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Daily energy fluxes, evapotranspiration and crop coefficient of soybean

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ABSTRACT

Evapotranspiration represents the main consumptive use of water in agricultural production and its magnitude is important for irrigation water management. Since water shortages are increasing in many areas, there is a pressing need to improve irrigation water management, for which farmers need reliable information and tools to make better irrigation decisions. There is a lack of knowledge about the water use and irrigation requirements of crops grown in different environments, especially of new crop hybrids. The overall objective of this study was to improve our understanding of the water requirements of soybean. Specific objectives were to: (1) measure and document the daily crop evapotranspiration (ETc) and other energy fluxes, (2) document the daily and seasonal behavior of crop coefficients (Kc), and (3) evaluate the impact of weather variables on alfalfa-reference (ETr) and grass-reference (ETo) evapotranspiration. Here we report results of direct ETc measurements using an eddy covariance system obtained from soybean fields at North Platte, Nebraska, during 2002, 2003, and 2005. We found considerable differences in weather conditions among seasons that affected the accumulation of growing degree days, crop development pattern, crop ETc and Kc. We found that ETr values were on average 32.3% greater than ETo, which is important when choosing Kc values for calculating crop ETc. We also found that vapor pressure deficit (VPD) explained 90 and 92% of the variability in ETo and ETr, respectively. We presented daily measurements of energy fluxes and Kc values and found that measured Kc values were quite variable and often deviated considerably from the average Kc curves given in FAO-56 due to wetting events (rain and irrigation) and crop stress. Therefore, we recommend using the dual Kc method, rather than the single Kc method, for irrigation scheduling. In addition, we found considerable differences in crop maturity among years and suggested that acceleration in maturity could be due to crop stress, especially during the reproductive period. We raised the need for accurate methods to quantify the effect of stress on crop maturity and its impact on Kc.

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1. Introduction

Evapotranspiration is an important component of the hydrologic cycle, which affects the water balance of all vegetated and non-vegetated landscapes. For vegetated landscapes, crop evapotranspiration (ETc) represents the major consumptive use of water. For commercial cropping systems, ETc needs to be met by rainfall, in rainfed production systems, or by a combination of rainfall and irrigation, in irrigated production systems. Shortages of irrigation water are becoming common in many regions of the world, especially in arid and semi-arid regions due to factors like drought, more restrictive laws regulating the use of water in agricultural production and increased competition for water resources with non-agricultural uses, such us domestic, industry, and the environment. Because of these shortages, there is a pressing need to find new ways to conserve and use water more efficiently. Meeting crop ETc with irrigation also can be an expensive and energy-intensive operation, especially when water is pumped from deep wells. Knowing the daily ETc requirements of crops can be used to help producers decide when to apply irrigation and how much water to apply to increase crop yields and farm profits while reducing costs, energy use, and negative environmental impacts.

Accurate ETc information not only aids in irrigation water management, but since the flux of water vapor by crop transpiration and the flux of CO_2 needed for photosynthesis both take place thought leaf stomata, crop ETc is usually well correlated to crop biomass and yield production, which can be used to estimate crop yield if ETc is known (Hanks, 1974; Payero et al., 2005a, 2006a; Raes et al., 2009; Steduto et al., 2007, 2009). Estimating crop yield for crops subjected to different levels of water stress is important for

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making irrigation scheduling decisions in real time, for comparing alternative irrigation management options, and for evaluating the economic impact of alternative cropping systems under a variety of growing environments, including the potential impact of future climate change scenarios (Cammarano et al., 2012; Power et al., 2008, 2009, 2011).

There are several methods to directly measure the daily ET of crops and other land surfaces, such as lysimeters (Allen and Fisher, 1990; Howell et al., 1995; Payero and Irmak, 2008; Pruitt and Angus, 1960; Yang et al., 2003), Bowen ratio (Payero et al., 2003; Perez et al., 1999; Tanner et al., 1987; Todd et al., 2000; Tomlinson, 1996), eddy covariance (Billesbach, 2011; Burba and Anderson, 2007; Goltz et al., 1969), surface renewal (Anandakumar, 1999; Castellvi et al., 2006; Paw et al., 1995), remote sensing (Li et al., 2008; Samani et al., 2009; Tasumi et al., 2003), scintillometers (Allen et al., 2011; Anandakumar, 1999; Kite and Droogers, 2001), and closed chambers (Scott et al., 1999; Steduto et al., 2002). But, these methods are usually limited to research applications since they require a high level of expertise and specialized equipment that is usually expensive and difficult to install and operate. Also, some of these methods require large fetch areas, which can be a limitation even at some research sites. Therefore, most potential end users of ETc information, like farmers, have no practical means of directly measuring crop ETc.

