# DEFICIT IRRIGATED CORN EVAPOTRANSPIRATION ESTIMATES USING CANOPY TEMPERATURE DATA

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## ABSTRACT

Sustainability of irrigated agriculture with declining water supplies is a primary agricultural issue in the U.S. Great Plains. Consequently, the paradigm of maximizing production through full irrigation must be abandoned. Imposing water deficits on crops during non-critical growth periods must be implemented to maximize net economic output per unit of water consumed by the plant. An irrigation timing and amount determination for such a scenario is not a simple, straight-forward procedure. Methods that monitor plant parameters would appear to be most promising. Several canopy temperature based irrigation timing techniques exist that determine when to irrigate but do not indicate how much to irrigate. The reference ET-crop coefficient procedure for determining crop ET which is used in fully irrigated crop conditions would be easiest to implement; however, the water stress coefficient used in that procedure may not be applicable for prolonged periods of water stress. Thus, the objective of this paper was to investigate use of a ratio of canopy temperature ($T_c$) measured over fully irrigated and water stressed corn as a substitute for the water stress coefficient presently used in the reference ET-crop coefficient concept. Preliminary results indicated that the $T_c$ ratio ($T_c$ of fully irrigated corn divided by the $T_c$ of water stressed corn) may be a reasonable quantitative water stress coefficient for calculating crop ET under water stress conditions. Furthermore, it lends itself to hourly incorporation of plant stress effects on crop ET if canopy temperature is continuously measured throughout the day.

## INTRODUCTION

Evapotranspiration (ET) is the combined processes of water lost from the soil surface by evaporation and from the plant by transpiration. There is no easy way of distinguishing between the two processes; consequently, ET is commonly computed using measured weather data, crop characteristics and soil factors. The Food and Agriculture Organization Irrigation and Drainage Paper No. 56, i.e., FAO 56 (Allen et al., 1998) distinguishes between reference crop evapotranspiration ($ET_o$), crop evapotranspiration under standard conditions ($ET_c$) and crop evapotranspiration under non-standard conditions ($ET_{c\ adj}$). The only factors affecting $ET_o$ are climatic parameters at a given location and time of year. $ET_c$ is crop evapotranspiration from well fertilized, disease-

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free crops grown in large areas with optimum soil water conditions to achieve full production under the prevailing climatic conditions. $ET_{c\ adj}$ is crop evapotranspiration resulting from non-optimal conditions such as soil water shortage, low soil fertility, soil salinity and/or the presence of pests and diseases. The ET from crops grown under standard conditions can be determined by adjusting $ET_o$ with crop coefficients ($K_c$) that relate $ET_c$ to $ET_o$. Estimated ET from crops grown under non-standard conditions is typically adjusted through use of a water stress coefficient ($K_s$) dependent on available soil water and/or by adjusting the crop coefficient to account for anomalies that affect crop growth.

Numerous methods for scheduling irrigations have been developed that are based on different types of information for making irrigation decisions. The easiest to implement is the reference ET-crop coefficient concept to estimate daily soil water depletions to determine when to irrigate and how much water to apply. This method was designed for water management of fully irrigated crops with limited water stress allowed. The paradigm of maximizing production through full irrigation must be abandoned in order to sustain irrigated agriculture with declining water supplies. Water deficits must be imposed on crops during non-critical growth periods to maximize net economic output per unit of water consumed by the plant. An irrigation timing and amount determination for such a scenario is not a simple, straight-forward procedure. When water deficits are imposed on crops due to limited water availability, a method that directly monitors a plant parameter to infer plant water status provides the most accurate assessment of crop water status.

Crop water status can be quantified using infrared thermometers (IRTs) to measure canopy temperature in canopy temperature based irrigation timing techniques. Some of these techniques have been available for more than 25 years. The crop water stress index (CWSI) developed by Idso et al. (1981) and Jackson et al. (1981) has been used to determine when to irrigate and has been shown to reduce applied water compared to other scheduling techniques (Wanjura et al., 1992). Unfortunately, the amount of water used by the crop to estimate irrigation amount is not determined by this index.

