Comparison of water stress coefficient using three alternative canopy temperature-based indices

Huihui Zhang[1*], Liyuan Zhang[2], Yaxiao Niu[2], Ming Han[3], Kevin Yemoto[1]

(1. *Water Management and Systems Research Unit, USDA-ARS. Fort Collins, CO 80526, USA*;

2. *College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China*;

3. *Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada*)

Abstract: In this study three crop canopy temperature-based water stress indices, standard deviation of the distribution of canopy temperature (CTSD), the ratio of canopy temperature of non-stressed to stressed canopy ($Tc_{–ratio}$) and Degrees Above Non-Stressed (DANS), were tested as the substitute of water stress coefficient (Ks) for maize crop water use estimation. Thermal imagery was taken from maize under various levels of deficit irrigation at different crop growth stages in 2015 and 2016 growing seasons. The Expectation-Maximization algorithm was used to estimate the canopy temperature distribution from thermal imagery under a range of crop coverage and water stress conditions. CTSD, $Tc_{–ratio}$ and DANS were calculated from the extract canopy temperature and converted to water stress coefficient denoted as $Ks_{–CTSD}$, $Tc_{–ratio}$, and $Ks_{–DANS}$. Crop transpiration estimated using three water stress coefficients were compared with sap flow measurements in 2015. The results further confirmed that CTSD responded well to irrigation events (timing and depth) on crops with water stress and was significantly correlated to leaf water potential and soil water deficit, especially when stress level was above moderate. $Ks_{–CTSD}$ was more sensitive to soil water deficit than $Tc_{–ratio}$ and $Ks_{–DANS}$. Crop transpiration estimated using $Ks_{–CTSD}$ preformed the best among all methods when compared with sap flow measurements ($R^2_{\_adj}$ =0.58, relative absolute error =0.63, and root mean square error =0.87 mm day^{-1}). Nash-Sutcliffe coefficient of 0.61 indicates the performance of the prediction model is sufficient and satisfactory. The canopy temperature-based index, CTSD, is easy to acquire from high resolution thermal imagery from remote sensing platforms, such as ground and unmanned aerial vehicles. It has a strong application potential to improve crop water stress detection and crop water use estimation for irrigation scheduling.

Keywords: canopy temperature, CTSD, maize, water stress, thermal, soil water deficit

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1 Introduction

The world population growth and associated increasing food demand require more efficient agricultural production monitoring systems[1]. In arid and semiarid areas, climate is characterized by long periods of drought, and rainfall is not sufficient to meet crop water requirements[2]. To ensure crops receive enough water and guarantee food security, irrigation is necessary to prevent crop water stress and ensure profitable yields[3]. To determine an optimal irrigation schedule and apply it efficiently, the accurate estimation of crop water use is the key.

Crop water use commonly is predicted by the FAO-56 dual crop coefficient methodology[4], as ETc = (Kcb*Ks+Ke)*ETr. It describes the relationship between the daily evapotranspiration of a given crop (ETc) and the grass or alfalfa-based reference evapotranspiration (ETr) by separating the single crop coefficient into the basal crop coefficient (Kcb), water stress coefficient (Ks) and soil water evaporation coefficient (Ke). The estimation of crop water use turns into the calculation of ETr, Kcb, Ke, and Ks. ETr could be calculated using the FAO Penman-Monteith formula and meteorological data[5]. Kcb is defined as the ratio between crop potential transpiration and ETr and used to determine crop potential transpiration under well-watered conditions. Crop canopy cover and normalized difference vegetation index (NDVI) have shown strong correlations with Kcb in many studies[6-8]. Ke is clearly correlated with canopy cover and irrigation/rainfall events and becomes negligible along with the growth of crop[4]. For crop under water limited conditions, actual transpiration will be limited by soil water supply, so Ks is multiplied by Kcb to account for the influence of water stress on crop transpiration. The accurate calculation of Ks has been the key to accurate estimation of crop water use[3].

Canopy temperature (Tc) has long been used as a crop water stress indicator, because of the clear leaf-temperature difference between water stressed and non-water stressed plants[9]. However, micro weather conditions within the field also have great influence on Tc apart from water supply[10,11]. To quantify the relationship between Tc and the degree of crop water stress, crop water stress index (CWSI) was proposed by[12], and later was used to provide a reliable way to calculate Ks, as 1 – CWSI[13-15]. However, due to the limitation of intensive measurements of canopy and weather

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Biography: **Liyuan Zhang**, PhD candidate, research interests: remote sensing, crop water stress estimation, Email: liyuanzhang@nwafu.edu.cnmailto: dustming@gmail.com; **Yaxiao Niu**, PhD candidate, research interests: remote sensing, crop biomass estimation, Email: niuyaxiao@nwafu.edu.cn; **Ming Han**, PhD candidate, research interests: remote sensing, hydrology/crop growth modeling, Email: dustming@gmail.com; **Kevin Yemoto**, BS, Engineering Technician, research interests: remote sensing, precision agriculture, soil science, GIS, Email: kevin.yemoto@usda.gov.

