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Conventional and simplified canopy temperature indices predict water stress in sunflower

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ABSTRACT

Canopy temperature has been used as an indicator of crop water stress, since a reduction in plant available water results in lower transpiration rates and consequently higher canopy temperatures. In this study, two indices based on remotely-sensed canopy temperature were used in northern Colorado to monitor water stress in sunflower under six levels of regulated deficit irrigation. The two indices included the widely-used Crop Water Stress Index (CWSI) and the simple Degrees Above Non-Stressed (DANS). The goal of the present study was to evaluate the sensitivity of CWSI and DANS to different levels of irrigation and to investigate their relationship with several crop parameters. In estimating CWSI, non-water-stressed baselines developed in this study were similar to those developed previously at another site in northern Colorado. Both CWSI and DANS were sensitive to irrigation timing/depth and soil water deficit in the root zone, increasing as water availability decreased. Four studied crop parameters, namely the fraction of Intercepted Photosynthetically Active Radiation (fIPAR), Leaf Area Index (LAI), Leaf Water Potential, and root growth were all affected by deficit irrigation treatments, with the first three parameters decreasing and the last one increasing with decrease in water application. All of these crop parameters were also strongly correlated with CWSI and DANS. Statistically significant relationships were developed to predict fIPAR, LAI, and relative root growth based on CWSI and DANS, with coefficients of determination that were similar among the two temperature-based stress indices. The results suggest that DANS, based solely on canopy temperature and estimated by a simple subtraction, may be used effectively in monitoring water stress and scheduling irrigations in deficit-irrigated sunflower in arid/semi-arid regions.

1. Introduction

Agricultural water resources are becoming more limited in arid and semi-arid parts of the world due to a combination of natural and anthropogenic factors, including but not limited to rapidly-growing demand from municipal, industrial, and environmental sectors and predicted increase in frequency and severity of droughts under a changing climate. As a result, the paradigm of full irrigation and maximized production per unit area of land is gradually being replaced with deficit irrigation and achieving maximum production per unit of applied water. Deficit irrigation (DI) is defined as deliberate application of water at rates lower than crop's required rate for producing optimum yield (Fereres and Soriano, 2007). Regulated Deficit Irrigation (RDI), the approach implemented in this study, is a variant of DI in which water stress is allowed only during stress-tolerant stages of growth in order to minimize yield loss. This approach has shown promising results in terms of improving water productivity and economic profitability, especially for tree crops and grapevines (Fereres and Soriano, 2007). However, applying an efficient and profitable DI regime requires comprehensive knowledge on crop response to water stress at different growth stages, as well as a precise management of water application timing and amount (Geerts and Raes, 2009; Mahan et al., 2012).

A wide range of approaches are employed to manage deficit irrigation, from evaluating visible signs of stress to measuring/modeling several soil and crop characteristics. Along this wide range of approaches, remote sensing of canopy temperature has been used extensively in monitoring crop water status. This approach is based on the physical relationship between transpiration rate and crop canopy temperature. The canopy temperature increases as the rate of transpiration (the main cooling process) decreases in response to water limitation in crop root zone, and

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vice versa. However, canopy temperature needs to be converted into standardized stress indices before it can be used in routine irrigation decision-making. Previously developed indices are mainly based on a comparison between actual canopy temperature and a desired temperature for the studied crop. Two main indices that have been used in practical applications are the Crop Water Stress Index (CWSI) of Idso et al. (1981) and Jackson et al. (1981), and the Biologically Identified Optimal Temperature Interactive Console (BIOTIC) of Upchurch et al. (1996).

In the CWSI method, the difference between measured canopy and air temperatures (dT_m) is compared against lower (dT_{LL}) and upper (dT_{UL}) limits of canopy-air temperature differential that can be reached under non-water-stressed and non-transpiring conditions, respectively:

$$CWSI = \frac{(dT_m - dT_{LL})}{(dT_{UL} - dT_{LL})} \tag{1}$$

Idso et al. (1981) and Jackson et al. (1981, 1988) each offered a different approach for estimating dT_{LL} and dT_{UL}, with the former developing an empirical approach and the latter outlining a theoretical one. The empirical approach has received more attention from practitioners due to its simplicity and reliance on only two variables in addition to canopy temperature, namely air temperature and relative humidity. Based on this approach, dT_{LL} and dT_{UL} can be estimated as linear functions of atmospheric vapor pressure deficit (VPD) and vapor pressure gradient (VPG), respectively:

$$dT_{LL} = m \times VPD + b \tag{2}$$

$$dT_{UL} = m \times VPG + b \tag{3}$$

where m and b are the slope and intercept of linear equations, respectively. The dT_{LL}–VPD and dT_{UL}–VPG relationships are also known as non-water-stressed baseline (NWSB) and non-transpiring baseline (NTB), respectively. The VPG represents the amount of change in saturated vapor pressure when air temperature is increased by an amount equal to the intercept of the NWSB. Detailed discussions and guidelines on developing NWSB/NTB, measuring canopy temperature, estimating CWSI, and interpreting the results are provided in Gardner et al. (1992a,b).

The greatest limitation of the empirical approach is perhaps the fact that NWSBs are crop and climate-specific. Thus, they must be developed for the studied crop under climatological conditions of the study area. For corn, Taghvaeian et al. (2012, 2014) showed that NWSBs developed at two independent sites in northern Colorado were essentially identical to that developed by Idso (1982) in Arizona and suggested that baselines for corn may be transferable under similar climatic conditions. The empirical approach has proved to be effective in monitoring crop water stress and managing precision irrigation and it some studies it has even outperformed the theoretical approach (Agam et al., 2013b). Recent studies have also shown the effectiveness of CWSI when applied to high-resolution imagery acquired by thermal cameras on ground-based (Agam et al., 2013a; Pou et al., 2014), Unmanned Aerial Vehicles (Gonzalez-Dugo et al., 2013), and aircraft platforms. Other efforts have used empirical and theoretical CWSI (along with other temperature based indices) to develop an automated precision irrigation system (O'Shaughnessy and Evett, 2010; O'Shaughnessy et al., 2012).

In the BIOTIC method, the measured canopy temperature is compared against a biologically-based canopy temperature at which the crop metabolic activity is believed to be at an optimum level. For practical applications, the biological-temperature threshold is combined with a time threshold to estimate a Time Temperature Threshold (TTT), which represents the time that crop canopy remains at a temperature higher than the temperature threshold (Mahan et al., 2005). An irrigation event is initiated once TTT reaches a certain time threshold. Compared to CWSI, TTT has two requirements that may negatively impact its adoption by farmers. The first limitation is that the temperature threshold is constant, not responding to variations in atmospheric parameters. As a result, additional computations are needed to determine if higher canopy temperatures were caused by water limitation or by other factors such as low vapor pressure gradient between leaf stomata and atmosphere. The second limitation is that evaluating the time threshold requires a continuous measurement of canopy and weather parameters, which consequently requires more intensive (and expensive) sensing and data-logging instrumentation and maintenance.

Despite achievements of CWSI and TTT methods in fostering deficit irrigation management, farmers may need indices that are computationally and instrumentally less expensive. One of the simplest methods to identify stress severity in crop canopies is to compare the temperature of the studied canopy with that of a well-watered, non-stressed canopy at a similar growth stage and a nearby location. Gardner et al. (1981a,b) reported that temperature variation among rows of sorghum and corn in plots under non-uniform irrigation reached 9.0 and 7.0 °C, respectively. When integrated over the study period, these temperature variations were highly correlated to sorghum yield. In a more recent study, Sepulcre-Canto et al. (2006) reported that the crown temperature difference between well-watered and stressed olive trees can be used for monitoring water stress and scheduling irrigations. Bausch et al. (2011) suggested that the temperature ratio of a non-stressed canopy to a stressed one (T_c ratio) can be used not only to determine irrigation timing, but also to adjust crop water use and estimate irrigation requirement. The advantage of indicators that use non-stressed canopy as a reference temperature is that they can be estimated based on a single type of measurement.

