataset B) was developed by eliminating these points (VPD > 2 kPa), resulting in improved estimation of T_c ($r^2 = 0.78$, fig. 3). A similar approach was suggested by Wanjura and Upchurch (1997) for eliminating data points when relative humidity was above a prescribed limiting value.

A comparison of the accuracy of T_c estimation using these datasets is given by Bockhold (2003). For eight out of nine combinations of crop, year, and period of the season, T_c estimation was improved with dataset B compared to A, as indicated by increased r^2, a better fit to the 1:1 line, or both. Therefore, further comparisons were done using dataset B.

For cotton and soybean in 2002, calculated T_c was a very good estimator ($r^2 \geq 0.78$) of measured T_c during the later part of the season (P2). Estimates were not good for P1, perhaps because a less complete canopy meant that IRT measurements of T_c were more affected by the surrounding environment (e.g., soil temperature). In 2003, soybean T_c was predicted moderately well in both P1 and P2 ($r^2 \geq 0.52$). Estimates of cotton T_c in 2003 were moderately successful ($r^2 = 0.47$) in P1, but not good in P2. In 2002, cotton was planted 36 days later (due to replanting) than in 2003, causing 2002 cotton growth stages to occur later in the year than in 2003, and perhaps explaining the difference in behavior between the two years.

Corn analysis was only done for P1 in 2003 because after this time it had reached full maturity and no longer needed irrigation. Although the relationship between calculated T_c and measured T_c showed relatively little scatter ($r^2 = 0.75$), calculated T_c underpredicted measured T_c by an average of 2.5°C, with the regression line nearly parallel to the 1:1 line (Bockhold, 2003). Examination of equation 5 shows that aerodynamic resistance is the only crop-related variable linearly related to T_c; thus, it is reasonable to conclude that the offset may be due to inaccuracy in estimating this variable. It may also be that the aerodynamic resistance of the corn canopy was not modeled well by equation 6.

Evaluation of Canopy Temperature as a Wet-Bulb Temperature

Equation 5 may underpredict T_c under certain conditions because the assumption that the canopy temperature is a wet-bulb temperature also assumes that the canopy resistance is much smaller than the aerodynamic resistance. Although this may be accurate at low VPD, at higher VPD this assumption may no longer be valid due to possible stomatal closure increasing the canopy resistance (Jackson et al., 1981). From the data collected in this study, T_c begins to be underpredicted when VPD exceeds 2 kPa. Above this point, canopy resistance should be measured and T_c calculated using equation 3. If the canopy resistance cannot be measured, then the data points where VPD is greater than 2 kPa should be removed, as was done in the calculations of T_c described earlier. This is likely not a problem for irrigation scheduling unless it occurs over more than two consecutive days.

Weather Conditions

Weather data were examined to determine if specific weather parameters could be contributing to underprediction of well-watered T_c. Table 1 lists the minimum, maximum, average, and standard deviation for net radiation (R_n), air temperature (T_a), wet-bulb temperature (T_w), vapor pressure deficit (VPD), and wind speed (u) for the primary growing season periods of 2002 and 2003. Mean R_n, T_a, VPD, and u were all greater in the early part of the season. Sensitivity analysis showed that T_c was positively and linearly related to T_w and had the greatest relative influence; a 50% increase or decrease in T_w had a corresponding 43% increase or decrease in calculated T_c. However, the average T_w showed little variability and was within 1.04°C of calculated well-watered T_c for all periods. Wind speed was used to estimate aerodynamic resistance and had a slight negative relationship with T_c except for very low wind speeds when calculated T_c increased rapidly. Of the four time periods studied over the two years, the best correlation occurred in P2 of 2002 (calculated canopy temperature of well-watered treatment, $r^2 = 0.78$), which had the highest minimum wind speed of the four periods in question (table 1).

Table 1. Measured weather data for the 2002 (Lee farm) and 2003 (Rhodes farm) growing seasons divided into periods 1 (P1) and 2 (P2).

