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Minimizing instrumentation requirement for estimating crop water stress index and transpiration of maize

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Abstract Research was conducted in northern Colorado in 2011 to estimate the crop water stress index (CWSI) and actual transpiration (T_a) of maize under a range of irrigation regimes. The main goal was to obtain these parameters with minimum instrumentation and measurements. The results confirmed that empirical baselines required for CWSI calculation are transferable within regions with similar climatic conditions, eliminating the need to develop them for each irrigation scheme. This means that maize CWSI can be determined using only two instruments: an infrared thermometer and an air temperature/relative humidity sensor. Reference evapotranspiration data obtained from a modified atmometer were similar to those estimated at a standard weather station, suggesting that maize T_a can be calculated based on CWSI and by adding one additional instrument: a modified atmometer. Estimated CWSI during four hourly periods centered on solar noon was largest during the 2 h after solar noon. Hence, this time window is recommended for once-a-day data acquisition if the goal is to capture maximum stress level. Maize T_a based on CWSI during the first hourly period (10:00–11:00) was closest to T_a estimates from a widely used crop coefficient model. Thus, this time window is recommended if the goal is to monitor maize water use. Average CWSI over the 2 h after solar noon and during the study period (early August to late September, 2011) was 0.19, 0.57, and 0.20 for plots under full, low-frequency deficit, and high-frequency deficit irrigation regimes, respectively. During the same period (50 days), total maize T_a based on the 10:00–11:00 CWSI was 218, 141, and 208 mm for the same treatments, respectively. These values were within 3 % of the results of the crop coefficient approach.

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Introduction

Maize (*Zea mays* L.) is one of the dominant crops in the USA, planted to produce food, feed, and fuel. The total area of American agricultural lands under maize reached 37.2 million ha in 2011 (USDA-NASS 2012). In the same year, 43 % of the land planted to maize was irrigated. The majority of these irrigated fields are located in the western USA Corn Belt, where competition over fresh water resources has escalated among different users during the past few decades. Municipalities in this region are struggling with water scarcity due to rapid population growth, and water transfer from agriculture is one of the least expensive water supply options. However, permanent transfer of water rights from farmers to municipalities with subsequent permanent fallowing, a scenario known as "buy and dry," can lead to deterioration of rural economies. Among several alternatives that have been offered for "buy and dry" (e.g., rotational fallowing, purchasing and leasing back, water banks), perhaps the most promising one is deficit irrigation, in which farmers decrease the frequency and/or the amount of irrigations and intentionally allow the crop to experience some level of water stress. The conserved consumptive use (CU) from water stress can be transferred to cities, and the resulting lower yield from

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deficit irrigation is compensated by the revenue generated from water transfer. Compared to traditional full irrigation practices, however, implementing a successful deficit irrigation regime requires more accurate and precise irrigation management, as crops have variable sensitivities to water stress at different growth stages (Bausch et al. 2011). For example, maize yield is sensitive to water stress during the tasseling, silking, and pollination stages, but less sensitive during vegetative, grain filling, and maturity stages. Hence, there is a need to develop irrigation management tools that are not only efficient in achieving an optimum level of deficit irrigation (Mahan et al. 2012), but are also easy to apply at farm and district levels by land owners and irrigation managers. Additionally, since water transfers are typically based on actual crop water consumptive use (not necessarily water applied), an understanding of crop evapotranspiration (ET) under water stress is also required.

Crop water stress index (CWSI) is one of these tools that was developed more than three decades ago (Idso et al. 1981; Jackson et al. 1981) and has been widely applied and studied since then (Idso et al. 1984; Stegman 1986; Steele et al. 1994; Irmak et al. 2000; Taghvaeian et al. 2012, 2013). This plant-water-status indicator can be calculated by determining the plant canopy-air temperature differential (dT) from measured temperature data, and then normalizing it using maximum and minimum limits that dT can potentially reach (Eq. 1):

$$\mathrm{CWSI} = \frac{(\mathrm{d}T_{\mathrm{m}} - \mathrm{d}T_{\mathrm{LL}})}{(\mathrm{d}T_{\mathrm{UL}} - \mathrm{d}T_{\mathrm{LL}})} \tag{1}$$

where $\mathrm{d}T_{\mathrm{m}}$, $\mathrm{d}T_{\mathrm{LL}}$, and $\mathrm{d}T_{\mathrm{UL}}$ are measured, lower limit, and upper limit of $\mathrm{d}T$, respectively. While $\mathrm{d}T_{\mathrm{m}}$ is obtained by subtracting the measured canopy temperature of the studied crop from the measured air temperature, lower and upper $\mathrm{d}T$ limits need to be estimated before CWSI can be computed using the above equation. Both empirical (Idso et al. 1981) and theoretical (Jackson et al. 1981) approaches have been presented for estimating $\mathrm{d}T_{\mathrm{LL}}$ and $\mathrm{d}T_{\mathrm{UL}}$. However, researchers and practitioners have paid considerably more attention to the former approach, as it requires only one more weather measurement, namely air water vapor pressure or air humidity. Based on this approach, lower and upper $\mathrm{d}T$ limits can be obtained from the following linear relationships (Idso et al. 1981):

$$\mathrm{d}T_{\mathrm{LL}} = m \times \mathrm{VPD} + b \tag{2}$$

$$\mathrm{d}T_{\mathrm{UL}} = m \times \mathrm{VPG} + b \tag{3}$$

where coefficients m and b are the slope and intercept of the linear equation, respectively, and VPD is atmospheric water vapor pressure deficit (kPa). VPG is vapor pressure gradient (kPa) estimated as the change in saturated vapor pressure if the ambient temperature increases by an amount equal to b (intercept of Eq. 2). Since the above relationships represent the minimum and maximum level of crop water stress, they are known as non-water-stressed and non-transpiring baselines, respectively. These baselines are crop and climate specific; thus, they need to be developed for each combination of crop and climate.

The empirical CWSI approach has been employed by numerous researchers to foster maize irrigation water management. Stegman (1986) used two CWSI thresholds (0.2 and 0.4) to time irrigation events of maize in North Dakota, USA. Allowing CWSI to reach a limit of 0.4 resulted in an irrigation application amount that was 61 % of the amount applied to the control (full irrigation) treatment. Crop ET was reduced to 86 % of that of the control treatment, suggesting that reducing irrigation amount resulted in a reduction in both ET and return-flow components. Interestingly, harvested grain yield was 91 % of that of the full irrigation treatment, meaning that maize water productivity increased from 2.3 to 2.5 kg m^{-3} (kg of grain per m^{-3} of water used by crop) by applying a CWSI-based irrigation scheduling. A few years later, Steele et al. (1994) conducted a similar study at the same site, comparing eight different irrigation timing criteria, including three levels of CWSI. Averaged over the 3 years of study, CWSI thresholds of 0.2, 0.4, and 0.6 resulted in 28, 43, and 54 % reduction in applied irrigation water and 2, 8, and 13 % decrease in grain yield, respectively. The conserved CU (or ET) was 2, 6, and 10 % for the same CWSI levels, respectively.

Aside from providing an estimate of crop water status, CWSI can be used to compute actual crop water transpiration (T_{a}). Having a quantitative estimate of the portion of applied water that has been transpired by crops is valuable in developing water transfer guidelines and policies that not only ensure the protection of return-flow-dependent downstream water rights and wetlands, but also lead to mutually beneficial agreements between farmers and municipalities. According to Jackson et al. (1981):

$$T_{\mathrm{a}} = (1 - \mathrm{CWSI}) \times T_{\mathrm{c}} \tag{4}$$

where T_{a} and T_{c} are crop transpiration rates (mm h^{-1} or mm day^{-1}) under actual and standard conditions, respectively. Standard conditions are defined by Allen et al. (1998) as disease-free, well-watered, and well-fertilized conditions. Thus, T_{a} approaches the T_{c} rate when CWSI is close to zero (no water stress) and T_{a} becomes small when CWSI approaches unity (severely stressed). For each crop, T_{c} can be estimated by multiplying the reference (alfalfa or grass) ET and the corresponding basal crop coefficient (K_{cb}) of that crop for the growth stage of interest.