Efforts have been made to determine irrigation requirements (how much to irrigate) by various techniques to compliment CWSI measurements (when to irrigate). Kjelgaard et al. (1996) used a canopy temperature energy balance (CTEB) model to determine daily ET. They found that CTEB ET estimates were within 10% of Bowen ratio energy balance ET values for substantial portions of two corn growing seasons. They determined that these ET estimates were within an acceptable uncertainty for ET estimates for use in most irrigation practices. However, the CTEB method is instrumentation intensive for practical use. Therefore, Kjelgaard et al. (1996) estimated net radiation from total incoming solar radiation and soil heat flux from net radiation and leaf area index to replace measured values. Based on these estimated values, CTEB ET estimates were similar to those obtained using measured values which indicated that a reasonable chance existed for reducing instrumentation requirements. However, soil heat flux estimates were also based on leaf area index values which are not readily available for specific crop conditions.

Colaizzi et al. (2003) investigated the relationship between the CWSI and $K_s$ to estimate the fraction of soil moisture depletion (fDEP). The FAO 56 $K_s$ (Allen et al., 1998) and Jensen $K_s$ (Jensen et al., 1970) algorithms were evaluated. The Jensen $K_s$ algorithm produced a better correlation between the CWSI and soil moisture than the FAO 56 $K_s$ algorithm. Disagreement was greatest for fDEP $< 0.6$ because the $K_s$ models are less sensitive to changes in fDEP in this range. Based on the estimate of $K_s$ from CWSI, fDEP and the root zone soil moisture depletion (how much to irrigate) were calculated. A potential problem with this approach is inadequate knowledge of soil properties (field capacity and permanent wilting points) due to spatially variable soils within a field and crop rooting depths, hence, total available water within the crop root zone is unknown.

A simple, robust method is needed to estimate $K_s$ for use in the reference ET-crop coefficient approach for estimating crop ET ($ET_{c\ adj}$) for canopy temperature-based irrigation timing techniques. Thus, the objective of this paper was to investigate use of measured canopy temperature of corn grown under standard conditions (fully irrigated) and non-standard conditions (water stressed) to calculate a ratio of canopy temperatures (standard condition divided by non-standard condition) as a substitute for $K_s$. This approach was inspired by techniques used for in-season assessment of plant N status whereby the target area was compared to a reference area that was supplied with sufficient N to alleviate N deficiency (Schepers et al., 1992; Bausch and Duke, 1996).

## METHODS AND MATERIALS

Data for this study were collected during the 2008 growing season at the Limited Irrigation Research Farm (LIRF) northeast of Greeley, CO. LIRF is a 16 ha field research facility to conduct research on crop response related to full and deficit irrigation in four crop blocks. Each crop block contains 24 plots that are 12 rows wide (0.76 m row spacing) by 40 m long. Crop rows have a north/south orientation. Six water treatments replicated four times are imposed on the particular crop grown within each block. The four crops rotated through the four crop blocks are winter wheat, field corn, sunflower (oil), and dry beans (pinto). The six water treatments applied to each of these crops are:

- #1 – 100% (fully meet predicted water requirements)
- #2 – 85% (receive 85% of treatment #1)
- #3 – 70% (receive 70% of treatment #1)
- #4 – 70% (receive 70% of treatment #1)
- #5 – 55% (receive 55% of treatment #1)
- #6 – 40% (receive 40% of treatment #1).

Treatment 3 is applied proportional to treatment 1 at each irrigation. Treatments 2, 4, 5, and 6 are targeted to be seasonally proportional to treatment 1 but the water applications are distributed in response to critical growth periods (Stewart et al., 1975). This results in water applications below the treatment amount between establishment and reproductive growth stages and during maturation growth stages, and water applications above the treatment amount during the critical reproductive growth stage. All treatments are irrigated equally during the germination and plant establishment period.

Irrigation water is delivered to the corner of each plot and applied through polyethylene header pipes to drip irrigation tubing (16mm thick walled tubing with 1.1 L/h conventional inline emitters on 30 cm spacing) laid on the surface near each plant row. Flow rates and volumes to each treatment are measured with turbine flow meters. Irrigation applications to each treatment are controlled and recorded with Campbell Scientific CR 1000 data loggers. Water is supplied from groundwater, stored in a 22,000 L storage tank, and pressurized with a pressure-controlled variable frequency drive booster pump.

An automated weather station is located near the plots in a 0.5 ha grass plot. Hourly data from the station is used to calculate ASCE Standardized Penman-Monteith (ASCE-EWRI, 2005) alfalfa reference evapotranspiration ($ET_r$). Basal crop coefficients (Allen et al., 2007) and the FAO 56 (Allen et al., 1989) $K_s$ procedure are used to calculate $ET_c$ from calculated $ET_r$.