The goal of this study was to investigate the application of temperature-based indices in monitoring sunflower water stress under variable levels of regulated deficit irrigation. The first index investigated was the empirical CWSI of Idso et al. (1981). For a second index, the difference between stressed (T_S) and non-stressed (T_{NS}) canopy temperatures was used in order to provide an index that encompasses a wider range of values and can be estimated by a simple subtraction. This index, named Degrees Above Non-Stressed (DANS), can be estimated based on only a single type of measurement (canopy temperature):

$$DANS = T_S - T_{NS} \tag{4}$$

Nowadays, canopy temperature can be measured easily, accurately, and non-destructively with infrared thermometers at affordable costs. The method requires a non-stressed crop canopy surrounded by irrigated area with a large enough fetch to minimize impacts of advection on canopy temperature and transpiration rate. In estimating DANS, it is important to ensure that the non-stressed crop is at about the same growth stage as the crop in the field of interest. This is mainly due to the fact that, for many crops, canopy temperature is affected by growth stage. For example, Idso (1982) showed that canopy temperatures of non-stressed wheat and barley were significantly different during pre- and post-heading stages. Nielsen (1994) also observed higher non-stressed leaf and canopy temperatures for sunflower during post grain-filling stages.

The specific goals of this study were:

- To develop sunflower NWSBs in northern Colorado and to compare them with previously developed NWSBs;
- To study the sensitivity of CWSI and DANS to several regulated deficit irrigation regimes; and,
- To investigate the relationship of CWSI and DANS with depth of applied water and soil water deficit, as well as four crop

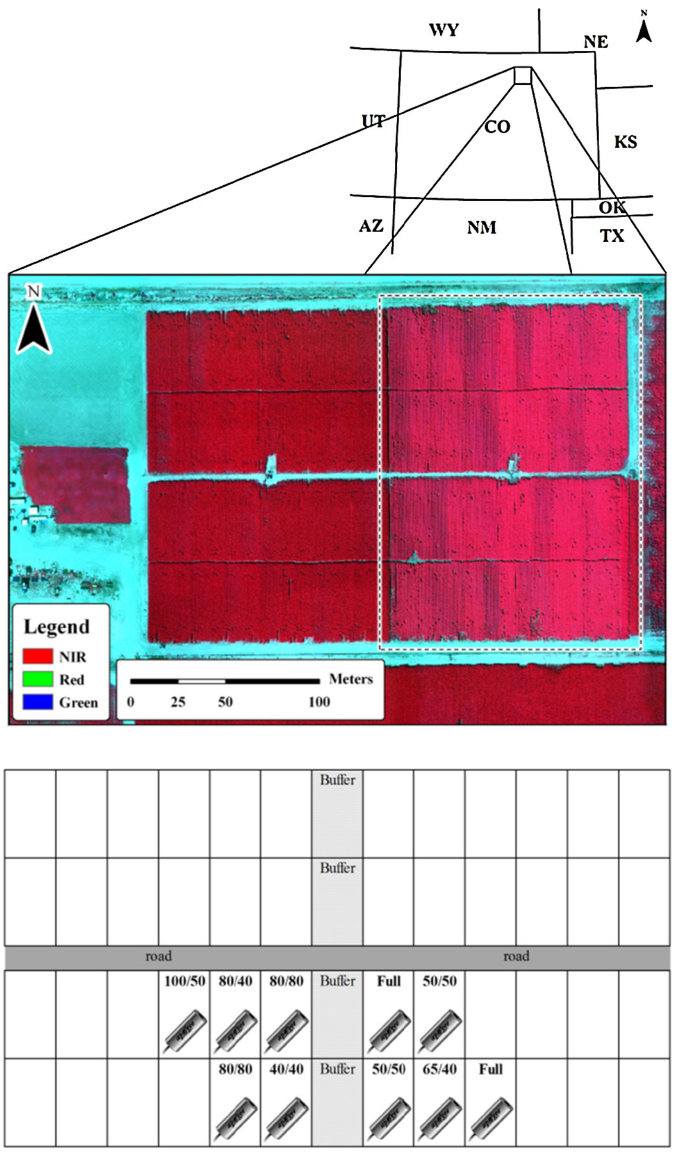

Fig. 1. Top: A false-color, high-resolution airborne image of Limited Irrigation Research Farm (LIRF), located in northern Colorado (40°26′57″ N, 104°38′12″ W, Elev. 1427 m). The sunflower plots were in the eastern section marked by dashed black line. Bottom: Experimental layout and sensor locations. Of the 48 total plots, only those treatments in which canopy temperature was monitored are identified.

parameters, namely canopy light interception, leaf area index, leaf water potential, and root growth.

2. Methods and materials

2.1. Study area and experimental treatments

The research experiment was conducted during the summer of 2012 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, Elev. 1427 m, Fig. 1). The alluvial soils of the study field are predominately sandy and fine sandy loam of the Olney and Otero series. Field capacity averages 25% (volumetric) with total available water being about half of field capacity. The long-term cumulative precipitation and alfalfa-based reference ET during sunflower growing season (May-Sep) at this site is 200 and 1000 mm, respectively. Syngenta sunflower hybrid 3495 NS/CL/DM was planted in all plots on 21 May 2012, with a population of 67,200 plant ha^{-1} and row spacing of 0.76 m. Each plot was 12 rows wide by 40 m long, and all measurements were taken from the middle six rows to avoid border effects. Treatments were laid out in a randomized block design with 4 replications.

Table 1
Experimental treatments and total applied water depths (percent of Full treatment in parentheses).

Treatment	Applied water depth (mm)[a]		
	Vegetative (06/20–07/19)	Reproductive (07/20–08/08)	Maturation (08/08–09/13)
Full	160	180	225
100/50	160 (100%)	159	78 (34%)
80/80	128 (80%)	187	146 (65%)
80/40	128 (80%)	173	38 (17%)
65/40	99 (62%)	182	38 (17%)
50/50	74 (46%)	194	89 (40%)
40/40	58 (36%)	195	38 (17%)

[a] Irrigation plus precipitation; precipitation was 34, 0, and 12 mm during vegetative, reproductive, and maturation stages, respectively. Total ET_r estimated at CoAgMet weather station during the three stages was 243, 137, and 220 mm, respectively.

To ensure seed germination, 38 mm of water was applied to the entire field during 4 irrigation events from 23 May to 6 June, using sprinkler irrigation. These irrigations were followed by 14 mm of rainfall on 7 June. Water was applied during the rest of the growing season using 16-mm drip irrigation tubing that was placed next to each row of sunflower. The 30-cm spaced in-line emitters discharged at a rate of 1.1 L h^{-1} for an irrigation application rate of 4 mm h^{-1}. The amount of water applied to each treatment was measured and recorded by turbine flow meters. In addition to a full irrigation treatment (Full) to meet the entire crop water use, six different levels of regulated deficit irrigation (RDI) were applied during vegetative and maturation periods to reduce sunflower water use to targeted levels. At all RDI treatments, attempts were made to avoid water stress during the critical reproductive stage. Differential irrigation treatments were initiated on 27 June, when sunflower was at V12 stage of growth. Application of RDI continued until 20 July (growth stage R3), when adequate irrigation was applied to all treatments to remove any soil water deficit. From this date a full irrigation regime was applied until 8 August, when sunflower was at R6 stage of growth. The RDI regime was resumed from this date until the end of sunflower maturation. Targeted levels of sunflower water use during vegetative/maturation periods under RDI regimes as a percentage of Full treatment included 100/50, 80/80, 80/40, 65/40, 50/50, and 40/40. Table 1 provides a list of implemented irrigation treatments along with actual depth of water applied during each growth period to achieve target levels.

Nutrient levels were maintained to avoid nutrient deficiencies on all treatments. At the time of planting, 41 kg N ha^{-1} and 56 kg P ha^{-1} were side dressed. Additional nitrogen was applied by fertigation on 27 June, 11 July, and 20 July for an additional total of 45 kg N ha^{-1} for the 40/40 treatment and 67 kg N ha^{-1} for all other treatments.

