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Assessing crop coefficients of sunflower and canola using two-source energy balance and thermal radiometry

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ABSTRACT

A new technique for the local adjustments in crop coefficients is presented. This is an alternative to conventional lysimeter measurements traditionally used for improved irrigation scheduling. The method is based on the combination of a two-source energy balance model and local measurements of radiometric temperatures. Two experimental campaigns were carried out on sunflower and canola in a cropland area located in Barrax, Albacete, in the summer of 2011 and spring of 2012, respectively. Radiometric temperatures of soil and canopy were collected, together with biophysical and meteorological variables. Combining all these data in a two-source energy balance model allowed separation of both the evaporation and transpiration components of the total evapotranspiration (*ET*). Model results were first compared to local measurements from a lysimeter. Estimation errors around ±0.20 mm/h and ±1.0 mm/d were observed for both sunflower and canola crops at hourly and daily scales, besides uncertainties lower than 3% for the cumulated *ET* for the whole campaigns. Results were then used to assess values of the different crop coefficients for this site and the two crops. Comparison with values proposed by FAO56 showed significant discrepancies that yielded to 1–2 mm/d uncertainty in terms of daily evaporation and transpiration values, and underestimations of 0.6 and 1.3 mm/d, together with estimation errors of ±1.1 and ±1.7 mm/d for sunflower and canola, respectively, in terms of daily *ET* values. Although partitioning of *ET* needs further study involving field data of evaporation and transpiration, these results reinforce the necessity for the local adjustment of the crop coefficients used as inputs in water balance models, and show the potential of the technique proposed to achieve this goal.

1. Introduction

An accurate estimation of actual evapotranspiration (*ET*) is known to be critical for better management of the water resources and more effective irrigation scheduling. *ET* can be calculated based on the product of reference evapotranspiration (ET_o) multiplied by a crop coefficient, K_c (Allen et al., 1998; Caselles et al., 1992). Beyond this method, *ET* can be estimated accounting for the evaporation from the soil (*E*) and the vegetation transpiration (*T*) through an evaporation coefficient, K_e, and a basal coefficient, K_{cb}, respectively, so that $K_c = K_{cb} + K_e$ (Wright, 1982; Allen et al., 1998). This dual crop coefficient technique has been widely applied and explored under a variety of climatic conditions worldwide (Allen et al., 1998; Williams and Ayars, 2005; López-Urrea et al., 2009, 2012; Campos et al., 2010; Liu and Luo, 2010). Most of these works show the necessity to pre-calibrate the values of K_{cb} recommended by FAO56.

Traditionally, crop coefficients are empirically determined for every crop and climatic condition using lysimetric measurements as a reference (Allen et al., 1998). Distinction between *E* and *T*, represented by K_e and K_{cb}, respectively, is not an easy task. Some efforts have been made to measure both components separately, using, for example, sap or stem flow measurements, the implementation of microlysimeters, or eddy covariance systems below the canopy (Agam et al., 2012; Colaizzi et al., 2012; Evett et al., 2012; Williams et al., 2004; Ham et al., 1990; Yunusa et al., 2004; Huixiao and Simmonds, 1997; Wilson et al., 2001). Sap flow measures provide an

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estimation of the plant transpiration, but whether these measurements are representative is still being questioned. Installing several microlysimeters to determine soil *E* seems a good, although rough, solution, whereas fetch problems arise when using eddy covariance systems near the soil level.

Energy balance is a nondestructive technique that merges remote sensing together with some biophysical and meteorological information into a physical model to extract the latent heat flux, directly related to the actual *ET* (Shuttleworth and Wallace, 1985; Norman et al., 1995; Kustas and Norman, 2000). In particular, two-source versions of this energy balance (TSEB) allow the estimation of separate *E* and *T* by establishing a separate balance for soil and canopy components, respectively, in a specific target (Norman et al., 1995; Li et al., 2005; Hu et al., 2009; Kustas et al., 2012; Colaizzi et al., 2012). In this paper, we use a simplified version of the two-source configuration (STSEB) (Sánchez et al., 2008, 2009). This version uses direct radiometric temperature measurements as the main input.

The objective of this work was to separate evaporation and transpiration in order to assess the crop coefficient values proposed by FAO56 as well as those obtained from lysimetric measurements. The effect of discrepancies in terms of crop coefficients on the estimated total *ET*, *E* and *T* were also evaluated.

Data from two different oilseed crops, sunflower and canola, were used in this study, corresponding to two separate experimental campaigns carried out in a cropland area of Barrax, Spain, during the growing season of 2011 and 2012.

Note that the main body of the methodology required for this work was already described in a previous paper by Sánchez et al. (2011). The present manuscript focuses on new aspects of *E*/*T* separation and the crop coefficients assessment. A brief description of the energy balance approach is given in Section 2, and the reader will be referred to the work mentioned above for further details on model equations or data processing.