Soil water content is measured in each plot between 30 and 200 cm depth with neutron attenuation (503 DR Hydroprobe moisture gauge, Campbell Pacific Nuclear) at an access tube near the center of each plot. Surface soil moisture content (0-15 cm) is measured with a MiniTrase portable TDR system (SoilMoisture). Irrigations are scheduled using measured soil water depletion and predicted soil water depletions based on $ET_c$ calculations.

Plant measurements are taken periodically to determine plant response to the various water treatments. Plant growth stage is assessed visually. Plant height measurements represent a visual mean across the top of the crop canopy, i.e., not individual plants. Canopy cover is assessed with a photosynthetically active radiation sensor (AccuPAR LP80, Decagon Devices, Inc.) from above and below canopy measurements and from images acquired with a digital camera (ADC, TetraCam, Inc.). Multi-spectral radiometers and infrared thermometers (IRTs) mounted on a mobile platform measure canopy reflectance and temperature, respectively. In addition to the IRTs mounted on the mobile platform, stationary IRTs (IRR-PN, Apogee Instruments, Inc.) are located in selected plots to continuously measure canopy temperature. These IRTs have a 36° field-of-view; they are positioned at a 60° view angle (30° below the horizontal), look 45° from North (northeast), and are 0.76 m above the crop canopy. They view an elliptical area with a theoretical major and minor axis of 2.9 m and 1.2 m, respectively. The IRTs are adjusted for crop height three times per week during vegetative growth.

Two adjacent 2 ha fields are each planted to one of the four crops so that each crop is grown in alternate years. Bowen ratio energy balance (BREB) instrumentation is installed near the center of each field to estimate $ET_c$. The crop in each of these fields is irrigated to meet full water requirements and measured $ET_c$ is compared to calculated water use in the 100% water treatment. The fields adjacent to these fields and the plot area (four blocks) are used as buffer areas and are planted to the same crops planted in the BREB fields.

Results presented in this paper are for corn grown during the 2008 growing season in one replication of the small plots with irrigation treatments 1 and 5. DeKalb brand 52-59 (VT3) corn seed was planted May 12 (DOY 133) at 80,000 seeds/ha. Nitrogen fertilizer applications were based on soil samples and applied preplant broadcast (50 kg/ha), at planting (33 kg/ha), and through the irrigation system (34 kg/ha).

## RESULTS AND DISCUSSION

The corn block was sprinkle irrigated (May 21) to achieve emergence which occurred about June 1 (DOY 153). A 30 mm precipitation event occurred on June 6 (DOY 158); the next measurable event (42 mm) was on August 6 (DOY 219). Stationary IRTs were installed on July 17 (DOY 199) for continuous canopy temperature measurements in irrigation treatments 1 and 5. Corn in treatment 1 at that time had 13 mature leaves [V13 growth stage (Ritchie et al., 1986)] whereas treatment 5 was at V10. Canopy cover was 77% and 50% for treatments 1 and 5, respectively; plant height was 1.3 m and 0.85 m, respectively. Thus, plant canopies were sufficiently dense to insure that the IRTs were viewing mostly plant material and very little, if any, soil.

Figure 1 shows the basal crop coefficient ($K_{cb}$) curves for irrigation treatments 1 and 5 adjusted for plant growth conditions and occurrence of effective cover as determined from canopy cover measurements averaged for the four replications within the corn