Based on Eq. (4), actual transpiration of the studied crop (maize in this case) can be calculated if CWSI and T_{c} are known. As stated before, CWSI can be estimated based on

three easy-to-obtain weather and crop parameters (air temperature, plant canopy temperature, and air relative humidity). Estimating T_c, however, typically requires the knowledge of grass- and/or alfalfa-based reference ET, as well as basal crop coefficient K_{cb} (Allen et al. 1998). Although K_{cb} values have been developed and reported for a wide variety of crops, reference ET cannot be estimated accurately without several meteorological data measured at standard weather stations. This requirement could limit the practical application of CWSI for quantifying crop water use, since weather stations with geo-climatic conditions similar to that of the study area do not exist at a close proximity for many irrigation schemes.

Atmometers can be used to provide reference ET data, as a simpler and more affordable alternative to weather stations. Atmometers were first introduced in the early nineteenth century and consisted of a porous porcelain medium that was connected to a water reservoir (Livingston 1935). The hydraulic connectivity between the water reservoir and the porous porcelain created a water potential gradient that responded to the evaporative water demand created by the surrounding atmosphere. Numerous modified atmometers have been introduced since then, including a ceramic Bellani plate-modified atmometer developed by Altenhofen (1985). This modified version uses a green canvas that tightly covers the evaporating cup (Bellani plate) and simulates the spectral reflectance and leaf water vapor conductance of well-watered reference crops (alfalfa and/or grass).

Previous studies have revealed that ET measurements of the modified atmometer have acceptable accuracy and precision (Broner and Law 1991). More specifically, the modified atmometer was found to be in good agreement with alfalfa reference ET (ET_r) estimated based on the 1982 Kimberly-Penman equation (Ervin and Koski 1997; Berrada et al. 2001), which was one of the accepted standard methods of estimating reference ET by the state of Colorado at that time. However, other experiments have found that the modified atmometer underestimates ET_r, especially under low air temperature or high wind speed conditions (Gleason et al. 2013). In this experiment, ET estimates from a modified atmometer were compared with ET_r estimated using data from a standard "reference" weather station to identify whether atmometers can be used as an alternative to a standard weather station in estimating CWSI-based crop transpiration. Due to low capital and maintenance costs, atmometers can be purchased by land owners and installed at a representative location near the crop fields.

In summary, the main goal of the present study was to outline a procedure that enables farmers to monitor crop water stress and transpiration under limited water availability using a simple methodology and minimum number of instruments (i.e., an infrared thermometer, an air temperature/humidity sensor, and a modified atmometer). The specific objectives of this study include:

- To develop the empirical non-water-stressed and non-transpiring baselines for maize and to compare them with baselines developed in other locations under similar climatic conditions;
- To calculate CWSI of maize under full, low-frequency deficit, and high-frequency deficit irrigation regimes;
- To estimate maize actual transpiration based on CWSI estimates and reference ET obtained from both a weather station and a modified atmometer; and,
- To compare CWSI-based maize transpiration with independent estimates obtained from a widely used crop coefficient approach.

Methods and materials

Study site and management

This study was conducted in a 5.5-ha research field (Lat. 40°26.65′ N, Long. 104°38.10′ W, Elev. 1,425 m), located near the city of Greeley in northern Colorado, USA (Fig. 1). Alluvial soils at this site were highly variable, ranging from coarser textures (sandy clay loam) near the north end of the field to finer textures (Nunn clay loam) toward the south end. Nitrogen fertilizer (170 kg ha^{-1} as Urea Ammonium Nitrate) and herbicide were aerially applied to the field on Apr 13 and tillage incorporated on Apr 18. Maize (DEKALB® DKC52-59, YieldGardVT Triple) was planted on May 3, 2011, at a density of 84,000 seeds ha^{-1}. Row spacing was 0.76 m and row direction was north–south. During planting, liquid Nitrogen (N) and Phosphorus (P) fertilizers were side-dressed at rates of 34 and 45 kg ha^{-1}, respectively. Due to dry soil conditions, the field was sprinkler irrigated on May 5–May 9 to facilitate germination, although nearly 100 mm of rainfall between May 12 and 26 eliminated the need for further early irrigation. The maize emerged on May 26 and final plant population varied between 74,000 and 78,000 plants ha^{-1}. The field was furrowed on Jun 27, glyphosate herbicide was applied on the following day, and furrow irrigation began on Jun 30. The maize tassled on August 4, reached physiological maturity in mid-September, and was harvested between late October and mid-November 2011.

Experimental treatments

The research field was divided into three sections across its width, resulting in three blocks (40 m wide and 380 m long) for implementing different irrigation treatments,

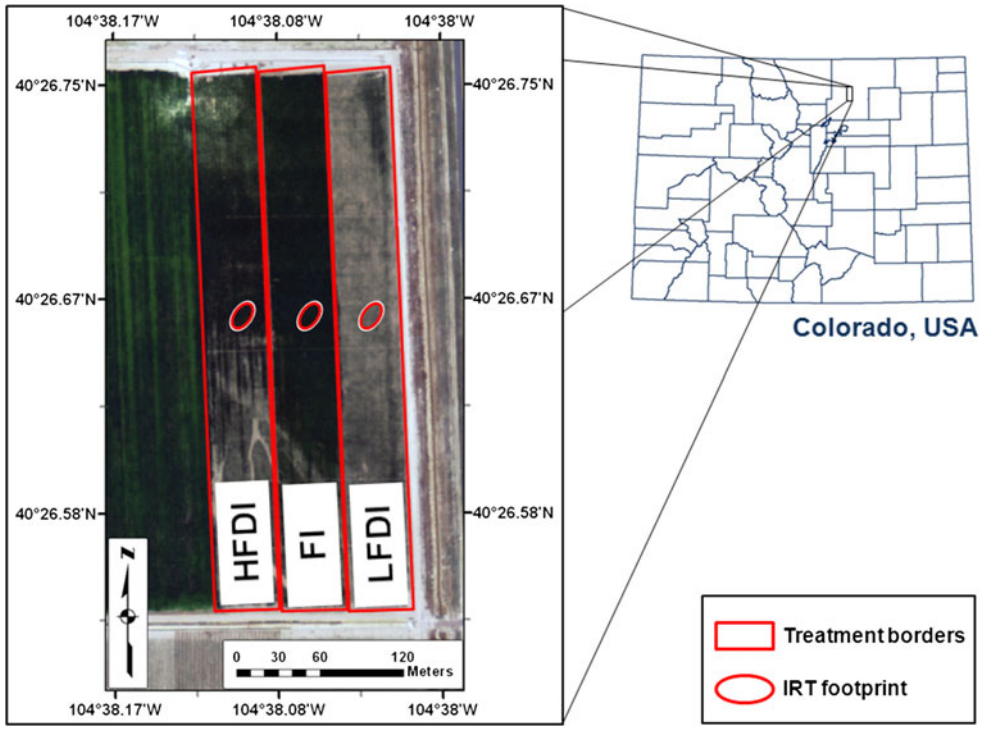

Fig. 1 The location of research farm in northern Colorado and plot layout for 2011