***Corresponding author:** Huihui Zhang, PhD, Research Physical Scientist, research interests: remote sensing, precision agriculture, irrigation management. Water Management and Systems Research Unit, USDA-ARS. 2150 Center Avenue, Bldg. D, Suite 320 Fort Collins, CO 80526, USA. Email: huihui.zhang@usda.gov.

parameters and complicated computation of CWSI, recent studies have investigated a few simple indices that only require a single type of measurement: canopy temperature. Bausch et al.[16] suggested replacing Ks with a ratio of canopy temperature measured over non-stressed and stressed maize canopy (Tc_{-ratio}). Taghvaeian et al.[17] proposed the Degrees Above Non-Stressed (DANS), which represents the difference between stressed and non-stressed canopy temperature, and compared the performance of CWSI and DANS in monitoring water stress for sunflower. In Kullberg et al.[18], the authors continued the investigation on maize and developed a local calibration procedure to convert DANS to Ks for crop water use estimation.

Besides infrared thermometry, researchers have also studied infrared thermography for crop water stress detection. Han et al. (2016)[19] developed a method to extract pure canopy temperature from high resolution thermal imagery and then derived the standard deviation of the distribution of canopy temperature (CTSD) as a water stress indicator in maize. Their results indicate that CTSD effectively responded to irrigation events and had the potential to be a tool for irrigation scheduling. After the development of CTSD, its sensitivity to crop water stress had been further evaluated for cotton and demonstrated high correlation (coefficient of determination (R^2) of 0.88) with stomatal conductance [20]. However, the performance of Ks derived from CTSD to estimate maize water use has not been assessed.

Therefore, in this study, we evaluated CTSD method performance using two years of experimental data and compared results with two other indices, Tc_{-ratio} and DANS, which are also based on canopy temperature measurement only. The specific tasks of this study were to (1) obtain canopy temperature distribution from ground-based high resolution thermal imagery taken in maize in 2015-2016 growing seasons in northern Colorado; (2) calculate CTSD, Tc_{-ratio} and DANS using the extracted canopy temperature; and (3) compare the performances of CTSD, Tc_{-ratio} and DANS for water stress detection and crop water use estimation.

2 Materials and Methods

2.1 Field experiment

A field experiment was conducted on maize during the 2015 and 2016 growing seasons at the USDA-ARS Limited Irrigation Research Farm (LIRF), in Greeley, Colorado, USA (40º26′57″N, 104º38′12″W, elevation 1427 m). The alluvial soils of the study field are predominantly sandy and fine sandy loam of Olney and Otero series. The maize (*Zea mays L.*, Dekalb DCK54-38RIB variety) was planted on Jun 1, 2015 and May 15, 2016 with planting density around 84,000 plants ha^{-1}. Maize reached late vegetative stage (V8), reproductive stage (R1), and maturation stage (R4) on Jul 6, Aug 2, and Aug 28 in 2015, and Jun 27, Jul 25, and Aug 13 in 2016, respectively. All plots were fully irrigated at planting and early vegetative stage to assure the emergence and good plant stands.

A total of 12 treatments were arranged in a randomized block design with four replications. Each treatment plot was 9 m wide (12 rows at 0.76 m spacing) by 43 m long, and all the measurements were taken from the middle six rows to reduce border effects. Treatments varied by levels of deficit irrigation (DI) applied during the late vegetative growth stage (Lveg, V8-VT) and maturation growth stage (Mat, R4-R6), but water stress was relieved (with full irrigation) during the sensitive reproductive stage (Rep). Each treatment was named for the target percentage of potential non-stressed ETc[4] during Lveg and Mat stages (e.g., “T(40/80)” treatment indicates a target of 40% of maximum ET during the late vegetative stage and 80% of maximum ET during the maturation stage). Five of the 12 treatments were selected for the study: T1(100/100), T3(80/80), T8(65/65), T12(40/40), and T13(40/80). Actual irrigation amounts for these treatments and rainfall by growth stage are shown in Table 1. During the growing season, irrigation water was applied through a surface drip irrigation system with drip tubing (16 mm outside diameter, 2 mm wall thickness, 30 cm in-line emitter spacing, 1.1 L h^{-1} emitter flow rate) placed on the soil surface next to each row of maize. Nitrogen fertilizer (Urea ammonium nitrate, UAN, 32%) was sidedress applied near the seed at planting at 41 kg ha^{-1} N. Additional nitrogen was applied through the irrigation water (fertigation) to meet fertility requirements in all the treatments.

Table 1 Total irrigation and rainfall amounts (mm) for each treatment in different growth stages in 2015 and 2016, where Lveg = late vegetative, Rep = reproductive, and Mat = maturation growth stages. Treatments (TRT) shown by number and target percentage of non-stressed ETc during Lveg and Mat stages [T (Lveg ET/Mat ET)]

TRT	2015			2016		
	Lveg	Rep	Mat	Lveg	Rep	Mat
T1(100/100)	166	151	164	168	153	142
T3(80/80)	126	120	134	135	133	99
T8(65/65)	84	112	69	87	138	40
T12(40/40)	40	113	0	50	149	0
T13(40/80)	40	136	124	50	148	99
Rainfall	10	23	9	26	24	40

2.2 Soil water balance measurements

Meteorological data were taken by on-site Colorado Agricultural Meteorological Network (CoAgMet, http://ccc.atmos.colostate.edu/~coagmet/) station GLY04. These data include hourly precipitation, air temperature, relative humidity (subsequently converted to vapor pressure deficit), solar radiation, and wind speed taken at 2 m above a grass reference surface. Alfalfa-based ETr was calculated from hourly weather data by the ASCE standardized Penman-Monteith equation[21], and daily ET values are sums of hourly values.

