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Comparison of canopy temperature-based water stress indices for maize

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ABSTRACT

Infrared thermal radiometers (IRTs) are an affordable tool for researchers to monitor canopy temperature. In this maize experiment, six treatments of regulated deficit irrigation levels were evaluated. The main objective was to evaluate these six treatments in terms of six indices (three previously proposed and three introduced in this study) used to quantify water stress. Three are point-in-time indices where one daily reading is assumed representative of the day (Crop Water Stress Index – CWSI, Degrees Above Non-Stressed – DANS, Degrees Above Canopy Threshold – DACT) and three integrate the cumulative impact of water stress over time (Time Temperature Threshold – TTT, Integrated Degrees Above Non-Stressed – IDANS, Integrated Degrees Above Canopy Threshold – IDACT). Canopy temperature was highly correlated with leaf water potential (R^2 = 0.895). To avoid potential bias, the lowest observation from the non-stressed treatment was chosen as the baseline for DANS and IDANS indices. Early afternoon temperatures showed the most divergence and thus this is the ideal time to obtain spot index values. Canopy temperatures and stress indices were responsive to evapotranspiration-based irrigation treatments. DANS and DACT were highly correlated with CWSI above the corn threshold 28 °C used in the TTT method, and all indices showed linear relationship with soil water deficit at high temperatures. Recommendations are given to consider soils with high water-holding capacity when choosing a site for non-stressed reference crops used in the DANS method. The DACT may be the most convenient index, as all it requires is a single canopy temperature measurement yet has strong relationships with other indices and crop water measurements.

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1. Introduction

Agricultural irrigation is of tremendous importance to global food security, producing 40% of the world's food supply from only 20% of the cultivated land (Garces-Restrepo et al., 2007). However, irrigated agriculture faces tremendous uncertainty in water supply due to prolonged droughts associated with climate change, as well as increased competition from environmental, municipal, and industrial water needs. The Northern Front Range of Colorado is an example of an agricultural area with a significant economy based on irrigated agriculture, where recent droughts and a constantly expanding municipal demand have reduced the irrigation water supply. To deal with the uncertainty of the water supply and the likelihood of less water available for irrigation, producers are increasingly utilizing growth-stage timed irrigation management called regulated deficit irrigation (RDI), where the crop is intentionally stressed at strategic growth stages in order to stretch irrigation supplies and/or reduce crop evapotranspiration (ET) while minimizing yield loss. Appropriately, regulated deficit irrigation has been the subject of much recent research in Northern Colorado (Bausch et al., 2010; DeJonge et al., 2011, 2012; Taghvaeian et al., 2012, 2014a,b).

Monitoring water stress is critical to optimizing yields under RDI, and often requires a high number of sensors for the continuous and precise monitoring of soil and crop water status (Playan et al., 2014). Infrared thermometry is an ideal method to monitor stress in that it is nondestructive, scalable from single plants to whole fields, can be measured continuously, and is less expensive than many alternative methods. Several recent studies have utilized the mobility of linear or center pivot irrigation systems to mount infrared thermal radiometers (IRTs), thereby getting a dynamic scan of the effects of canopy temperature (Nayak, 2005; O'Shaughnessy et al.,

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2012b; Peters and Evett, 2008). More recent studies have utilized unmanned aerial vehicles (UAVs) with mounted infrared thermal imaging cameras to quantify water stress (Bellvert et al., 2013).

Canopy temperature increases when solar radiation is absorbed, but is cooled when that energy is used for evaporating water (latent energy or transpiration) rather than heating plant surfaces. Canopy temperature commonly follows a diurnal curve, with daytime temperatures rising due to increases in solar radiation and temperature. A water stressed plant will reduce transpiration and will typically have a higher temperature than the non-stressed crop. This effect has also been explored as a response to nutrient stress (Lin et al., 2012; Zhou et al., 2005) and disease stress (Hatfield and Pinter, 1993), but water stress has been the primary object of study. Colaizzi et al. (2012) showed that canopy temperature-based algorithms are strongly correlated to important quantifiable crop outputs such as yield, water use efficiency, seasonal ET, midday leaf water potential, irrigation rates, and herbicide damage. Variability of canopy temperature has been used by Gardner et al. (1981b) and more recently González-Dugo et al. (2006) to indicate water stress, and the latter noted the need to quantify the complex relationship between canopy temperature, water stress, and spatial water availability.

Several indices have been developed for monitoring and quantifying water stress using infrared thermometry. All of the indices use T_c (crop canopy temperature) as a main driver for evaluation, typically as a single daily measurement at an assumed peak stress time, or by evaluating time above a temperature threshold. Little research has been published that integrates T_c or resulting indices over individual days, showing the cumulative effects of stress magnitude and time. Differences between canopy temperature, T_c, and air temperature, T_a, have often been used to quantify water stress. Based on the growing degree day concept, Idso et al. (1977) proposed use of the Stress Degree Day (SDD), which is the simple subtraction of the air temperature from the canopy temperature of a crop. They showed that the accumulation of daily midafternoon temperature differences, $T_a - T_c$, throughout the season is linearly related to the final yield of the crop. A main drawback to SDD is that environmental conditions such as air humidity can affect the index (Clawson et al., 1989). In a recent example, using single daily readings from 1400 h, this method was found to be correlated with stem water potential and soil water content in peach trees (Wang and Gartung, 2010) and was used as the primary input for deficit irrigation scheduling (Zhang and Wang, 2013). However, this method was largely abandoned after the introduction of the Crop Water Stress Index (CWSI) in the early 1980s (Idso et al., 1981; Jackson et al., 1981).

The CWSI is the canopy minus air temperature relative to the extreme differential of a well-watered crop, dT_{LL}, and of a non-transpiring canopy, dT_{UL}. Two different methods have been used to establish the CWSI baseline temperatures: an empirical approach (Idso et al., 1981) and a theoretical approach (Jackson et al., 1981, 1988). The empirical approach has advantages due to its reliance on only two variables (air temperature and relative humidity) in addition to canopy temperature. Based on this approach, dTLL is estimated as a linear function of atmospheric vapor pressure deficit (VPD), and the dTLL-VPD relationship is known as a non-water stressed baseline (NWSB). Likewise, dTUL is estimated as a linear function of the vapor pressure gradient (VPG), and the dTUL-VPG relationship is referred to as a non-transpiring baseline (NTB). Gardner et al. (1981a,b) provided details on developing NWSBs/NTBs, measuring canopy temperature, estimating CWSI, and interpreting results. The greatest limitation of this empirical approach is that NWSBs are crop, growth-stage, and climate-specific. Recently developed NWSBs for corn in northern Colorado (Taghvaeian et al., 2012, 2014a) are nearly identical to those developed by Idso (1982) in Arizona and Nielsen and Gardner (1987) in central Nebraska, suggesting that baselines may be transferrable not only based on location but possibly under similar climatic conditions. Even if appropriate baselines are available, obtaining concurrent measurements of air temperature and relative humidity and then estimating CWSI may limit the implementation of this method by farmers. Applications of CWSI for corn have been the topic of numerous recent studies (Chen et al., 2010; Irmak et al., 2000; Kar and Kumar, 2010; Li et al., 2010; Payero and Irmak, 2006; Zia et al., 2011, 2013).

