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Application of an energy balance method for estimating evapotranspiration in cropping systems

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ABSTRACT

Accurate quantification of evapotranspiration (ET, consumptive water use) from planting through harvest is critical for managing limited water resources for crop irrigation. Our objective was to develop and apply a land-crop surface residual energy balance (EB) method for quantifying ET and to estimate ET of corn (*Zea mays* L.) for the first time in the climate of the lower Mississippi Delta region. Actual ET (ET_e) was estimated as the residual term of the energy balance equation from measurements of net solar irradiance (R_n) and computed sensible heat (H) and ground heat (G_o) fluxes. The H flux was computed from measurements of the air and crop canopy temperature differential and modeling the aerodynamic resistance (r_a) to heat and water transport in the turbulent atmospheric boundary layer above the canopy. The G_o flux was estimated by measuring heat flux at 8 cm depth and accounting for heat storage in the soil layer above it. The developed EB procedure was tested using simultaneous measurements of EB data and lysimetric ET in a cotton (*Gossypium hirsutum* L.) field at Bushland, Texas, USA in 2008. The lysimeter measured ET compared well with the computed ET_e under cotton (RMSE of daily ET = 1.2 mm, and seasonal ET within 1% error). Further, we quantified irrigated corn ET using EB in a silt loam soil at Stoneville, Mississippi, USA in 2016. The computed seasonal values of ET_e were greater than shortgrass reference ET (ET_o) by 27 mm and less than alfalfa reference crop ET (ET_r) by 80 mm. The instrumentation used in the EB method can be moved, and the estimated ET was comparable with lysimeter measured ET. As such, this method provides a cost-effective, viable alternative for quantifying ET, which should be broadly tested in other locations and cropping systems.

1. Introduction

The eddy-covariance (EC), and energy balance (EB) methods provide two scientifically sound methods for indirect but potentially accurate measurements of water fluxes from cropping systems (Baldochi, 2003; Gowda et al., 2014; Parent and Anctil, 2012; Shurpali et al., 2013; Uddin et al., 2013). Because of the availability of fast response sensors and data loggers for automated measurement and storage of water and eddy transport data in the plant canopy boundary layer, the EC technique is gaining a reputation as the preferred method for quantifying ET (Amiro, 2009). Even after several physical and instrument corrections are applied to the flux data, it has a widely acknowledged energy balance closure error between energy inputs and outputs, introducing an amount of doubt in the reliability of the measured ET under limited irrigation water management (Amiro, 2009; Allen et al., 2011; Baldochi, 2003; Foken et al., 2006; Liu et al., 2017; Tallec et al., 2013). While the search for energy balance closure in the EC technique continues, the EB approach, in which all the components of energy exchange in the system other than latent heat energy are measured and accounted for in the frictional sub-layer immediately above the plant canopy, provides an alternative approach for fast measurement and quantification of crop ET in field crops in medium size experiments (Amiro, 2009; Tanner, 1960).

In the EB method, an energy balance equation is applied to a soil-crop land area using remote or tower-mounted atmospheric boundary layer sensors and near-surface soil sensor measurements of the system variables (Bhattarai et al., 2016; Cammalleri et al., 2012). In this approach, ET (expressed as latent heat flux, *LE*) is estimated as the residual term of the energy balance equation when other fluxes in the equation are either measured or calculated. Typically, the sensible heat

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flux (H) is quantified assuming an air-diffusion (flow) resistance to heat and water transport across the turbulent atmospheric boundary layer above the plant canopy (also known as bulk transfer approach), and soil heat flux is measured using buried heat flux plates, adjusted to estimate the soil surface heat flux (G_o) (Allen et al., 2007a,b; Heilman and Kanemasu, 1976; Su 2002). Many models and methods for estimating land surface ET from satellite remote sensing data (SEBAL – surface energy balance algorithm for the land model, for example), make use of the general EB approach (Brunet et al., 1991; Bastiaanssen et al., 1998; Cammalleri et al., 2012; McShane et al., 2017). Verma et al. (1976) developed a resistance-energy balance (resistance refers to the method for computing sensible heat flux) procedure for monitoring ET from sorghum (*Sorghum bicolor* L.) and millet *(Panicum melimeurn* L.) cropping systems that compared well with lysimetric measurements. Heilman and Kanemasu (1976) developed an EB based ET model that uses the diffusion resistance to heat transport in the energy balance equation. They obtained ET estimates within 4% and 15% bias on a seasonal basis of lysimetric measurements for soybean (*Glycine Max* L.) and sorghum, respectively. Simultaneous measurements of energy flux data with EB and EC approach reported comparable results in estimated ET in a boreal forest system (Amiro, 2009). Kimball et al. (1999, 1995, 1994) and Triggs et al. (2004) used the EB approach for comparing free-air CO_2 enrichment effects on ET from cotton (*Gossypium hirsutum* L.), sorghum, and wheat *(Triticum estivum* L.) crops. In these studies, in general, the values of sensible heat (H) in the EB procedure were derived from the measurements of the air and crop canopy temperature differential and modeling the aerodynamic resistance (r_a). In vegetated land surfaces, plant-soil surface temperature should represent the temperature of the apparent source/sink of sensible heat flux within in the plant canopy. As such, it should form the base measurement for quantification of the air and canopy temperature differential (Blonquist et al., 2009). This apparent temperature, known as aerodynamic temperature (T_o) is not a directly measurable variable, so crop canopy surface radiative temperature (T_s) is commonly measured using an infrared thermometer and used as a surrogate for T_o in the computations of H in cropping systems. In relatively homogenous surfaces, the difference between T_s and T_o may not be substantial, but in heterogeneous crop canopy surfaces the differences can be substantial, and this can lead to significant errors in the estimation of H, which in turn leads to unreliable LE estimates using the EB method (Chávez et al., 2010, 2005). The variable T_o is defined as the temperature at the zero-plane displacement height (d, the level to which the ground surface must be raised for the wind profile to follow a logarithmic shape) plus the surface roughness length (height at which wind velocity becomes zero) for sensible heat transfer (Z_h), i.e. ($d + Z_h$). Thus, T_o results from the interactions of T_s with the complex canopy characteristics linked to its architecture. As such, no known physical relationships exist between the two that can be used for predicting the value of one from the other. In this context, empirical relationships were derived and used in the literature for computing the value of T_o from plant canopy and environmental variables in energy balance studies (Chávez et al., 2005). For computations of T_o in this study, we used the equation developed by Chávez et al. (2010) for corn and Chávez et al. (2005) for cotton crops. Such empirical relationships linking crop-specific characteristics with environmental variables were applied for simulating crop processes in cropping system models across the globe. Examples include the CERES-rice model (Ritchie, 1998), APSIM model (Robertson and Carberry, 1998), CropSyst model (Stöckle et al., 2003), and in modeling ecosystems (Norby et al., 2016; Rogers, 2014).

