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Integration of vegetation indices into a water balance model to estimate evapotranspiration of wheat and corn

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Abstract

Vegetation indices (VIs) have been traditionally used for quantitative monitoring of vegetation. Remotely sensed radiometric measurements of visible and infrared solar energy, which is reflected or emitted by plant canopies, can be used to obtain rapid, non-destructive estimates of certain canopy attributes and parameters. One parameter of special interest for water management applications, is the crop coefficient employed by the FAO-56 model to derive actual crop evapotranspiration (ET). The aim of this study was to evaluate a methodology that combines the basal crop coefficient derived from VIs with a daily soil water balance in the root zone to estimate daily evapotranspiration rates for corn and wheat crops at field scale. The ability of the model to trace water stress in these crops was also assessed. Vegetation indices were first retrieved from field hand-held radiometer measurements and then from Landsat 5 and 7 satellite images. The results of the model were validated using two independent measurement systems for ET and regular soil moisture monitoring, in order to evaluate the behavior of the soil and atmosphere components of the model. ET estimates were compared with latent heat flux measured by an eddy covariance system and with weighing lysimeter measurements. Average overestimates of daily ET of 8 and 11% were obtained for corn and wheat, respectively, with good agreement between the estimated and measured root-zone water deficit for both crops when field radiometry was employed. Satellite remote-sensing inputs overestimated ET by 4 to 9%, showing a non-significant lost of accuracy when the satellite sensor data replaced the field radiometry data. The model was also used to monitor the water stress during the 2009 growing season, detecting several periods of water stress in both crops. Some of these stresses occurred during stages like grain filling, when the water stress is know to have a negative effect on yield. This fact could explain the lower yield reached compared to local yield statistics for wheat and corn. The results showed that the model can be used to calculate the water requirements of these crops in irrigated areas and that its ability to monitor water stress deserves further research.

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Integration of vegetation indices into a water balance model

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1 Introduction

Recent studies have shown that the global demand for food will increase for at least another 40 years. It is estimated that the global population will reach nine billion people by the middle of this century (Charles et al., 2010). One consequence of the rapid growth in world population is that the pressure on water resources is increasing (Rijsberman, 2006). In the future, less water will be available for agricultural production as a result of competition with the industrial and domestic sectors. At the same time, food production will need to increase to feed the growing population (FAO, 2006). In arid and semi-arid regions, the very availability of water is a major limitation on crop production due to insufficient rainfall to compensate for the evaporative losses of crops. Improvements in water management in irrigated areas and adequate irrigation scheduling are essential, not only to improve water productivity, but also to increase the sustainability of irrigated agriculture (Hsiao et al., 2007). One of the most important components of the water balance is evapotranspiration (ET), i.e. the water transferred to the atmosphere by soil evaporation and plant transpiration. Several techniques, such as Bowen ratio energy balance, eddy covariance and weighing lysimeters, provide ET measurements, but these are expensive, they are limited to point or small experimental field scales and can only be fully exploited by trained research personnel (Allen et al., 1998). Several studies have evaluated remote sensing techniques for estimating crop evapotranspiration on a large scale (Anderson et al., 2007; González-Dugo and Mateos, 2008; Teixeira et al., 2009). In the course of the past few decades, besides advances in sensor development, several methodologies for incorporating optical and thermal remote-sensing data into energy and water balance models have been developed, producing estimates of actual ET (Kustas and Norman, 1999; Allen et al., 2007; Neale et al., 1989). These remote sensing approaches provide an opportunity to extend the area of application of these models from point to basin or regional scales, producing a better representation of vegetation heterogeneity.