As IRT technology was improving in the late 1970s and early 1980s (the same time as the development of CWSI), a few studies explored the difference between a stressed and non-stressed canopy temperature of the same crop, referred to as TSD or Temperature Stress Day (Clawson and Blad, 1982; Gardner et al., 1981a,b). The method has the advantage of requiring only two canopy temperature measurements. However, because TSD is affected by some environmental dependencies (namely humidity), Clawson et al. (1989) proposed a unification of the TSD from Gardner et al. (1981a) with the CWSI from Idso et al. (1981). However, this simple canopy temperature difference methodology has been largely ignored. In a recent study from northern Colorado, (Taghvaeian et al., 2014b) evaluated water stress in sunflower using both CWSI and a newly named TSD index, Degrees Above Non-Stressed Canopy (DANS), which is the difference of canopy temperatures between a stressed and non-stressed crop. Both indices were evaluated at several times during mid-day and afternoon. Both CWSI and DANS responded to irrigation amount, and were strongly correlated with plant measurements including fraction of intercepted photosythetically active radiation (fIPAR), leaf area index (LAI), leaf water potential, and root growth. The authors noted that while DANS is much simpler than the CWSI method, it can still effectively be used to monitor water stress and schedule irrigations. Bausch et al. (2010) introduced T_c ratio (ratio of T_c vs T_{cNS}, or canopy temperature of a non-stressed crop) as a substitute for the water stress coefficient used in the reference ET and crop coefficient concept. However because of scaling issues (i.e. the same temperature difference yields different T_c ratio values at high vs. low temperatures), the T_c ratio was not evaluated in this study.

The temperature-time threshold (TTT) method has been used as a technique for evaluating crop water stress and scheduling irrigation. The technique is patented as Biologically-Identified Optimal Temperature Interactive Console (BIOTIC) for Managing Irrigation, under U.S. patent no. 5,539,637 (Upchurch et al., 1996). The technique recommends irrigation when the canopy temperature exceeds a threshold temperature for a specified duration. The TTT method has been used effectively for several crops including soybean (Evett et al., 2002; Peters and Evett, 2008), sorghum (O'Shaughnessy et al., 2012b), cotton (O'Shaughnessy and Evett, 2010; Wanjura et al., 1995; Wanjura and Upchurch, 2000), and corn (Evett et al., 2000, 2002; Lamm and Aiken, 2008; Wanjura and Upchurch, 2000). For example, using a 2.5 h threshold TTT for irrigation scheduling of corn corresponded well to a 100% ETc treatment (Lamm and Aiken, 2008). Corn studies in the literature typically used 28 °C as the critical temperature, noted as the center of the thermal kinetic window for optimum growth (Burke, 1996). A similar method was recently explored where a CWSI threshold was used instead of a temperature threshold (O'Shaughnessy et al., 2012a). While the TTT method has many advantages in its simplicity, requiring only a temperature threshold and the daily amount of time T_c is above that threshold, it does have some drawbacks. First, canopy temperature is largely driven by ambient temperature, which is independent of the level of crop stress. For example, if irrigation is followed by a very hot day, even a well-watered crop will have a high canopy temperature, possibly indicating a false need for additional irrigation. Second, the TTT method only measures time above the threshold, but does not include severity above this threshold. For example, the method assumes the same stress

for canopy temperature 5 °C and 1 °C over the threshold. Generally, higher temperatures would indicate more severe stress. Over 30 years ago, Gardner et al. (1981a) measured accumulated T_c differences of stressed and non-stressed canopy temperatures, and related values to maximum yield and ET from several irrigation treatments. However, a limitation in their method was that this accumulation was done using only spot measurements at one time per day (similar to DANS method).

Studies of canopy temperature typically use one major method (most often CWSI) to quantify the water stress indicated by canopy temperature. Wanjura and Upchurch (2000) compared results of TTT (referred to in their paper as stress time index, ST) with CWSI in corn and cotton, concluding that the theoretical CWSI procedure may be a superior method for comparing water stress across environments, but noting the difficulty in its application due to additional required measurements. O'Shaughnessy et al. (2012a) used a combination CWSI-TTT method to trigger automatic irrigations in sorghum, noting similar yield results to irrigation treatments based on water balance. Taghvaeian et al. (2014b) compared CWSI and DANS on deficit irrigated sunflower, concluding that the simplified DANS may be used effectively in monitoring water stress and scheduling irrigations. Other researchers such as Kacira et al. (2002) have concluded that the complexity of the CWSI technique must be reduced to meet the practical concerns of field applications and growers. It is conceivable that simplified methods to quantify water stress may have computational advantages over CWSI, especially if they can be closely related to water stress indicators.

This study utilizes a 2-year, regulated deficit irrigation corn field trial in northern Colorado to evaluate canopy temperature-based crop water stress indices. Specific objectives of this study were to:

1. Evaluate and compare six thermal canopy stress indices (CWSI, DANS, TTT, and three newly defined indices) as indicators of water stress.
2. Quantify daily stress index differences due to irrigation treatments, at three major growth stages.
3. Compare stress index values to soil water deficit.

2. Methods and materials

2.1. Study area and experimental treatments

The field experiment was conducted during the summers of 2012 and 2013 at the USDA-ARS Limited Irrigation Research Farm (LIRF), located near the city of Greeley in northern Colorado, USA (40°26′57″N, 104°38′12″W, elevation 1427 m). The alluvial soils of the study field are predominately sandy and fine sandy loam of the Olney and Otero series. Planting and nitrogen details, as well as major growth stages, are given in Table 1. Each plot was 9 m wide (12 rows at 0.76 m spacing) by 43 m long, and all measurements were taken from the middle six rows to reduce border effects. Treatments were varying levels of regulated deficit irrigation (RDI), where varying levels of stress are imposed during the vegetative growth stages and/or the maturity growth stages, but no stress is invoked during the sensitive reproductive growth stages (i.e. beginning at tasseling and silking in corn, Table 1). The 12 treatments are named for the target percent of maximum crop ET goal during vegetative and maturity growth stages, respectively (e.g. an 80/40 treatment would target 80% of maximum ET during the vegetative growth stages and 40% of maximum ET during the maturity growth stages). Six of the 12 treatments were selected to study canopy temperature: 1 (100/100), 2 (100/50), 3 (80/80), 6 (80/40), 8 (65/65), 10 (65/40) and 12 (40/40). Rainfall and actual irrigation amounts by growth stage are shown in Table 2. During the growing season, water was applied using 16 mm drip irrigation tubing that was placed next to each row of corn. The 30-cm spaced in-line emitters discharged at a rate of 1.1 L h^{-1} for an irrigation application rate of 5 mm h^{-1}. The amount of water applied to each treatment was measured by turbine flow meters and recorded. Irrigations were applied every 4 or 5 days during mid-season. Irrigation amounts were based on target ET_c levels minus any preceding precipitation, and soil water deficit as determined by water balance (described in next section). Fertilizers were applied to avoid nutrient deficiencies on all treatments. Treatments were laid out in a randomized block design with four replications. Crops were grown in a corn/sunflower rotation such that the plots in the two years were in different locations.

Table 1
Agronomic details and dates for field experiment.

Hybrid	2012 Dekalb DCK52-04	2013 Dekalb DCK52-04
Planting Population (seeds/ha)	84,000	85,500
Planting Date	April 30	May 15
Reproductive Date (R1)	July 22	July 23
Maturity Date (R4)	August 15	August 16
Harvest Date	October 18	November 4
N sidedressing (kg/ha)	April 30 (42)	May 15 (34)
Additional N applications[a] (kg/ha)	June 6 (34)	July 1 (21)
	June 19 (30)	July 15 (26)
	June 25 (39)	July 24 (28)
	July 4 (28)	
IRT measurement dates and growth stages[b]		
Vegetative	June 9–July 22 V7–VT	July 1–July 23 V12–VT
Reproductive	July 23–August 15 R1–R3	July 24–August 16 R1–R3
Maturity	August 16–September 4 R4–R5	August 17–October 17 R4–R6

[a] Amounts given are for nonstressed treatment (Trt 1). Amounts varied slightly between treatments, but no treatments were ever put under nitrogen stress.
[b] As determined by Abendroth et al. (2011).

2.2. Soil water content measurements

An access tube installed in the middle row of each plot was used to determine soil water content (SWC) by neutron attenuation (neutron moisture meter) and subsequent soil water

Table 2
Irrigation amounts and rainfall (mm) for each treatment, by major growth stage[a] (Vegetative = VE-VT, Reproductive = R1–R3, Maturity = after R3), during 2012 and 2013 growing seasons. All treatments had goal 100% ET during Reproductive growth stages. There were four replicates of each treatment unless otherwise indicated.