Soil water content was measured two or three times each week on the days before or after irrigation in the crop row in each plot with a portable time domain reflectometer (Minitrase, Soil Moisture Equipment Corp, Santa Barbara, CA) in the surface 15 cm, and a neutron soil moisture meter (CPN-503 Hydroprobe, InstroTec, San Francisco, CA) in 30 cm depth increments to 2.0 m. The neutron moisture meter was calibrated gravimetrically at the site and the calibration was used to convert instrument counts to volumetric soil water content (SWC). Field capacity for each plot and soil depth was estimated in the field as the SWC the day after an irrigation or precipitation event that resulted in a SWC increase deeper in the profile (i.e. drainage). Soil water deficit (SWD) for each soil layer was calculated as the difference between field capacity and SWC. Root zone depth was estimated based on plant water uptake, and average SWD for the root zone was integrated across each depth measurement.

2.2. Plant measurements

The temperature of sunflower canopy was measured on a continuous basis using infrared thermometers (IRTs, model: SI-121, Apogee Instruments, Inc., Logan, UT, USA) with a 36° field of view and ±0.2 °C accuracy. The IRTs were angled 23° below horizon and 45° east of north to ensure viewing only sunflower canopy and no underlying soil. 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 target that was about 2.2 m^2 in size. All IRTs were controlled by dataloggers (model: CR1000, Campbell Scientific Inc., Logan, UT, USA), where temperature was measured at 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. The emissivity correction was also applied to all measurements. Since the IRTs were viewing only crop canopy and no underlying soil, an emissivity value of 0.98 was used after Fuchs and Tanner (1966). No correction was implemented to account for the effect of reflected radiation from the background (sky) due to two main reasons. First, a large emissivity value reduces the potential magnitude of this error to less than 1.0 °C (Blonquist et al., 2009). Second, the error is further reduced after estimating stress indices. In case of CWSI, the index is estimated by normalizing measured temperatures using dT_{LL} and dT_{UL} values that were calculated under similar conditions with no background correction. In case of DANS, the sky condition was the same for concurrently measured canopy temperatures over studied and reference (non-stressed) plots and any background-induced variation in temperatures was canceled out.

Four additional plant measurements were taken for comparison against stress indictors: Intercepted Photosynthetically Active Radiation (IPAR), Leaf Area Index (LAI), midday Leaf Water Potential (Ψ_L), and root growth. The IPAR was calculated by subtracting the PAR values measured below and above canopy by a PAR ceptometer (model: Sunfleck, Decagon Devices, Inc., Pullman, WA, USA). The ratio of IPAR to PAR (fIPAR) was then calculated. All treatment plots were measured within 45 min of solar noon on 19 July 2012 at the end of sunflower vegetative growth stage. This measurement date was chosen to capture the cumulative effect of water stress on canopy light interception at the end of the vegetative stage.

To calculate LAI, five adjacent plants from two locations in each plot were collected on 20 July 2012. The row length of each sampling multiplied by the row spacing was used to calculate the total ground area for each location. All leaf blades longer than 10.2 cm (definition of an active leaf for sunflower) for each group of five plants were separated, dried at 55 °C, and weighed. A representative subsampling of 25 leaves from four treatments were run through a leaf area meter (LI-3100 Leaf Area Meter, LI-COR Biosciences, Lincoln, NE, USA), dried, weighed and used to calculate specific leaf area (SLA, $cm^2\,g^{-1}$). Total leaf area for each sampling was calculated from leaf dry weight and SLA. LAI of each sampling was calculated from total leaf area divided by ground area. LAI for each plot was determined as the average of two samplings collected from each plot.

Midday Ψ_L was measured with a Scholander-type pressure chamber (Model 3005 Series Plant Water Status Console with 18 cm long chamber, Soilmoisture Equipment Corp., Santa Barbara, CA, USA) within two hours past solar noon on four dates: 05 July, 19 July, 10 Aug., and 28 Aug. 2012. Fully expanded leaves in the sun, typically the third leaf from the top of the plant, was cut mid-petiole and wrapped in a damp cloth during the measurement. Four leaves, each collected from a different plant, were measured per plot.

Root growth was assessed with a minirhizotron camera system (BTC100X Minirhizotron Video Microscope, Bartz Technology Corp., Carpinteria, CA, USA). One clear acrylic tube per plot was inserted 30° from vertical in a guide hole cut with a metal sampling tube (Giddings Machine Co., Greeley, CO, USA) so that no air gap was formed between the tube and soil. Digital images, 3.3 cm^2, down to a depth of 1 m were captured with the camera approximately every 2 weeks starting in June. Root growth was analyzed on three dates for this study: 24 July, 7 Aug., and 21 Aug. 2012. Root length in every 5th digital image down the tube was measured with Rootfly software (Copyright 2008 Clemson University, Clemson, SC, USA; http://www.ces.clemson.edu/~stb/rootfly/) and reported as the total root length per unit area of windows observed.

2.3. Weather data

Key weather data were measured at an automated weather station (station ID: GLY04) located on a 0.4 ha grass plot adjacent to the research plots. This station is operated and maintained by the Colorado Agricultural Meteorological Network (CoAgMet) program at Colorado Climate Center, Colorado State University, Fort Collins, CO, USA. Hourly data were downloaded from the weather station (http://www.coagmet.colostate.edu) and used to calculate alfalfa-based reference ET (ET_r) following the ASCE standardized procedure (ASCE-EWRI, 2005). Table 2 summarizes several weather data averaged during each of the three sunflower growth stages during the study period.

3. Results and discussion

3.1. Sunflower NWSBs

In order to develop sunflower NWSBs, canopy temperatures measured continuously on the Full treatment on several clear-sky days following irrigation events were selected and then subtracted from corresponding air temperature measurements at the CoAgMet station to estimate dT_{LL} values. Graphs of obtained dT_{LL} versus concurrently measured VPD had a linear section lasting about four hours around the local solar noon (about 1230 MST). This linear section was considered as sunflower NWSB. It was observed, however, that the slope and intercept of NWSB changed after the R6 growth stage, when anthesis was completed and ray flowers were wilted or lost. A similar observation was made by Nielsen (1994) who reported that sunflower NWSBs based on both leaf and canopy temperatures had different slopes and intercepts during V13-R5 and R6–R8 stages. He attributed this difference to the decrease in sunflower transpiration and increase in head temperature after sunflower transitioned into grain-filling stage. Idso (1982) reported a similar change in NWSBs for wheat and barley. Hence,

Table 2
Average daily weather parameters for each of sunflower growth stages during the study period (2012).

Parameter	Vegetative (06/20–07/19)	Reproductive (07/20–08/08)	Maturation (08/09–09/13)
Mean air temp. (°C)	23.9	23.6	20.1
Max. air temp. (°C)	33.7	34.1	30.1
Min. air temp. (°C)	14.7	14.5	10.6
Mean Vapor pressure (kPa)	1.33	1.36	1.06
Max. relative humidity (%)	89.2	87.6	86.5
Min. relative humidity (%)	18.4	16.3	19.3
Wind run ($km\,d^{-1}$)	171.9	136.1	134.4
Solar irradiance ($MJ\,m^{-2}\,d^{-1}$)	25.6	23.8	20.4

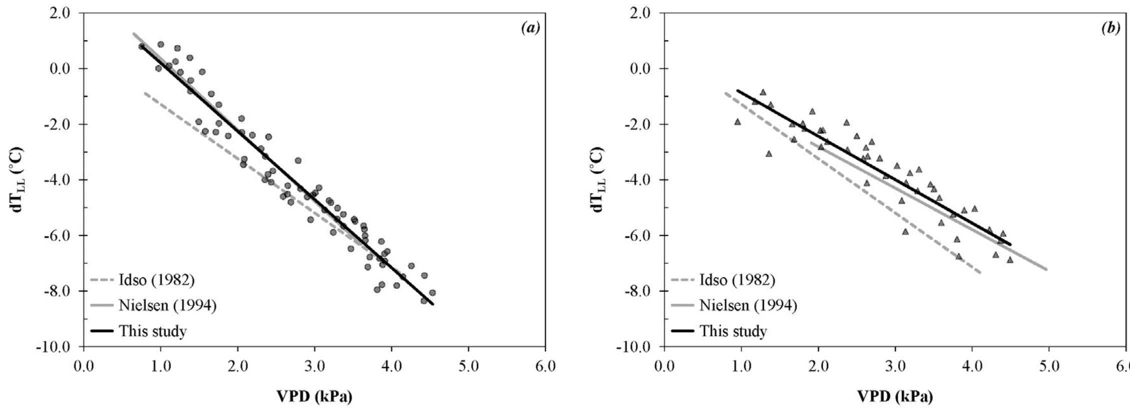

Fig. 2. Sunflower NWSBs developed in this study during pre (a) and post-R6 (b) periods overlaid on those developed by Nielsen (1994) and Idso (1982).

different NWSBs were developed in this study for the pre- and post-R6 periods. Fig. 2 shows the developed NWSBs overlaid on those developed by Idso (1982) for sunflower at a site in Kansas, and by Nielsen (1994) for sunflower at a site in Colorado, approximately 140 km east of the site of the present study. Table 3 provides more information about the slope, intercept, and coefficients of determination of developed NWSBs.