namely full irrigation (FI), low-frequency deficit irrigation (LFDI), and high-frequency deficit irrigation (HFDI) treatments. The middle block with the largest mid-season ground vegetation coverage (Fig. 1) was under FI, the east-most block with the smallest coverage was under LFDI, and the western block with medium ground coverage was under HFDI. Irrigation water was supplied by a well with a discharge capacity of 36.0 L sec^{-1} and applied to the furrows from the north end of the field with aluminum-gated pipe. For each treatment, water inflow was measured by a magnetic flow meter (model: HM300, Seametrics Inc., Kent, Washington, USA) and tailwater runoff was measured using a broad-crested weir flume installed in the downstream end of the tailwater collection ditch. Flume water stage was measured and logged with pressure transducers (model: Level Troll 500, In-Situ Inc., Fort Collins, Colorado, USA). During the growing season, FI and HFDI treatments received six irrigations between early Jul and mid-September, with total net water application (inflow minus runoff) depths of 1,117 and 587 mm, respectively. The LFDI received only two irrigations (mid-July and early September) with a total net application depth of 825 mm. The goal of applying infrequent but large amounts of water at LFDI was to implement a deficit irrigation practice while maintaining the historical deep percolation and surface runoff (historical return flows) that would occur under a full irrigation regime. The cumulative precipitation depth was 199 mm during the growing season.

Instrumentation

Several sensors were installed near the middle of each treatment (Fig. 1). The first sensor was an infrared thermometer (IRT, model: SI-121, Apogee Instruments, Inc., Logan, Utah, USA) with a 36° field of view and a band-pass filter in the thermal portion (8–14 μm) of the electromagnetic (EM) spectrum. According to the manufacturer, the accuracy of this sensor is ±0.2 °C over a temperature range of −10 to 65 °C. The IRTs were installed 1.0 m above the canopy at a view angle of 23° below the horizon (facing northeast) to avoid viewing any background soil. Maize canopy temperature at each treatment was sensed and recorded by the IRT sensors each minute. This temperature was corrected for the effect of sensor body temperature using manufacturer calibrated algorithms and then averaged over 30-min periods. The second instrument at each location was an air temperature/humidity sensor (model: HMP45C-L30 Vaisala, provided by Campbell Scientific Inc., Logan, Utah, USA) placed at a height of 1.0 m above the canopy. For all sensors, measurement and control functions were performed by data loggers (model: CR1000, Campbell Scientific Inc., Logan, Utah, USA). In order to investigate the differences in canopy cover among treatments, a handheld multi-spectral radiometer (model: MSR5, CROPSCAN Inc., Rochester, Minnesota, USA) was used on a weekly basis to measure surface reflectance within the IRT footprint at several wavebands. Soil adjusted vegetation index (SAVI) was

then calculated using the equation developed by Huete (1988):

$$\mathrm{SAVI} = 1.5 \times (\rho_4 - \rho_3)/(\rho_4 + \rho_3 + 0.5) \quad (5)$$

where ρ_3 and ρ_4 are surface reflectance in red and near infrared portions of the EM spectrum, respectively. The data collection and analysis were performed over a 50-day period (August 4–September 22, 2011) during the growing season. Maize was at VT/R1 growth stage at the beginning of study period, and canopy had reached full cover in the FI treatment. By the end of the study period, the maize had reached physiological maturity and leaves were largely senesced, especially in the deficit treatments.

The alfalfa-based reference ET (ET_r) was calculated following the ASCE-standardized procedure (ASCE-EWRI 2005), using the data collected at a standard weather station (station name: GLY04) located about 400 m from the research field. The station was operated and maintained by the Colorado Agricultural Meteorological Network (CoAgMet) program at Colorado Climate Center, Colorado State University, Fort Collins, Colorado, USA. Hourly and daily data were downloaded from the CoAgMet website (CoAgMet 2011). Table 1 presents some of the average weather parameters during the growing season and the 50-day study period.

A modified atmometer (model E, ETgage Company, Loveland, Colorado, USA) was installed and kept at about 80 % of maize canopy height and a few meters away from the IRT at FI treatment in order to provide an independent estimate of reference ET. Keeping the atmometer at 80 % of canopy height was to ensure that its evaporating surface was in the same region as the main transpiring portion of the maize canopy. At heights above the canopy or close to the ground surface, the microclimatic parameters deriving the evaporation process (especially wind speed) are different than those the crop canopy is subject to. It is suggested to adjust the atmometer height during all growth stages to maintain it at about 80 % of the canopy height. The green canvas of the atmometer was a C2 style, which is a thin polyester cloth cover that simulates an in-canopy, well-watered leaf surface. This automatic atmometer model is equipped with a calibrated glass vial that has a volume corresponding to 0.25 mm of water evaporated (or ET). Attached electronics fill the vial as soon as it empties and record the associated time stamp. Recorded atmometer data were downloaded to a personal computer and further analyzed to estimate atmometer-based daily reference ET (ET_g). For the first time stamp in each day, it was assumed that the 0.25 mm of ET was divided between that day and the previous day proportional to the length of that time interval that occurred in each day. Since obtaining an estimate of the lower dT limit is a basic step in estimating CWSI, a small thermistor was embedded under the green canvas cover and the wafer that prevents rainwater from entering the instrument to investigate the possibility of using the temperature of this evaporating surface as a surrogate for the temperature of a non-water-stressed crop. Obtaining promising results would eliminate the need to develop non-water-stressed baseline for the specific climate of the study area.

Table 1 Average daily weather parameters for the entire growing season and the study period

Parameter	Growing season (May 3–October 21)	Study period (August 4–September 22)
Mean air temp. (°C)	17.9	19.4
Max. air temp. (°C)	27.2	29.3
Min. air temp. (°C)	9.4	10.8
Vapor pressure (kPa)	1.11	1.23
Min. relative humidity (%)	23.5	22.3
Wind run (km d^{-1})	179.6	129.5
Solar radiation (W m^{-2})	237.3	228.0

Crop water stress index (CWSI)

Canopy temperature and weather data measured within the FI treatment on several sunny days after significant irrigation and/or precipitation events were selected for establishing the non-water-stressed baseline. It was assumed that under selected conditions, dT_m values were equal to dT_{LL} values. Plotting these hourly values with their corresponding VPD had a linear segment that extended for 4 h around the solar noon, which occurred within a few minutes of 12:00 mountain standard time (MST) during the study period at the study location. This linear segment was extracted and used to obtain the coefficients of Eqs. (2) and (3). The upper and lower limits of dT and consequently CWSI were estimated for each hour during this time frame, namely 10:00–11:00, 11:00–12:00, 12:00–13:00, and 13:00–14:00 MST.

Maize actual transpiration (T_a)

Based on CWSI

Maize T_a was calculated for all treatments, using Eq. (4). To calculate maize transpiration under standard conditions (T_c), reference ET values were obtained from the CoAgMet weather station and from the atmometer water depletion readings and were then multiplied by the alfalfa-based table basal crop coefficients (K_{cb}) presented in the ASABE monograph (Allen et al. 2007, table 8.8, based on a full-cover date of July 19). The K_{cb} values varied from 0.67 to

0.96 during the study period, with an average value of 0.84. Since CWSI values were estimated for four hourly periods, four estimates of daily T_a were obtained for each day. Implemented methods and procedures to estimate daily T_a were similar to those explained in detail in Taghvaeian et al. (2012).