Treatment # (%vegetative ET/%maturity ET)	2012			2013		
	Veg	Rep	Mat	Veg	Rep	Mat
1 (100/100)	271	169	169	205	101	141
2 (100/50)	268	152	35	205	96	52
3 (80/80)	211	168	133	157	102	104
6 (80/40)	209	158	29	157	102	24
8 (65/65)[b]	165	167	56	113	123	83
10 (65/40)[b,c]	163	164	29	113	124	25
12 (40/40)	95	169	29	60	132	24
Rainfall	34	0	12	23	26	104

[a] As determined by Abendroth et al. (2011).
[b] Three replicates in 2012.
[c] No T_c observations in 2013.

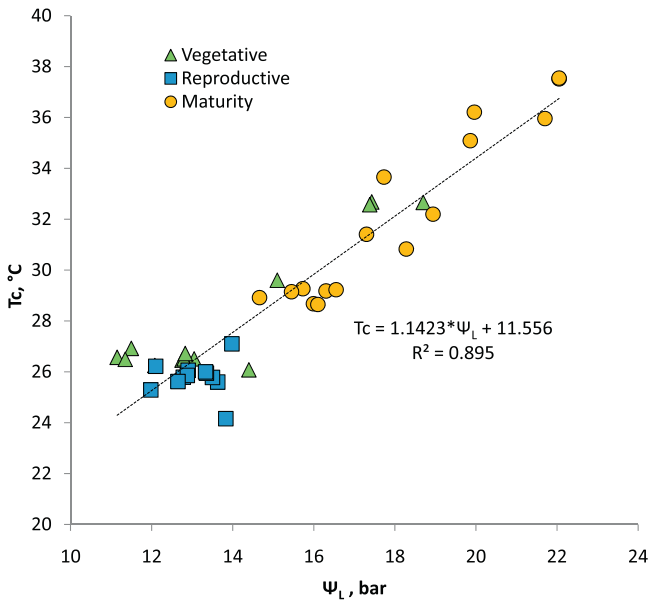

Fig. 1. Canopy temperature from 1400 h (T_c) vs. midday leaf water potential (Ψ_L) taken on three dates in 2013 (growth stage in parentheses): 23 July (vegetative), 15 august (reproductive), and 3 September (maturity).

deficit. The neutron moisture meter was calibrated with volumetric soil samples in 2007 ($N = 125$, $R^2 = 0.92$) and was validated annually. Measurements were taken at 30 cm depth increments to 2 m. Time domain reflectometry (TDR) was used to measure soil moisture content in the top 15 cm from the surface. Field capacities from each layer were estimated based on observations of SWC from the previous 5 years of study on the site. Permanent wilting point (1500 kPa) was estimated from pressure plate analysis to be 50% of field capacity (30 kPa). Total available water (TAW, cm) in the top 105 cm of soil was calculated from the field capacity values at various depths:

$$TAW = z_i(\theta_{FC} - \theta_{WP})_i \quad (1)$$

where Z_i is the thickness of soil layer i, and θ_{FC} and θ_{WP} are volumetric field capacity and wilting point, respectively. Using a management allowable depletion of 50% which is common for corn, the threshold θ_t where stress occurs was assumed to be halfway between θ_{WP} and θ_{FC}, so it is assumed that 50% of the TAW can be depleted from the root zone before water stress and ET reduction occurs (Allen, 1998). Soil water deficit was calculated as

$$SWD = \sum z_i(\theta_{FC} - \theta_{obs})_i \quad (2)$$

where θ_{obs} is the observed volumetric soil water content at the given layer.

2.3. Plant measurements

In order to verify that canopy temperature can be used as an indicator of plant water stress, T_c was compared with midday leaf water potential (Ψ_L), which 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 on four dates: 23 July, 15 August, and 3 September, all in 2013 (Fig. 1). Fully collared leaves in the sun, in the upper third top of the canopy, were cut from the 30 cm from the tip of the leaf, the mid-rib was cut out, and 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.

2.4. Environmental measurements

Environmental measurements were obtained by the on-site Colorado Agricultural Meteorological Network (CoAgMet, http://ccc.atmos.colostate.edu/~coagmet/) station GLY04 (40.4487°N, 104.638°W). This data includes precipitation, air temperature, relative humidity (and subsequent vapor pressure deficit), solar radiation, and wind speed taken at 2 m above a grass reference surface (Andales et al., 2009). All data were summarized by hourly means.

2.5. IRT measurements

Temperature of the corn canopy was acquired on a continuous basis using infrared thermal radiometer (IRT, model: SI-121, Apogee Instruments, Inc., Logan, Utah, USA) with a 36° field of view and ±0.2 °C accuracy over the temperature range of −10 to 65 °C. The IRTs were attached to telescoping posts and angled 23° below horizon and 45° from north (looking northeast) to ensure viewing primarily crop canopy once canopy cover was nearly complete. Although IRTs were installed early in vegetative growth, data was omitted until 80% canopy cover was reached. The IRTs were kept at a height of about 0.8 m above the top of canopy throughout the growing season (adjusted twice per week during vegetative growth), resulting in an elliptical horizontal target around 2.2 m^2 in size. All IRT temperatures were measured by data-loggers (model: CR1000, Campbell Scientific Inc., Logan, Utah, USA), every 5 s and averaged on 30 min intervals. Measured values were corrected for the effect of sensor body temperature using calibration equations provided by the manufacturer.

2.6. Index estimation

The CWSI method compares the difference between measured canopy and air temperatures (dT_m), and the lower (dT_{LL}) and upper (dT_{UL}) limits of canopy-air temperature differential. The latter two values were found under non-water-stressed and non-transpiring conditions, respectively:

$$\text{CWSI} = \frac{(dT_m - dT_{LL})}{(dT_{UL} - dT_{LL})} \quad (3)$$

Non-stressed baselines for CWSI were created for the field using combined data from 2012 and 2013. The equation for the lower baseline had a strong relationship with VPD ($T_c - T_a = -1.79 \times \text{VPD} + 2.34$, $R^2 = 0.97$) which was similar to the original Idso (1981) lower baseline and very similar to baselines determined for eastern Colorado and in an adjacent field (Taghvaeian et al., 2012, 2014a). 5 °C was used as the upper baseline based on observation. CWSI values of 0 indicate no stress and values of 1 indicate maximum stress. Depending on atmospheric, crop, and soil water conditions, it is occasionally possible to measure dTm values greater than the upper baseline, thus CWSI can be slightly greater than 1.

The DANS and TTT methods were calculated as

$$DANS(h) = T_c(h) - T_{cNS}(h) \quad (4)$$

$$TTT = \sum_{h=0}^{24} h, \quad \text{when } T_c > T_{critical} \quad (5)$$

where T_c is the canopy temperature (°C) of the crop of interest at a given time h, T_{cNS} is the canopy temperature of a nearby cooler non-stressed crop of the same variety and maturity at the same time, and $T_{critical}$ is the threshold temperature for the crop (i.e. 28 °C for corn).

The TTT method assumes that stress is not occurring in the crop until it reaches the temperature threshold or $T_{critical}$, and calculates the amount of time that T_c is greater than $T_{critical}$. The DANS method gives a single value of canopy temperature above a non-stressed canopy temperature, and while it is also simple to implement, it requires maintenance of the non-stressed comparison plot and temperature measurements of both canopies. Blending elements of the DANS (difference in canopy temperature, or degree of stress) with TTT (time above a threshold, or time length of stress), three new indices were created for evaluation.

