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Research Paper

Crop evapotranspiration calculation using infrared thermometers aboard center pivots

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ABSTRACT

Irrigation scheduling using remotely sensed surface temperature can result in equal or greater crop yield and crop water use efficiency compared with irrigation scheduling using in-situ soil water profile measurements. Crop evapotranspiration (*ETc*) is useful for irrigation scheduling, and can be calculated using surface temperature. Recent advances in wireless infrared thermometers (IRTs) have made surface temperature measurement a viable alternative to in-situ soil water profile measurements, and wireless IRTs are practical for deployment aboard moving irrigation systems, such as center pivots. However, *ETc* calculation has not been tested using IRTs aboard center pivots in conjunction with recent advances in a two-source energy balance (TSEB) model. We compared daily *ETc* calculated by a TSEB model to daily *ETc* estimated by a simple soil water balance (SSWB), where the SSWB used volumetric soil water measured by a field calibrated neutron probe to the 2.4-m depth. Crops included two seasons each of corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and grain sorghum (*Sorghum bicolor* L.) at Bushland, Texas, USA. Discrepancies of TSEB vs. SSWB daily *ETc* were similar for each crop and season, and had root mean squared error from 1.5 to 1.8 mm per day, mean absolute error from 1.1 to 1.5 mm per day, and mean bias error from −0.51 to 0.63 mm per day. A sensitivity analysis was conducted for daily evaporation (*E*), daily transpiration (*T*), and *ETc* calculated by the TSEB model. These were most sensitive to radiometric surface temperature, air temperature, the reference temperature used in time scaling (i.e., to convert instantaneous to daily *E*, *T*, and *ETc*), and incoming solar irradiance. Because over half of the irrigated area in the USA is now by center pivot, *ETc* calculated using IRTs aboard center pivots will be useful to maintain or increase crop water productivity.

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1. Introduction

In-field quantification of crop evapotranspiration (*ETc*) and water stress will play an increasing role in managing and enhancing crop water productivity (Ahmad et al., 2009; Evans and Sadler, 2008; Senay et al., 2009; Zwart and Bastiaanssen, 2007). Specific applications include irrigation scheduling and irrigation automation (Jones, 2004; O'Shaughnessy et al., 2015; Osroosh et al., 2015); additional applications include detection and mitigation of abiotic and biotic stresses, which may be caused by malfunctioning irrigation equipment, salinity or other soil and water constituents inhibiting crop economic yield, pests, and disease (Falkenberg et al., 2007; Li et al., 2008). Numerous methods exist for estimating *ETc*, including the crop coefficient-reference evapotranspiration approach (Allen et al., 1998; Anderson et al., 2017; Howell et al., 2004; Hunsaker et al., 2005), lysimetry (Howell et al., 1995, 1997), boundary layer measurements (Bowen ratio, eddy covariance, scintillometry, surface renewal; Alfieri et al., 2012; French et al., 2012; Liu et al., 2011; Todd et al., 2000), in-situ soil water profile measurement (Evett et al., 2012), and radiometric canopy temperature measurement (Maes and Steppe, 2012). The latter is derived from, or assumed equal to, remotely sensed directional brightness temperature of vegetated surfaces (Norman and Becker, 1995). Routine estimates of *ETc* using canopy temperature measurements have several practical advantages compared with alternative methods. Also, many forms of water stress indices used in irrigation scheduling or to detect abiotic or biotic stress are based on actual *ETc* relative to a non-water stressed *ETc* value, where actual *ETc* is estimated by in-field canopy temperature measurements (Jackson, 1982; Moran et al., 1994; Jones, 2004).

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The advantages of using canopy temperature to estimate *ETc* are at once the result of, and contingent on, meeting certain requirements of real-time farm management (Jackson, 1984). These include spatial resolution (several meters), repeat frequency (no more than a few days), and turnaround time (interval from field measurement to useful data product; no more than a few minutes). These are in addition to the obvious requirements of reasonable instrument cost, precision, accuracy, and extent of field area coverage. The recent development of unmanned aerial vehicles (UAVs) have overcome many technical barriers to meeting these requirements (Bellvert et al., 2014; Berni et al., 2009; Gago et al., 2015; Zarco-Tejada et al., 2013), but regulatory barriers may restrict UAVs from flying in certain areas (Thomasson et al., 2016; Woldt et al., 2015). Moving irrigation systems have long been recognized as a possible platform for ground-based radiometers, particularly infrared thermometers (IRTs) used to measure canopy temperature (Phene et al., 1985; Sadler et al., 2002). Center pivots now occupy over 50% and 80% of the irrigated area in the USA and US Great Plains, respectively (USDA, 2014). Their widespread adoption, along with proper design, installation, and management, offer unprecedented opportunity to increase crop water productivity, but nonetheless represent a primary consumer of freshwater resources (Moore et al., 2015). Center pivot rotational speeds can be managed where angular positions of sprinklers are distributed to different times of the day. This is intended to improve irrigation distribution uniformity over the season by distributing daytime and nighttime differences in evaporative and wind drift losses more uniformly throughout the field (Han et al., 1994; Playán et al., 2005; Steiner et al., 1983). This can also distribute midday and afternoon coverage of IRTs (when *ETc* typically reaches diurnal maxima) to all angular positions of the field, albeit there is a tradeoff between field coverage and repeat frequency (Haberland et al., 2010).

