Agricultural Water Management 143 (2014) 71–81

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Mapping crop evapotranspiration by integrating vegetation indices into a soil water balance model

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ARTICLE INFO

Article history:
Received 5 March 2014
Received in revised form 19 June 2014
Accepted 27 June 2014
Available online 18 July 2014

Keywords:
Crop coefficient
Eddy covariance
FAO-56 model
Soil water monitoring

ABSTRACT

The approach combines the basal crop coefficient (K_{cb}) derived from vegetation indices (VI_s) with the daily soil water balance, as proposed in the FAO-56 paper, to estimate daily crop evapotranspiration (ET_c) rates of orange trees. The reliability of the approach to detect water stress was also assessed. VI_s were simultaneously retrieved from Worldview 2 imagery and hyper-spectral data collected in the field for comparison. ET_c estimated were analysed at the light of independent measurements of the same fluxes by an eddy covariance (EC) system located in the study area. The soil water depletion in the root zone of the crop simulated by the model was also validated by using an *in situ* soil water monitoring. Average overestimate of daily ET_c of 6% was obtained from the proposed approach with respect to EC measurements, evidencing a quite satisfactory agreement between data. The model also detected several periods of light stress for the crop under study, corresponding to an increase of the root zone water deficit matching quite well the *in situ* soil water monitoring. The overall outcomes of this study showed that the FAO-56 approach with remote sensing-derived basal crop coefficient can have the potential to be applied for estimating crop water requirements and enhancing water management strategies in agricultural contexts.

1. Introduction

In arid and semi-arid regions, the availability of water is a major limitation on crop production due to insufficient rainfall to compensate crop water requirements. Improvements in water management in irrigated areas and adequate irrigation scheduling are essential also to increase the sustainability of irrigated agriculture (Hsiao et al., 2007; Padilla et al., 2011).

Evapotranspiration (ET), *i.e.* the water transferred to the atmosphere by soil evaporation and plant transpiration, is one of the most relevant components of the soil water balance.

In the Mediterranean agriculture, perennial crops like citrus species are predominant, with about 1 Mha of extension and consequent large water requirements for their sustainability. In Southern Italy, and in Sicily in particular, citrus species represent one of the most relevant components in the agricultural economy, as well as in the utilization of water resources (Capra et al., 2008; Consoli and Vanella, 2014). Therefore, the monitoring of citrus orchards water needs and consumption is a major challenge for developing a regionally sustainable irrigation strategy. In the region, in fact, the evaporative demand (*i.e.* around 1200 mm/year according to reference evapotranspiration estimates (Allen et al., 1998)) is very large when compared with rainfall, which mean is about 600 mm/year.

Accurate estimation of ET constitutes a very important part of irrigation system planning and designing, and accurate spatial determination is crucial to achieving sustainable agriculture (Er-Raki et al., 2007). Several techniques, such as eddy covariance (EC) , Bowen ration (BR), and weighted lysimeters provide ET measurements, but these are expensive, often limited to small experimental field scales (*i.e.* fetch requirements) and labourious.

Numerous studies have evaluated remote sensing techniques for estimating crop ET on a large scale (Barbagallo et al., 2009; González-Dugo and Mateos, 2008; Teixeira et al., 2009; Padilla et al., 2011; Mateos et al., 2013) and several methodologies, integrating thermal and optical remote sensing data into energy and water balance models, have been developed to estimate crop evapotranspiration fluxes (Kustas and Norman, 1999; Allen et al., 2007). The use of remote sensing to estimate ET is presently being developed along two approaches: (i) land surface energy balance (EB) method, that uses remotely sensed surface reflectance in the visible (VIS) and near-infrared (NIR) portion of the electromagnetic spectrum and surface temperature from an infrared thermal band (Idso et al., 1975; Moran, 1989; Hatfield and Pinter, 1993; Norman et al., 1995; Chavez et al., 2005; Allen et al., 2007; González-Dugo

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http://dx.doi.org/10.1016/j.agwat.2014.06.012
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et al., 2009) and (ii) reflectance-based crop coefficient and reference ET approach where the crop coefficient (K_c) is related to vegetation indices (VI_s) derived from canopy reflectance values (Rouse et al., 1974; Huete, 1988; Neale et al., 1996; Chavez et al., 2005; Er-Raki et al., 2013; González-Dugo et al., 2013; Mateos et al., 2013). The first approach is based on the rationale that ET is a change of the state of water using available energy in the environment for vapourization. Remote sensing based EB models convert satellite sensed radiances into land surface temperature to estimate ET as residual of the surface energy balance equation. The current limited availability of high-resolution thermal satellite sensors hampers their use in the applied research, and thus evidences the importance of models based on readily available optical data as alternative options for ET estimate. In particular, in this second approach VIS and NIR reflectance measurements are used to compute vegetation indices such as the normalized difference vegetation index (NDVI, Rouse et al., 1974) or the soil adjusted vegetation index (SAVI, Huete, 1988) and these indices can be used to obtain rapid, non-destructive estimates of certain canopy attributes and parameters. One parameter of special interest for water management application is the crop coefficient (K_c) which employed the FAO-56 model to derive actual crop ET. The crop coefficient is defined as the ratio of the crop ET (ET_c) to the reference crop ET_0 (grass) and represents an integration of the effects of the following characteristics distinguishing a given crop from the reference one: crop height (affects aerodynamic resistance and vapour transfer), albedo (affects net radiation), canopy resistance (to vapour transfer), and evaporation from soil (Allen et al., 1998). The K_c can be calculated using a single method that combines the effects of crop transpiration and soil evaporation into a unique coefficient (K_c) or a dual method that separates the plant transpiration, represented by a basal crop coefficient (K_{cb}) and the soil evaporation coefficient (K_e). The single model is commonly used because of its simplicity, requiring only phenological data and standard meteorological information to determine ET estimates. The dual model is more precise than the single approach and mainly oriented towards applied researches on irrigation scheduling for high-frequency water applications (Padilla et al., 2011). In the relatively recent years progresses have been make on the estimation of the K_c temporal evolution from remote sensing measurements of vegetation indices (VI_s). Some authors have in fact suggested that relationships between crop coefficient and VI_s are linear (Neale et al., 1989), but others have found non-linear relationships (Hunsaker et al., 2005). These relationships have been studied for several crops and recently for potato (Jayanthi et al., 2007), cotton and sugarbeet (González-Dugo and Mateos, 2008), wheat (Er-Raki et al., 2007), grapes (Campos et al., 2010; Serrano et al., 2012; Er-Raki et al., 2013), and citrus orchard (Barbagallo et al., 2009; Consoli and Barbagallo, 2012; Consoli and Vanella, 2014). Among the more interesting studies, Neale et al. (1996) obtained reflectance-based K_c data that were related to the SAVI; Tasumi et al. (2005) showed a method to estimate K_c using a satellite-based model and a parameterization of K_c using NDVI to obtain daily ET; Er-Raki et al. (2007) obtained fairly good comparisons between estimates of actual ET for winter wheat obtained using NDVI-based K_{cb}, and measurements of ET by the eddy covariance (EC) system.