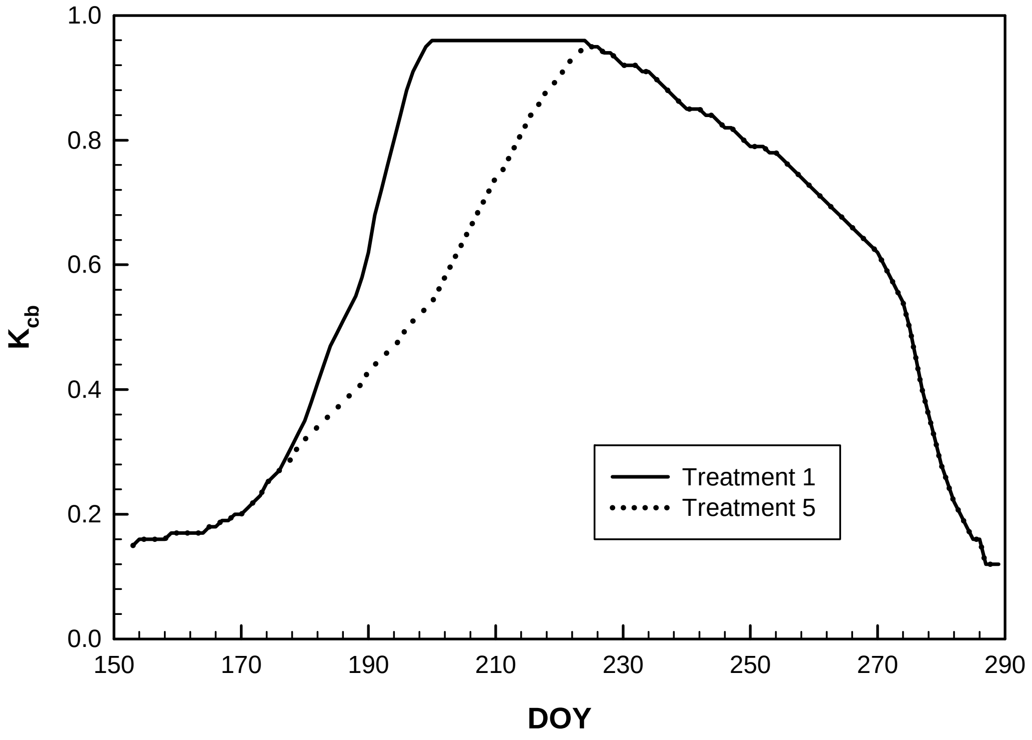

Figure 1. Corn Basal Crop Coefficient Curves for the Two Irrigation Treatments

block. Effective cover was assumed to occur when canopy cover reached 80%; however Stegman et al. (1980) considered effective cover for ET of agricultural crops to occur around a leaf area index of 3 and/or 75% ground cover. Treatment 1 reached effective cover on July 18 (DOY 200) whereas effective cover for treatment 5 occurred on August 12 (DOY 225). Figure 2a shows the difference in corn growth and condition on July 31 (DOY 213) for the two treatments; treatment 1 (right side of the image) was at the V18 growth stage and had a plant height of 2.1 m while treatment 5 (left side of the image) was at V15 with a plant height of 1.1 m. Figures 2b (treatment 5) and 2c (treatment 1) were taken with a nadir view camera on the mobile platform on the same day; canopy cover determined from these images was 63% and 91%, respectively.

Figure 2. Images Showing Differences between the Two Corn Irrigation Treatments on July 31 (DOY 213)

The 25 day period between occurrences of effective cover for the two irrigation treatments was selected for comparing canopy temperature of the water stressed treatment to the well irrigated treatment. At the end of this 25-day period, irrigation treatment 1 was 2.6 m in height and in the R2 (blister) growth stage while treatment 5 was 1.6 m tall and at the R1 (silk) growth stage. Figure 3 shows the canopy temperature minus air temperature for treatment 1 to indicate that corn in that treatment was not under water stress. Irrigations occurred on DOY 200 (24.1 mm), 204 (32.5 mm), 207 (28.5 mm), 211 (26.4 mm), 214 (28.6 mm), and 218 (22.4 mm). As mentioned earlier, a rainfall event occurred on DOY 219 (42.0 mm). The solid line is a trace of the temperature difference averaged over 30-min intervals throughout each day. Air temperature measurements used were those measured at the upper air sensor (1.2 m above the canopy) on the Bowen ratio mast in the Bowen ratio corn block. Canopy minus air temperature differences were mostly negative, i.e., the canopy was cooler than the air indicating freely transpiring corn. A positive temperature difference occurred sometimes around 0730 to 0930 MST which may be related to dew on the corn leaves. The filled circles represent the 1300 to 1500 MST temperature difference average which is typically the warmest time period during the day. A temperature difference greater than or slightly less than zero occurred on DOY 221 and DOY 222 following the rain event on DOY 219.