For the pre-R6 period, the NWSB of this study was almost identical to the one developed by Nielsen (1994) and both had steeper slopes and larger intercepts compared to Idso (1982). It should be noted, however, that Idso (1982) did not report if his baseline represented the entire growing season or specific growth periods, limiting any growth-stage specific comparison of the results of the present and Nielsen (1994) studies with that of Idso (1982). For the post-R6 period, the NWSB developed in this study was similar to that of Nielsen (1994) too. The difference between dT_{LL} values estimated by each of these baselines varied from 0.21 to 0.39 °C over their common range of VPD (1.91–4.49 kPa). The baseline of Idso (1982), however, predicted significantly cooler canopy temperatures than the other two NWSBs. At VPD of 3.00 kPa, for example, sunflower dT_{LL} estimated by Idso (1982) was 1.20 and 0.89 °C smaller than those of this study and Nielsen (1994), respectively.

The study by Nielsen (1994) was conducted in summer of 1990 (over two decades prior to this study) using different sunflower varieties. Yet, developed NWSBs are similar; suggesting that NWSBs developed under similar climatic conditions can be used for morphologically-similar varieties of sunflower without the need for site and variety specific calibrations. Previous studies have also suggested that the same NWSBs can be used for similar varieties of corn (Taghvaeian et al., 2014) and wheat (Idso et al., 1984). Another similarity between the present and Nielsen (1994) studies is the observed change in NWSBs as sunflower transitioned into the grain-filling stage. This change should be considered in estimating CWSI as warmer heads affect the measured canopy temperature. Using the pre-R6 NWSB for the post-R6 period would have attributed higher temperatures to water stress and led to an erroneously larger CWSI.

In estimating CWSI, the non-transpiring baseline (NTB) is estimated using the same slope and intercept developed for NWSB. The only difference is that VPG is used instead of VPD (Eqs. (2) and (3)). The change in NWSB slope and intercept from pre- to post-R6 stage resulted in a change in dT_{UL} estimates. Since the absolute value of slope in Eq. (2) decreased after the crop reached grain-filling stage, unrealistically small dT_{UL} values were estimated during this period. For 1300–1400 h, for example, average dT_{UL} estimated during post-R6 period was 0.95 °C, significantly smaller than the pre-R6 estimate of 4.52 °C. Such small estimates cannot represent the maximum stress (non-transpiring) conditions as plots under low and moderate water stress had dT_m values that frequently exceeded the small upper limit, resulting in CWSI increasing above the theoretical limit of unity. To overcome this issue, a constant dT_{UL} value of 5.0 °C was considered for the entire study period. Gardner et al. (1992a) stated that using a constant dT_{UL} would not introduce a significant error into CWSI calculations. Taghvaeian et al. (2012, 2014) also showed that estimated corn dT_{UL} values had negligible hourly and daily variations, suggesting that a constant dT_{UL} may be used for corn in northern Colorado.

Table 3
Sunflower NWSBs developed in this study.

Growth stage	VPD range (kPa)	NWSB slope	NWSB intercept	R^2
R1–R5	0.75–4.53	−2.45	2.65	0.95
R6–R8	0.95–4.49	−1.56	0.69	0.84

3.2. Sunflower stress indices

Sunflower CWSI was estimated based on canopy and weather parameter measurements that were made during four consecutive hourly periods on each day of the study period: 1000–1100, 1100–1200, 1200–1300, and 1300–1400 MST. Within each treatment, CWSI increased from 1000 to 1300 and stayed the same over the last hour or decreased slightly (data not shown). The rate of hourly CWSI increase appeared to be a function of irrigation treatment, ranging from zero for Full to 0.13 h^{-1} for 40/40. A similar pattern in hourly CWSI was reported for corn by Irmak et al. (2000) and Taghvaeian et al. (2012, 2014). Table 4 summarizes the average values of daily CWSI for each irrigation treatment during each of the vegetative, reproductive, and maturation periods during the

Table 4
Average CWSI for each irrigation treatment during vegetative, reproductive, and maturation stages, based on canopy and weather measurements made during 1200–1300 hourly period on each day.

Treatment	Average CWSI[a]		
	Vegetative (07/09–07/19)	Reproductive (07/20–08/08)	Maturation (08/09–09/03)
Full	0.05	0.11	0.12
100/50	0.04	0.13	0.24*
80/80	0.12	0.16	0.15
80/40	0.11	0.14	0.26*
65/40	0.20**	0.11	0.37**
50/50	0.35**	0.14	0.19
40/40	0.59**	0.17*	0.32**

[a] Treatments with average CWSI significantly different than Full treatment are marked by * and ** for $P < 0.05$ and $P < 0.01$, respectively.

Table 5
Average DANS (°C) for each irrigation treatment during vegetative, reproductive, and maturation stages, based on canopy measurements made during 1200–1300 hourly period on each day.

Treatment	Average DANS (°C)[a]		
	Vegetative (07/09–07/19)	Reproductive (07/20–08/08)	Maturation (08/09–09/03)
100/50	−0.09	0.20**	1.24**
80/80	0.77**	0.56**	0.30**
80/40	0.69**	0.33**	1.46**
65/40	1.62**	−0.01	2.52**
50/50	3.05**	0.36**	0.70**
40/40	5.69**	0.75**	1.94**

[a] Treatments with average DANS significantly different than zero are marked by * and ** for $P < 0.05$ and $P < 0.01$, respectively.

1200–1300 hourly period, which had highest CWSI values. As this Table shows, sunflower water stress increased as water application decreased during vegetative growth stage. The two treatments that received full irrigations during this period (Full and 100/50) had the lowest CWSI, while 40/40 had an average CWSI of 0.59. Water stress was relieved to a large extent by applying full irrigations during reproductive stage, with CWSI values that did not exceed 0.17 for any treatment. During maturation period, the average CWSI increased for all treatments with applied water less than that of the 80/80 treatment.

Similar to CWSI, sunflower DANS during the afternoon hours were larger than values before noon (data not shown). Table 5 presents values of DANS measured during the 1200–1300 time period and averaged over each of the three growth stages. During the vegetative period, 100/50 was 0.09 °C cooler than Full on average (IRT's manufacturer-quoted accuracy is ±0.20 °C). Other treatments were warmer than Full, with DANS values that increased with the increase in water limitation, from 0.77 °C at 80/80 to 5.69 °C at 40/40. During the reproductive period, DANS clearly showed a relief from water stress for all treatments, with average values being less than 0.75 °C. Signs of water stress were evident during the maturation period when deficit irrigation was resumed, with DANS reaching 2.52 °C in 65/40. Relationships between CWSI and DANS for each hourly period are shown in Fig. 3. As expected, DANS and CWSI were strongly correlated, with correlation coefficients of 0.80, 0.85, 0.86, and 0.85 for hourly periods of 1000–1100, 1100–1200, 1200–1300, and 1300–1400, respectively.

Daily evolution of CWSI and DANS over the study period is depicted in Fig. 4 for all treatments and hourly periods. Although all time periods show similar trends, stress indices were larger during the two hours after solar noon (around 1230) compared to the two hours before. Water stress indices were also sensitive to timing and amount of irrigation events. The largest values of both stress indices were observed at 40/40, where severe stress was detected on 16 July prior to applying 20 mm of water. This amount of water, however, was not enough to maintain the stress at low levels and both stress indices started to increase rapidly during the following hot and dry days. The CWSI and DANS respectively reached about 0.60 and 7.0 °C on 20 July, 2012, immediately prior to applying 59 mm of irrigation that filled the root zone and reduced both indices to near zero. Subsequent irrigation applied to 40/40 maintained water stress at about the same levels during the reproductive stage. Deficit irrigation was resumed as the crop transitioned into maturation, causing CWSI and DANS to rise again. The sensitivity of the indices to the timing and amount of irrigation implies that these indices can be used effectively in monitoring water stress in sunflower and in managing deficit irrigation scheduling.