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The current limited availability of high-resolution thermal satellite sensors hinders their use in irrigation scheduling and water management at field scales, and thus underlines the importance of models based on readily available optical data as a more plausible option for these applications. This approach is usually based on the FAO-56 method, which represents ET as a product of a reference evapotranspiration value (ET_o), which takes atmospheric demands into account, and a crop coefficient that considers the characteristics of the crop (Doorenbos and Pruitt, 1977; Allen et al., 1998). The crop coefficient can be calculated using a single method that combines the effect of crop transpiration and soil evaporation into a unique coefficient (K_c), or a dual one that separates the plant transpiration, represented by a basal crop coefficient (K_{cb}) and the soil evaporation coefficient (K_e). The single model is widely used because it requires only phenological information and standard meteorological data to produce acceptable estimated ET values (Er-Raki, 2007). The dual model is mainly oriented towards research and real-time irrigation scheduling for high-frequency water applications (Allen et al., 1998). A great deal of research has been done in the course of the past 30 years on estimating the standard values and temporal evaluation of crop coefficients (Allen et al., 1998; Wright, 1982), which can be estimated from remote spectral measurements because both the basal crop coefficient and the vegetation indices are sensitive to leaf area index (LAI) and ground cover fraction (fc) (Choudhury et al., 1994). This coefficient may be derived from multispectral vegetation indices (VI) obtained by remote sensing (Jackson et al., 1980; Heilman et al., 1982; Bausch and Neale, 1987; Neale et al., 1989; Calera et al., 2004). Some authors have suggested that relationships between K_{cb} and VI are linear (Bausch and Neale, 1987; Neale et al., 1989; Gonzalez-Piqueras et al., 2003), but others have found non-linear relationships (Hunsaker et al., 2003, 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 (Duchemin et al., 2006; Er Raki et al., 2007) and grapes (Campos et al., 2010).

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We used a combined methodology of basal crop coefficient derived from vegetation indices obtained initially from a hand-held radiometer and then from a series of satellite images and a daily water balance in the root zone of the crop. This combined methodology enables us to calculate the daily corn and wheat crop coefficient and daily ET. A further objective was to determine the ability of the model to assess water stress in both crops. A validation was performed using field soil moisture measurements and two different instruments to measure ET; an eddy covariance system and a weighing lysimeter.

2 Materials and methods

2.1 Description of the model

The model used to estimate ET was developed in the Bajo-Guadalquivir Irrigation Scheme in Southern Spain (González-Dugo and Mateos, 2008). Daily ET was computed using the dual approach in the form popularized by the FAO56 manual. This approach separates crop transpiration from soil surface evaporation as follow:

$$\mathrm{ET_c} = (K_{\mathrm{cb}} K_{\mathrm{s}} + K_{\mathrm{e}})\ \mathrm{ET_o} \quad (1)$$

Reference evapotranspiration ($\mathrm{ET_o}$, mm d^{-1}) was estimated using the Penman-Monteith equation (Allen et al., 1998), with daily solar radiation, air temperature, wind speed, and relative humidity data supplied by weather stations. The water stress coefficient, K_{s}, quantifies the reduction in crop transpiration due to soil water deficit, and K_{e} is the soil evaporation coefficient that describes the evaporative component of $\mathrm{ET_c}$. This coefficient is at its maximum when the topsoil is wet following rain or irrigation, and is calculated as:

$$K_{\mathrm{e}} = K_{\mathrm{r}}\ (K_{\mathrm{cmax}} - K_{\mathrm{cb}}) \quad (2)$$

where K_{r} is a dimensionless evaporation reduction coefficient that depends on the cumulative depth of water depleted from the topsoil. (Allen et al., 1998) and K_{cmax} is

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the maximum value of K_c following rainfall or irrigation. Since evaporation is restricted at any moment by the energy available at the exposed soil fraction, the value of K_e cannot exceed the product $f_{ew} \times K_{cmax}$, where f_{ew} is the fraction of the soil surface not covered by vegetation and wetted by irrigation or precipitation (Allen et al., 1998).

The K_{cb} in Eq. (1) may be derived from multiespectral vegetation indices obtained by remote sensing. VIs are transformations of two or more spectral bands designed to assess vegetation condition, foliage, cover, phenology and processes related to the fraction of photosynthetically active radiation absorbed by a canopy (fPAR) (Asrar et al., 1989; Baret et al., 1991; Glenn et al., 2008) VIs are also essential tools in land-cover classification, climate and land-use-change detection, drought monitoring and habitat loss, to name just a few applications (Glenn et al., 2008). SAVI (Soil Adjusted Vegetation Index, Huete, 1988) is one of the most used indices highlighting the ability of the index to minimize the effect of the soil on vegetation quantification. It was taken into account due to the positive results obtained in previous work (González-Dugo and Mateos, 2008). The SAVI index was calculated as follow:

$$\mathrm{SAVI} = \frac{(\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}})}{(\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}} + L)}(L+1) \quad (3)$$

where ρ_{NIR} and 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).

