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Estimating maize water stress by standard deviation of canopy temperature in thermal imagery

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ABSTRACT

A new crop water stress indicator, standard deviation of canopy temperature within a thermal image (CTSD), was developed to monitor crop water status. In this study, thermal imagery was taken from maize (*Zea mays* L.) under various levels of deficit irrigation at different crop growing stages. The Expectation-Maximization algorithm was used to estimate the canopy temperature distribution from thermal imagery under a range of crop coverage and water stress conditions. Soil water deficit (SWD), leaf water potential (ψ), stomatal conductance, and other crop water stress indices were used to evaluate the CTSD. We found that the temperature differences between sunlit and shaded parts of the canopy would increase with larger canopy resistance in the sunlit part of the crop canopy. The CTSD well described impact of irrigation events (timing and depth) on crop water stress. All water stress measurements showed statistically significant relationship with CTSD. Although CTSD is not sensitive to small changes in water stress, the result suggests that the canopy temperature standard deviation could be used as a water stress indicator. This index has strong application potential because it only relies on the canopy temperature itself, and is easy to calculate. Moreover, it may also be applied to high resolution thermal imagery from other remote sensing platforms, such as unmanned aerial vehicles.

1. Introduction

Agriculture is a major water user in semi-arid regions, and efficient agricultural water use is critical to sustain and maximize benefits of limited water resources. Agricultural water resources will be reduced due to drought associated with climate change, non-sustainable use of groundwater, and increased competition from municipal, environmental, and industrial water needs. Hence, there is a need to achieve maximum production per unit of applied irrigation water. Managed deficit irrigation may be a way to achieve higher water productivity (i.e., yield per unit water consumed). However, to achieve this delicate balance between water use and crop yield requires comprehensive knowledge of crop response to water stress and optimized irrigation scheduling (Geerts and Raes, 2009). Monitoring tools that provide accurate information regarding crop water stress are critical for managing deficit irrigation.

Among the existing stress monitoring methods, traditional soil- and plant-based monitoring methods are time consuming and limited due to the difficulty and expense of satisfactorily representing the heterogeneous conditions in the root zone (Ben-Gal et al., 2009; Campbell and Campbell, 1982). Indirect monitoring of canopy temperature using thermal imagery which has high resolution either temporally (i.e., continuous) or spatially, could cover sufficient representative area and has high adoption potential (Agam et al., 2013).

Canopy temperature has long been recognized as an indicator of plant water status. Several crop water stress indices based on canopy temperature have been developed. The first crop water stress index (CWSI) was developed by Idso et al. (1981) to establish a relationship between the canopy-to-air temperature difference and vapor pressure deficit (VPD). This method is simple, but requires additional data, and is site-dependent. Shortly after the method was developed, Jackson et al. (1981) developed a theoretical approach to calculate the upper and lower bounds of the canopy-air temperature difference. Recently, more experiments were carried out to obtain the boundaries of canopy-air temperature difference using direct measurements over wet or dry reference surfaces (Cohen et al., 2005; Wang et al., 2005). However, the locations of reference surfaces need to be selected and designed carefully. Some parameters required by CWSI and logistical concerns of canopy-air temperature difference may restrict adoption by farmers (Testi et al., 2008). To overcome this prob-

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lem, Degrees Above Non-Stressed (DANS) index and Degrees Above Canopy Threshold (DACT) index were found to have strong relationships with traditional CWSI indices and crop water measurements, both of these methods only require canopy temperature measurement (DeJonge et al., 2015; Taghvaeian et al., 2014). However, for DANS an additional canopy temperature from a comparable well-irrigated treatment is needed, which may be difficult to establish in practice. Previous research also tried to examine the canopy temperature variability as a water stress index to indicate crop water stress (Aston and van Bavel, 1972; Clawson and Blad, 1982; González-Dugo et al., 2006); however their results were not based on canopy temperature distribution, and may limited by the number and location of canopy temperature sampling points or resolution of airborne thermal imagery. The ability of canopy temperature variability to indicate crop water stress is still not well examined.