Variable	Min.	Max.	Avg.	SD
P1 (DOY 186-210) 2002				
R_n (W m^{-2})	200.01	764.25	471.70	150.58
T_a (°C)	23.33	36.11	30.73	2.65
T_w (°C)	19.52	26.80	24.60	1.24
VPD (kPa)	0.28	3.65	1.78	0.81
u (m s^{-1})	0.72	7.44	3.98	1.49
P2 (DOY 211-235) 2002				
R_n (W m^{-2})	200.75	734.25	449.71	143.81
T_a (°C)	20.23	36.28	29.18	2.80
T_w (°C)	17.10	27.55	24.06	2.60
VPD (kPa)	0.06	3.30	1.41	0.72
u (m s^{-1})	0.86	6.24	3.23	1.10
P1 (DOY 186-210) 2003				
R_n (W m^{-2})	201.13	685.51	434.73	129.21
T_a (°C)	20.51	36.51	30.12	2.95
T_w (°C)	17.84	27.22	23.56	2.05
VPD (kPa)	0.39	3.76	1.84	0.66
u (m s^{-1})	0.58	5.79	3.02	0.92
P2 (DOY 211-235) 2003				
R_n (W m^{-2})	200.44	762.42	424.11	119.44
T_a (°C)	21.78	35.92	29.09	2.76
T_w (°C)	20.20	28.19	24.21	1.83
VPD (kPa)	0.28	3.29	1.36	0.52
u (m s^{-1})	0.59	5.06	2.40	0.73

Effect of Limiting VPD

Weather data were further examined to determine the effect of removing data points where VPD was above 2 kPa on the ability to meet the 3 h time threshold. This reduced time was due to atmospheric instability or low net radiation caused by cloud cover. The number of days where a minimum of 3 h of continuous data were not present to examine the time threshold for dataset A was six and fourteen for years 2002 and 2003, respectively, therefore missing possible irrigations. In dataset B, where points with VPD > 2 kPa were removed, an additional three and four days had insufficient data in 2002 and 2003, respectively. In 2002, two of these days were in P1 and in 2003 all four of the days were in P1. This would be expected because the average VPD was higher in period 1 than in period 2 for both years.

Differences in Canopy Temperature among Treatments

The average measured T_c values of each treatment for the two periods in 2002 and 2003 are shown in table 2. It is assumed that a higher average T_c would indicate greater water stress. For corn, T_c was significantly different among all treatments, with the highest T_c occurring under dryland management and the lowest for the well-watered treatment. The IR treatment was 0.34°C higher and dryland 1.06°C higher than the well-watered treatment. Average T_c for the well-watered and IR treatments in P1 of 2003 was 28.72°C and 29.06°C, respectively, both above the optimum threshold T_c of 28°C given by Wanjura and Upchurch (2000). This indicates that T_c in a humid environment can be greater than the optimum temperature even under adequate irrigation, as suggested by Wanjura and Upchurch (1997). Based on the numbers from this study, the optimum threshold temperature may be up to 1.0°C greater in humid environments than the threshold temperature for corn in arid environments.

Table 2. Average measured canopy temperatures (T_c) for corn, cotton, and soybean for dataset A during period 1 (P1) and period 2 (P2) for 2002 (Lee farm) and 2003 (Rhodes farm).[a]

		2002		2003	
Treatment		P1	P2	P1	P2
Corn	IR	--	--	29.06 c	--
	100%	--	--	28.72 d	--
	50%	--	--	30.78 b	--
	Dryland	--	--	31.28 a	--
Cotton	IR	29.80 b	27.14 c	28.55 c	28.42 b
	100%	29.03 c	26.96 c	28.96 b	29.47 a
	50%	29.24 c	28.68 b	29.26 b	29.33 a
	Dryland	31.40 a	29.69 a	30.30 a	29.25 a
Soybean	IR	30.71 b	27.56 c	28.62 b	27.90 ab
	100%	29.07 d	28.00 b	28.43 b	28.18 a
	50%	31.34 a	29.77 a	29.58 a	27.49 c
	Dryland	29.99 c	26.84 d	29.21 a	27.60 bc

[a] Within a crop, year, and time period, values followed by the same letter are not statistically significant difference at the 5% level.

Results were slightly different for cotton. For both periods in 2002, the lowest T_c occurred in the well-watered treatment. However, this T_c was not statistically different from the semi-stressed treatment in P1 and the IR treatment in P2. In 2003, IR was significantly lower than all other treatments, while the well-watered and semi-stressed treatments were not significantly different from each other in either period. In all cases except P2, 2003, dryland had the highest T_c. Similar to corn, the average T_c of both the IR and well-watered treatments were greater than the optimum T_c of 28°C. The canopy temperature averaged over both years for P1 and P2 was 28.61°C and 28.48°C for well-watered and IR, respectively, indicating that the optimum threshold temperature for cotton in humid environments could be raised approximately 0.5°C above the 28.0°C threshold used for arid conditions.