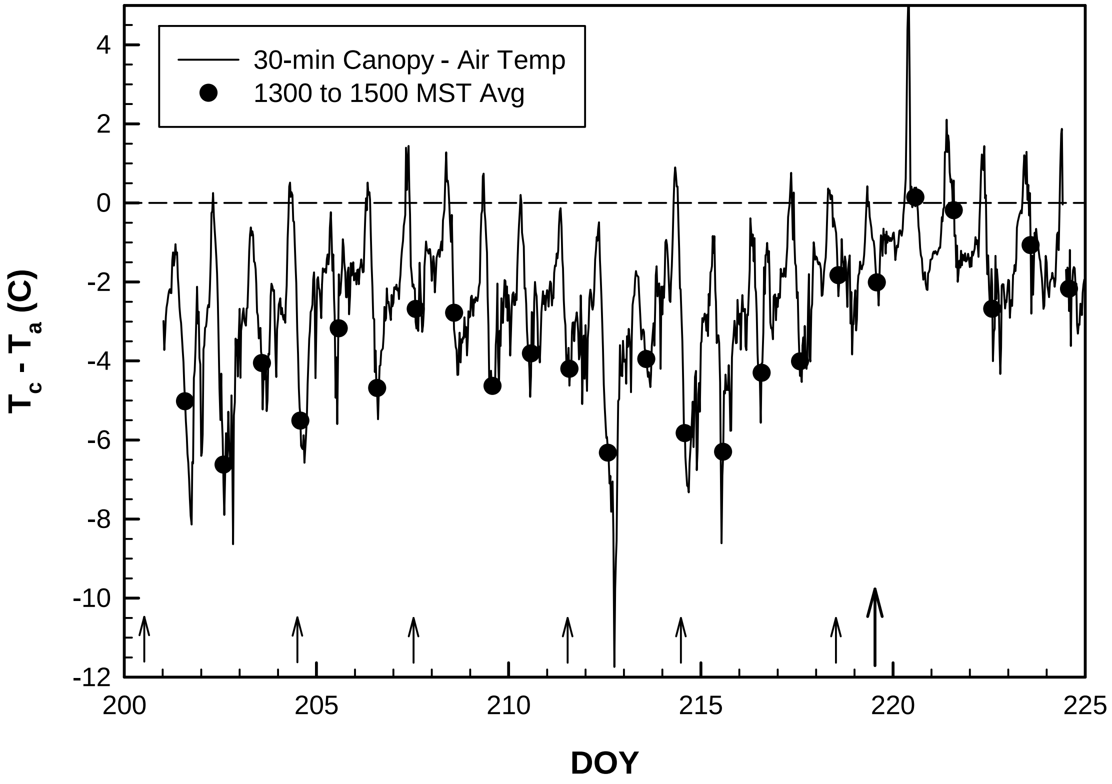

Figure 3. Canopy Temperature minus Air Temperature for Treatment 1 (Well-Watered Corn). Short Arrows are Irrigation Dates; Long Arrows are Precipitation Events.

The solid line in Figure 4 represents the 30-min time trace throughout the day of canopy temperature in the well irrigated treatment (treatment 1) divided by the canopy temperature in the water stressed treatment (treatment 5). The filled circles represent the 1300 to 1500 MST average canopy temperature ($T_c$) ratio for each day. If treatment 5 was not water stressed and the canopy temperature measured by the IRT in treatment 5 produced the same canopy temperature measured by the IRT in treatment 1, the $T_c$ ratio would equal one. As canopy temperature in the water stressed treatment increased due to less available soil water and reduced transpiration, the $T_c$ ratio became less than one similar to $K_s$ calculated from total available soil water within the crop root zone and measured root zone depletion. This is shown in Figure 5. However, the swings in magnitude of the $T_c$ ratio are not as dramatic as the $K_s$ values. A time offset exists between the $K_s$ and $T_c$ ratio values since the $T_c$ ratio represents the 1300 to 1500 MST time period. Use of canopy temperature may be a more realistic parameter than soil water content to represent a stress coefficient due to the complicated physiological processes that plants undergo as they encounter water stress and compensate for this stress. Treatment 5 irrigations occurred on DOY 204 (22.3 mm), 211 (15.7 mm), 214(19.9 mm), and 218 (17.8 mm) during the 25-day evaluation period. Notice that the $T_c$ ratio values following the irrigation event on DOY 218 and the precipitation event on DOY 219 are around 0.96 to 0.98 instead of 1. One would think after 60 mm of

