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Comparison of three crop water stress index models with sap flow measurements in maize

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A B S T R A C T

Both empirical and theoretical models have been widely used to calculate a crop water stress index (CWSI) − a metric often used to describe crop water status. The purpose of this study was to determine the accuracy, limitation, and uncertainty of an empirical (CWSI-E) and two theoretical models compared with sap flow measurement in maize. One theoretical model used a calculated aerodynamic resistance (CWSI-T1), and the other theoretical model used seasonal average aerodynamic resistance (CWSI-T2). Considering the uncertainty of crop coefficient and sap flow measurement, CWSI-T2 and CWSI-E models gave reasonable overall estimates of water stress. The average root mean square deviation at each growth stage from each model ranged from 0.16 to 0.33. CWSI-T2 and the CWSI-E provided relatively accurate prediction of crop stress, both between growth stages and irrigation events. However, CWSI-T1 did not accurately predict water stress between growth stages or between irrigation events. By including climate factors, crop water stress estimated by CWSI-T2 showed less variation and uncertainty than CWSI-E. The uncertainty of both CWSI-T2 and CWSI-E decreased with increasing vapor pressure deficit (VPD), and CWSI-E show larger crop water stress prediction uncertainty. The intercept of non-water stress baseline was the main source of the uncertainty for CWSI-E and CWSI-T2. Considering both uncertainty and stability, we recommend CWSI-T2 model (i.e., seasonal average aerodynamic resistance) for maize water stress assessment.

1. Introduction

Agriculture is a major water user in semi-arid regions, and utilizing agricultural water efficiently is critical to sustain and maximize the benefits of limited irrigation water. Water resources for agriculture have been reduced due to drought associated with climate change, non-sustainable use of groundwater, and increased competition from municipal, environmental, and industrial water needs. Combined with the increasing global population, there is a need to achieve maximum production per unit of applied irrigation water. Regulated deficit irrigation, defined as a regime that purposely reduce applied irrigation water in specific crop growing stages (Chalmers et al., 1981), may be a way to achieve higher water productivity (i.e., crop produced per unit water consumed). However, a comprehensive knowledge of crop response and crop water use under water stress is needed to achieve the best balance between irrigation water use and crop yield (Geerts and Raes, 2009). Therefore, the development of tools that enable accurate estimation of crop water stress or crop water use is critical for deficit irrigation management.

The crop water stress index (CWSI) has been recognized as an indicator of plant water status based on canopy temperature, ambient air temperature, and relative humidity. Two methods for calculating CWSI have been widely used and evaluated: an empirical method (CWSI-E) developed by Idso et al. (1981) and a theoretical method (CWSI-T1) developed by Jackson et al. (1981). The empirical method establishes a relationship between canopy-to-air temperature difference and vapor pressure deficit (VPD). The theoretical method uses surface energy balance equation, whilst accounting for variation in climate, and calculates the divergence between the upper and lower boundaries of canopy-to-air temperature difference. CWSI calculated from both methods have shown good relationships with other crop water stress indicators, such as soil water content (DeJonge et al., 2015; Taghvaeian et al., 2012; Taghvaeian et al., 2014a; Wang et al., 2005) and leaf water potential (Ballester et al., 2013; Gonzalez-Dugo et al., 2014). CWSI from both methods have also been used for irrigation scheduling (Colaizzi et al., 2012; Emekli et al., 2007; Nielsen, 1990; O'Shaughnessy et al., 2010; Yazar et al., 1999).

However, there remain limitations of both methods that require

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careful consideration. The empirical method has been criticized for two reasons: 1) sensitivity of the empirical non-water stress baseline to the changes of climate variables, such as radiation and wind speed (Gonzalez-Dugo et al., 2014; Jackson et al., 1988; Payero and Irmak, 2006). For example, the empirical baseline may change yearly for the same crop in the same field. Horst et al. (1989) has reported significant differences ($P < 0.01$) between the CWSI baseline equations in 1986 and 1987 for common Bermuda grass, buffalo grass and tall fescue. A similar result has been reported for mandarin and orange (Gonzalez-Dugo et al., 2014). 2) CWSI calculated by the empirical method showed large fluctuations, especially under low VPD condition or with significant variation in climate (Stockle and Dugas, 1992). Compared to the empirical method, the advantage of CWSI-T1 is its stability under various climate conditions (Jackson et al., 1988; Yuan et al., 2004). The shortcoming of CWSI-T1 is that it may not give significantly different values for well-watered and stressed crops, which may attribute to the incorrect estimation of aerodynamic resistance, r_a (Agam et al., 2013; Stockle and Dugas, 1992). Jackson et al. (1988) suggested that a seasonal average aerodynamic resistance should be applied (CWSI-T2). There are several successful applications of theoretical approach by calculating a seasonal average aerodynamic resistance (Clawson et al., 1989; Jalali-Farahani et al., 1993).