An access tube installed in the middle row of each plot was used to determine soil water content (SWC) by a neutron moisture meter (CPN-503 Hydroprobe, InstroTek, San Francisco, CA①, USA). The soil water content was measured at depths of 30 cm, 60 cm and 90 cm, two times per week before or after irrigation in each plot throughout each growing season. SWC at 0-15 cm layer was measured with a portable time domain reflectometer (MiniTrace, Soilmoisture Equipment Corp, Santa Barbara, CA, USA) in the row near the neutron moisture meter access tube. Field capacities from each layer were estimated based on observations of SWC from the current season and the previous 5 years of study on the site. The soil water deficit (SWD) for the active root zone of each plot was calculated by sum of the difference between SWC and field capacities in each layer, normalized by layer thickness. Soil water storage changes (ΔS) were calculated by a soil water balance, with precipitation (P) and

① Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

irrigation (I) as water inputs, and runoff (RO) and deep percolation (DP) and evapotranspiration (ETc) as water outputs ($\Delta S = P + I - RO - DP - ETc$). For the experimental field, RO was assumed to be zero due to relatively small field slope and precipitation amounts, adequate soil infiltration, good surface residue, and drip irrigation. DP was assumed to occur when P exceeded SWD in the full root zone (105 cm) at the time of precipitation and was calculated as P minus SWD. ETc was estimated as: ETc = P + I – ΔS, when there were SWC data. For other days, a daily time step soil water balance model was developed based on the FAO-56 dual crop coefficient approach[4] to estimate daily ETc. The model was based on alfalfa ETr and initial and full-cover Kcb of 0.15 and 0.96, respectively[22], adjusted for measured crop canopy growth and senescence. When measured canopy cover (fc) was between 0.2 and 0.8, Kcb was linearly increased from 0.15 to 0.96, using Kcb = 0.15 + 1.01*fc[23]. The model predicted the daily soil evaporation, transpiration, DP, and SWD. More details on soil water balance calculation have been described elsewhere[24].

2.3 Thermal imagery acquisition and processing

The thermal imagery of plant canopy was obtained using an infrared camera, FLIR A655sc (FLIR Systems, Inc., Portland, USA) with a sensor size of 640×480 pixels, an accuracy of ±2°C or ±2% of reading, and a spectral range of 7.5-13.0 µm. The camera was attached to a boom that was mounted on a high-clearance tractor so that the camera was elevated about 7 m above the ground. Nadir view thermal images were taken near solar noon twice a week from each treatment plot throughout the 2015-2016 growing seasons. The target ground area of each image was about 3.2 m×2.3 m at the center row of each plot and the pixel size of the images was about 5 mm. Specific parameters of emissivity, distance to the object, background temperature and relative humidity were provided to FLIR Research IR software before taking images each measurement day. The measured thermal imagery was obtained in the FLIR Systems' proprietary format and then converted to gray-scale images which were further processed in R[25].

In order to obtain CTSD, Expectation-Maximization (EM) algorithm was applied to estimate canopy temperature distribution in each thermal image[26]. The pixel distribution of canopy temperature in a thermal image can be described by a Gaussian distribution[27]. The temperature distribution of a thermal image may contain sunlit canopy, or shaded canopy, and bare soil. It could be viewed as a combination of two or more Gaussian distributions. Thus, we could fit the temperature distribution of a thermal image with Gaussian distributions to obtain the distribution of pixels that represent canopy temperature only. More details on acquiring CTSD by EM algorithms in "mixtools" of R package can be found in Han et al. (2016)[19]. Besides CTSD, we also calculated Tc_{-ratio} and DANS using the canopy temperature extracted from each image.

2.4 Water stress coefficient (Ks)

Water stress coefficient ($Ks_{\_WB}$) calculated using FAO-56 soil water depletion method[4] in the soil water balance (WB) is shown as:

$$K_{S\_WB} = \frac{TAW - SWD}{(1-p) * TAW} \tag{1}$$

where, *TAW* is the total available soil water in the root zone (mm); *SWD* is the root zone depletion (mm), and *p* is the fraction of *TAW* that a crop can extract from the root zone without suffering water stress. In the study area, *TAW* is 50% of field capacity and *p* is 50%.

The three abovementioned canopy-temperature based stress indicators, CTSD, Tc_{-ratio} and DANS, were used in the place of $Ks_{\_WB}$ and are hereafter noted as Ks_{-CTSD}, Tc_{-ratio} and Ks_{-DANS}, respectively. Tc_{-ratio} can be used directly as a substitute of Ks[16]. CTSD and DANS have units of degree C and need to be normalized as stress coefficients to represent stress levels. After investigating CTSD values in 2015-2016 and 2012-2013 seasons[19], CTSD values ranged from 0-6°C, where 0-2°C indicates no water stress and stress level increased up to 6°C. Thus, CTCD was normalized by assuming Ks_{-CTSD} is equal to 1 when CTSD value is smaller than 2.0°C and decreases linearly to 0 at the maximum CTSD value of 6°C. To convert DANS values to the substitute for Ks_{-DANS}, the procedure was followed as described in Kullberg et al. (2016)[18] using equation Ks= Max (1–DANS/x, 0), where x = 27.7.