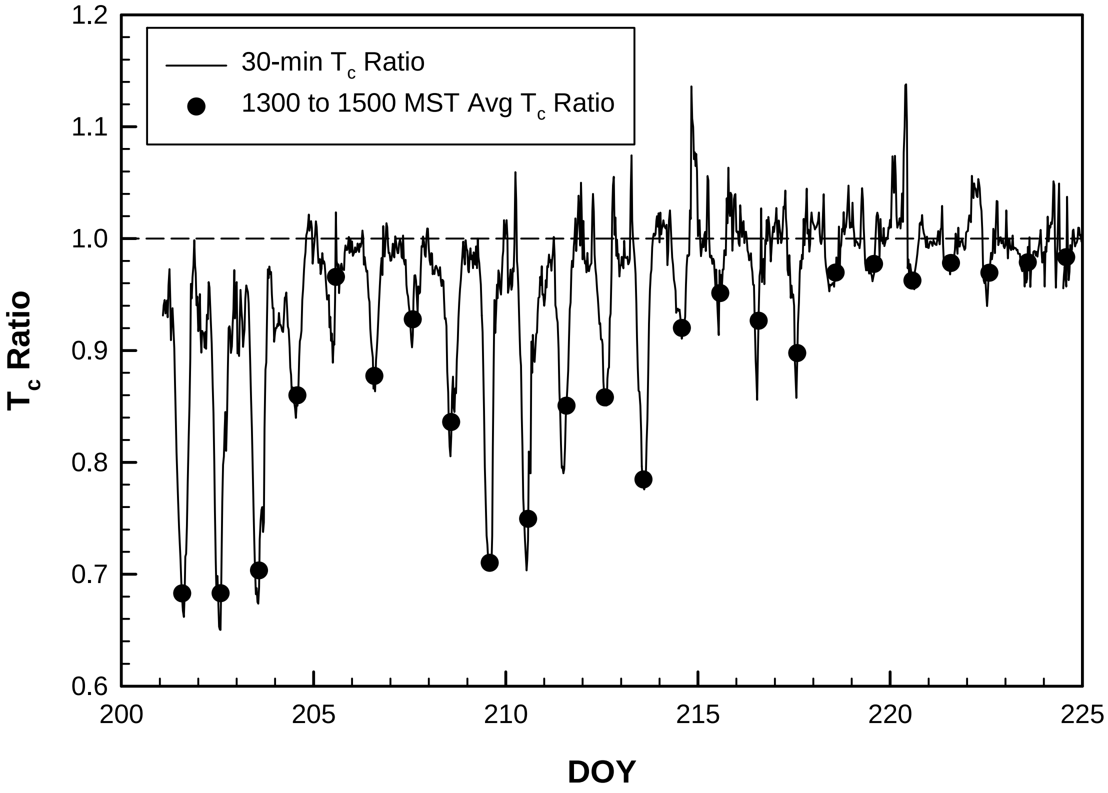

Figure 4. Canopy Temperature ($T_c$) Ratio Calculated from $T_c$ (well irrigated) Divided by $T_c$ (water stressed) for Corn Irrigation Treatment 5