To further investigate the effect of water application on sunflower water stress, the total depth of applied water during each deficit irrigation period (vegetative and maturation) was plotted

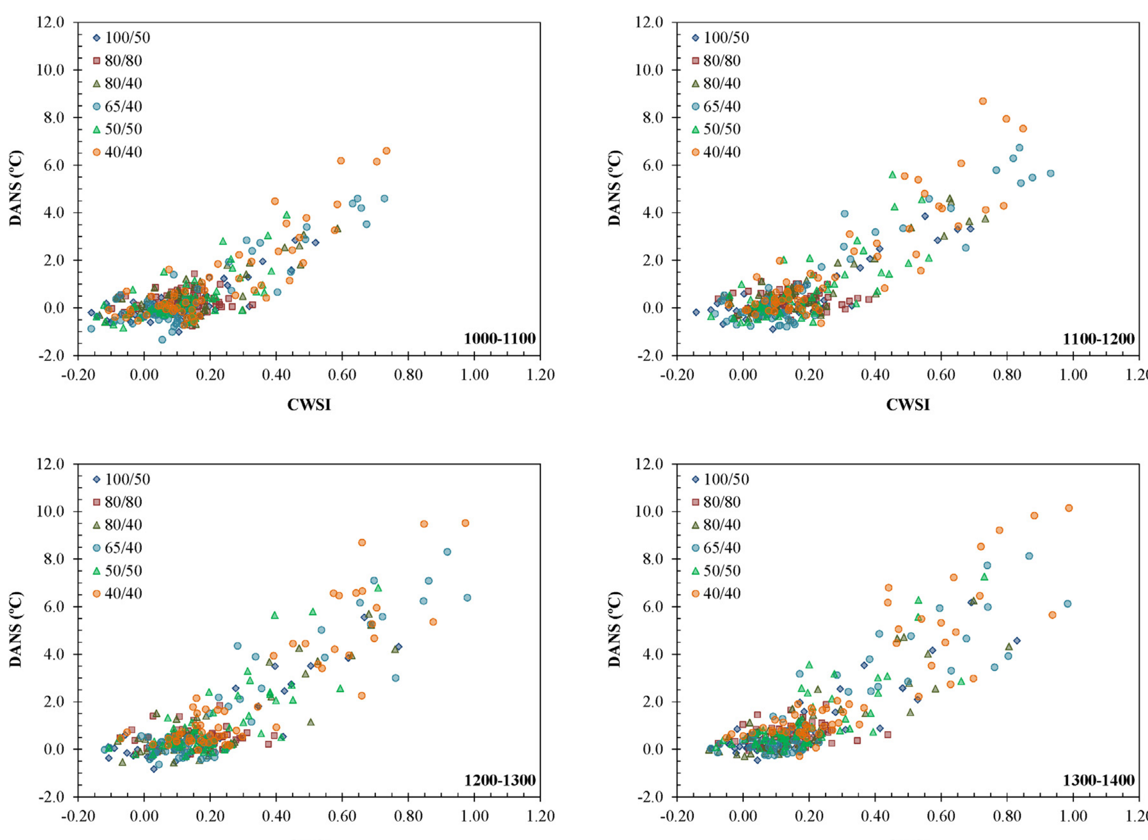

Fig. 3. Scatterplots of DANS vs. CWSI determined for each mid-day hour in this study. Each point represents a measurement day.

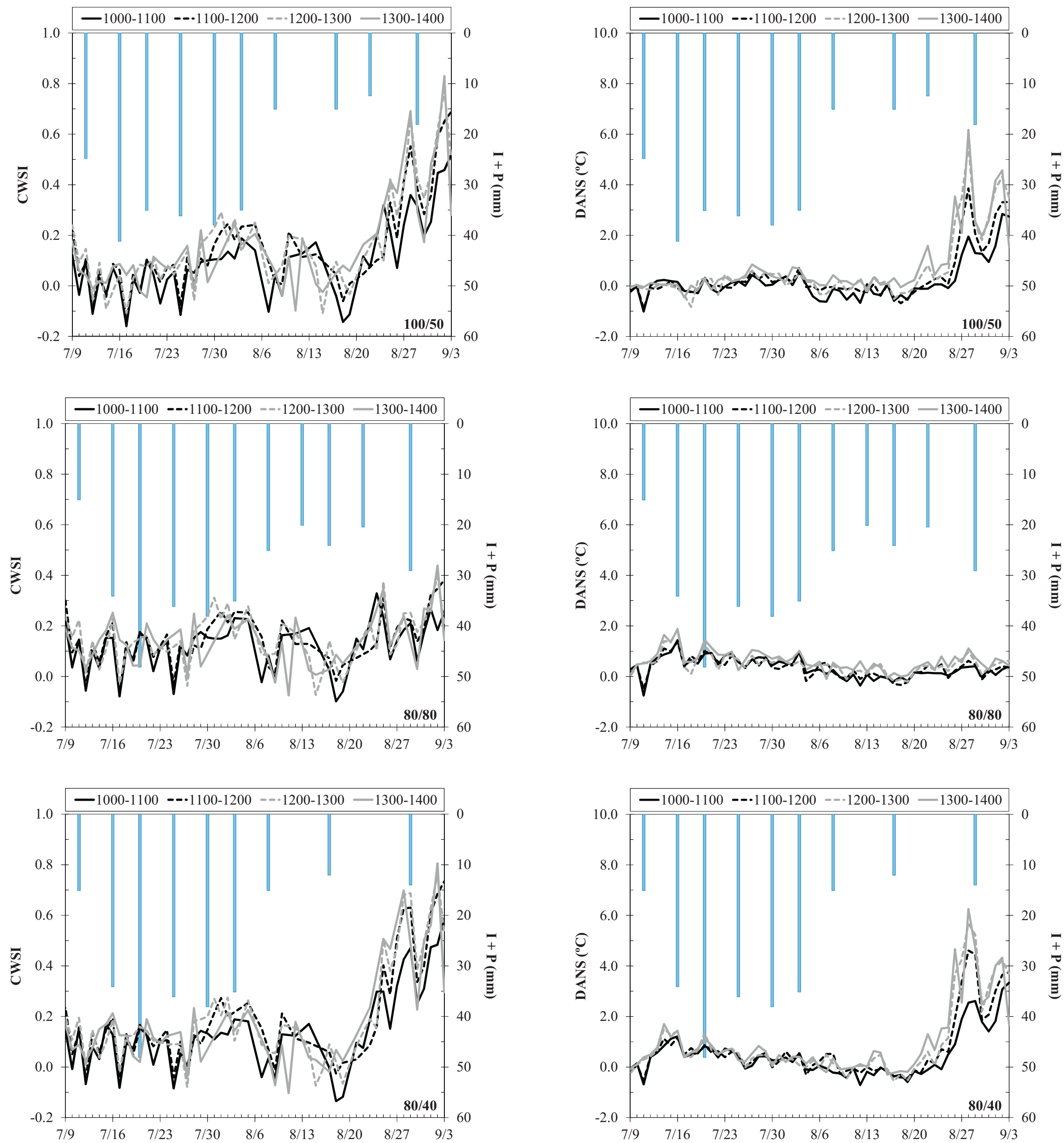

Fig. 4. CWSI (left) and DANS (right) evolution during the study period for all treatments and measurement hours. The depths of individual irrigation (*I*) and precipitation (*P*) events are plotted as vertical bars.

against average CWSI and DANS values during the same periods (Fig. 5). Since the two growth periods had different irrigation requirements, the total applied water depths in Fig. 5 were normalized through dividing them by the total depth of water applied to Full to obtain relative values of water application. The results showed that for both vegetative and maturation periods, CWSI and DANS increased with the decrease in relative applied water. For maturation period, however, the values of stress indices were smaller than vegetative period at the same level of water application. This is perhaps due to the reduced atmospheric demand during the maturation stage. As presented in Table 2, average solar radiation and air temperature were smaller during maturation. In other words, sunflower appeared to be less sensitive to deficit irrigation at this stage. Exponential curves fitted to the data points were all significant, but had larger coefficients of determination during vegetative than maturation stages (Fig. 5).