2.5 Plant measurements

Leaf water potential was measured at the same time as image collection to evaluate the performance of CTSD as an indicator of crop water stress. Leaf water potential was measured with a Scholander-type pressure chamber (Model 3005 Series Plant Water Status Console with 18 cm long chamber, Soil Moisture Equipment Corp., Santa Barbara, CA, USA) within two hours past solar noon. Fully collared leaves in the sun, in the upper third of the canopy, were cut 30 cm from the tip of the leaf; the leaf blade on either side of the mid-rib was cut so the mid-rib could pass through the lid of the chamber. Leaves were wrapped in a damp cloth during the measurement. Four leaves, each collected from a different plant, were measured per plot and measurements were averaged within each plot.

Whole plant transpiration was measured on two plants per plot in T1(100/100), T8(65/65), T12(40/40), and T13(40/80) treatments with stem heat balance sap flow EXO sensors (Dynamax, Inc, Houston, TX, USA)[28]; thus a total of eight sensors was installed for each treatment. Data were collected from Jul 28 to Sept 20, 2015. Sensor installation, setting and data collection were the same as given by Han et al. (2018)[29].

2.6 Statistical analysis

The relationships and their interaction among observations, such as CTSD, soil water deficit, leaf water potential, and crop transpiration, were compared using simple linear regression model (using *lm* function in *R*). After calculating water stress coefficient, Ks, by the four methods, crop transpiration was calculated and compared with sap flow measurements in 2015. Adjusted coefficient of determination ($R^2_{\_adj}$), root mean square error (RMSE), relative absolute error (RAE), and Nash-Sutcliffe coefficient (NSE)[30] were used to evaluate the performance of each method.

3 Results and Discussion

3.1 CTSD vs. leaf water potential

Maize midday leaf water potential was measured concurrently with thermal image collection from T1(100/100), T8(65/65) and T12(40/40) on July 15, 2015, which was within the Lveg period (deficit irrigation). Significantly different values (p<0.05) among treatments were found, showing that the plants experienced water stress by deficit irrigation treatments during Lveg. CTSD was significantly correlated (p<0.001) with leaf water potential (Figure 1) as found in other studies for canopy temperature-based indices[17,19,31].

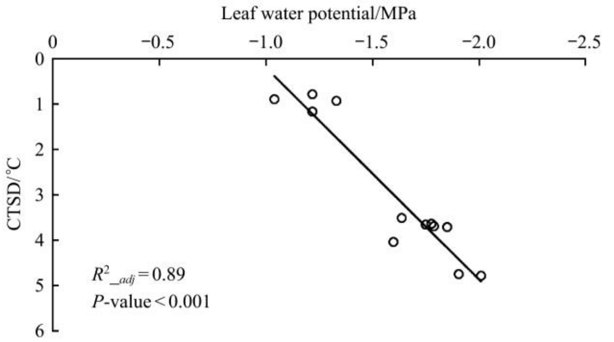


Figure 1 The relationship between canopy temperature standard deviation (CTSD) and leaf water potential based on data collected in 2015

3.2 CTSD- treatment response

CTSD values responded to irrigation treatments in 2015-2016 (Figure 2). T1(100/100) was irrigated to meet 100% crop water need, and irrigation amount was reduced proportionally in other treatments in the Lveg and Mat stages. In general, the trend of CTSD responded to water treatments, with higher values in Lveg, decreasing values during the reproductive stage, and increasing values during Mat, when water stress was resumed, in both growing seasons. Three measurements were taken on DOYs 217, 222, and 225 during the reproductive stage in 2015. There were significant differences in CTSD (p<0.05) among treatments on DOY 217, when full irrigation just resumed starting the reproductive stage and more stressed plants in the previous deficit treatment period need more time to recover. No significantly different CTSD values were found by DOY 222 & 225. The CTSD of treatments greater than 65% of ETc were less than 2.0°C, and the CTSD of 40% treatments were slightly higher than 2.0°C during this period, which confirmed the finding in 2012-2013[19]. The deficit irrigation treatments resumed after DOY 235 (Aug 25, 2015) and the CTSD of T1(100/100) stayed around 2.0°C, while CTSD of other stressed treatments increased to 3.0°C.

In 2016, deficit irrigation treatments started around DOY 179 (June 27, 2016, V8 stage), and all the treatments began to develop stress gradually. CTSD showed no significant difference on DOY 175 and slight difference showed in 40% treatments five days later, and then started to show more different among treatments. The CTSD values in DOY 188-196 clearly show three different levels, where 100 and 80% of ETc treatments had values below 2.0°C, 65% of ETc treatment had value between 2.0-3.0°C, and 40% of ETc treatment had values above 3.0°C. By the end of the Lveg, CTSD reached the maximum among 65 and 40% of ETc treatments. Once full irrigation resumed on DOY 210, CTSD values in all treatments were brought back to below 2.0°C and show no significant difference between treatments throughout the rest of reproductive stage (p-value > 0.05).