There has been considerable research effort trying to develop accurate procedures to estimate ETc from weather data (Allen et al., 1998; Doorenbos and Pruitt, 1977) and to integrate this knowledge into empirical and mechanistic crop simulation models (Evett et al., 1995; Jones and Kiniry, 1986; Keating et al., 2003) and irrigation management tools (Chauhan et al., 2013; Evett and Lascano, 1993; Payero et al., 2011; Power et al., 2011; Rosa et al., 2012a,b). These models and tools need to be validated with field data, which is challenging because accurate field measurements of ETc are scarce and crop hybrids change rapidly, creating the need to collect more field data. For example, for the application of the FAO-56 methodology to estimate ETc (Allen et al., 1998), we rely on crop coefficient values that were derived primarily from field measurements recorded decades ago. Since then, the hybrids of major field crops like soybean, cotton, and maize have changed from conventional hybrids to genetically modified (GM) hybrids and there is some evidence that these new GM hybrids behave differently to water inputs and water stress compared to conventional hybrids (Yeates et al., 2006, 2009).

The overall objective of this study was to improve our understanding of the water requirements of soybean. Specific objectives were to: (1) measure and document the daily crop evapotranspiration (ETc) and other energy fluxes, (2) document the daily and seasonal behavior of crop coefficients (Kc), and (3) evaluate the impact of weather variables on alfalfa-reference (ETr) and grass-reference (ETo) evapotranspiration.

2. Methods

2.1. Site description and crop management

Field data for this study were collected from two soybean fields located at the University of Nebraska-Lincoln West Central Research and Extension Center, North Platte, Nebraska (41.1° N, 100.8° W, 861 m above mean sea level). Data were collected during 2002, 2003, and 2005 from fields that were under a ridge-tilled maize-soybean rotation and had a Cozad silt loam soil (*Fluventic Haplustolls*). In 2002, measurements were made in a 9.2 ha field (296 m × 311 m). In 2003 and 2005, measurements were made in an adjacent 11.5 ha field (265 m × 433 m) with similar soil and crop management practices. Surface irrigation with gated pipes was used in 2002 and 2003, and a lateral (linear)-move sprinkler irrigation system was used in 2005. Groundwater pumped from a deep well was used for irrigation. Since the fields were dedicated to commercial production, the farm manager made all crop management decisions, aiming at maximizing profits following local management guidelines and "*rules of thumb*." Each year, the crop was planted at 0.76-m row spacing and at a depth of approximately 2.5 cm with an east-west planting direction. Genetically modified roundup ready (RR) hybrids were planted each year. The hybrids were selected mainly for their high yield potential based on performance in local yield trials. In west central Nebraska soybean is usually planted in mid to late May and harvested in October. The hybrids, planting and harvest dates are shown in Table 1.

Table 1
Soybean hybrids, planting and harvest dates during 2002, 2003, and 2005 at North Platte, Nebraska.

Year	Hybrid	Planting date	Harvest date
2002	Asgrow AG2602 (RR)	25 May	20 October
2003	Renze 2600 (RR)	21 May	7 October
2005	LG Seeds C2820 (RR)	20 May	3 October

RR: roundup ready.

2.2. Field measurements

Each year, the energy fluxes and basic meteorological variables were measured using an eddy covariance system (ECS) (Campbell Scientific, Inc., Logan, Utah) installed on a tower at the center of the soybean field, which provided more than 130 m of fetch in all directions. At the study site, the predominant wind direction was from north-west to south-east. In 2002, measurements were made from January to October. In 2003, because of equipment problems measurements were made from 66 to 86 days after planting (DAP) and from 113 DAP until the end of the year. In 2005, measurements were made from May through October. This paper focuses on the data collected during the soybean growing season. The ECS was installed so that the sensors (except for those buried in the soil) were at least 1 m above the crop canopy. Sensors used in the study and the variables measured are listed in Table 2.

Data from the sensors were sampled, processed and stored in a SM16M data storage module using a CR23X datalogger that was housed in an environmental enclosure (Campbell Scientific, Inc., Logan, Utah). A deep-cycle marine battery (12 V, 75 A), recharged by a solar panel, was used to power the ECS. The data sampling frequency was 10 Hz (10 times a second) for the CSAT3, FW05, and KH20 sensors, and once per minute for all other sensors. Data were stored as 30-min averages and daily averages were calculated during post-processing.

The 30-min averages included solar radiation (R_s), net radiation (R_n), latent heat flux (LE), and sensible heat flux (H) (all in units of W m^{-2}). Soil heat flux (G) was calculated from the output of two HFT3 soil heat flux plates, one TCAV soil temperature sensor (which included four soil thermocouples), and one CS615 water content reflectometer (Campbell Scientific, Inc., Logan, Utah). The soil heat flux plates were installed at a depth of 0.08 m below the soil surface, 1 m apart. Two soil thermocouples were installed about 0.01 m to one side of each soil heat flux plate at depths of 0.02 and 0.06 m below the soil surface. The CS615 sensor was installed horizontally midway between the two soil heat flux plates at a depth of 0.025 m. Soil heat flux was calculated by combining the energy flux measured by the soil heat flux plates and the change in heat stored above the plates (Hanks and Ashcroft, 1980; Payero et al., 2005b).

The site was visited at least once a week and data were downloaded from the datalogger to a laptop for further processing. During each visit, sensors were inspected and maintained, and