Based on crop coefficient modeling

Independent estimates of maize T_a were obtained by applying a daily crop coefficient model outlined in the FAO paper 56 (Allen et al. 1998). In the FAO56 approach, T_a is calculated using the following equation:

$$T_a = \mathrm{ET_r} \times K_{cb} \times K_s \tag{6}$$

where K_s is a soil–water-dependent stress coefficient and other parameters have been defined previously. The K_s was calculated using the following equation (Allen et al. 1998):

$$K_s = \frac{\mathrm{TAW} - D_r}{(1-p)\mathrm{TAW}} \tag{7}$$

where D_r is the root zone soil water depletion (mm), TAW is total available soil water in the root zone (mm) assumed as half of field capacity, and p is the fraction of TAW that the crop can extract from the root zone without suffering water stress, assumed as 0.5 (Allen et al. 1998). Soil moisture content used to determine D_r was measured by time domain reflectometry in the top 15 cm from the soil surface, and by neutron moisture meter in subsequent layers below. Root zone depth was determined from soil moisture content observations, i.e., when soil moisture content in a given soil layer starts to significantly decrease, it is assumed that the roots have reached that layer. All three treatments had a constant root zone depth of 1.10 m during the study period.

Unlike the CWSI approach, the K_{cb} values used in the FAO56 approach were estimated somewhat differently. In this approach, the variation in K_{cb} was not determined based on the time after planting, but as a linear function of the percent canopy cover. The percent canopy cover estimates were obtained for each treatment by processing visible light photos, taken on a weekly basis at a nadir view angle. The implemented linear relationship yielded a K_{cb} value of 0.15 at zero canopy cover and a maximum K_{cb} of 0.96 at 80 % canopy cover and above. These minimum and maximum limits are similar to those presented at the ASABE monograph for field corn (Allen et al. 2007).

The difference between CWSI-based and FAO56-based maize T_a estimates was evaluated using two statistical indicators, namely the mean bias difference (MBD) and the root mean square deviation (RMSD):

$$\mathrm{MBD} = \frac{1}{n}\sum_{i=1}^{n}(T_{\mathrm{a-CWSI}} - T_{\mathrm{a-FAO56}}) \tag{8}$$

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_{\mathrm{a-CWSI}} - T_{\mathrm{a-FAO56}})^2} \tag{9}$$

where $T_{\text{a-CWSI}}$ and $T_{\text{a-FAO56}}$ are maize T_a based on CWSI and FAO56 methods, respectively, and i represents each day during the study period of n total days.

It should be noted that FAO56 also presents a procedure for estimating water evaporation from soil surface (E), which can be performed using electronic spreadsheets. Combining the CWSI-T_a with FAO56-E estimates will provide information that is more useful than just the T_a, as changing the frequency of irrigation events alters the E portion of actual ET and should be considered in documenting conserved CU.

Results and discussion

Reference and standard condition crop water use

Comparing the atmometer $\mathrm{ET_g}$ with CoAgMet $\mathrm{ET_r}$ on a daily basis during the study period revealed that the atmometer tended to underestimate smaller and overestimate larger $\mathrm{ET_r}$ values (Fig. 2). These errors, however, canceled each other to a large extent during the study period, resulting in a difference between the two estimates that was 0.2 mm day^{-1} on average. During the 50 days of study, the average daily and cumulative $\mathrm{ET_r}$ were 5.1 mm day^{-1} and 256 mm, respectively. The same parameters for $\mathrm{ET_g}$ were only 4 % larger at 5.3 mm day^{-1} and 266 mm, respectively. The results suggest that atmometer data can be used as a surrogate to standard

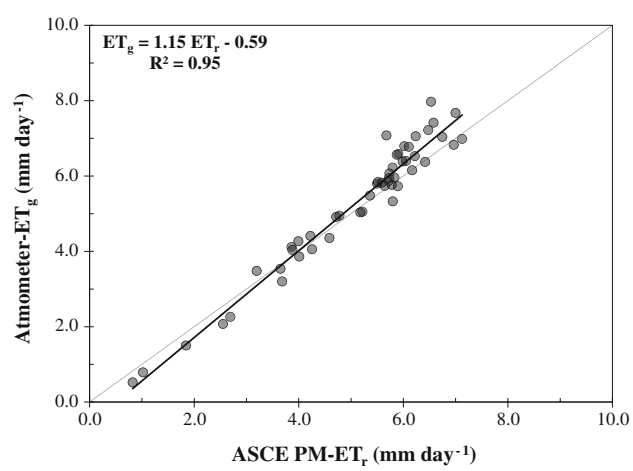

Fig. 2 Atmometer $\mathrm{ET_g}$ versus weather station $\mathrm{ET_r}$ for each day during the study period, along with the regression (*solid black*) and 1-to-1 (*solid gray*) lines

weather station data, especially when periods longer than daily are considered in the analysis. Previous studies have also found that atmometer accuracy can be significantly improved by averaging the results over 3- and 7-day periods (Irmak et al. 2005; Gávilan and Castillo-Llanque 2009). The average and cumulative maize T_c were 4.4 mm day^{-1} and 220 mm, respectively, for the 50-day study period.

Baselines

Non-water-stressed baseline was developed through the procedure explained in the previous sections and resulted in the following linear relationship with a goodness of fit (R^2) of 0.97:

$$dT_{LL} = -1.99 \times \mathrm{VPD} + 3.04 \quad (10)$$

The above equation is very similar to those developed by Idso (1982) in Arizona and Taghvaeian et al. (2012) in northeastern Colorado (Fig. 3). It should be noted that climatic conditions were fairly similar in these regions, but different maize varieties were used in these studies. This observation is consistent with the findings of Idso et al. (1984) that seven different varieties of wheat had similar non-water-stressed baselines. The similarity between baselines developed in this experiment and those that were previously developed suggests that the same set of baselines can be used to estimate CWSI for morphologically similar species of maize in regions with similar climatic conditions (e.g., central USA High Plains), eliminating the need to develop baselines for each farm and/or irrigation district. The baseline developed by O'Toole and Hatfield (1983) in northern California was also fairly similar to Eq. (10), with a slope and intercept of −1.89 and 3.36, respectively.

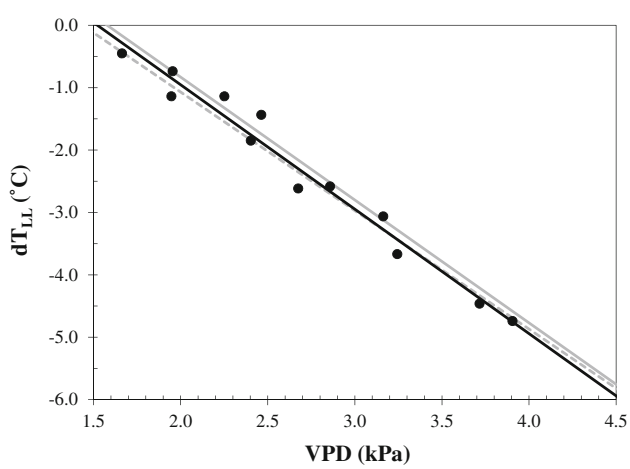

Fig. 3 Non-water-stressed baseline developed in this study (*data points* and *solid black line*), along with baselines developed by Idso (1982) (*solid gray line*) in Arizona and by Taghvaeian et al. (2012) (*dashed gray line*) in northeastern Colorado

Each treatment in this experiment was equipped with an independent air temperature/humidity sensor, so slightly different dT_{LL} and dT_{UL} values were estimated for each treatment. As a result, observed variations among hourly CWSI estimates were not only caused by differences in measured canopy temperature, but also by differences in measured air temperature and relative humidity that were coupled with the canopy/plant water stress level. The effect of obtaining weather data from within different treatments is discussed in more detail in the following sections. Table 2 presents lower and upper dT limits, computed for each treatment and averaged over the 50 days of study (August 4–September 22, 2011).