The relationships between CWSI/DANS and soil water deficit (SWD), estimated based on soil water content measurements, are presented in Fig. 6. More scatter in data points was observed for CWSI-SWD, but both plots suggest there is a SWD threshold above which temperature-based stress indices start to increase rapidly. For SWD values less than about 90 mm, CWSI and DANS remained less than about 0.30 and 1.00 °C, respectively. For SWD values above 90 mm the stress indices increased rapidly and reached 1.00 and 8.00 °C, respectively. The SWD values were always less than 75 mm during the reproductive stage, when water stress was avoided.

The relationships such as those presented in Fig. 6 can be used to obtain information on soil water thresholds. In this case, the data

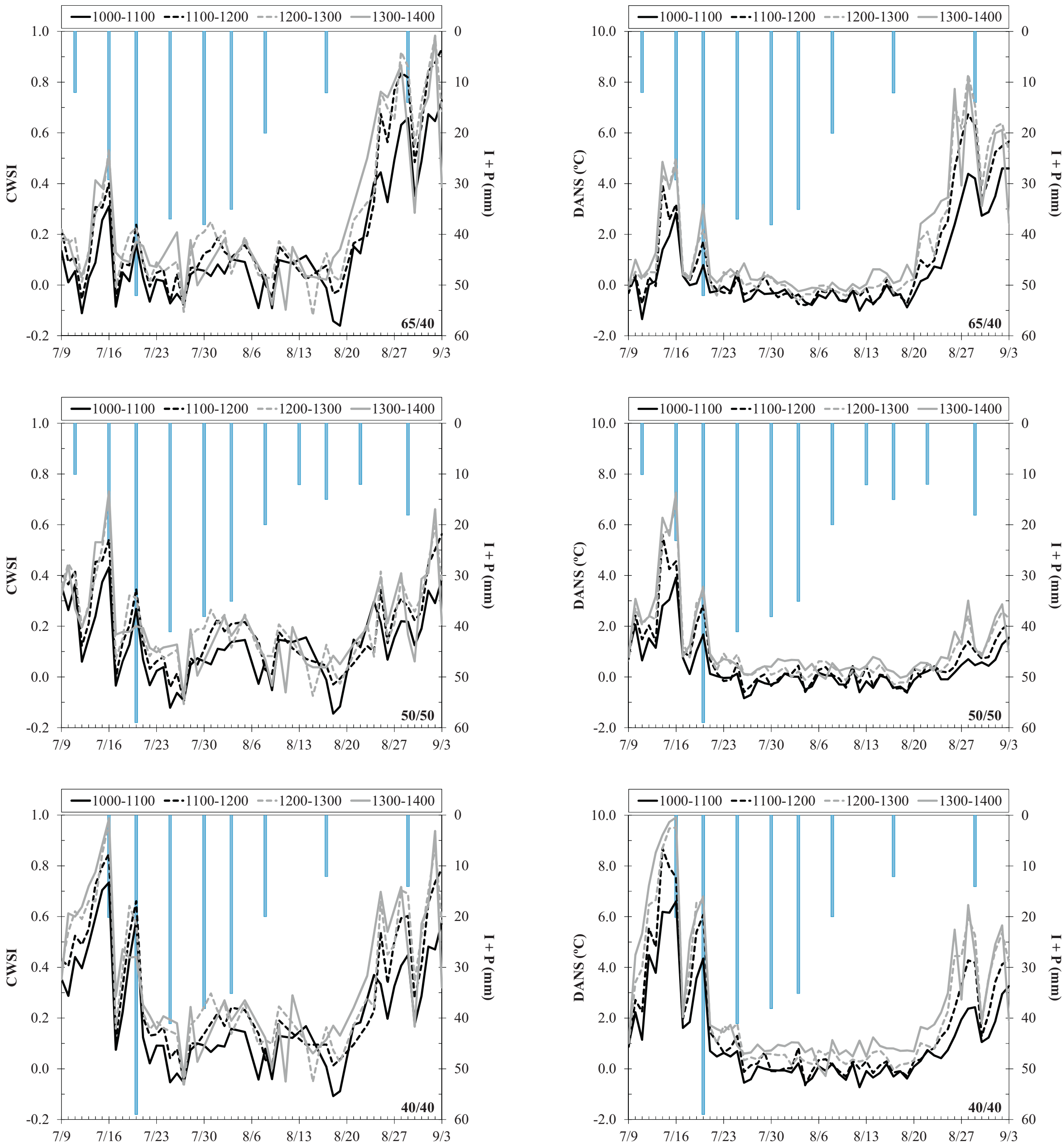

Fig. 4. (*Continued*)

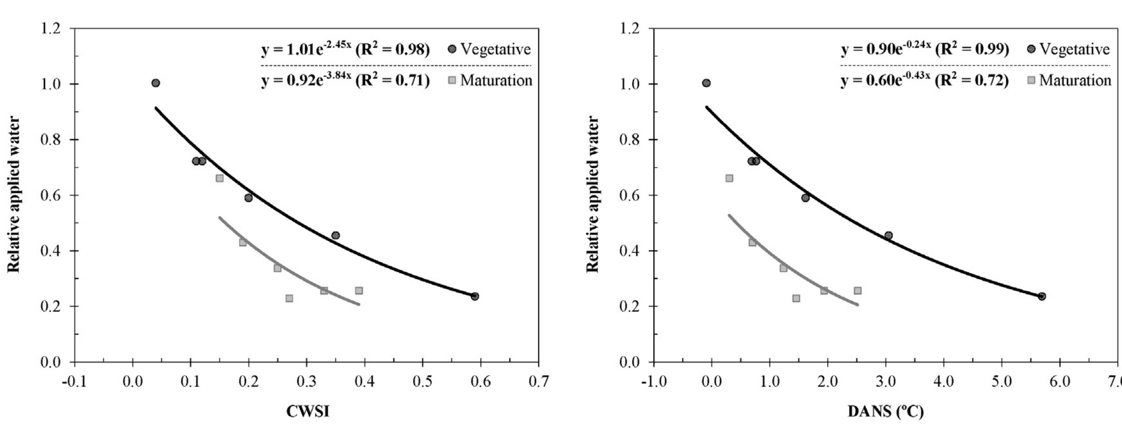

Fig. 5. Average CWSI (left) and DANS (right) during vegetative and maturation stages as affected by relative fraction of total applied water.

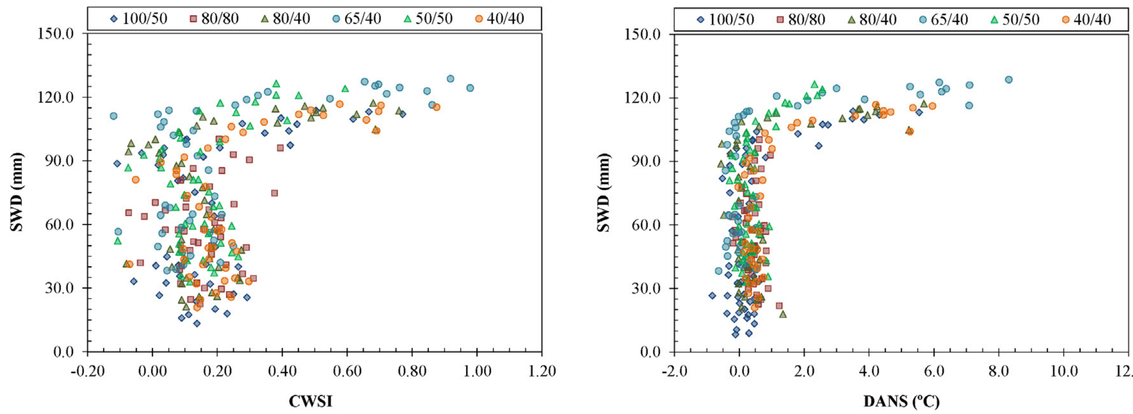

Fig. 6. Daily CWSI (left) and DANS (right) plotted against soil water deficit (SWD) in sunflower root zone.

suggest that the readily available water (RAW) limit, also known as management allowed depletion (MAD), is about 90 mm since stress was induced after reaching this limit. This is also confirmed by the fact that stress was negligible during the reproductive stage, when SWD was kept less than 75 mm. The maximum SWD of about 130 mm, however, is at some point in between RAW and the permanent wilting point (PWP), as sunflower always recovered from stress when water was applied after reaching this limit. The above information along with data on soil total available water (TAW) can be also used to construct and modify water stress coefficient (K_S) curves used for estimating crop evapotranspiration based on the FAO-56 approach (Allen et al., 1998).