An equation described by González-Dugo et al. (2009) to compute the basal crop coefficient (K_{cb}) from SAVI was used in this study:

$$K_{cb} = \frac{K_{cbmax}}{f_{cbmax}}\left(\frac{\mathrm{SAVI} - \mathrm{SAVI}_{min}}{\mathrm{SAVI}_{max} - \mathrm{SAVI}_{min}}\right) \quad \text{if} \quad f_c < f_{cmax} \quad (4)$$

$$K_{cb} = K_{cbmax} \quad \text{if} \quad f_c \geq f_{cmax} \quad (5)$$

where f_{cmax} is the f_c at which K_{cb} is maximum (K_{cbmax}). Maximum SAVI and minimum SAVI values can be found in Table 1.

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A soil root-zone water balance was calculated by keeping track of the main incoming and outgoing water fluxes at the boundaries of the root zone in order to calculate K_e and K_s in Eq. (1). The root-zone depth (Z_r) was calculated as a function of K_{cb}.

$$Z_r = Z_{rmin} + (Z_{rmax} - Z_{rmin}) \frac{K_{cb}}{K_{cbmax}} \tag{6}$$

where Z_{rmax} and Z_{rmin} are the maximum effective root depth and the effective root depths during the early stages of crop growth (Table 1). The minimum effective root depth is treated here as the depth of the soil layer from which the seed can extract water to germinate, and a value of 0.4 m was adopted. The change in the root zone water content, ΔS_w, was calculated as the difference between the water inflows and outflows.

$$\Delta S_w = S_{wf} - S_{wi} = R - \mathrm{ET} - D \tag{7}$$

where S_{wf} and S_{wi} (mm) are the root-zone water content at the beginning and end of the water balance period, R is infiltrated rainfall and D is deep drainage, both during the water balance period. Eq. (7) may be expressed in terms of root-zone water deficit, calculated daily:

$$\mathrm{RZWD}_i = \mathrm{RZWD}_{i-1} + \mathrm{ET}_i + D_i - R_i \tag{8}$$

where the subscript i indicates a given day and RZWD_i and RZWD_{i-1} are the root-zone water deficits on day i and i-1, respectively.

It is understood that the root zone is full of water, RZWD = 0, when its water content is at field capacity, and that it is empty when the water content reduces plants to the wilting point. The root-zone water-holding capacity (RZWHC) is the depth of water between these two extremes.

The stress coefficient, K_s, is calculated on the basis of the relative root-zone water deficit as:

$$K_s = \frac{\mathrm{RZWHC} - \mathrm{RZWD}_i}{(1-p)\ \mathrm{RZWHC}} \quad \text{if} \ \ \mathrm{RZWD}_i < (1-p)\ \ \mathrm{RZWHC} \tag{9}$$

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$$K_s = 1 \quad \text{if} \quad \mathrm{RZWD}_i > (1-p) \quad \mathrm{RZWHC} \tag{10}$$

where p is the fraction of the RZWHC below which transpiration is reduced.

2.2 Description of experimental sites and model input data

2.2.1 Site description

Two experimental sites grown with wheat and corn were monitored during the 2008 (corn) and 2009 (corn and wheat) growing seasons (Fig. 1). Two contiguous drip-irrigated corn fields were selected in the Bembézar Irrigation Scheme of Hornachuelos (Province of Cordoba, southern Spain) for the consecutive field measurement campaigns. Both fields were large enough, 8 and 7.4 ha, respectively, to be clearly observed by a satellite remote sensor with a spatial resolution of 30 m, thus avoiding edge effects. The planting dates were 7 March 2008 and 5 March 2009 respectively, and PR31D58 corn was used in both seasons. The second site was a rainfed bread wheat field of 1.5 ha, located in the IFAPA Alameda del Obispo (City of Cordoba) experimental farm, where a weighing lysimeter has been in operation since 1985. It was planted on 19 December 2008 with the *Lubrican* cultivar. The Mediterranean climate of this area is characterized by an annual average precipitation of around 600 mm, very dry summers and average air temperatures of 10 °C in winter and 27 °C during the summer.

Soil properties such as texture and depth were measured in the wheat field and in one of the corn fields. Soil water content at field capacity and wilting point were derived from texture data using the Rosetta pedotransfer function model (Schapp et al., 2001). The same water content limits were used for both corn fields, in view of their close proximity and the similarity of their soil types.