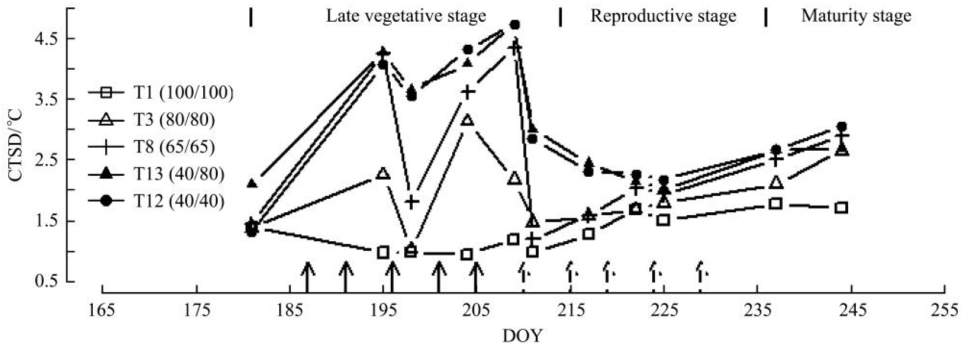


Figure 2 Time series of canopy temperature standard deviation (CTSD) for T1(100/100), T3(80/80), T8(65/65), T13(40/80), and T12(40/40) in 2015. The black arrows indicate irrigation events with amount less than 15 mm, while the dash arrows mean irrigation events with amount larger than 15 mm

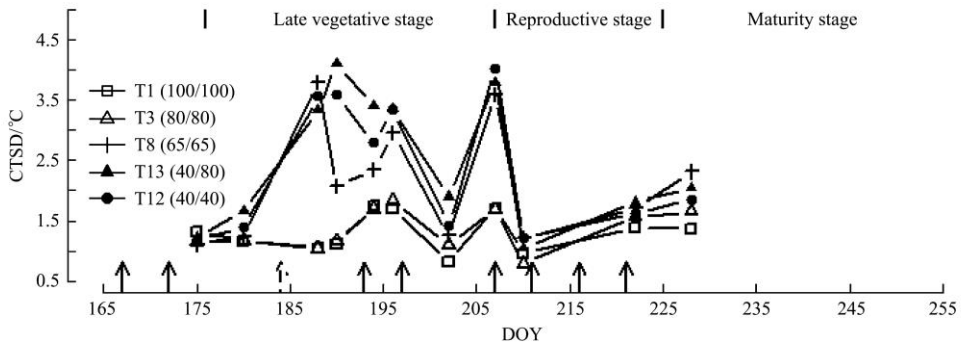


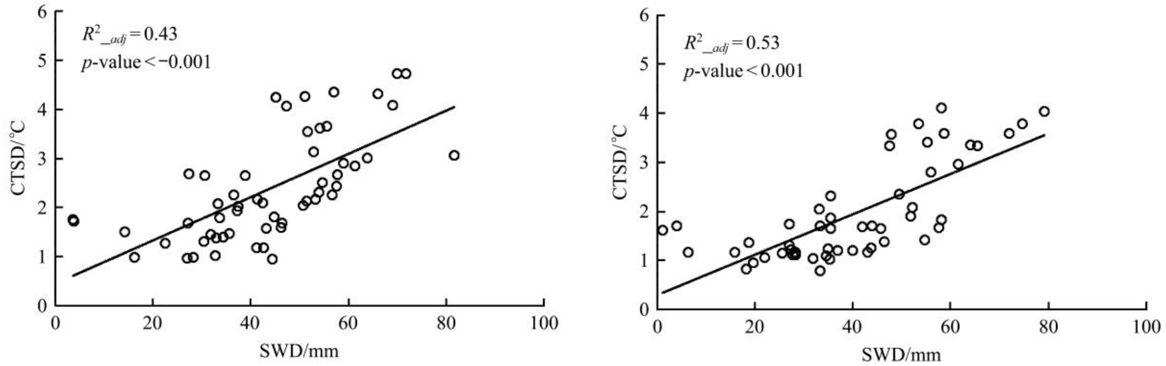
Figure 3 Time series of canopy temperature standard deviation (CTSD) for T1(100/100), T3(80/80), T8(65/65), T13(40/80), and T12(40/40) in 2016. The black arrows indicate irrigation events with amount less than 15 mm, while the dash arrows mean irrigation events with amount larger than 15 mm

In general, it can be concluded that CTSD values of plants with full or 80% of ETc varied between 0 and 2.0°C throughout the seasons, and moderate stress treatment, like 65% of ETc, had CTSD value between 2.0 to 3.0°C, and CSTD values above 3.0°C indicate plants suffer severe stress.

3.3 Comparison with soil water deficit

The relationship between CTSD and soil water deficit, estimated based on soil water content measurements taken in 2015 and 2016, are shown in Figure 4. Typically, the CTSD values were below 2.0°C when SWD values were less than 40 mm. The

SWD value means (for this field soil) that the volumetric SWC is greater than the 80% of the field capacity (no water stress). This also strengthens the assumption that mild or no stress is experienced for CTSD < 2.0°C. CTSD increased as SWD was increasing. There was a statistically significant (p<0.05) correlation between CTSD and SWD above 40 mm. This suggests CTSD is sensitive to the declining of water availability in the root zone[19].