Soybean differed from corn and cotton in that the highest T_c was not consistently in the dryland treatment. In fact, the statistically lowest T_c in P2, 2002, was under dryland conditions, and although not the numerically lowest in P2, 2003, the dryland treatment was not significantly different than the lowest value, which was in the semi-stressed treatment. In both years, well-watered had the lowest T_c in period P1, but this was not significantly different than IR in 2003. Irrigation of soybean is not always considered profitable in the mid-south, and in terms of water stress as measured with average T_c, these data would tend to confirm this. The canopy temperature averaged over both years for P1 and P2 was 28.42°C and 28.70°C for well-watered and IR treatments, respectively, indicating that the optimum threshold temperature for soybean in humid environments could be raised over 1.0°C above the 27.0°C threshold for arid conditions. In summary, the average T_c for all three crops was greater in a humid environment compared to the threshold temperature for each under arid conditions. It is not certain how this would affect total irrigation, but it is possible that this would delay some irrigation in humid compared to arid environments.

Yield and Irrigation Water Use Efficiency

Yield results, irrigation amounts, and irrigation water use efficiencies (IWUE) for 2002 are shown in table 3. Analysis of variance using SAS (version 8.2, SAS Institute, Inc., Cary, N.C.) indicated no significant difference among treatments based on average soybean yields. Since there was little varia–

Table 3. Mean yield, irrigation amount, and irrigation water use efficiency (IWUE) for year 2002 (Lee farm).

Treatment		Yield[a] (Mg ha^{-1})	Irrigation[b] (cm)	IWUE[a] (Mg ha^{-1} m^{-1})
Cotton	IR	1.22 a	7.50	3.97 a
	100%	0.94 a	18.35	0.07 a
	50%	1.12 a	9.18	2.13 a
	Dryland	0.93 a	0.00	--
Soybean	IR	3.46 a	12.50	-1.27 a
	100%	3.36 a	34.20	-0.87 a
	50%	3.60 a	17.35	-0.38 a
	Dryland	3.66 a	0.00	--

[a] Yield and IWUE values for the same crop followed by the same letter are not significantly different at the 5% significance level.
[b] Mean irrigation amount for three replications.

tion in T_c among treatments, the dryland treatment was never water stressed more than the well-watered treatment, and no yield increase would be expected. There was also no significant yield difference among treatments for cotton.

The IWUE is defined as the increase in yield over the yield of the dryland treatment divided by the irrigation depth per unit area. The IWUE was negative in soybean because the average yield of the dryland treatment was greater than the other treatments. A negative IWUE also indicates that irrigation was not required to produce higher yields. A determinate soybean cultivar was planted on a silty clay loam in 2002, whereas an indeterminate cultivar was planted on a fine sand in 2003. Growth stage R1 was reached three weeks later in 2002 compared to soybean in 2003, even though the emergence date was a week earlier. In 2002, cotton had a positive IWUE, but there was no significant difference among treatments. The well-watered crop received more than twice the irrigation water of the IR treatment. The semi-stressed treatment was also irrigated with more water than the IR treatment; therefore, the IR treatment was the best irrigated treatment because the least amount of water was applied and there was no significant yield increase for irrigation.

Yield results, irrigation amounts, and IWUE for 2003 are shown in table 4. Based on analysis of variance, the statistically greatest average corn yield occurred in the well-watered treatment, followed by IR. The IWUE was greatest for IR but not significantly different from well-watered. However, the IR treatment resulted in 85% of the maximum

Table 4. Mean yield, irrigation amounts, and irrigation water use efficiencies (IWUE) for year 2003 (Rhodes farm).

Treatment		Yield[a] (Mg ha^{-1})	Irrigation[b] (cm)	IWUE[a] (Mg ha^{-1} m^{-1})
Corn	IR	8.52 b	8.48	36.04 a
	100%	10.00 a	19.96	22.77 a
	50%	5.32 c	4.22	-3.44 b
	Dryland	5.46 c	0.00	--
Cotton	IR	1.19 a	11.87	1.41 a
	100%	1.27 a	14.68	1.58 a
	50%	1.01 a	1.88	-2.02 a
	Dryland	1.04 a	0.00	--
Soybean	IR	2.78 a	7.63	1.34 b
	100%	2.73 a	12.88	0.51 b
	50%	2.99 a	2.13	15.14 a
	Dryland	2.66 a	0.00	--

[a] Yield and IWUE values for the same crop followed by the same letter are not significantly different at the 5% significance level.
[b] Mean irrigation amount for three replications.

yield while requiring less than 50% of the irrigation water. Semi-stressed and dryland had the lowest yields but were not statistically different. Corn yields paralleled differences in average T_c (table 2), with the highest yielding treatment having the lowest T_c.

