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Comparison of canopy temperature-based water stress indices for maize

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ABSTRACT

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

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1. Introduction

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

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

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

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

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

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

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

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