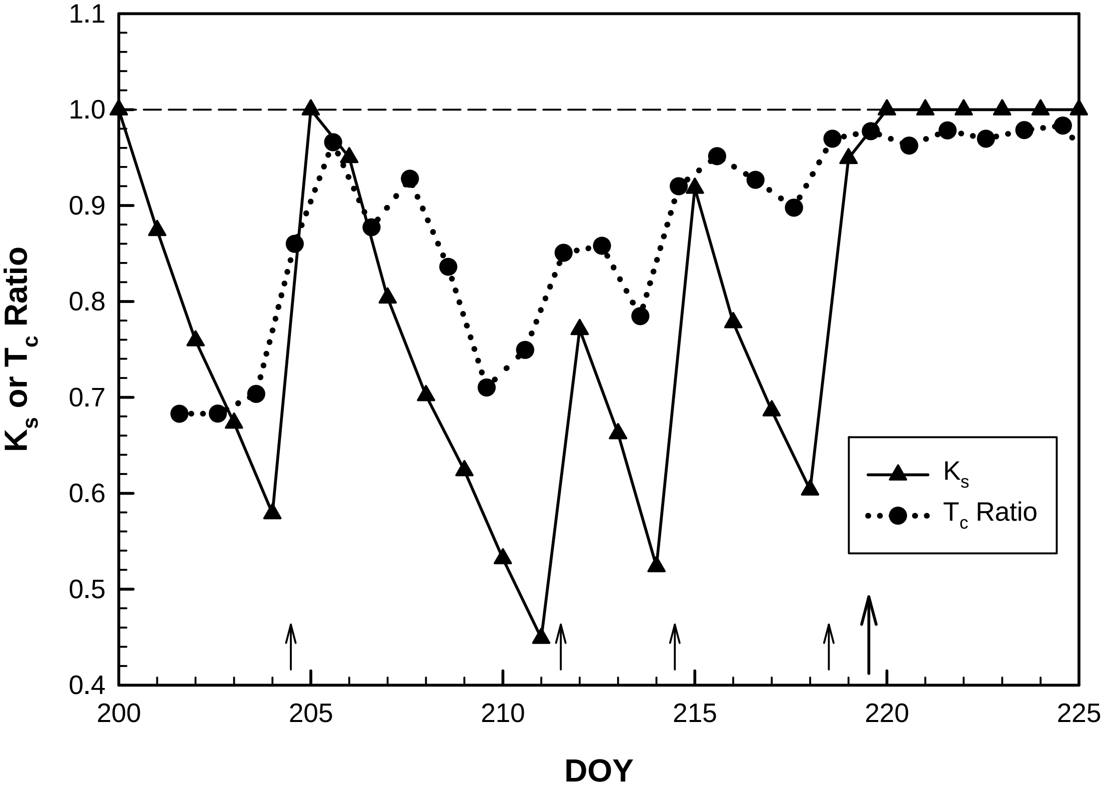

Figure 5. Comparison of the $T_c$ Ratio with the $K_s$ Stress Coefficient for Irrigation Treatment 5. Irrigation Dates are Short Arrows; Long Arrows are Precipitation Events.

combined irrigation and rainfall that the $T_c$ ratio should equal 1; this may be due to canopy temperature being measured by two separate but well calibrated IRTs. Ideally, canopy temperature measurements should be measured with a common sensor to minimize sensor bias. However, this may not be practical. This difference may be real because the plant may not be capable of transpiring at its assumed potential rate due to earlier water stress. Figure 6 shows that $ET_{c\ adj}$ determined from the $T_c$ ratio technique was greater than what was determined by the $K_s$ technique for most of the comparison period. Cumulative $ET_{c\ adj}$ was 13 mm greater for the $T_c$ ratio technique over the 25-day investigative period. However, for DOY 221 to 224 (a well watered time period) $ET_{c\ adj}$ was essentially the same for the $K_s$ and $T_c$ ratio techniques for treatment 5 ignoring the time offset associated with the $T_c$ ratio and not much different from $ET_c$ for treatment 1.

## CONCLUSION

A ratio of canopy temperature ($T_c$) measured over corn in a well irrigated plot and a water stressed plot ($T_c$ well divided by $T_c$ stressed, i.e., $T_c$ ratio) was investigated for comparison to the water stress coefficient ($K_s$) traditionally used in the reference ET-crop coefficient procedure to estimate crop ET. Based on the time period selected to compare the two techniques, this preliminary investigation indicated that the $T_c$ ratio technique has potential as a quantitative water stress coefficient for water stressed crops and merits