Similar observations have been made by other researchers. Lacape et al. (1998) found that cotton CWSI did not change significantly until about half of TAW was depleted by crop roots. CWSI increased rapidly after this limit was passed. Colaizzi et al. (2003) reported that CWSI-based K_S estimates remained fairly stable until about 60% of TAW was depleted by cotton and then dropped rapidly. An increase in CWSI with decrease in water application and/or water availability in the root zone have also been reported for sunflower (Nielsen and Anderson, 1989), corn (Cárcova et al., 1998; Yazar et al., 1999; Taghvaeian et al., 2012), cotton (Ünlü et al., 2011), tomato (López-López et al., 2011), turfgrass (Taghvaeian et al., 2013), and wheat (Garrot et al., 1994).

3.3. Canopy growth

The effect of water stress on canopy growth was investigated using two plant parameters, namely fIPAR and LAI, measured at the end of the first deficit irrigation period (19 July 2012). Irrigation treatments had significantly different light interception ($P < 0.01$), with fIPAR decreasing from 94% at Full to 53% at 40/40. These values are similar to observations by Albrizio et al. (2007), who reported fIPAR values ranging between 86% for well-irrigated and 48% for dryland sunflower at a similar growth stage, but planted under the Mediterranean climate of southern Italy. Fig. 7 shows scatterplots of fIPAR versus CWSI and DANS (1200–1300), averaged over the ten-day period from the beginning of canopy temperature measurements to fIPAR measurement. The fIPAR decreased with the increase in both stress indices, suggesting that prolonged water stress significantly limited the growth of sunflower canopy. Linear relationships fitted to both datasets were statistically significant, with coefficients of determination of 0.94 and 0.98 for DANS and CWSI relationships, respectively. The PAR measurements (above canopy) varied less than 2% among experimental plots, with an average of 1719.0 μmol m^{-2} s^{-1}.

Similar to fIPAR, the LAI values decreased from 3.62 to 1.44 as water application decreased. The sensitivity of sunflower LAI to water application has been observed in previous studies. Albrizio et al. (2007) reported a decrease in LAI from 3.70 to 1.82 at well-irrigated and dryland treatments, respectively. In southeastern Australia, Connor et al. (1985) observed that LAI values for sunflower at early reproductive stage decreased from above 2.00 to less than 1.00 as water application was reduced from full-irrigation to dryland. Fig. 8 shows the relationships between LAI measured on 20 July 2012 (the end of the first deficit irrigation period) and the two stress indices based on 1200–1300 hourly measurements and averaged over the period from the beginning of canopy temperature measurement until the LAI measurement date. The relationships were highly significant and were best modeled by exponential relationships with near 0.90 coefficients of determination. This confirms the fIPAR results that water stress significantly reduced canopy development in sunflower and that this reduction can be estimated from the increase in stress indices. The fIPAR relationships had less scatter compared to LAI ones, which may be due to the fact that fIPAR measurements account for the effect of leaf wilting, as a wilted leaf has a smaller light interception compared to a turgid one. Previous studies have reported similar CWSI-LAI relationships. For broccoli, for example, Erdem et al. (2010) showed that a high CWSI level of 0.91 resulted in a 60% decrease in LAI compared to well-watered plants.

3.4. Leaf Water Potential

Sunflower midday Ψ_L was measured on four days during the study period: 5 July, 19 July, 10 August, and 28 August, 2012. The first two days were during the vegetative period of deficit irrigation, the third day was during the reproductive stage when all treatments received full irrigations, and the last day was during sunflower maturation after deficit irrigations had been resumed. The results showed that irrigation treatments had significantly different Ψ_L values ($P < 0.01$) on all measurement days except the third one, showing that full irrigations applied during the reproductive stage were successful in alleviating the stress that was experienced during the vegetative stage.

Historically, Ψ_L has been used as an indicator of water stress, but it can be a challenging measurement to acquire. Several researchers have found that CWSI can be used as a surrogate to Ψ_L (Jackson, 1991; Ben-Asher et al., 1992; Meron et al., 2010; O'Shaughnessy et al., 2011). Relationships between Ψ_L and temperature-based stress indices for different crops at different locations would enable irrigation managers to relate one parameter to the other and use previously developed guidelines for Ψ_L-based irrigation scheduling to manage irrigations using measurements of canopy temperature.

Fig. 9 shows Ψ_L values measured in this study on three dates during deficit irrigation application, plotted against CWSI and

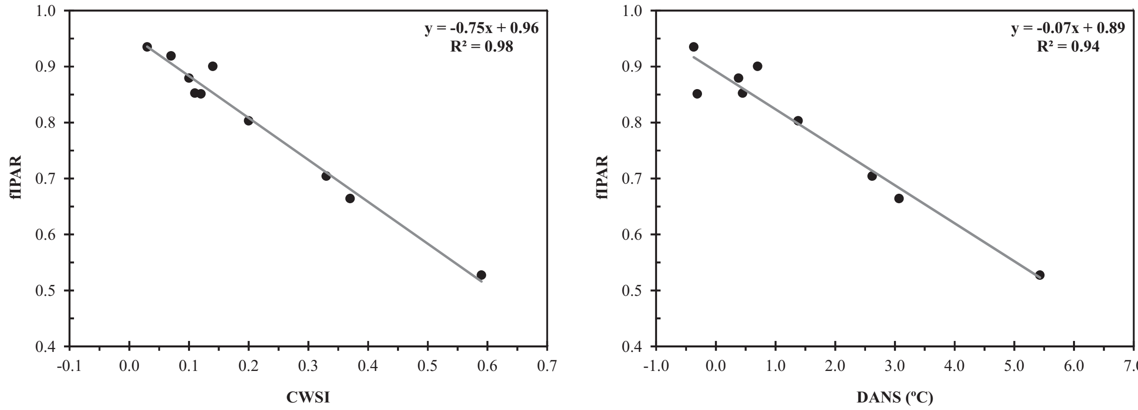

Fig. 7. Sunflower light interception (fraction of intercepted light, fIPAR) measured at the end of first deficit irrigation period (9–19 July), plotted against average CWSI (left) and DANS (right) during the same period.

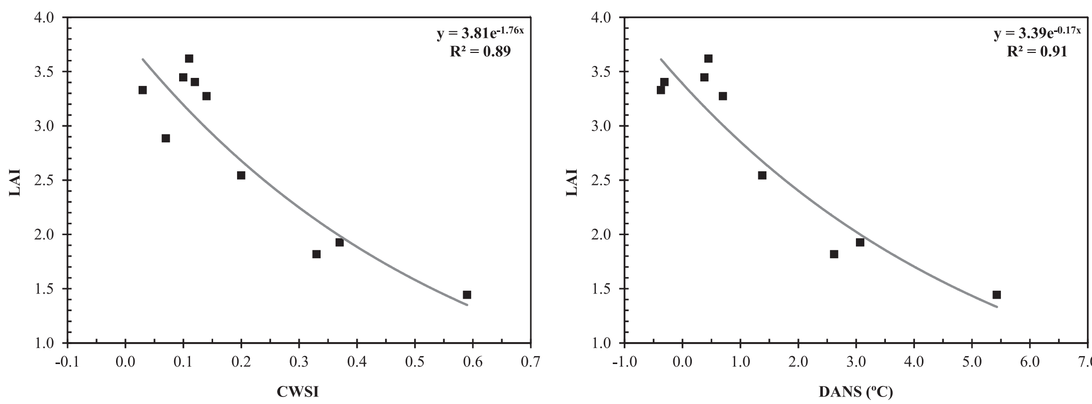

Fig. 8. Sunflower leaf area index (LAI) measured at the end of first deficit irrigation period, plotted against average CWSI (left) and DANS (right) during the same time period.