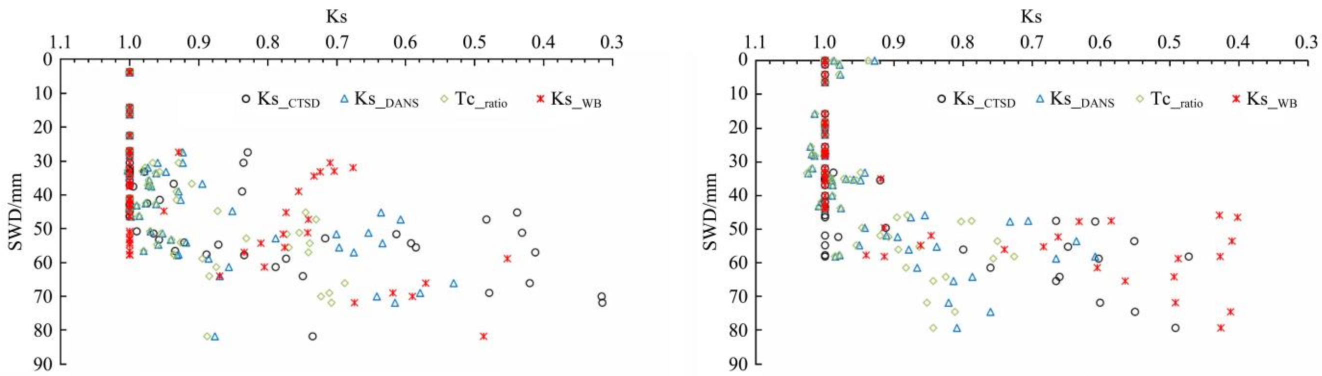


a. 2015 b. 2016

Figure 4 The relationship between canopy temperature standard deviation (CTSD) and soil water deficit (SWD) in 2015 and 2016

3.4 Ks comparison

Figure 5 shows the relationships of $Ks_{–CTSD}$, $Ks_{–DANS}$, $Tc_{–ratio}$ and $Ks_{\_WB}$ with soil water deficit (SWD). The values from these three canopy-temperature based indices were above 0.8 when SWD was less than 40 mm, although a few $Ks_{–WB}$ values fell between 0.6 and 0.8 at 30-40 mm SWD in 2015, indicating overestimation of the stress. More scatter in data points was observed for $Ks_{\_CTSD}$-SWD compared to the other three relationships, although they all suggested increased stress when SWD was greater than 40 mm. Thus, stress was induced after SWD reached 40 mm, and $Ks_{–CTSD}$ was sensitive to changes in SWD. Both $Ks_{–CTSD}$ and $Ks_{–WB}$ reached 0.3 for severe stress; however, $Ks_{–DANS}$ and $Tc_{–ratio}$ were all maintained above 0.55. $Tc_{–ratio}$ in 2016, with a range of 0.9-0.85, was not sensitive to SWD changes from 50-90 mm.



a. 2015 b. 2016

Figure 5 Soil water deficit (SWD) vs. water stress coefficients (Ks) calculated by four different methods in 2015 and 2016: CTSD, DANS, $Tc_{–ratio}$, and soil water depletion

Large canopy temperature contrasts among treatments (e.g., about 9°C difference between T1(100/100) and T12(40/40) in DOY 188 and 190 in 2016) resulted in large differences in $Tc_{–ratio}$ (e.g., 1.0 for SWD between 47.5 mm and 58.7 mm). For days without larger canopy temperature contrasts, however, $Tc_{–ratio}$ values remained high and didn't decrease with increasing stress level, even though large ranges in SWD (50 mm to 80 mm) were observed. Based on this result, we conclude that $Tc_{–ratio}$ is not suitable for crop water stress detection.

3.5 Estimated crop transpiration vs. sap flow measurements in 2015

The daily crop transpiration was calculated as ETr multiplied by Kcb and Ks, which was calculated by four different methods: soil water depletion method ($Ks_{–WB}$), and three canopy temperature-based indices ($Ks_{–CTSD}$, $Ks_{–DANS}$ and $Tc_{–ratio}$). The results were compared with daily sap flow measurements from DOY 209 to 244 in 2015. Ks values for T1(100/100) were 1.0 for all methods due to fully irrigated treatments without stress; therefore, the estimated transpiration was the same for all methods. Here, only results from deficit irrigation treatments were presented. Overall, CTSD method preformed the best among four methods with the highest R^2_{adj}, smallest RAE, and a slightly higher RMSE than the other two canopy temperature-based methods (Figure 6 and Table 2). NSE value of 0.61 means the performance of the prediction model is satisfactory[32]. The performance of $Ks_{–DANS}$ was acceptable, but it could be improved if the empirical coefficients used to scale DANS to Ks values could be further investigated. Although all three canopy temperature-based indices were scaled to be the alternative of Ks, both DANS and $Tc_{–ratio}$ had values outside of the range of 0-1 as dimensionality restrictions[31]. Therefore, CTSD was shown to be a more effective and practical tool for crop water stress assessment without complexity of calculation, need for concurrent measurement of non-stressed crop canopy temperature as a reference, or dimensionality restriction.

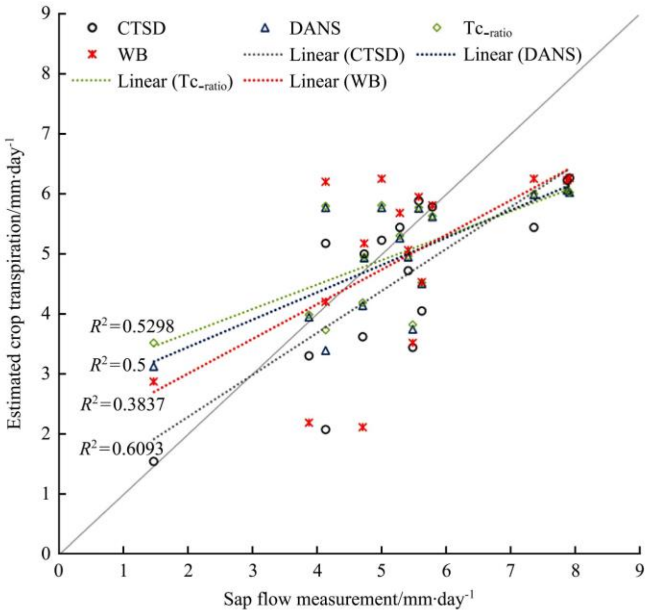


Figure 6 Measured sap flow and estimated actual crop transpiration using water stress coefficient determined by four methods: $Ks_{–CTSD}$, $Ks_{–DANS}$, $Tc_{–ratio}$ and $Ks_{–WB}$ in 2015