The transpiration cooling effect on canopy temperature is well known (Clum, 1926; Curtis, 1936; Gates, 1968). The water released from the leaf stomata (transpiration) consumes energy and reduces the leaf temperature. Sunlit leaves receive more direct radiation than shaded leaves of the canopy, and sunlit leaves are therefore assumed to have higher temperature than that of shaded leaves. When non transpiration occurred (no transpiration cooling effect), the temperature difference between sunlit and shaded leaves is maximum. When water is available for the plant to transpire, the transpiration rate in sunlit portions of the canopy would be higher than the transpiration rate in shaded portions (Irmak et al., 2008). Thus the temperature difference between sunlit and shaded leaves may decrease as transpiration increases (more cooling effect on sunlit leaves). Based on the above principle, instead of evaluating crop water stress by comparing canopy temperature between a well-watered and water-stressed crop, the temperature difference between sunlit and shaded leaves of a canopy may be a new indicator for crop water stress evaluation.

In this study, a method to obtain canopy temperature distribution from thermal imagery was developed. Standard deviation of canopy temperature was used to as a new crop water stress index (CTSD), and evaluated by various water stress measurements.

2. Materials and methods

2.1. Field experiment

A field experiment was conducted on maize during the 2012 and 2013 growing seasons at the 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 are predominantly sandy and fine sandy loam of Olney and Otero series. The 12 treatments (Table 1, Column 1) were arranged in a randomized block design with four replications. Each treatment plot was 9 m wide (12 rows at 0.76 m spacing) by 43 m long; and all the measurements were taken from the middle six rows to reduce border effects. Treatments were varying levels of regulated deficit irrigation (RDI). The deficit irrigation was applied during the late vegetative growth stage and/or the maturity growth stage, but water stress was relieved during the sensitive reproductive and early vegetative stages. Treatments are named for the target percent of maximum non-stressed crop ET during late vegetative and maturity growth stages, respectively (e.g. an 80/40 treatment would target 80% of maximum ET during the vegetative stage and 40% of maximum ET during the maturity stages). Total actual irrigation and precipitation amounts for each treatment by growth stage are shown in Table 1. During the growing season, water was applied using 16 mm drip irrigation tubing, which was placed next to each row of maize. Fertilizers were applied to avoid nutrient deficiencies on all the treatments. Meteorological data were taken by on-site Colorado Agricultural Meteorological Network station GLY04 (CoAgMet, http://ccc.atmos.colostate.edu/∼coagmet/). This data includes daily 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 maximum ET was determined by reference evapotranspiration and crop coefficient (Allen et al., 1998a).

2.2. Energy balance of plant canopy

The energy balance for a plant canopy, which includes both sunlit and shaded leaf area, can be calculated by the following equation:

$$R_n = G + H + \lambda E \tag{1}$$

where R_n is the net radiation (W m^{-2}), G is the heat flux below the canopy (W m^{-2}), H is the sensible heat flux (W m^{-2}) from canopy to the air, and λE is the latent heat flux to the air (W m^{-2}). According to Monteith and Unsworth (2013), H and λE for both sunlit and shaded leaves can be calculated with the following equations:

$$H = \rho c_p (T_c - T_a)/r_a \tag{2}$$

$$\lambda E = \rho c_p (e* - e)/\gamma(r_a + r_c) \tag{3}$$

where: ρ is the air density (kg m^{-3}), c_p is the heat capacity of air (J kg^{-1} °C), T_c is the temperature of the canopy, T_a is the air temperature, e* is the air saturated vapor pressure at T_c (Pa), e is the air vapor pressure (Pa), γ is the psychrometric constant (Pa °C^{-1}), r_a is the aerodynamic resistance (s m^{-1}), and r_c is the canopy resistance (s m^{-1}).

Table 1
Irrigation treatment and total irrigation and precipitation amount (mm) in different growth stages.

Treatment(%vegetative ET/%maturity ET)	Late vegetative stage		Reproduction stage		Maturity stage		Total	
	2012	2013	2012	2013	2012	2013	2012	2013
TR1(100/100)	305	228	169	127	181	254	655	609
TR2(100/50)	302	228	152	122	47	165	501	515
TR3(80/80)	245	180	168	128	145	217	558	525
TR4(80/65)	245	181	163	128	68	196	476	505
TR5(80/50)	243	180	160	128	44	165	447	473
TR6(80/40)	243	180	158	128	41	137	442	445
TR7(65/80)	200	136	173	149	136	217	509	502
TR8(65/65)	199	136	167	149	68	196	434	481
TR9(65/50)	197	136	165	150	56	165	418	451
TR10(65/40)	197	136	164	150	41	138	402	424
TR11(50/50)	157	101	173	158	57	165	387	424
TR12(40/40)	129	83	169	158	41	137	339	378