DANS calculated from concurrently-measured canopy and air temperature. For CWSI, data points are overlaid on a polynomial relationship that was developed by Nielsen and Anderson (1989) based on single-day measurements of sunflower Ψ_L and CWSI at the leaf level. As depicted in Fig. 9, larger negative Ψ_L values were observed as CWSI and DANS increased. Observed correlations were statistically insignificant on some of the measurements dates. For CWSI, the correlation on 5 July (−0.77) was the only significant ($P < 0.05$) correlation. The Ψ_L-CWSI values observed on this date were close to those observed by Nielsen and Anderson (1989). For DANS, correlations on 19 July (−0.77) and 28 August (−0.78) were significant ($P < 0.05$).

Several previous studies have developed statistically significant Ψ_L-CWSI relationships for alfalfa (Hutmacher et al., 1991), cotton (Howell et al., 1984; Jackson, 1991; Ben-Asher et al., 1992; Meron et al., 2010; O'Shaughnessy et al., 2011), corn (Zia et al., 2011), soybean (Nielsen, 1990; O'Shaughnessy et al., 2011), and winter wheat (Howell et al., 1986), as well as for orchard crops such as sweet lime (Sepaskhah and Kashefipour, 1994) and pistachio (Testi et al., 2008). In this study no significant relationship could be developed to predict sunflower Ψ_L using CWSI, but the Ψ_L-DANS relationship was statistically significant ($P < 0.01$): $\Psi_L = -0.12 \times \text{DANS} - 1.54$ ($R^2 = 0.66$). In evaluating relationships between Ψ_L and CWSI/DANS it should be noted that Ψ_L was measured for a few sunlit leaves,

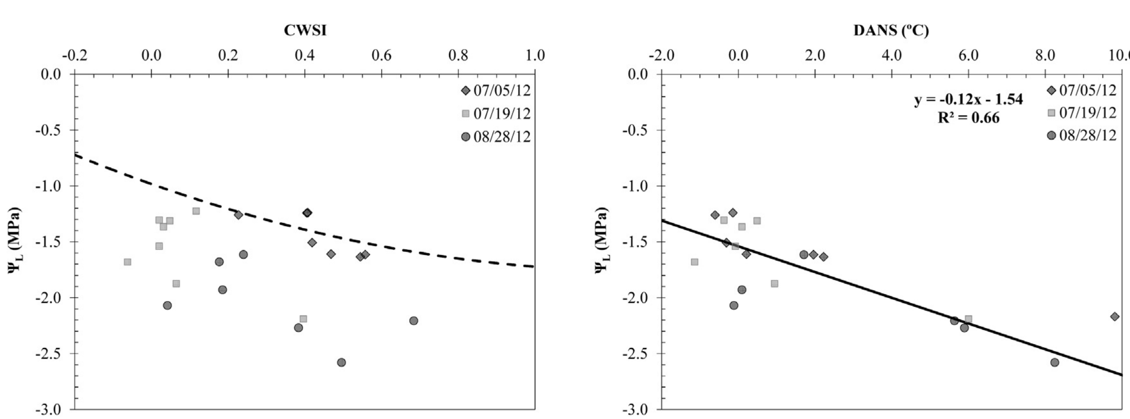

Fig. 9. Plots of midday Leaf Water Potential (Ψ_L) vs. CWSI (left) and DANS (right) measured on three days during the application of deficit irrigation treatments. The dashed black line represents the Ψ_L-CWSI relationship developed by Nielsen and Anderson (1989). The solid black line represents the Ψ_L-DANS relationship developed in this study.

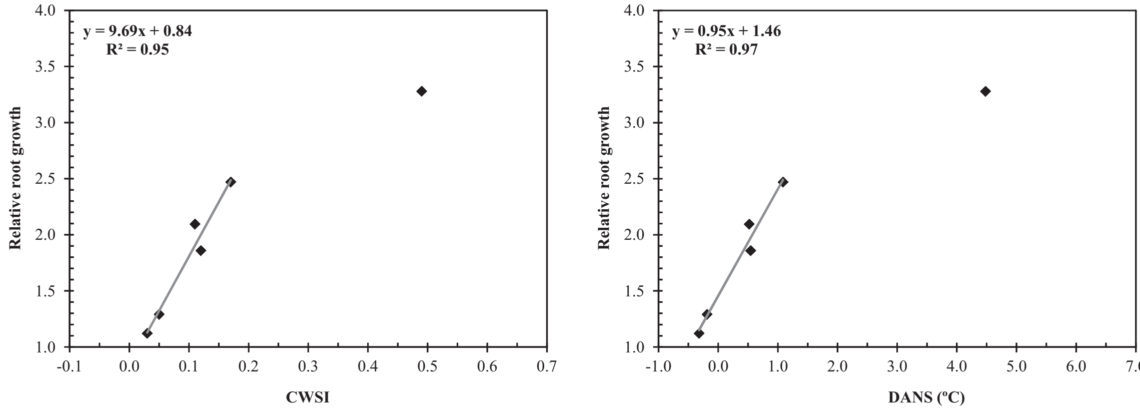

Fig. 10. Sunflower relative root growth measured on 24 July 2012 vs. average CWSI (left) and DANS (right) for the period ending on this date, along with linear regression lines for all but the 40/40 treatment.

while the stress indices were estimated for the canopy in IRTs' field of view, which is comprised of many sunlit and shaded leaves. Stronger relationships may be obtained if CWSI/DANS are estimated at the leaf level.

3.5. Root growth

Sunflower root systems showed a rapid growth from the initial minirhizotron measurements (26 June) until 24 July 2012, four days after the first period of deficit irrigation application was ceased. Root growth after this date had a negligible rate. The results showed that the decrease in water application resulted in an increase in sunflower root length per unit area, with values ranging from 75.4 cm cm^{-2} at Full to 247.2 cm cm^{-2} at 40/40 for images taken on 24 July, 2012. This over threefold increase in root length density suggests that sunflower allocated more resources to producing roots to search for water. Smaller values of fIPAR and LAI at treatments with higher stress level suggest that root growth was achieved at the cost of above-ground biomass production.

The relationships between root growth and stress indices are shown in Fig. 10. To improve comparability of these data with those of other studies, root growth values were normalized by dividing them by the values measured for the Full treatment, to give relative root growth estimates. Except for treatment 40/40, statistically significant ($P < 0.01$) linear relationships were observed between root growth and stress indices. The CWSI-based and DANS-based relationships predicted that relative root growth for 40/40 would be 5.6 and 5.7, respectively. However, the measured relative root growth at this treatment was significantly smaller at 3.3, suggesting that there is a stress threshold above which the plant does not have sufficient resources to continue to increase root density in response to stress.

4. Conclusion

A field study was conducted in northern Colorado to investigate the ability of two stress indices based on canopy temperature to quantify water stress in sunflower under variable levels of regulated deficit irrigation. The two indices were the widely-used Crop Water Stress Index (CWSI) and the simplified Degrees Above Non-Stressed (DANS). The CWSI non-water-stressed baselines developed for periods before and after grain-filling were similar to those developed for the same crop over two decades ago at a site 140 km east of the research field in this study, suggesting that CWSI baselines may be used under similar climatic conditions without being calibrated for each site and crop variety.

Both stress indices responded to irrigation amounts and timing and increased with water limitation. In addition, they were strongly correlated with fraction of Intercepted Photosynthetically Active Radiation (fIPAR), Leaf Area Index (LAI), Leaf Water Potential (Ψ_L), and root growth. Based on collected data, regression equations were developed to predict fIPAR, LAI, and relative root growth from CWSI and DANS estimates. In all cases, regression equations based on both stress indices had similar coefficients of determination, suggesting that CWSI and DANS performed similarly in this study. This finding is encouraging as DANS can be estimated using only one type of measurement, namely the canopy temperature. The calculation process (subtraction) is also simpler than CWSI and other temperature-based indices. However, further studies are required to test the performance of DANS for other crops and under different climatic conditions.

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