2. Materials and methods

2.1. Study site and measurements

This study was conducted during the growing seasons of 2011 and 2012 in "Las Tiesas" experimental farm (2° 5′W, 39° 14′N, 695 m a.s.l) close to Albacete (Central Spain). The climate is semi-arid, Temperate Mediterranean. The soil is classified as *Petrocalcic Calcixerepts*, with a silty-clayloam texture (13.4% sand, 48.9% silt and 37.7% clay). A weighing lysimeter (2.7 m long, 2.3 m wide and 1.7 m deep) with a resolution of 0.04 mm equivalent water depth was located in the center of a 100 × 100 m plot, where sunflower (*Helianthus annuus* L.) and canola (*Brassica napus* L.) were planted (Fig. 1). For a detailed description of the site, the automatic weather station placed in the area, and technical features of the lysimeter see Sánchez et al. (2011) and López-Urrea et al. (2006).

In the summer of 2011 sunflower was sowed in rows (N–S orientated) of 76-cm spacing with a plant population of 12.4 plants m^{-2}, whereas in spring of 2012 canola was sowed in rows (N–S orientated) of 15 cm spacing with a plant population of 155 plants m^{-2}. Efforts were made to keep the crop inside the lysimeter at the same growth rate and plant population as the crop outside to minimize edge effects. During the experiments crops were irrigated using a sprinkling system, avoiding water stress conditions at anytime. Plant samples from three separate areas were obtained periodically to measure crop development. Fractional vegetation cover (P_v), and crop height were measured from the three samples, and modeled for the entire experiments (Fig. 2).

Radiometric surface temperatures were measured using two Apogee SI-211 thermal Infrared Radiometers (IRT). These instruments have a broad thermal band (6–14 μm) with an accuracy of ±0.3 °C, and 28° field of view. One was placed at a height of 2 m above the canopy level, looking at the surface with nadir view. A second radiometer was placed at a height of 40 cm (20 cm) in the sunflower (canola) experiment directly pointing to the soil between rows with a viewing angle of 30° (Fig. 1c). Sky brightness temperature was measured by a third Apogee radiometer pointing at the sky with an angle of 53° (Rubio, 1998). These radiance values were used for the atmospheric correction of the surface temperature. IRTs were calibrated before the experiment following methodology described in Sánchez et al. (2011). Canola was planted on DOY 90 and harvested on DOY 206, and IRT measurements were collected for the period 100–190, whereas sunflower was planted on DOY 166 and harvested on DOY 269, and IRT measurements were limited to the period 169–230 due to technical problems. In both cases the IRT measurements covered most of the crops' phenological development.

2.2. Energy balance approach

A wide variety of field experiments and associated studies have shown the feasibility of using thermal remote sensing in the retrieval of surface energy fluxes (Shuttleworth and Wallace, 1985; Norman et al., 1995; Kustas and Norman, 2000; Li et al., 2005; Sánchez et al., 2008; Kustas et al., 2012; Colaizzi et al., 2012). Norman et al. (1995) introduced a remote sensing-based two source modeling framework for computing surface fluxes using temperature observations together with the Priestley–Taylor equation to obtain an initial solution and start an iterative process. If the partitioning of composite land-surface temperature into soil and canopy temperatures is known, or can be inferred, *E* and *T* can be computed directly as a residual to the component energy budgets. In this paper, we use a simplified version of the two-source configuration (STSEB) (Sánchez et al., 2008, 2009). This version uses direct radiometric temperature measurements as the main input, and includes a simple approach to predict the net radiation partitioning between soil and vegetation. Feasibility of STSEB to obtain accurate *ET* values has been already assessed in a corn crop (Sánchez et al., 2008), in a forested area (Sánchez et al., 2009) and, more recently, in a sorghum crop (Sánchez et al., 2011). The latent heat flux, λET, represents the energy required for *ET*, and is computed as the residual of the surface energy balance, which simplified form is given by

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

where R_n is the net radiation flux (W m^{-2}), *H* is the sensible heat flux (W m^{-2}), and *G* is the soil heat flux (W m^{-2}).

According to this approach, the addition between the soil and canopy contributions to the total sensible heat flux, H_s and H_c, respectively, are weighted by their respective partial areas as follows:

$$H = P_v H_c + (1 - P_v) H_s \tag{2}$$

$$H_c = \rho C_p \frac{T_c - T_a}{r_a^h} \tag{3}$$

$$H_s = \rho C_p \frac{T_s - T_a}{r_a^a + r_a^s} \tag{4}$$

where ρC_p is the volumetric heat capacity of air (J K^{-1} m^{-3}), T_s is the soil temperature (K), T_c is the canopy temperature (K), T_a is the air temperature at a reference height (K), and ${r_a}^h$, ${r_a}^a$, and ${r_a}^s$ are the aerodynamic resistances to heat transfer between the surface and the air (s m^{-1}), as a function of wind speed and canopy height. A summary of the expressions to estimate these resistances can be seen in Sánchez et al. (2008).

Net radiation is computed from a balance between the incoming and outgoing short-wave and long-wave radiances. This requires additional surface parameters, albedo (α) and emissivity (ε), and