Within each treatment, the absolute value of both dT_{LL} and dT_{UL} increased in magnitude with time due to the continuous increase in VPD. A similar pattern was observed at another maize field in northeastern Colorado (Taghvaeian et al. 2012). The rate of increase in dT_{LL} decreased with time, and it was also dependent on irrigation treatment. The LFDI had the largest and the FI had the smallest rates of increase in absolute dT_{LL} with hourly periods. The rates of increase for HFDI were fairly similar to those of FI. This irrigation-dependent nature of hourly variation in dT_{LL} suggests that if data can be collected only once a day, the selection of the measurement time has a greater influence on the results for collection sites under a higher level of stress.

In addition to the hourly rate of change, the value of dT_{LL} showed considerable variations among treatments. The average dT_{LL} at LFDI was 54, 28, 24, and 23 % smaller than the corresponding value at FI during 10:00–11:00, 11:00–12:00, 12:00–13:00, and 13:00–14:00 h, respectively. For HFDI, dT_{LL} values were between those of the other two treatments and very close to the estimates at FI. The differences in dT_{LL} among treatments indicate that the following scenarios would have happened if data from only one air temperature/humidity (T_{air}/RH) sensor had been available:

- If the T_{air}/RH sensor was installed at FI, larger dT_{LL} values (less negative) would have been assigned to LFDI, resulting in a smaller estimate of CWSI at LFDI.

Table 2 Estimated lower and upper limits of dT (°C), averaged over the study period

Hourly period (MST)	FI		LFDI		HFDI	
	dT_{LL}	dT_{UL}	dT_{LL}	dT_{UL}	dT_{LL}	dT_{UL}
10:00–11:00	−0.41	4.24	−0.63	4.26	−0.43	4.24
11:00–12:00	−1.13	4.35	−1.45	4.37	−1.17	4.35
12:00–13:00	−1.73	4.43	−2.15	4.46	−1.80	4.43
13:00–14:00	−2.10	4.47	−2.59	4.51	−2.18	4.48

- If the T_{air}/RH sensor was installed at LFDI, smaller dT_{LL} values would have been assigned to FI, resulting in a larger estimate of CWSI at FI.

It should be noted that estimating a different dT_{LL} for LFDI is mainly due to the fact that this treatment had a warmer and drier microclimate (larger VPD), caused by high stress resulting from low-frequency application of irrigation water, a significantly reduced maize canopy, and earlier senescence resulting from the stress. Figure 4 depicts the variation in SAVI for each treatment during the study period. The SAVI estimates were consistent with field observations that senescence started in late August and early September. Average SAVI during the first 3 weeks of study (pre-senescence) was 0.45 at LFDI, 29 % and 20 % smaller than average SAVI at FI (0.63) and HFDI (0.56) treatments, respectively. According to Bausch (1993), a SAVI equal to and larger than 0.64 indicates that maize canopy is at effective full cover. Average SAVI during the last 4 weeks of study (post-senescence) was 0.36, 0.58, and 0.49 for LFDI, FI, and HFDI treatments, respectively.

In comparison to dT_{LL}, the rate of increase in the magnitude of dT_{UL} with hourly periods was significantly lower and more similar among studied treatments, with an average of 0.08 °C h^{-1}. Taghvaeian et al. (2012) reported an increase rate of 0.10 °C h^{-1} in dT_{UL} during similar hourly periods (10:00 to 14:00 MST). Averaged dT_{UL} for all treatments and hours was 4.38 °C, very close to the average dT_{UL} of 4.60 °C that was measured from August 3 to September 12, 1995 over a severely stressed maize canopy in Southern Turkey (Irmak et al. 2000). A similar average dT_{UL} of 4.14 °C was estimated by Taghvaeian et al. (2012) who implemented a similar approach to estimate CWSI, but used weather parameters that were collected at an alfalfa-based weather station rather than within experimental treatments. For each hourly period, among-treatment variations in dT_{UL} were not significant (less than 1 %). In addition, dT_{UL} values had fairly small day-to-day fluctuations. This confirms the recommendation of Gardner et al. (1992) that a constant value may be used for the upper dT limit without introducing any significant error.

Since a constant dT_{UL} may be used in calculating CWSI, obtaining dT_{LL} from another method such as the readings of an artificial surface would completely eliminate the need to develop locally calibrated baselines. In order to investigate this possibility, modeled dT_{LL} values at FI were compared against atmometer-based dT (dT_{atm}) estimates, calculated by subtracting the temperature of atmometer evaporating cup from the air temperature. The dT_{atm} values, however, were significantly larger than their corresponding dT_{LL}. For 12:00–13:00 h, for example, dT_{LL} was −1.73 ± 1.79 °C (mean ± SD), compared to dT_{atm} of 2.30 ± 2.29 °C. On numerous days, dT_{atm} was even larger than predicted dT_{UL} for the same day, reaching values as large as 8.0 °C (Fig. 5). Further studies are required to identify reasons behind this overestimation and to investigate the feasibility of using other artificial wet surfaces for dT_{LL} estimation.

Crop water stress index (CWSI)

Estimated lower and upper dT limits were used along with dT_m measurements for CWSI calculations. The evolution of CWSI over the study period is portrayed in Fig. 6 for all treatments and hourly periods. In general, little or no stress was detected at FI and HFDI during the first 3 weeks of the study. The CWSI started to increase at these two treatments over the remaining 4 weeks until it reached values larger than 0.50 at the end of the study period. However, this increase seems to be more influenced by deterioration of stomata as the maize entered into maturity and senescence

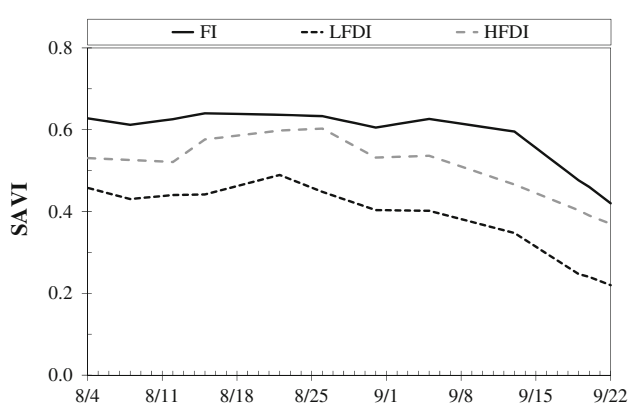

Fig. 4 Variations in SAVI for each treatment during the study period

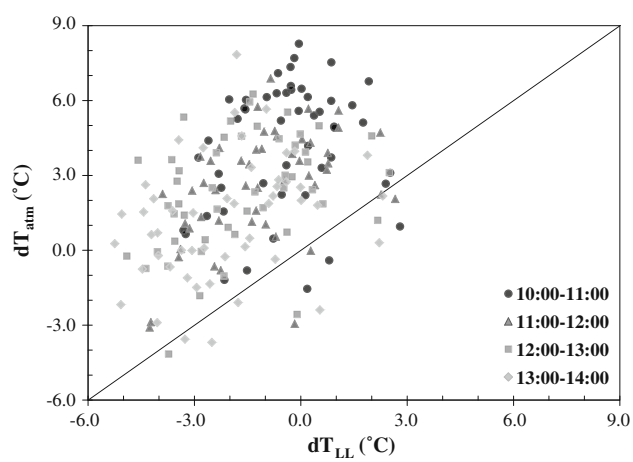

Fig. 5 Scatterplot of the lower limit of canopy-air temperature differential, obtained from the measurements under atmometer's evaporating cup (dT_{atm}) versus the baseline (dT_{LL}) for each hourly period during the study