The first new index is similar to DANS, as it quantifies the temperature difference above the critical temperature for the crop instead of a non-stressed canopy temperature. Degrees Above Critical Temperature (DACT) is estimated as:

$$DACT(h) = \max[0, T_C(h) - T_{critical}] \quad (6)$$

Assuming that the crop is not stressed if the canopy temperature is below $T_{critical}$, DACT will give a value of zero to indicate no stress. The second and third new indices integrate DANS and DACT respectively over the course of a day:

$$IDANS = \int_{h=0}^{24} (T_c - T_{cNS})dh = \sum_{h=0}^{24} ([T_c(h) - T_{cNS}(h)]) \quad (7)$$

$$IDACT = \int_{h=0}^{24} \max[0, (T_c - T_{critical})] dh = \sum_{h=0}^{24} \max[0, T_c(h) - T_{critical}(h)] \quad (8)$$

All six index values (CWSI, DANS, TTT, DACT, IDANS, IDACT) were calculated for each plot, and treatment index means shown in this study are an average of the index values, not the index obtained from average T_c for a given treatment. In other words given four T_c values for a treatment, index values are calculated individually for all four replicates and then averaged, rather than first averaging the T_c values and then determining a single index value.

3. Results

3.1. Comparison of canopy temperature and leaf water potential

Midday corn T_c was highly correlated with midday Ψ_L on three days in 2013, one in each major growth stage, with $R^2 = 0.895$ combining all data (Fig. 1). As expected, during the drought sensitive reproductive stage in which all treatments were taken out of stress, both T_c and Ψ_L were relatively low. This trend suggests that canopy temperature and its subsequent thermal indices can be used to quantify water stress.

3.2. Choosing "least stressed" canopy temperature

Past studies using methods that use T_c and T_{cNS} to create an index (i.e., T_c ratio and DANS) have calculated T_{cNS} as the mean T_c from multiple replicates of a "non-stressed" treatment (Bausch et al., 2010; Taghvaeian et al., 2014b). Thus, by definition, individual replicates with higher temperatures will predict stress but replicates with lower temperatures than the mean may predict no stress and even result in numerical values for indices that are unreasonable (i.e. T_c ratio > 1 or DANS < 0). In order to avoid such numerical issues, this study used the coolest observed T_c value from the non-stressed Treatment 1 (100/100 treatment in Table 2) as T_{cNS}. This technique is similar to surface energy balance methods (i.e. METRIC or SEBAL) that will select a "cold pixel" or coolest observation as a baseline (Allen et al., 2007; Bastiaanssen et al., 1998). This approach makes the assumption that the only variability in T_c measurements is due to soil water holding capacity and irrigation treatment differences. While under extremely hot, dry, and windy conditions stress is likely in even the highest irrigation treatment, but by using the coolest observation from the most heavily irrigated treatment, it is likely to choose the *least stressed* observation. Occasionally another observation from another low-stress treatment may be cooler than our T_{cNS}, but it is likely these occurrences would be infrequent with negligible difference.

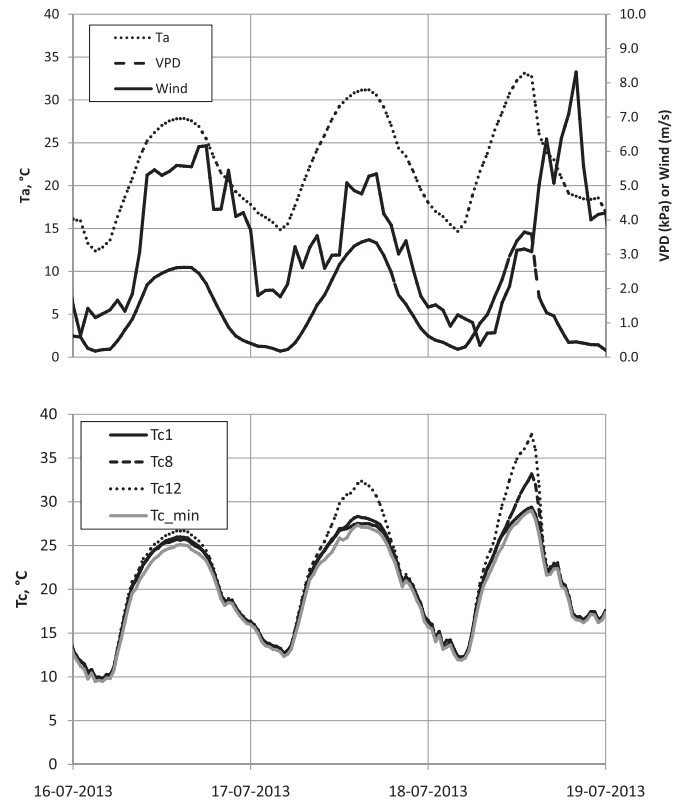

Fig. 2. Three days of weather parameters (top) and canopy temperature measurements (T_c, bottom) following irrigation to all three treatments on 7/15/2013. T_a = air temperature; VPD = vapor pressure deficit. Tc1, Tc8, and Tc12 denote mean (n = 4) canopy temperature by treatments 1 (100/100), 8 (65/65), and 12 (40/40) respectively. T_c-min denotes lowest observed T_c from all individual measurements (n = 26).

3.3. Hourly trends

Canopy temperature, vapor pressure deficit, and often wind will typically follow a diurnal curve that is largely influenced by the solar radiation cycle (Fig. 2). However, it is particularly interesting that canopy temperatures converge at nighttime, regardless of treatment (lower Fig. 3). Typically, all IRT temperatures should be within 0.5 °C in the nighttime hours, and this method was used as a verification of properly calibrated sensors. The largest range in T_c measurements was observed during the early afternoon hours (as also shown in Fig. 2), indicating the maximum amount of differential stress throughout the day and justifying use of measurements at these times to represent "spot" indices such as CWSI and DANS. Other authors have used similar methods, such as the canopy temperature variability (σ_{Tc}) as an indicator of crop water stress variability (González-Dugo et al., 2006), although Nielsen and Gardner (1987) found that corn canopy temperature variability was poorly correlated with CWSI. Other studies have specifically found that canopy temperature and consequently stress indices peak one to 2 h after solar noon for maize (Irmak et al., 2000; Taghvaeian et al.,

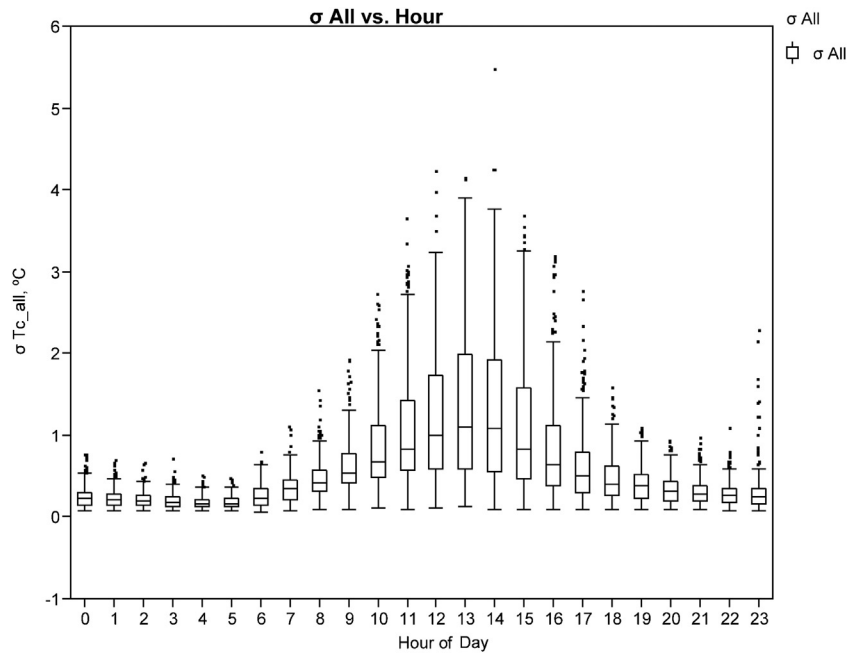

Fig. 3. Boxplot of the standard deviation σ of all T_c observations at a given hour (including all treatments) vs. hour of day. Boxes indicate 25% and 75% quantiles, tails indicate 5% and 95% percentiles, points indicate outliers.