Table 2 Statistical analysis of comparison between sap flow measurements and the estimated crop transpiration using water stress coefficient determined by the four methods: Ks_{CTSD}, Ks_{DANS}, Tc_{ratio} and Ks_{WB}

Methods	R^2_{adj}	RMSE/mm·day^{-1}	RAE	NSE
$Ks_{–CTSD}$	0.58	0.87	0.63	0.61
$Ks_{–WB}$	0.34	1.137	0.79	0.38
$Tc_{–ratio}$	0.46	0.697	0.71	0.49
$Ks_{–DANS}$	0.50	0.697	0.69	0.53

4 Conclusions

High resolution thermal imagery was taken from maize under various levels of deficit irrigation at different crop growth stages in 2015 and 2016 growing seasons. CTSD, $Tc_{–ratio}$ and DANS were calculated using the extract canopy temperature from the thermal imagery and converted to water stress coefficients denoted as $Ks_{–CTSD}$, $Tc_{–ratio}$, and $Ks_{–DANS}$. Crop transpiration estimated using these three water stress coefficients were compared with sap flow measurements in 2015. CTSD responded well to irrigation events for both growing seasons and was significantly correlated to leaf water potential and soil water deficit, especially when stress level was above moderate. Compared to $Tc_{–ratio}$ and $Ks_{–DANS}$, $Ks_{–CTSD}$ was more sensitive to soil water changes. Crop transpiration estimated using $Ks_{–CTSD}$ performed better than $Tc_{–ratio}$, $Ks_{–DANS}$, and soil water balance method when compared with sap flow measurements, with R^2_{adj} of 0.58, relative absolute error of 0.63, and RMSE of 0.87 (mm day^{-1}). Nash-Sutcliffe coefficient of 0.61 indicates the performance of the prediction model is sufficient and satisfactory.

CTSD is easy to acquire from high resolution thermal imagery from remote sensing platforms, such as unmanned aerial vehicles. Also, CTSD does not require images for non-stress canopy as a reference like DANS and $Tc_{–ratio}$ do. It has strong application potential to improve crop water stress detection and crop water use estimation for irrigation scheduling.

[References]

[1] Funk, C. C., M. E. Brown. Declining global per capita agricultural production and warming oceans threaten food security. Food Security, 2009; 1(3): 271–289. DOI: 10.1007/s12571-009-0026-y

[2] Xu, X., M. Zhang, J. Li, Z. Liu, Z. Zhao, Y. Zhang, S. Zhou, and Z. Wang. Improving water use efficiency and grain yield of winter wheat by optimizing irrigations in the North China plain. Field Crops Research, 2018; 221: 219–227. doi: 10.1016/j.fcr.2018.02.011

[3] Tang, J., W. Han, and L. Zhang. UAV multispectral imagery combined with the FAO-56 dual approach for maize evapotranspiration mapping in the north China Plain. Remote Sensing, 2019; 11(21): 2519. doi: 10.3390/rs11212519

[4] Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. Crop evapotranspiration-guidelines for computing crop water requirements-FAO irrigation and drainage paper 56. FAO, Rome, 1998; 300(9): D05109.

[5] Er-Raki, S., A. Chehbouni, and B. Duchemin. Combining satellite remote sensing data with the FAO-56 dual approach for water use mapping in irrigated wheat fields of a semi-arid region. Remote Sensing, 2010; 2(1): 375–387. doi: 10.3390/rs2010375

[6] Er-Raki, S., A. Chehbouni, N. Guemouria, B. Duchemin, J. Ezzahar, and R. Hadria. Combining FAO-56 model and ground-based remote sensing to estimate water consumptions of wheat crops in a semi-arid region. Agricultural Water Management, 2007; 87(1): 41–54. doi: 10.1016/j.agwat.2006.02.004

[7] Tasumi, M. and R. G. Allen. Satellite-based et mapping to assess variation in ET with timing of crop development. Agricultural Water Management, 2007; 88(1-3): 54–62. doi: 10.1016/j.agwat.2006.08.010

[8] Zhang, H., R. G. Anderson, and D. Wang. Satellite-based crop coefficient and regional water use estimates for hawaiian sugarcane. Field Crops Research, 2015; 180: 143–154. doi: 10.1016/j.fcr.2015.05.023

[9] Tanner, C. B. Plant temperatures. Agronomy Journal, 1963; 55(2): 210–211. doi: 10.2134/agronj1963.00021962005500020043x

[10] Clawson, K. L., R. D. Jackson, and P. J. Pinter. Evaluating plant water stress with canopy temperature differences. Agronomy Journal, 1989; 81(6): 858–863. doi: 10.2134/agronj1989.00021962008100060004x