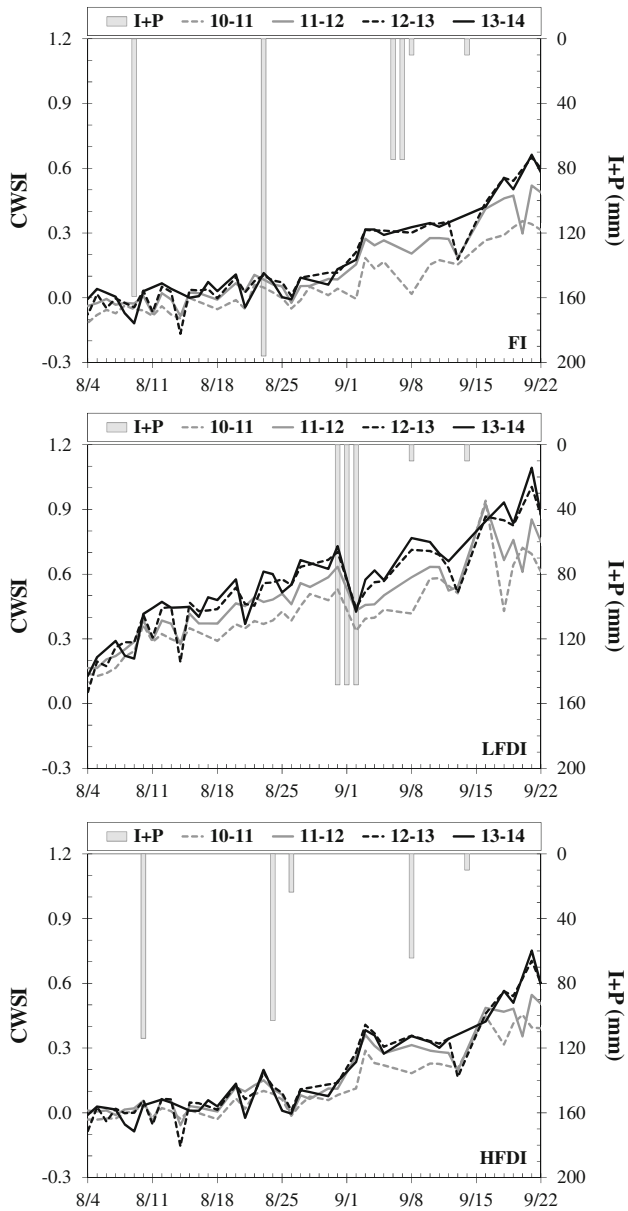

Fig. 6 CWSI during each hourly period for FI (*top*), LFDI (*middle*), and HFDI (*bottom*) treatments. The depth of water application in each irrigation/precipitation event is plotted on a secondary axis as *vertical bars*

stages, rather than closure of stomata due to water stress. Further studies are required to differentiate the effect of these two phenomena on CWSI estimates. At LFDI, CWSI was always larger, starting from about 0.20 and approaching a non-transpiring condition. The SAVI variation indicated that the LFDI treatment also began to senesce earlier than the other treatments. Within each treatment, CWSI increased from a.m. to p.m. hours.

The average CWSI during the study period was smallest for FI and largest for LFDI for each hourly period (Table 3). Stress indices had the largest magnitudes and

Table 3 Mean and median CWSI for each treatment and hour during the study period

Hourly periods (MST)	FI		LFDI		HFDI	
	Mean	Median	Mean	Median	Mean	Median
10:00–11:00	0.07	0.02	0.43	0.41	0.13	0.08
11:00–12:00	0.14	0.08	0.50	0.50	0.18	0.11
12:00–13:00	0.18	0.11	0.56	0.56	0.20	0.13
13:00–14:00	0.19	0.10	0.59	0.59	0.20	0.12

smallest hour-to-hour variations during the last 2 h (12:00–14:00). Hence, this seems to be the appropriate data collection window if the goal is to capture the maximum stress level experienced by the crop. The CWSI, averaged over these 2 h and the entire study period, was 0.19, 0.57, and 0.20 at FI, LFDI, and HFDI, respectively. Limiting the averaging period to the first 3 weeks of study (before senescence) decreased the CWSI values to 0.02, 0.40, and 0.04 for the same treatments, respectively. Based on these results, neither the full nor the high-frequency deficit irrigation plots experienced any significant water stress. It is also worth mentioning that at HFDI, the same level of stress appeared approximately 1 h earlier compared to FI. For example, average CWSI of 0.18 was observed at the 12:00–13:00 time period at FI, while HFDI reached this level during the 11:00–12:00 time period.

For practical applications of the CWSI method, it is likely that only one T_{air}/RH sensor will be installed in the study area, as opposed to the configuration in this experiment, where each treatment was equipped with a separate sensor. Thus, we studied the effect of having only one source of T_{air}/RH data on computed CWSI. Using the data collected at FI reduced the estimated stress level at LFDI. In this treatment, CWSI averaged over the last two hourly periods (12:00–14:00) and during the first 3 weeks of study decreased from 0.40 to 0.35. The effect for HFDI was not significant, reducing CWSI from 0.04 to 0.03. This negligible effect was not surprising, as T_{air}/RH measured at FI and HFDI were similar. Using the data that were collected at LFDI with a sparser canopy had a larger effect, increasing the average CWSI from 0.02 to 0.10 for FI and from 0.04 to 0.11 for HFDI.

It should be noted that these variations in CWSI were the result of changing the location of T_{air}/RH sensor, and foliage temperatures were still measured independently at each treatment. The findings suggest that for CWSI-based irrigation scheduling, obtaining T_{air}/RH data from a stressed and sparse location alone results in irrigation events occurring sooner than what is needed for less-stressed areas. In contrast, relying on the data collected at non-water-stressed and full-cover canopies translates into a delay in irrigation events for areas with a partial cover and

a higher level of stress. Thus, the effect of the location of data collection should be considered if significant variability in crop growth and stress level exists in the area of interest. At many irrigation districts, the weather variables are measured over alfalfa or grass reference surfaces at standard weather stations, which are usually kept under non-water-stressed and full-cover conditions. If this is the case, CWSI thresholds for irrigation scheduling of sparse canopies need to be set more conservatively.

Maize actual transpiration

Maize T_a was first estimated for all treatments based on CWSI estimates (Eq. 4) and T_c estimates that were computed using CoAgMet ET_r data. As expected, FI had the highest T_a rates. HFDI had slightly and LFDI had significantly lower T_a rates, respectively. During the first 3 weeks of the study, transpiration rates at FI and HFDI were similar to the expected rates under standard conditions, but decreased during the last 4 weeks due to maize senescence. Figure 7 presents daily T_a rates for all treatments and based on the CWSI estimates of all hourly periods.

Table 4 provides mean and cumulative maize transpiration estimates during the study period. Among- and within-treatment variations in T_a were similar to those of CWSI, but inverse: estimates were largest during a.m. and smallest during p.m. hours. The variation in T_a estimates caused by using CWSI at different hourly periods was dependent on the irrigation treatment, with an average of 3 % for FI and HFDI and 9 % for LFDI.

Total CWSI-based maize transpiration averaged over all hours was 205, 122, and 199 mm at FI, LFDI, and HFDI, respectively. These values were 11, 47, and 14 % smaller than maize T_c during the same period (231 mm). The small difference between T_a estimates at FI and HFDI indicates that reducing irrigation depths, for the furrow-irrigated field in this study, did not have a noticeable impact on maize transpiration. Since irrigation frequencies were similar for these two treatments, evaporation from soil surface is expected to be similar. Hence, the reduction in applied water for HFDI mostly resulted in a reduction in deep percolation and improved irrigation application efficiency. For LFDI, on the other hand, T_a was reduced by half compared to FI. However, applied irrigation water to LFDI was more than half of the water applied to FI, meaning that the seasonal return flow was partially maintained.