2012, 2014a), sunflower (Taghvaeian et al., 2014b), olive (Agam et al., 2013), and peach (Wang and Gartung, 2010) canopies.

Figs. 2 and 4 give examples of typical canopy temperature and stress index trends following irrigation applied to all three treatments on 7/15/2013 (35 mm on Treatment 1, 15 mm on Treatment 8, and 10 mm on Treatment 12). The first day shows minimal differences in T_c between treatments, indicating stress recovery following the irrigation in all treatments. However, the two subsequent days showed increasing levels of water stress, as indicated by canopy temperature and subsequent stress indices. CWSI indicated a small amount of midday water stress for Treatment 12 on the first day (CWSI > 0.1), moderate stress on the second day (CWSI > 0.5), and severe stress on the third day (CWSI ~ 1.0). On the third day there was also moderate stress for Treatment 8 (CWSI > 0.5) and some stress for Treatment 1 (CWSI > 0.1). Because CWSI is dependent on not only T_c but also Ta and VPD, it has an advantage in that it can indicate stress in treatments that may be intended to be non-stressed, such as Treatment 1. It is also interesting that CWSI can be much more indirectly sensitive to other meteorological factors, for example on the third day the wind increased dramatically (thus cooling the crop and reducing stress), but when the wind decreased slightly (Fig. 2), CWSI was the only responsive index (Fig. 4). However, a major limitation is shown in that this method is only valid in daylight hours, and typically only in the afternoon on sunny days. As the lower baseline for CWSI was developed for midday hours under ideal conditions, application of the CWSI is limited to a short window of time under certain ideal conditions such as near clear-sky solar radiation. Alternately, if the upper baseline is set too low, it is possible for CWSI values to be greater than 1, which poses issues in interpretability. In Fig. 4, CWSI is shown in a continuous fashion including all times of day, in order to show these numerical anomalies.

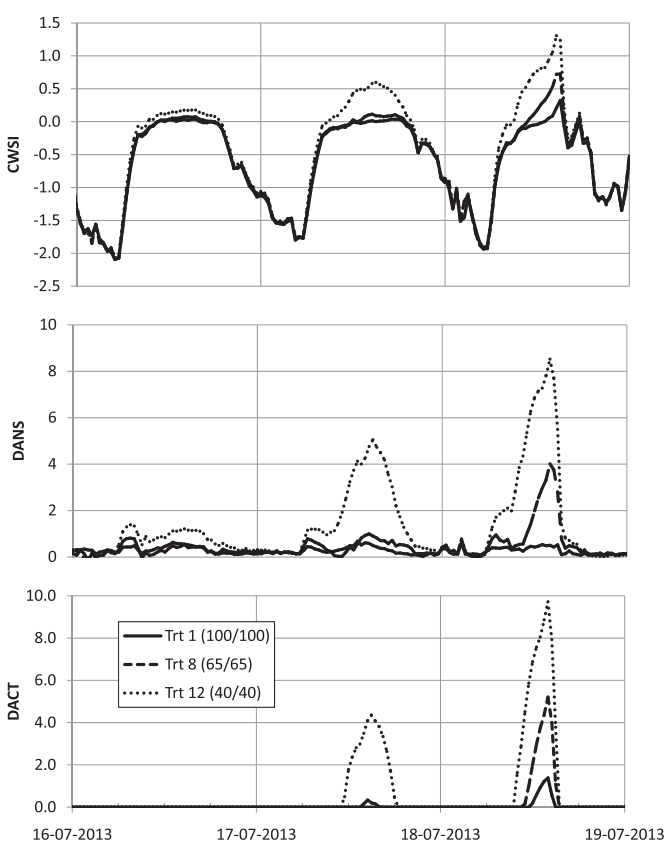

Fig. 4. Indices for CWSI (top), DANS (middle), and DACT (bottom) for 7/16-7/18/2013 obtained from data shown in Fig. 2. Lines are treatment means for Treatment 1 (100/100), 8 (65/65), and 12 (40/40).

Because DANS compares T_c with T_{cNS}, which in this study was assumed as the lowest observed T_c value from Treatment 1, it is expected that most often DANS ≥ 0. Likewise, since DACT is zero for T_c < 28° C, we are ensured that DACT ≥ 0. Both DANS and DACT show similar trends to CWSI, in that Treatment 12 shows minimal or no stress on the first day, moderate stress on the second day, and severe stress on the third day. Treatment 8 also shows moderate stress on the third day. Nighttime values for DANS also complement the idea illustrated by Fig. 3 that the evening temperatures converge, by having the lowest DANS values at nighttime.

Values for the daily time-based indices (TTT, IDANS, and IDACT) can be obtained from the information in Fig. 2 (Table 3). The same

Table 3
Values for daily indices obtained by T_c values in Fig. 2.

Index	Treatment	Day		
		7/16/13	7/17/13	7/18/13
TTT (h)	1	0	1.0	3.3
	8	0	1.9	3.6
	12	0	6.1	5.4
IDANS (°C h)	1	15.1	13.0	13.0
	8	13.5	18.8	37.2
	12	30.9	76.9	93.5
IDACT (°C h)	1	0	0.4	3.4
	8	0	1.1	12.5
	12	0	19.2	33.9

general trends regarding Treatment responses during the three days are similar for the daily indices. TTT and IDACT are particularly easy to interpret and have similar trends, as both depend on $T_c > 28\,^{\circ}$C before a value greater than zero is experienced. IDANS is somewhat more difficult to interpret, since T_{cNS} will change not only day to day, but hourly. However the trend is generally true in that the severity of the stress increases from day 1 to day 3, and between treatments 1, 8, and 12. Since IDANS (like DANS) is based on the difference from T_{cNS}, and T_{cNS} is assumed as the lowest observation from Treatment 1, both DANS and IDANS are numerically greater than 0 and IDANS values in this example are between 13.0 and 30.9 °C h while indicating no stress in other indices. It is therefore assumed in this study that the IDANS threshold for the non-stressed condition is about 30 °C h. Further studies are required to validate this threshold for various other sites and crops.

3.4. Daily indices – response to treatments

Many previous studies have shown multiple treatments on overlapping line graphs, and when indices jump in value from day to day it can be difficult to read and interpret. Because the treatment structure of this study varies among the three major growth stages (vegetative growth, reproductive, and maturity) in terms of target ET and thus stress, it was decided to aggregate measurements during these growth stages. A non-stressed treatment may occasionally have a small amount of stress (Fig. 4), whereas an intentionally stressed treatment should be under stress at most times but of course would have less stress following irrigation or precipitation events. To more easily interpret this large dataset, Figs. 5–8 present boxplots of CWSI, DANS, DACT, and TTT, separated by year and major growth stage, and also by treatment. Daily indices for CWSI, DANS, and DACT were daily values calculated at 1400 h. Boxplots for IDANS and IDACT were not shown, as they were visually very similar to DANS and DACT, respectively. Values for CWSI were screened for days when incoming solar radiation was greater than 80% clear sky solar radiation at 1400 h, and all indices were screened for periods when canopy cover was greater than 70%. DANS and DACT were included regardless of solar radiation. Middle of the box represents 50th percentile, ends of box represent 25th and 75th percentile, and end of tails represent 5th and 95th percentile.

The plots generally had the same trend between treatments. In the vegetative growth stage, Treatments 1, 2, 3, and 6 all had 100% or 80% ET and the indices generally indicated little stress, whereas indices for Treatments 8, 10, and 12 indicated much more stress. During the reproductive growth stage, stress was typically minimized as was the goal of the treatments. Likely due to reduced canopy cover resulting from the vegetative stage stress, indices CWSI (Fig. 5) and DANS (Fig. 6) showed slight increased stress in Treatment 12 during the reproductive stage. Due to omission of inadequate canopy and cloudy days for CWSI, the vegetative stage for Treatment 12 had no viable observations to show in 2013 (Fig. 5).