Irrigation scheduling can be automated using canopy temperature measured by stationary IRTs (Evett et al., 2000; Upchurch et al., 1996; Wanjura et al., 1992). The concept was extended to moving IRTs aboard center pivots, and resulted in crop yield and water use efficiency comparable or greater than manual irrigation scheduling using soil water profile measurements by a neutron probe (O'Shaughnessy and Evett, 2010a; O'Shaughnessy et al., 2012a, 2013; Peters and Evett, 2008). The canopy temperature-based algorithms used in these studies included the time-temperature threshold (Wanjura et al., 1992), crop water stress index (Jackson et al., 1981), and an integrated crop water stress index (O'Shaughnessy et al., 2012a). These algorithms do not distinguish between soil and canopy temperature, which can differ by more than 30 °C, and can influence the apparent surface temperature during partial canopy cover. This has sometimes resulted in unneeded irrigation events occurring early in the season prior to full canopy cover (O'Shaughnessy et al., 2011a,b).

A two-source energy balance (TSEB) model may provide a way to reduce errors in *ETc* and crop water stress calculations by partitioning surface temperature into soil and canopy components. The TSEB model of Norman et al. (1995) and Kustas and Norman (1999) uses directional brightness surface temperature, does not require much greater input data compared with the theoretical crop water stress index, and solves the energy balance of the soil and canopy regimes separately. In addition to calculating the soil and canopy temperature components, the TSEB calculates soil evaporation (*E*) and canopy transpiration (*T*), which can be combined as *ETc*. Previous studies tested the TSEB for corn and soybean in Central Iowa (USA) with partial to full canopy cover (Anderson et al., 2005; Li et al., 2005). In Bushland, Texas (USA), which is a semiarid climate noted for large advected sensible heat flux, the TSEB model was shown to calculate *ETc* and latent heat flux for fully irrigated cotton with relatively small discrepancies (<20%) compared with *ETc* measured by lysimeters and eddy covariance, respectively (Anderson et al., 2012; Cammalleria et al., 2014; Kustas et al., 2012). Recent studies also improved *E* and *T* partitioning, along with *ETc* calculations, for the fully irrigated cotton at that study location (Colaizzi et al., 2016a; Song et al., 2016). These studies used stationary wired IRTs and stationary inverted pyrgeometers at 15-min intervals and small spatial scales, and one-time-of-day satellite measurements at larger spatial scales. However, no TSEB model version has been tested for moving IRTs aboard center pivots, and relatively few TSEB studies have considered different crops grown over multiple seasons, which entail relatively wide ranges of climatic and growing conditions typical of the Southern High Plains region of the USA (Baumhardt et al., 2016). Further, the recent TSEB model version has not been tested using recently developed wireless IRTs and wireless sensor networks (O'Shaughnessy and Evett, 2010b; O'Shaughnessy et al., 2011b).

The objective of this study was to test the TSEB model in calculating *ETc* using moving IRTs aboard center pivots. A secondary objective was to conduct a sensitivity analysis of *E*, *T*, and *ETc* to selected input variables (likely as having the most uncertainty in practice) for a small, medium, and large canopy. Although separate *E* or *T* measurements were presently not available in the center pivot fields, their inclusion in the sensitivity analysis was deemed important in assessing the impact of different canopy sizes. A forthcoming paper will extend the TSEB model to include thermal-based indices for irrigation scheduling, and compare these to existing indices.

2. Materials and methods

2.1. TSEB model overview

The TSEB model version used here was described in Colaizzi et al. (2016a). This was essentially the series resistance TSEB version described by Norman et al. (1995) and Kustas and Norman (1999) with several modifications designed for ground based IRTs and row crops. The series resistance formulation was chosen over the parallel resistance alternative because the former was shown to be less sensitive to input variables over a wider range of vegetation cover (Li et al., 2005). The modifications included submodels to calculate the vegetation view factor in an IRT footprint (Colaizzi et al., 2010), partitioning net shortwave and net longwave radiation to the soil and canopy components (Colaizzi et al., 2012a,b), calculation of surface soil heat flux in crop interrows (Colaizzi et al., 2016b,c), replacing the Priestley-Taylor with the Penman-Monteith equation to calculate initial crop transpiration (Colaizzi et al., 2012c, 2014, 2016a), and calculation of daily *ETc* from one-time-of-day IRT measurements by the time scaling method (Peters and Evett, 2004). In addition, leaf area index (*LAI*) is a required input throughout the TSEB model. However, only canopy width (w_C), canopy height (h_C), and plant population measurements were available in the present study, and *LAI* measurements were available only in a few seasons and in a limited number of plots. Therefore, *LAI* was estimated by an allometric method that used plant population, h_C, and cumulative growing degree days (Colaizzi et al., 2017).

The TSEB model with series resistance includes an aerodynamic resistance (r_A), canopy boundary layer resistance (r_X), and soil surface resistance (Fig. 1). Sensible heat fluxes (H) are transferred through these resistances by temperature gradients, and are related to available energy and latent heat fluxes (LE) by

$$LE = R_N - G_0 - H \quad (1)$$

where R_N is net radiation, G_0 is surface soil heat flux, and all terms have W m^{-2} units. In this sign convention, R_N is positive towards the canopy, and all other terms are positive away from the canopy.