Therefore, it is important to know the accuracy and consistency of these three models for CWSI calculation before any application. As mentioned previously, many studies have proven good relationships between CWSI and measured water stress indicators; however, few had used sap flow measurement to assess the accuracy and consistency of CWSI models. Sap flow methodology, which provides a measurement of whole plant transpiration, has been widely used to determine crop coefficient and evaluate simulated crop water transpiration and crop water stress by various models (Cammalleri et al., 2013; Chabot et al., 2002; Jara and Stockle, 1999; Zhao et al., 2015). The transpiration measurement by sap flow would have 5% to 10% of actual transpiration error, which have been obtained by comparing with other measurements (Green et al., 2003; Zhang et al., 2011). The performance of CWSI models can be evaluated by comparing model outputs with water stress determined from sap flow measurement.

The objectives of this study were to: 1) compare the performance of CWSI among one empirical model and two theoretical models with sap flow measurement; 2) evaluate the uncertainty among the three CWSI models.

2. Materials and methods

2.1. Field experiment

2.1.1. Study site and management

Field data were collected from maize during the 2015 growing season at USDA-ARS Limited Irrigation Research Farm (LIRF), in Greeley, Colorado, USA (40°26′57″N, 104°38′12″W, elevation 1427 m). The alluvial soils of the study field were predominantly sandy and fine sandy loam of Olney and Otero series. The maize (Zea mays L.) was planted on Jun 1, 2015 with planting density around 85,000 plants ha^{-1}, and the dates when maize reached the late vegetative stage (V8), beginning of reproductive stage (R1), beginning of maturation stage (R3), and harvest were Jul 9, Aug 2, Aug 24 and Nov 2, 2015, respectively. Final plant populations varied from 77,000 to 82,000 plants ha^{-1}. Deficit irrigation was regulated by withholding during the late vegetative growth stage (V8 to R1) and/or the maturation growth stage (R3 to R6), but applying water during the sensitive reproductive (R1 to R3) and early vegetative stages (planting to V8). A total of 12 irrigation treatments were arranged in a randomized block design consisting of four blocks with each treatment replicated once in each block. Each treatment plot had 12 rows at 0.76 m spacing (9 m wide by 43 m long). All measurements were taken from the middle four rows to reduce border effects. Treatments are named for the target percent of maximum non-stressed crop ET (Evapotranspiration) during late vegetative and maturation growth stages, respectively (e.g. a 40/80 treatment would target 40% of maximum ET during the vegetative stage and 80% of maximum ET during the maturation stages). Sap flow measurements were taken in 100/100, 65/65, 40/40, and 40/80 treatments, so only these four treatments were included in this study and the actual irrigation amounts that were achieved for the four treatments are shown in Table 1. During the growing season, irrigation water was applied through a surface drip irrigation system with drip tubing (16 mm outside diameter, 2 mm wall thickness, 30 cm in-line emitter spacing, 1.1 L h^{-1} emitter flow rate) placed on the soil surface next to each row of maize. Irrigation applications to each treatment were measured with turbine flow meters (Badger Recordall Turbo 160 with RTR transmitters). Meters were cross calibrated to ensure accuracy and consistency. Irrigation applications were controlled by and recorded with a Campbell Scientific CR1000 data logger. A constant pressure water supply controlled with a variable speed drive booster pump, low pressure loss in the delivery system, and relatively flat topography resulted in predicted water distribution uniformity among and within plots exceeding 95% (Trout and Bausch, 2017). Nitrogen fertilizer (Urea ammonium nitrate, UAN, 32%) was applied near the seed at planting at 34 kg N ha^{-1}. Additional nitrogen was applied through the irrigation water (fertigation) to meet fertility requirements in all the treatments. More details for calculation of maximum ET and measurement of soil water deficit can be found in DeJonge et al. (2015).

Hourly meteorological data were acquired by an on-site standard ET weather station (10 m away from the field), which is belong to Colorado Agricultural Meteorological Network (CoAgMet, http://ccc.atmos.colostate.edu/~coagmet/). The data includes precipitation, air temperature, relative humidity (and subsequent vapor pressure deficit), solar radiation, and wind speed taken at 2 m above a grass reference surface. The net solar radiation was determined following the procedure in Allen et al. (1998) and Jensen and Allen (2016). The crop phenology developments as well as basic climate factors in each stage were shown in Table 2.

Table 1
Irrigation treatments evaluated in the study, with irrigation and precipitation amounts (mm) during major growth stages in 2015. The values on either side of the '/' denote the target ET values for vegetative and maturation stages of development. For example, 40/80 indicates that 40% of maximal ET was applied during vegetative growth stage and 80% of maximal ET was applied during maturation growth stage.

Treatment (% vegetative ET/% maturation ET)	Vegetative	Reproductive	Maturation
	Jun 2–Aug 1	Aug 2–Aug 24	Aug 25–Nov 3
100/100	166	116	200
65/65	84	112	70
40/40	40	113	0
40/80	40	111	149
Precipitation	76	23	38

2.1.2. Canopy ground cover, yield and temperature measurements

A Canon EOS 50D DSLR camera (Canon Inc., Tokyo, Japan)[2] was used to measure canopy ground cover. The camera was attached to a boom that was mounted on a high clearance tractor so that the camera was elevated about 7 m above the ground. Nadir view RGB images were taken near solar noon twice a week from each treatment plot. The camera field of view encompassed 4 rows × 4 m. All images were processed in Python 3.5 (Python Software Foundation, Wilmington, DE,

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