As in 2002, there was no significant yield difference among treatments for either cotton or soybean. For corn and cotton, the IR and well-watered treatments had the highest IWUE but were not significantly different, with IR being greater for corn and well-watered being greater for cotton. The IWUE for semi-stressed was negative for both corn and cotton, with yields not significantly different from dryland. Since IWUE was positive for both well-watered and IR treatments in both crops, this indicates that too little water was applied in the semi-stress treatment to be of a yield benefit. Recall that in an effort to make better use of "potential" rainfall, this treatment was varied in 2003 compared to 2002 (i.e., irrigation was scheduled only once instead of twice per week, with 50% of the net weekly irrigation requirement replaced minus rainfall). In 2002, the semi-stressed treatment received about 50% of the irrigation amount applied to the well-watered treatment for both cotton and soybean. But in 2003 it was only 21% for corn, 13% for cotton, and 17% for soybean. Although this was too little irrigation for corn and cotton, this method resulted in the highest and significantly different IWUE in 2003 for soybean, as well as the greatest average soybean yield.

Cost of water and commodity price are important factors when determining if yield or IWUE is more important. If water is inexpensive and readily available, then yield gain tends to be more important than IWUE. However, if irrigation water is expensive or limited, then IWUE may become more important. For example, in this study, the yield of the well-watered corn treatment was 1.48 Mg ha^{-1} greater than that of the IR treatment, but the IR treatment had a higher IWUE (36.04 Mg ha^{-1} m^{-1} compared to 22.77 Mg ha^{-1} m^{-1}); thus, the IR treatment was irrigated with 11.48 cm less water than the well-watered treatment. If the price of corn was \$91.34 Mg^{-1} (USDA-NASS 2002-2003 average) and the cost of water was \$0.02 m^{-3}, then the increased yield of the well-watered treatment would result in an income increase of \$135.18 ha^{-1} at a water cost increase of only \$22.96 ha^{-1}, making the well-watered treatment more profitable. In this case, yield would be more important than IWUE. However, if the water cost increased to \$0.12 m^{-3}, then the increase in water cost would be \$137.76 ha^{-1}, making the greater IWUE more significant than the yield gain, and the IR treatment would be more profitable. Over the past ten years, average U.S. corn prices have varied from a low of \$63.40 Mg^{-1} to a high of \$215.39 Mg^{-1} (USDA-ERS, 2010), making the best option uncertain, especially when considering that the price varied by over 240% for the two-year period from 2006 to 2008.

Conclusions

The objective of this research was to evaluate the effectiveness of canopy temperature measured with infrared thermometers as an irrigation scheduling tool in humid environments. The method used in this research was to compare the measured canopy temperature to a calculated canopy temperature for a well-watered crop, and irrigate when the measured temperature was above the calculated temperature for three consecutive hours on two consecutive days.

The estimate of well-watered canopy temperature was calculated from weather and crop data collected at the site, assuming that the canopy temperature was a wet-bulb temperature. The calculated canopy temperature was compared to the temperature of a well-watered treatment, showing that canopy temperature was underpredicted at times when the vapor pressure deficit was above 2 kPa because the canopy temperature could no longer be assumed to be at the wet-bulb temperature. Therefore, the aerodynamic resistance could no longer be assumed to be much larger than the canopy resistance due to stomatal closure. It was also found that this equation may require adjustment to accurately calculate canopy temperature in corn.

Weather data were examined to determine which variables had the most effect on the calculation of canopy temperature. Wind speed changed between and within crop years and affected calculated canopy temperature by changing calculated aerodynamic resistance. Vapor pressure deficit was not included in the calculation directly, but it changed during the season and high vapor pressure deficits resulted in underprediction of canopy temperature.

For a method to be effective, the irrigation water use efficiency (IWUE) and/or yield must increase. Which is more important depends on water cost and grain commodity prices. The use of the temperature-based irrigation scheduling method did not result in a yield change in cotton or soybean. In corn, the IR method had lower yields than the well-watered treatment, which was supported by the average canopy temperature of the well-watered treatment being lower than that of the IR treatment. The IWUE values of the IR treatment were 60% greater but were not significantly different from those of the well-watered treatment. However, total irrigation depth was less than half of the well-watered treatment.

Results from this study indicate that canopy temperature methods of irrigation scheduling in humid environments show potential but also have limitations. Care must be taken in applying results for any single day. Further work is needed to determine if conditions of excessive cloud cover and high VPD can be accommodated with this technique and to further refine the threshold temperatures for corn, soybean, and cotton for humid environments.

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