Intensive, ground-based continuous monitoring of all the EB components in a cropped field are required for quantifying ET based on the EB approach (Brown and Rosenberg, 1973; Amiro, 2009). As such, application of this technology for quantifying ET in cropping systems remained sporadic, possibly due to the difficulties in making these continuous measurements and their storage and transmission for developing algorithms for computing resistances customized to those measurements. With the advent of the modern fast response sensors, data loggers, and wireless communication system, this is no longer considered a hindrance in adopting this technology in field research.

Recently corn growers in the Mississippi (MS) Delta region planted an estimated 750,000 acres (303,500 ha) of corn and produced about 134 bushels per acre (5400 kg ha^{-1}) grain yield and 97.82 million bushels (6,140,161 Mg) in 2010 (Mississippi State University Extension service, http://msucares.com/crops/soybeans/index.html). The long-term average annual rainfall received over the Mississippi Delta region was approximately 1300 mm, with about 30% received during the core crop growing periods from April to August (Saseendran et al., 2016a). The crop growing season rainfall is also characterized by large inter- and intra- seasonal variabilities in their amounts and temporal distributions. To stabilize returns from crops raised in the region, farmers often provide supplementary irrigations, drawing water from the Mississippi River Valley Alluvial Aquifer. In the absence of reliable information on the water needs of the crops, farmers often provide arbitrary irrigations. Agricultural water use from this aquifer has been reported to far exceed its long-term recharge rates (Powers, 2007). Global warming associated with increasing anthropogenic greenhouse gasses in the atmosphere was also reported to increase pressure on irrigation water requirements in the region (Saseendran et al., 2016b). Accurate, timely quantification of water requirements (or ET) of major crops (cotton, corn, soybeans, and rice) grown in the region is essential for scheduling irrigations for optimizing water use efficiency (WUE) in these cropping systems and to match irrigation withdrawals with the recharge rates of the aquifer.

In these contexts, our objectives were to provide a synthesis of components in the EB approach and (1) develop a state-of-the-science algorithm for computation of ET based on the EB approach, (2) test the ET quantified using this algorithm with cotton ET measured using a large-scale field lysimeter at Bushland, TX, USA, and (3) use the EB algorithm to quantify ET in corn at Stoneville, MS, USA, for the first time in the history of MS Delta, and compare it with grass and alfalfa reference crop ET computed from climatological data for the location.

2. Methodology

2.1. The energy balance (EB) approach for estimating evapotranspiration (ET)

An energy balance equation for a crop-soil surface can be written as

$$R_n = LE + G_0 + H + \Delta S_{air} + \Delta S_{bm} + \Delta S_{ph} \quad (1)$$

where R_n is the net radiation (positive downward), LE is the latent heat flux (positive upward), G_o is the soil heat flux (positive downward), H is the sensible heat flux (positive upward), S_{bm} is the energy stored in the biomass, S_{air} is the energy stored in the air layer, and S_{ph} is the energy used in photosynthesis, where Δ denotes the change per unit time (s). Units are Wm^{-2} for energy flux and J m^{-2} for energy storage. Based upon previous work (Meyers and Hollinger, 2004) and screening calculations, we assume that in summer crops (3–4 months duration) like corn and cotton, S_{air}, S_{bm}, and S_{ph} are negligible compared with other terms in Eq. (1). Meyers and Hollinger (2004) estimated the solar energy stored in the carbohydrate bonds from photosynthesis, in the biomass, and in the soil under corn. When these processes were considered independently, each component was found to be insignificant (< 5%) (Meyers and Hollinger, 2004). However, when these losses were combined, the total loss comprised 8–14% of the net solar energy. Energy stored in the soil and plant canopy accounted for majority of this change in energy storage. In the present study, however, heat storage changes in the soil water and minerals were included in Eq. (3). We did not compute the storage changes in crop-biomass based on observations from past studies: Leuning et al. (2012) and Anderson and Wang (2014) reported no net energy gain or loss due to heat storage changes in the biomass because, on a daily basis, energy stored in the