[11] Gerhards, M., M. Schlerf, U. Rascher, T. Udelhoven, R. Juszczak, G. Alberti, F. Miglietta, and Y. Inoue. Analysis of airborne optical and thermal imagery for detection of water stress symptoms. Remote Sensing, 2018; 10(7): 1139. doi: 10.3390/rs10071139

[12] Idso, S. B., R. D. Jackson, P. J. P. Jr, R. J. Reginato, and J. L. Hatfield. Normalizing the stress-degree-day parameter for environmental variability. Agricultural Meteorology, 1981; 24(1): 45–55. doi: 10.1016/0002-1571(81)90032-7

[13] Han, M., H. Zhang, J. L. Chávez, L. Ma, T. J. Trout, and K. C. DeJonge. Improved soil water deficit estimation through the integration of canopy temperature measurements into a soil water balance model. Irrigation Science, 2018; 36(3): 187–201. doi: 10.1007/s00271-018-0574-z

[14] Zhang, H., M. Han, J. Chávez, and Y. B. Lan. Improvement in estimation of soil water deficit by integrating airborne imagery data into a soil water balance model. International Journal of Agricultural and Biological Engineering, 2017; 10: 37–46. DOI: 10.3965/j.ijabe.20171003.3081

[15] Bellvert, J., K. Adeline, S. Baram, L. Pierce, B. Sanden, and D. Smart. Monitoring crop evapotranspiration and crop coefficients over an almond and pistachio orchard throughout remote sensing. Remote Sensing, 2018; 10(12): 2001. doi: 10.3390/rs10122001

[16] Bausch, W., T. Trout, and G. Buchleiter. Evapotranspiration adjustments for deficit-irrigated corn using canopy temperature: A concept. Irrigation and drainage, 2011; 60(5): 682–693. doi: 10.1002/ird.601

[17] Taghvaeian, S., L. Comas, K. C. DeJonge, and T. J. Trout. Conventional and simplified canopy temperature indices predict water stress in sunflower. Agricultural Water Management, 2014; 144: 69–80. doi: 10.1016/j.agwat.2014.06.003

[18] Kullberg, E.G., K.C. DeJonge, and J.L. Chávez. Evaluation of thermal remote sensing indices to estimate crop evapotranspiration coefficients. Agricultural Water Management, 2017; 179: 64–73. DOI: 10.1016/j.agwat.2016.07.007

[19] Han, M., H. Zhang, K. C. DeJonge, L. H. Comas, and T. J. Trout. Estimating maize water stress by standard deviation of canopy temperature in thermal imagery. Agricultural Water Management, 2016; 177: 400–409. doi: 10.1016/j.agwat.2016.08.031

[20] Zhang, Z., J. Bian, W. Han, Q. Fu, S. Chen, and T. Cui. Cotton moisture stress diagnosis based on canopy temperature characteristics calculated from uav thermal infrared image. Nongye Gongcheng Xuebao/

Transactions of the Chinese Society of Agricultural Engineering, 2018; 34(15): 77–84. DOI: 10.11975/j.issn.1002-6819.2018.15.010

[21] Allen, R. G., I. A. Walter, R. L. Elliott, T. A. Howell, D. Itenfisu, M. E. Jensen, and R. L. Snyder. The ASCE standardized reference evapotranspiration equation. The ASCE Standardized Reference Evapotranspiration Equation, 2005.

[22] Jensen, M. E. and R. G. Allen. Evaporation, evapotranspiration, and irrigation water requirements. American Society of Civil Engineers.

[23] Trout, T. J., L. F. Johnson, and J. Gartung. Remote sensing of canopy cover in horticultural crops. HortScience, 2008; 43(2): 333–337. doi: 10.21273/HORTSCI.43.2.333

[24] Trout, T. J. and W. C. Bausch. USDA-ARS colorado maize water productivity data set. Irrigation Science, 2017; 35(3): 241–249. doi: 10.1007/s00271-017-0537-9

[25] Team, R. C. R: A language and environment for statistical computing, 2013.

[26] Benaglia, T., D. Chauveau, D. R. Hunter, and D. S. Young. Mixtools: An R package for analyzing finite mixture models. Journal of Statistical Software, 2009; 32(6): 1–29. http://dx.doi.org/10.18637/jss.v032.i06

[27] Meron, M., V. Alchanatis, Y. Cohen, and J. Tsipris. Aerial thermography for crop stress evaluation - a look into the state of the technology, in Precision agriculture'13. 2013, Springer. p. 177–183.

[28] Sakuratani, T. A heat balance method for measuring water flux in the stem of intact plants. Journal of Agricultural Meteorology, 1981; 31(1): 9–17. doi: 10.2480/agrmet.37.9

[29] Han, M., H. Zhang, K. C. DeJonge, L. H. Comas, and S. Gleason. Comparison of three crop water stress index models with sap flow measurements in maize. Agricultural Water Management, 2018; 203: 366–375. doi: 10.1016/j.agwat.2018.02.030

[30] Nash, J. E. and J. V. Sutcliffe. River flow forecasting through conceptual models part i — a discussion of principles. Journal of Hydrology, 1970; 10(3): 282–290. doi: 10.1016/0022-1694(70)90255-6

[31] DeJonge, K. C., S. Taghvaeian, T. J. Trout, and L. H. Comas. Comparison of canopy temperature-based water stress indices for maize. Agricultural Water Management, 2015; 156: 51–62. DOI: 10.1016/j.agwat.2015.03.023

[32] Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 2007; 50(3): 885–900. doi: 10.13031/2013.23153