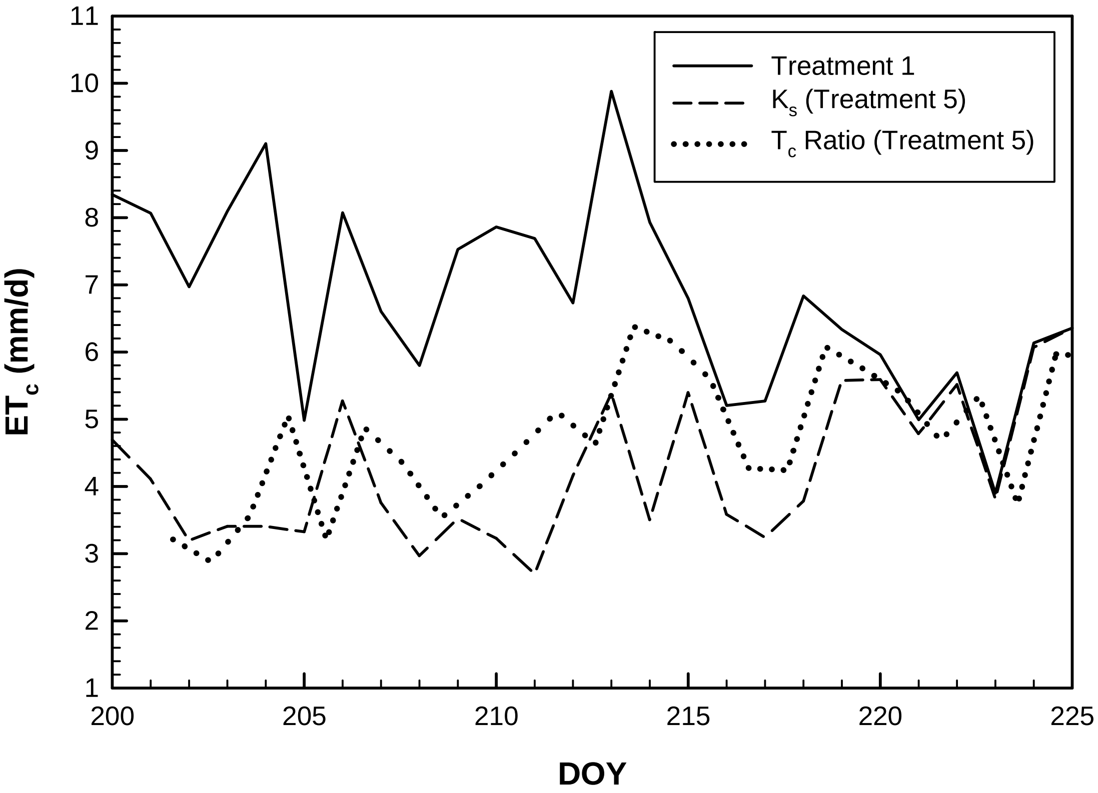

Figure 6. Comparison of $ET_{c\ adj}$ for the $T_c$ Ratio and $K_s$ Techniques for Irrigation Treatment 5 with $ET_c$ for Irrigation Treatment 1

additional study. Furthermore, the $T_c$ ratio lends itself to hourly incorporation of plant stress effects on crop ET when using hourly calculated reference ET. To determine which technique is more correct would require continuous soil water content measurements throughout the potential root zone in several locations in both irrigation treatments as well as daily plant water status (leaf water potential and stomatal conductance) measurements in both treatments.

## DISCLAIMER

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

## REFERENCES

Allen R.G., J.L. Wright, W.O. Pruitt, L.S. Pereira, and M.E. Jensen. 2007. Water requirements. In: Hoffman G.J., R.G. Evans, M.E. Jensen, D.L. Martin, R.L. Elliott (eds.) Design and operation of farm irrigation systems, 2nd edition. ASABE, St. Joseph, MI, 863 pp.

Allen, G.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. United Nations Food and Agriculture Organization, Irrigation and Drainage Paper 56, Rome, Italy, 300 pp.

ASCE-EWRI. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Technical Committee report to the Environmental and Water Resources Institute of the American Society of Civil Engineers from the Task Committee on Standardization of Reference Evapotranspiration. ASCE-EWRI, Reston, VA, 173 pp.

Bausch, W.C. and H.R. Duke. 1996. Remote sensing of plant nitrogen status of corn. Transactions of the ASAE. 39: 1869-1875.

Colaizzi, P.D., E.M. Barnes, T.R. Clarke, C.Y. Choi, and P.M. Waller. 2003. Estimating soil moisture under low frequency surface irrigation using Crop Water Stress Index. Journal of Irrigation and Drainage Engineering. 129: 27- 35.

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

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

Jensen, M.E., D.C.N. Robb and C.E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. Journal of Irrigation and Drainage Engineering. 96: 25-38.

Kjelgaard, J.F., C.O. Stockle, and R.G. Evans. 1996. Accuracy of canopy temperature energy balance for determining daily evapotranspiration. Irrigation Science. 16: 149-157.

Ritchie, S.W., J.J. Hanaway, and G.O. Benson. 1986. How a corn plant develops. Specialty Report 48, Iowa State Extension Service, Iowa State University, Ames, IA, 21 pp.

Schepers, J.S., D.D. Francis, M.F. Vigil, and F.E. Below. 1992. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Communications in Soil Science and Plant Analysis. 23: 2173-2187.

Stegman, E.C., J.T. Musick, and J.I. Stewart. 1980. Irrigation water management. In: Jensen, M.E. (ed.) Design and operation of farm irrigation systems. ASAE Monograph No. 3, 829 pp.

Stewart, J.I., R.D. Misra, W.O. Pruitt, and R.M. Hagan. 1975. Irrigating corn and grain sorghum with deficient water supply. Transactions of the ASAE. 18: 270-280.

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