In the maturity growth stage, the treatment effects became more obvious and interesting to compare. For example, in comparing the pairs of Treatments 1 and 2, 3 and 6, and 8 and 10, each pair received the same irrigation (Table 2) until the beginning of the maturity phase (100%, 80%, and 65% ET, respectively). At this time, the latter in each pair received less irrigation, thus invoking more stress. In almost all cases, the median and quartiles comparing indices from treatment to treatment indicated a response to the reduced water in the late maturity stage. It is also interesting to compare Treatments 3, 10, and 12, as they received respectively smaller levels of irrigation during vegetative growth (Table 2). The indices showed increased maturity phase stress from Treatment 3 to Treatment 10, but reduced stress from treatments 10 to 12. While the comparison between the three can only be made in 2012 (2013 had no T_c observations in Treatment 10), this effect could possibly be due to "preconditioning" of the plant that allows a more stressed plant to respond less negatively to later stresses (Westgate and Boyer, 1985).

Regarding response of individual indices to treatments, CWSI had good overall response with values typically ranging between zero and one (Fig. 5). However, despite filtering data for clear sky solar radiation, there were still many negative values which should be interpreted as non-stressed. Although the computed baseline was very close to past studies, this could indicate that the non-water-stressed baseline may need further adjustment. DANS showed good response to treatments, with values ranging from just below 0 °C, to over 10 °C at the most stressed end (Fig. 6). On the low end, low stress treatments such as Treatments 1, 2, 3, and 6 in the vegetative phase, had values that typically ranged between 0 and 2 °C. Since DANS is based on the assumption of the lowest observation representing non-stressed T_{cNS}, the value must always be positive, and it can be interpreted that when using this method any DANS less than 1 °C can be considered non-stressed (or minimal stress). Although boxplots are not shown, similarly IDANS values of 50 °C h or less can be assumed to generally be non-stressed for the same reasons. DACT (Fig. 7) had very similar trends to DANS in terms of treatment response. The DACT index is very easy to calculate since it is simply the temperature above 28 °C. In the reproductive stage, DACT indicates that the attempt to remove stress from low water treatments was largely met, with only outliers typically having values above zero. Of all the indices, TTT showed the widest range of values within each treatment, rendering it very difficult to interpret (Fig. 8). While DACT is also based on $T_{critical} = 28\,^{\circ}$C and had similar results to CWSI and DANS, the TTT method determines the time above $T_{critical}$ and doesn't consider the magnitude. For example, in the reproductive growth stage in 2012, several treatments had TTT means > 1 h, DACT indicates that while the temperature may have been over 28 °C for several hours, the magnitude at 1400 h was minimal (Fig. 7).

3.5. Daily indices correlation

All six stress indices were compared with each other (Fig. 9). Using the average temperature for each treatment (T_{cmean}), the data were separated into three 1400 h canopy temperature ranges ($T_{cmean} < 27\,^{\circ}$C, $27\,^{\circ}\text{C} < T_{cmean} < 29\,^{\circ}$C, and $T_{cmean} > 29\,^{\circ}$C) which represent non-stressed, marginally stressed, and highly stressed temperatures respectively as based on $T_{critical} = 28\,^{\circ}$C for corn (Burke, 1996). In order to get a full comparison of all days, no data were omitted based on solar radiation conditions (including CWSI).

The lowest temperature (non-stressed) range generally had low correlations between indices, thus was not shown in graphical detail for this temperature range. The most highly correlated indices were TTT and IDACT ($r = 0.90$). This correlation was likely biased upward since both TTT and IDACT theoretically are zero

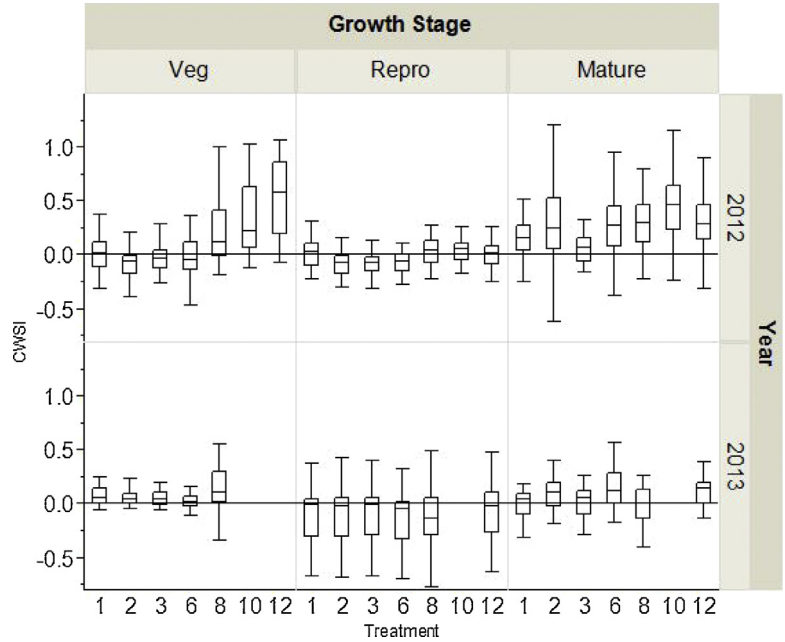

Fig. 5. Boxplots of CWSI for each treatment, separated by growth stage and year. Horizontal lines across Fig. indicate CWSI = 0.

if $T_c < 28\,^{\circ}$C; however, because these three correlation plots were segregated by T_{cmean}, occasionally T_{cmean} will be greater than zero if the individual observation is not. Also highly correlated were DANS and IDANS ($r = 0.81$), which is logical since they are based on the same parameters. No other two indices had correlation coefficients greater than 0.56 in this temperature range.

As T_{cmean} increased to between 27 °C and 29 °C, the indices had similar relationships as at the lower temperatures, but more pronounced (Fig. 9). The relationship between TTT and IDACT was similar to before ($r = 0.88$). All other comparisons of indices had some relationship, with all r values above 0.24, and eleven of the fifteen comparisons had r values above 0.50. At the highest temperature range ($T_{cmean} > 29\,^{\circ}$C), all of the indices were highly correlated, indicating that at high mean canopy temperatures all of these indices are good indicators of stress. The TTT index was the least correlated with the other five indices, with $0.53 < r < 0.78$. For all other comparisons not including TTT, $r > 0.80$, indicating that the magnitude of each index is scalable at these high temperatures.

CWSI, which has been the most commonly used index since its inception in the early 1980s (Idso et al., 1981; Jackson et al., 1981), was correlated most closely with DACT ($r = 0.92$), followed by DANS ($r = 0.90$), IDACT ($r = 0.80$), and IDANS ($r = 0.80$). The high correlation with DANS and DACT is likely because they, like CWSI, were instantaneous readings taken at the same time, whereas IDACT and IDANS (as well as TTT) are integrated values across the entire day. Comparisons of CWSI at lower temperatures may be biased somewhat