During the study, average FAO56-based maize T_a was 4.3, 2.9, and 4.0 mm day^{-1} for FI, LFDI, and HFDI, respectively. The cumulative values were 213, 144, and 201 mm for the same treatments, respectively. Estimating MBD and RMSD (Table 5) revealed that the difference between the results of CWSI and FAO56 approaches

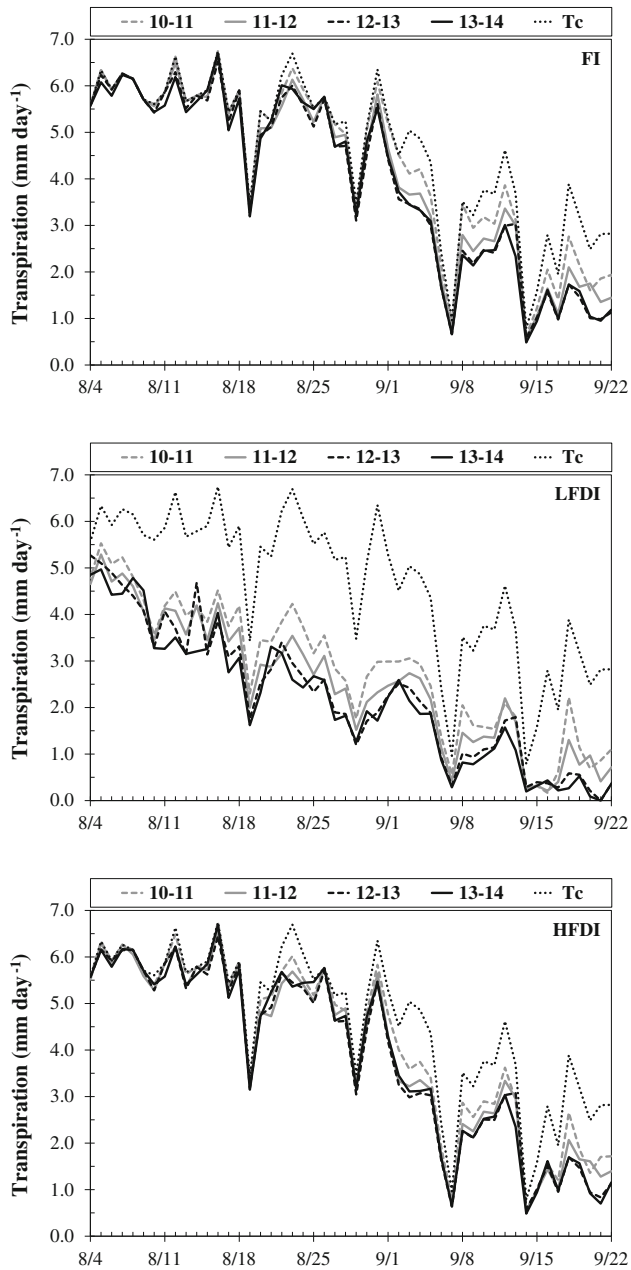

Fig. 7 Maize daily transpiration for FI (*top*), LFDI (*middle*), and HFDI (*bottom*) treatments, estimated based on the CWSI for each hourly period and transpiration rates under standard conditions (Tc)

Table 4 Mean daily (Mean, mm day^{-1}) and cumulative (Cum, mm) T_a during the 50-day study period computed based on CWSI calculated for a given hourly time period

Hourly periods (MST)	FI		LFDI		HFDI	
	Mean	Cum	Mean	Cum	Mean	Cum
10:00–11:00	4.4	218	2.8	141	4.2	208
11:00–12:00	4.1	206	2.5	125	4.0	199
12:00–13:00	4.0	198	2.3	113	3.9	194
13:00–14:00	4.0	198	2.1	107	3.9	195

Table 5 Mean bias difference and root mean square deviation (both in mm day^{-1}) between CWSI- and FAO56-based estimates of maize daily T_a

Hourly periods (MST)	FI		LFDI		HFDI	
	MBD	RMSD	MBD	RMSD	MBD	RMSD
10:00–11:00	0.08	0.42	−0.05	0.42	0.13	0.58
11:00–12:00	−0.15	0.58	−0.36	0.53	−0.05	0.65
12:00–13:00	−0.30	0.71	−0.60	0.78	−0.15	0.74
13:00–14:00	−0.31	0.72	−0.73	0.88	−0.13	0.74

increased with time, but it never exceeded 0.9 mm day^{-1} for any treatment and hourly period. This similarity is not surprising, as previous studies have showed that temperature-based indicators (e.g., CWSI) are highly correlated with K_s coefficients obtained from modeling/measuring soil moisture deficit, especially under surface irrigation regimes (Bausch et al. 2011; Colaizzi et al. 2003a, b). Other studies have showed that CWSI-based T_a estimates are also similar to those obtained by applying complex surface energy balance methods (Taghvaeian et al. 2012, 2013).

The increase in MBD and RMSD with time suggests that under the conditions of this study, 10:00–11:00 MST is the most appropriate window for taking once-a-day thermometry readings if the goal is to monitor maize transpiration. Collecting data during the 2 h after solar noon cannot be recommended for estimating T_a as water stress is highest during this period, and thus, it does not provide a good representation of the average daily stress experienced by the studied crop. The difference between the results of CWSI and FAO56 methods during the first hourly period was only 2, 2, and 3 % of the FAO56 results for FI, LFDI, and HFDI, respectively.

It is worth reminding the readers that K_{cb} values used in estimating FAO56-T_a were adjusted for the effect of sparser canopy at LFDI, but such an adjustment was not performed in estimating CWSI-T_a. The small difference between the results of these two approaches, however, suggests that adjusting the K_{cb} for the effect of canopy cover was not required in the CWSI approach. This is mainly due to the fact that the sparser canopy at LFDI affected the microclimate at this treatment, which consequently affected the measured canopy temperatures. The change in the microclimate is portrayed in the difference in air temperature/humidity measurements among experimental treatments, where LFDI had a hotter and drier microclimate. In other words, at the same soil moisture deficit level, the temperature of a sparser canopy will be higher than the temperature of a denser canopy, due to the interaction between exposed soil and the studied crop. Hence, adjusting the K_{cb} for CWSI approach would have resulted in double-counting the effect of canopy cover variations.

The fact that 10:00–11:00 MST provided closest results is promising in applying the CWSI approach to air- and spaceborne imagery for mapping the conserved consumptive use under deficit irrigation regimes. The local overpass time of Landsat 8 is around 10:39 MST. Commercial airborne remote sensing systems also prefer to fly earlier in the day to avoid afternoon turbulence. A major caveat, however, is that thermal detectors onboard these platforms have a nadir-looking angle, which introduces challenges in obtaining the canopy temperatures when underlying soil is viewed by the sensors (e.g., at earlier stages of growth). This may impose temporal and spatial limitations on the application of air- and spaceborne imagery. In case of this study, where ground-based remote sensing techniques were used for measuring canopy temperature, the issue of viewing underlying soil was avoided by installing IRTs at an oblique angle. At early stages of growth, when even an oblique IRT would view parts of the exposed soil, the average temperature of several leaves can be used in calculations. The leaf temperature can be measured using small portable handheld IRTs. The use of leaf temperature measurements in CWSI estimation is recommended not only for open canopy covers, but also during the grain-filling stage of some crops (e.g., sunflower), when the head becomes too hot that measuring canopy temperature would falsely indicate a severe water stress (Nielsen 1994).