In this study we adopted the FAO-56 "dual" crop coefficient approach, where the basal crop coefficient (K_{cb}) is derived from vegetation indices obtained from a series of satellite images acquired during May–July 2012, and a daily water balance in the root zone of the crop. The combined methodology allows the calculation of the daily crop coefficient and crop ET of an orange orchard in the semi-arid region of Sicily (South Italy). A validation of the approach was performed using field soil moisture measurements and an eddy covariance system for ET direct measurement.

2. Materials and methods

2.1. Description of the model

The FAO-56 dual crop coefficient approach, in the form popularized by the FAO 56 manual (Allen et al., 1998) describes the relationship between daily evapotranspiration of a given crop (ET_c) and reference evapotranspiration (ET_0) by separating the single crop coefficient (K_c) into the basal crop coefficient (K_{cb}), soil water evaporation (K_e) coefficient and water stress coefficient (K_s). Crop transpiration, represented by the basal crop coefficient, K_{cb}, is separated from soil surface evaporation as follow:

$$ET_c = (K_{cb} K_s + K_e) ET_0 \tag{1}$$

where ET_c and ET_0 are in mm d^{-1}.

In the study, daily ET_c was calculated by combining the FAO-56 dual crop coefficient model with spectral data provided by remote sensors. The ET_0 was estimated using the Penman–Monteith equation with hourly data of solar radiation, wind speed, air temperature and relative humidity supplied by a weather station managed by the Sicilian Agro-meteorological Service (SIAS) and located close to the experimental site. The water stress coefficient, K_s, quantifies the reduction in crop transpiration due to soil water deficit, where $K_s = 1$ for non-stress conditions and $K_s < 1$ when there is a shortage of water in the root zone. K_e is the soil evaporation that describes the evaporative component of ET_c.

The procedure for calculating each coefficient is described as follows.

2.1.1. The basal crop coefficient, K_{cb}

The dual crop coefficient approach calculates the actual increase in crop coefficient K_c for each day as a function of plant development (K_{cb}) and the wetness of the soil surface (soil evaporation). The vegetation indices, VI_s, are sensitive to leaf area index, LAI, and the crop ground cover fraction, f_c (Choudhury et al., 1994), which has been used to estimate K_{cb} from VI (Bausch and Neale, 1987; Neale et al., 1989). Vegetation indices (VI_s) are transformation of two or more spectral bands designed to assess vegetation condition, land-cover classification, climate and land-use change detection (Glenn et al., 2008). SAVI, the soil adjusted vegetation index (Huete, 1988) is one of the most used indices able to minimize the effect of the soil on vegetation quantification. The relationship between SAVI and the ground-cover fration is in fact approximately linear in the range from bare soil to near full ground cover (Qi et al., 1994) and SAVI is less sensitive than other VI_s to soil differences (Qi et al., 1994).

In order to integrate the remote sensing data into the dual crop coefficient model, the parameter K_{cb} in Eq. (1) was derived from SAVI by an equation described by González-Dugo et al. (2009) and Mateos et al. (2013):

$$K_{cb} = \frac{K_{cb,\max}}{f_{c,\max}} \left(\frac{SAVI - SAVI_{\min}}{SAVI_{\max} - SAVI_{\min}} \right) \quad \text{if} \quad f_c < f_{c,\max} \tag{2}$$

$$K_{cb} = K_{cb,\max} \quad \text{if} \quad f_c \geq f_{c,\max} \tag{3}$$

where $f_{c,\max}$ is the ground-cover fraction (f_c) at which K_{cb} is maximal ($K_{cb,\max}$); the subscripts max and min refer to values of SAVI for very large leaf area index (LAI, m^2 m^{-2}) and bare soil, respectively. The values adopted in the model are derived from field measurements and can be found in Table 1.

The SAVI index was calculated as follows:

$$SAVI = \frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red} + L)} (L + 1) \tag{4}$$

ρ_{NIR}, ρ_{red} are the reflectance in the near-infrared and red spectra, respectively, and L is a soil normalization factor, generally taken to be 0.5 (Huete, 1988).