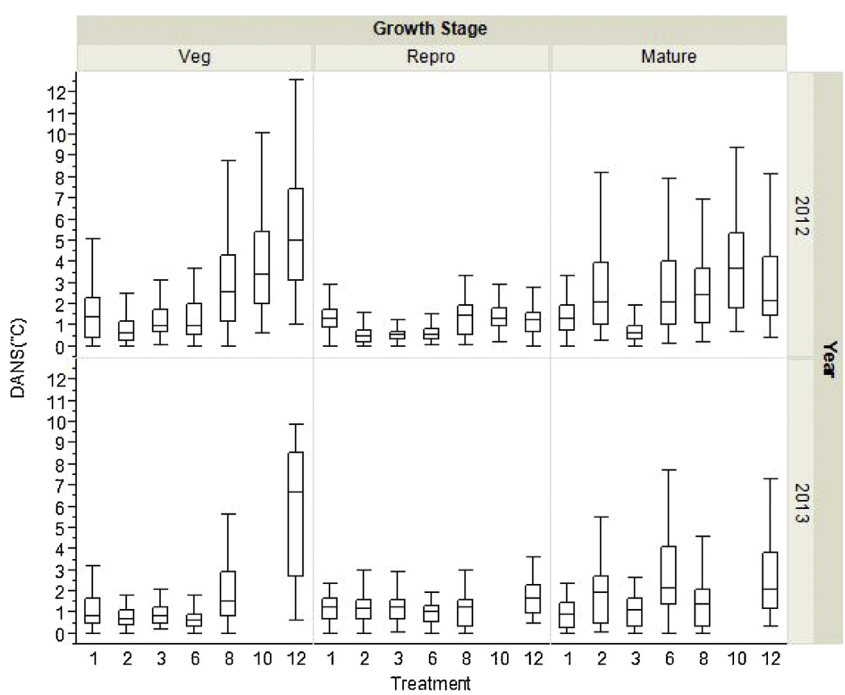

Fig. 6. Boxplots of DANS for each treatment, separated by growth stage and year.

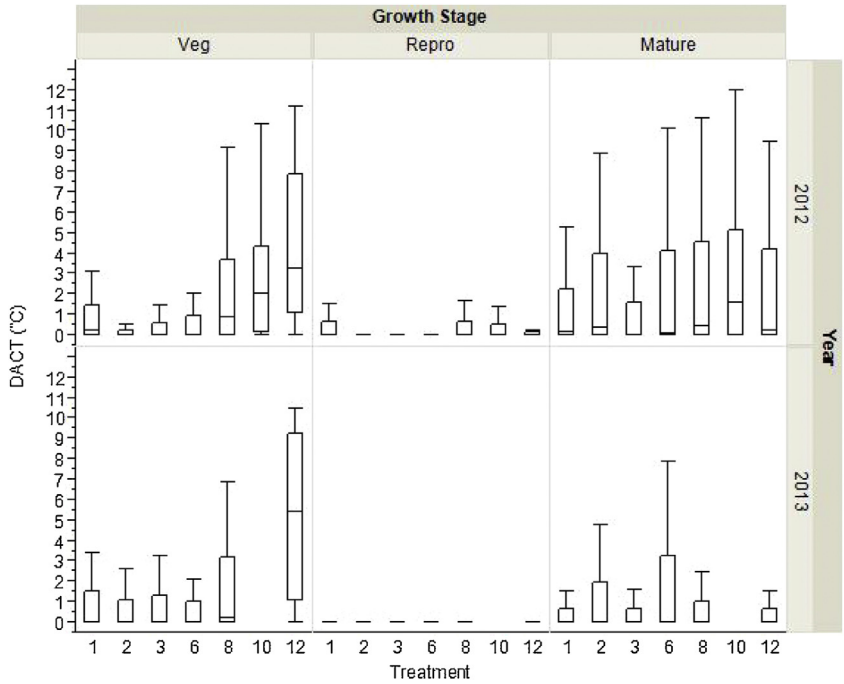

Fig. 7. Boxplots of DACT for each treatment, separated by growth stage and year.

because of occasionally negative CWSI values (due to no omissions of cloudy data), however inclusion of all data reiterates the fact that an index should be useful with minimal restrictions.

3.6. Daily indices and soil water deficit

All six indices were evaluated as a function of soil water deficit, after again being separated into three canopy temperature ranges (T_{cmean} < 27 °C, 27 °C < T_{cmean} < 29 °C, and T_{cmean} > 29 °C). CWSI data (only) had cloudy days with solar radiation/clear sky radiation < 80% sorted out. For lower temperatures, CWSI, DACT, TTT, and IDACT had index values around zero for most values of SWD, but especially near SWD = 0. On the other hand, DANS and IDANS had index values of 1 °C and 35–40 °C h respectively at SWD = 0. For the lower and middle temperature ranges, there was essentially no relationship with any index and soil water deficit (R^2 < 0.04 in all cases), therefore only responses for T_{cmean} > 29 °C are shown graphically (Fig. 10). Above 29 °C, there is a positive linear slope with all indices, with DANS (R^2 = 0.320) and CWSI (R^2 = 0.319) as the highest. IDACT had the next highest correlation (R^2 = 0.214) followed by IDANS (R^2 = 0.176) and DACT (R^2 = 0.138), and lastly by TTT (R^2 = 0.059). Similarly Fig. 9 shows that each index is more

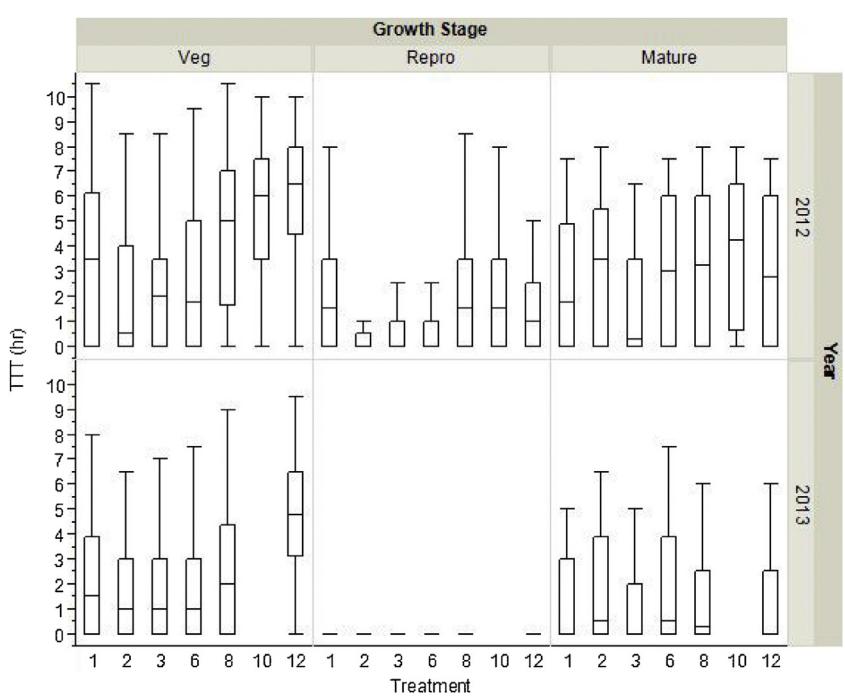

Fig. 8. Boxplots of TTT for each treatment, separated by growth stage and year.

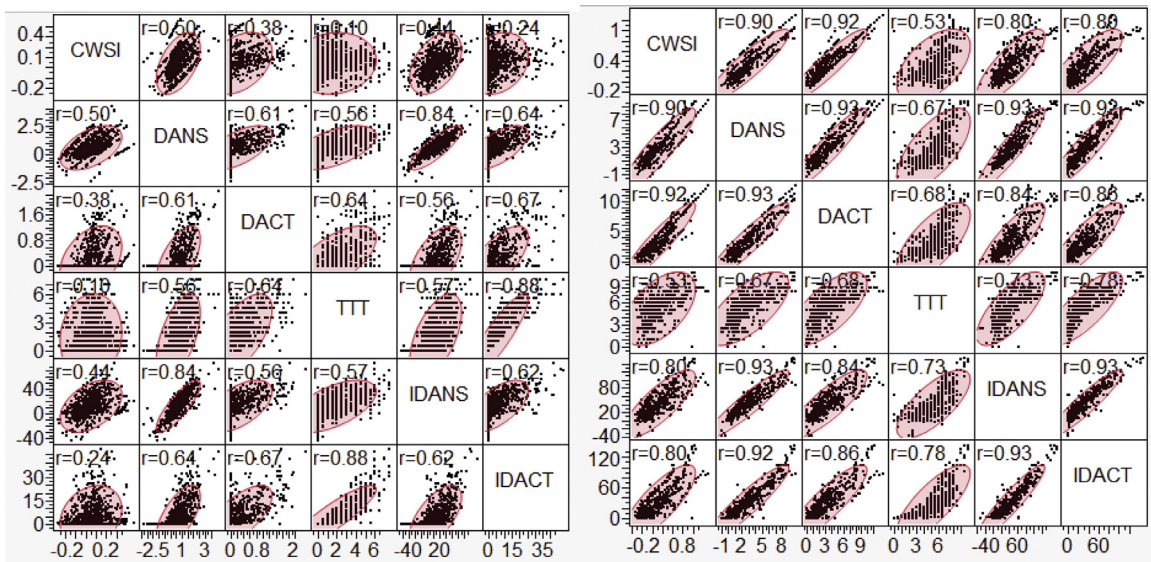

Fig. 9. Correlation scatterplots between six stress indices (1400 h for CWSI, DANS, DACT and daily for TTT, IDANS, IDACT) separated by treatment T_{cmean}. Ellipse $\alpha = 0.95$ indicating that 95% of the data resides inside the ellipse.