Relying on the T_{air}/RH data that were collected only at FI (and not at each treatment) resulted in a 0.5 and 6.0 % increase in cumulative T_a for HFDI and LFDI, respectively. Using weather parameters measured at LFDI, on the other hand, reduced total T_a of FI and HFDI by 5.1 and 4.8 %, respectively. Using atmometer data resulted in a 5 % increase in total maize T_a, which was equivalent to less than 0.2 mm day^{-1} during the study period. Although the results of this study showed that the CWSI approach can be used effectively in estimating crop water stress and transpiration, a major drawback of this method is its inability to provide information on soil evaporation, which is a significant component of total consumptive water use in arid/semiarid regions and under surface irrigation regimes. To overcome this limitation, CWSI-T_a estimates can be combined with soil evaporation estimates, obtained from widely used modeling approaches such as the one presented in FAO56. The advantages of implementing the CWSI approach in estimating T_a, compared to using the FAO56 for estimating both T_a and E, include the ability of CWSI method to be applied to air- and spaceborne imagery, as well as the fact that it does not require a priori knowledge on several spatially heterogeneous variables used in the FAO56 approach, such as the root depth and soil water holding parameters (TAW, RAW, etc.).

Conclusion

This study was conducted in a maize field in northern Colorado to explore the possibility of minimizing instrumentation requirements in estimating the CWSI and actual transpiration (T_a) under different irrigation regimes. The developed non-water-stressed baseline was similar to those developed in Arizona and northeastern Colorado for different varieties of maize. This similarity suggests that carefully developed baselines can be utilized for morphologically similar varieties of maize planted in regions with similar climates. The results also showed that applying a low-frequency deficit irrigation regime resulted in significantly larger CWSI values compared to high-frequency deficit and full irrigation treatments.

Maize T_a estimates based on the CWSI method were similar to those obtained by applying a crop coefficient model (FAO56). The difference was smallest when the required data were collected during 10:00–11:00 MST. In calculating CWSI-based T_a, obtaining reference evapotranspiration estimates from atmometer readings and from the measurements over a standard weather station did not result in a significant variation when the analysis period was longer than a few days. Thus, maize CWSI and consequently transpiration under actual field conditions can be determined using only three inexpensive and widely available sensors: an infrared thermometer to measure foliage temperature, an air temperature/humidity sensor, and a modified atmometer.

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References

Allen RG, Pereira LS, Raes D, Smith M (1998) FAO irrigation and drainage paper no. 56, crop evapotranspiration (Guidelines for computing crop water requirements), FAO Water Resources, Development and Management Service, Rome, Italy, pp 300

Allen RG, Wright JL, Pruitt WO, Pereira LS, Jensen ME (2007) Water requirements. In: Hoffman GJ, Evans RG, Jensen ME, Martin DL, Elliott RL (eds) Design and operation of farm irrigation systems, 2nd edn. American society of agricultural and biological engineers, St. Joseph, MI, pp 208–288

Altenhofen J (1985) A modified atmometer for on-farm ET determination. Advances in evapotranspiration: proceedings of national conference on advances in evapotranspiration, American Society of Agricultural Engineers, St. Joseph, MI, USA, pp 177–184

ASCE-EWRI (2005) The ASCE standardized reference evapotranspiration equation. Task Committee on Standardization of Reference Evapotranspiration, Environment and Water Resources Institute of the ASCE

Bausch WC (1993) Soil background effects on reflectance-based crop coefficients for corn. Remote Sens Environ 46(2):213–222

Bausch WC, Trout T, Buchleiter G (2011) Evapotranspiration adjustments for deficit-irrigated corn using canopy temperature: a concept. Irrig Drain 60:682–693

Berrada A, Hooten TM, Cardon GE, Broner I (2001) Assessment of irrigation water management and demonstration of irrigation scheduling tools in the full service area of the Dolores project: 1996–2000, Part II: calibration of the watermark soil moisture sensor and ETgage atmometer. Technical report TR01-7. Colorado State University, Fort Collins, CO

Broner I, Law RAP (1991) Evaluation of a modified atmometer for estimating reference ET. Irrig Sci 12:21–26

CoAgMet (2011) Website accessed on Dec. 7, 2011. At: http://ccc.atmos.colostate.edu/~coagmet/

Colaizzi PD, Barnes EM, Clarke TR, Choi CY, Waller PM (2003a) Estimating soil moisture under low frequency surface irrigation using crop water stress index. J Irrig Drain Eng ASCE 129:27–35

Colaizzi PD, Barnes EM, Clarke TR, Choi CY, Waller PM, Haberland J, Kostrzewski M (2003b) Water stress detection under high frequency sprinkler irrigation with water deficit index. J Irrig Drain Eng ASCE 129:36–43

Ervin EH, Koski AJ (1997) A comparison of modified atmometer estimates of Turfgrass evapotranspiration with Kimberly-Penman alfalfa reference evapotranspiration. Int Turf Soc 8:663–670

Gardner BR, Nielsen DC, Shock CC (1992) Infrared thermometry and the crop water stress index. I. History, theory, and baselines. J Prod Agric 5(4):462–466

Gávilan P, Castillo-Llanque F (2009) Estimating reference evapotranspiration with atmometers in a semiarid environment. Agric Water Manage 96:465–472

Gleason DJ, Andales AA, Bauder TA, Chávez JL (2013) Performance of atmometers in estimating reference evapotranspiration in a semi-arid environment. Agric Water Manage (in press)

Huete AR (1988) A soil-adjusted vegetation index (SAVI). Remote Sens Environ 25:295–309

Idso SB (1982) Non-water-stressed baselines: a key to measuring and interpreting plant water stress. Agric Meteorol 27:59–70

Idso SB, Jackson RD, Pinter PJ Jr, Reginato RJ, Hatfield JL (1981) Normalizing the stress-degree-day parameter for environmental variability. Agric Meteorol 24(1):45–55

Idso SB, Reginato RJ, Clawson KL, Anderson MG (1984) On the stability of non-water-stressed baselines. Agric Forest Meteorol 32:177–182

Irmak S, Haman DZ, Bastug R (2000) Corn: determination of crop water stress index for irrigation timing and yield estimation of corn. Agron J 92:1221–1227

Irmak S, Dukes MD, Jacobs JM (2005) Using modified Bellani plate evapotranspiration gauges to estimate short canopy reference evapotranspiration. J Irrig Drain Eng ASCE 131(2):164–175

Jackson RD, Idso SB, Reginato RJ, Pinter PJ Jr (1981) Canopy temperature as a crop water stress indicator. Water Resour Res 17(4):1133–1138

Livingston BE (1935) Atmometers of porous porcelain and paper, their use in physiological ecology. Ecol 16(3):438–472

Mahan JR, Young AW, Payton P (2012) Deficit irrigation in a production setting: canopy temperature as an adjunct to ET estimates. Irrig Sci 30:127–137

Nielsen DC (1994) Non water-stressed baselines for sunflowers. Agric Water Manage 26:265–276

O'Toole JC, Hatfield JL (1983) Effect of wind on the crop water stress index derived by infrared thermometry. Agron J 75:811–817

Steele DD, Stegman EC, Gregor BL (1994) Field comparison of irrigation scheduling methods for corn. Trans ASAE 37(4):1197–1203

Stegman EC (1986) Efficient irrigation timing methods for corn production. Trans ASAE 29(1):203–210

Taghvaeian S, Chávez JL, Hansen NC (2012) Infrared thermometry to estimate crop water stress index and water use of irrigated maize in Northeastern Colorado. Remote Sens 4(11):3619–3637

Taghvaeian S, Chávez JL, Hattendorf MJ, Crookston MA (2013) Optical and thermal remote sensing of turfgrass quality, water stress, and water use under different soil and irrigation treatments. Remote Sens 5(5):2327–2347

USDA-NASS (2012) Crop production 2011 summary. United States Department of Agriculture, National Agricultural Statistics Service, January 2012. ISSN: 1057-7823, pp 95