responsive at high canopy temperatures (i.e. above 29 °C) than at lower temperatures.

4. Discussion

The use of canopy temperature and infrared thermometry can be a powerful tool to monitor and quantify water stress. Stress indices such as DANS use a non-stressed T_c as a reference, so ideally the site for T_{cNS} would be placed in an area with finer soils that have sufficiently high water holding capacities or irrigation frequencies to minimize the potential of any stress through the season. This idea also has promoted our adoption of T_{cNS} as the lowest observed single value among all individual observations. Using this method, we minimize the potential bias because of unexpected stress in the "unstressed" canopy. We assume the non-stressed temperature is represented by the *least stressed observation*. This can be somewhat problematic in some cases: first, if the IRTs are poorly calibrated and measurement uncertainty results in a low-temperature bias in the T_{cNS} value. This issue can be minimized by frequent calibration, and checking divergence of nighttime temperatures observed by all sensors (Fig. 3). Using DANS and its related IDANS can have numerical issues in their interpretation (such as in Table 3 where IDANS was around 30 °C h for days where no stress was indicated by other indices or in Fig. 10 where DANS and IDANS are greater than 0 for SWD = 0), so interpretation must be made with caution. Similar conclusions using TSD were found by Gardner et al. (1981a). However, if this limitation is understood, it remains a better alternative for DANS than taking an average of a "non-stressed" treatment that may still be prone to temperature bias.

Additionally, use of lowest observation as T_{cNS} can also have interpretation issues when the least stressed observation is actually under some water stress, such as a very hot/windy/dry day where all crops will likely wilt. Days like this will likely be well represented by CWSI, but DANS or IDANS would have values of zero for the coolest observation, regardless of whether the crop is in stress or not. However, this response can also be an advantage of

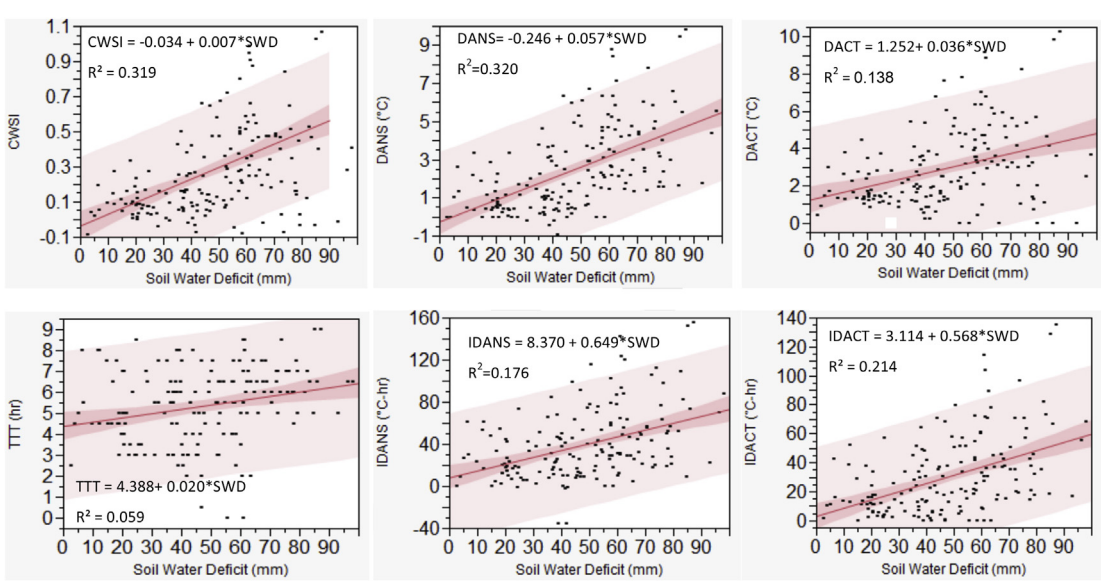

Fig. 10. All six indices (1400 h for CWSI, DANS, DACT and daily for TTT, IDANS, IDACT) vs. soil water deficit (mm), when treatment $T_{cmean} > 29$ °C. Dark band indicates 95% confidence of the mean, light band indicates 95% confidence of the data.

DANS because it does not confuse water stress with heat stress or other environmental impacts. For example, as Fig. 4 shows, CWSI becomes negative when the wind suddenly increases, while water status has clearly not changed over such a short period; DANS (and even DACT) do not reflect this drop due to wind. Even well-watered crops may close stomata on very hot/dry/windy days, resulting in higher CWSI but little difference in DANS; therefore CWSI may falsely indicate the need for an irrigation, where DANS will not.

The CWSI has its advantages in that it responds not only to temperature but also VPD. However, other researchers have commented that the complexity of the CWSI may limit its practicality of use by farmers (Kacira et al., 2002). While CWSI is often viewed as the standard index for quantifying water stress, the additional need of data (VPD), prior computation (baselines), and ideal conditions (clear sky) make it more cumbersome than indices that require only measures of T_c. Additionally, Fig. 1 indicates that the canopy temperature alone can be highly correlated with physiological stress measurements such as midday leaf water potential. Because T_c-based indices DANS and DACT are so highly correlated with CWSI at high temperatures, they could have been used as effectively as CWSI without the need for the additional measurements that are required by CWSI. Although the integrated daily indices shown in this study are also useful regardless of sky conditions and require no prior computation, the simpler methods of DANS and DACT may have the most promise for practical use. By assessing T_c at peak stress in the early afternoon, there may be opportunities for spatial crop stress assessment via unmanned aerial vehicles or other monitoring equipment.

A noted advantage of non-dimensional crop indices such as CWSI is that they are typically considered to be scalable to a stress crop coefficient K_s for ET estimation (i.e. $K_s = 1 - \text{CWSI}$). This was also the basis behind the T_{cratio} approach (Bausch et al., 2010), although as previously mentioned it has dimensionality restrictions. Although new indices such as DANS and DACT and their integrated counterparts have dimensional values outside of the range of 0–1, the fact that they are highly correlated with CWSI at high temperatures (Fig. 9) suggests that they could be fitted empirically to serve the same purpose [i.e. $K_s = 1 - \text{DACT}(^\circ\text{C})/10$].

5. Conclusions

A two-year study of regulated deficit irrigation of corn was used to evaluate three existing and three new water stress indices based on canopy temperature. All thermal indices were responsive to irrigation treatment differences at major growth stages. Ideally, any model or index should be meaningful, simple, interpretable, and transferrable. The results of this study show that alternative indices such as DANS or DACT (and their integrated surrogates) have similar representation of water stress to CWSI, despite requiring fewer parameters and prior calculation. Future studies are recommended to evaluate these new indices under other conditions and comparison with plant physiological measurements of water stress and evapotranspiration data, as well as the impacts of soil texture on water stress.

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