Soil and crop parameters values used in the model applications are listed in Tables 1 and 2 respectively. Soil parameters such as the depth of soil surface evaporation layer (Z_e), readily evaporable water (REW) and total evaporable water (TEW) were adapted from values tabulated in Allen et al. (1998).

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2.2.2 Meteorological measurements

Daily and semi-hourly weather data for both sites were provided by two meteorological stations belonging to the Agroclimatic Information Network of Andalusia (RIA in Spanish) (Gavilán et al., 2008), with one station located inside the Bembezar Irrigation Scheme, and the second one 100 m from the wheat plot. The stations are controlled by a CR10X datalogger (Campbell Scientific, Logan, UT) and are equipped with sensors to measure air temperature and relative humidity (HMP45C probe, Vaisala, Helsinki, Finland), solar radiation (pyranometer SP1110 Skye Instruments, Llandrindod Wells, UK), wind speed and direction (wind monitor 05103, RM Young, Traverse City, MI) and rainfall (tipping bucket rain gauge ARG 100, Vector Instruments, Rhyl, UK).

2.2.3 Spectral data acquisition and processing

Field canopy reflectance measurements were performed using a hand-held radiometer (ASD-FieldSpec, Analytical Spectral Devices, Boulder, CO) over corn in 2008 season and wheat in 2009. The spectral range of the instrument, between 325 and 1075 nm (with a sampling interval of 1 nm), covered the visible and near-infrared (NIR) regions of the spectrum required for computing the vegetation indices and overlapping Landsat red and NIR spectral bands. Twenty-point regularly distributed measurements were taken over each field at midday and under cloudless conditions. Six additional measurements were taken over the weighing lysimeter surface inside the wheat experimental field. The reflectance spectrum was calculated as the ratio between the reflected and incident spectra on the canopy, obtaining the incident spectrum from the light reflected by a white reference panel close to a Lambertian surface (Spectralon, Labsphere, North Sutton, NH). SAVI index values were averaged for each day of measurement.

Satellite remote data were provided by TM and ETM+ sensors, onboard LANDSAT 5 and 7, during the 2009 corn and wheat seasons. All cloudless satellite images for both growing periods (a total of 13 images) were calibrated and geometrically

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and atmospherically corrected. The geometric correction was applied using reference ground control points acquired from a 1-m resolution ortho-photograph taken in 2004. At-surface reflectance was obtained from the correction of the shortwave bands of the images using the atmospheric radiative transfer model MODTRAN 4 (Berk et al., 1998).

A list of the sensors and dates used throughout the study for both crops is shown in Table 3.

2.3 Validation data

The model was validated using field measurements of soil moisture and ET. ET was measured using two different instrumentation sets; an eddy covariance system (EC) mounted on a micrometeorological flux tower, and a weighing lysimeter.

2.3.1 Eddy covariance measurements and adjustment of turbulent fluxes

Half-hourly sensible (H) and latent (LE) heat fluxes over the corn plot were measured using an eddy covariance system consisting of a Datalogger CR23X (Campbell Scientific), a three-axis sonic anemometer CSAT3 (Campbell Scientific), a fine thermocouple (model 127, chromel-constantan 0.013 mm diameter) attached to the anemometer, a krypton hygrometer KH20 (Campbell Scientific), a net radiometer Q-7.1 (Radiation and Energy Balance Systems, Seattle, WA), two soil heat flux plates HFP01 (Hukseflux Thermal Sensors, Delft, The Netherlands) and four parallel soil thermocouples (TCAV). The distance between the sonic anemometer and the hygrometer measuring paths was 0.20 m, and both were located at a height of $z = 1.5$ m, above the canopy. Sampling frequency was 10 Hz. Fetch was at least around 200 m in all directions. Corrections were applied to latent heat flux to account for air density fluctuations due to heat and vapor transfer (Webb et al., 1980; Tanner et al., 1993) and O_2 radiation absorption (Tanner et al., 1993). The net radiometer was located 1.5 m above the canopy and net radiation data (R_n) were corrected for wind speed measured with the sonic anemometer according to the manufacturer's recommendations. Soil heat flux (G) was determined at two locations (within the row and midway between rows). The combination method (Fuchs and Tanner, 1967) was employed, using the measurement of soil thermocouples at 0.02 and 0.06 m and heat flux measured with the soil heat flux plates at 0.08 m. Measurements of R_n and G were performed at 10 s intervals and the mean reading was recorded half-hourly. The system was installed on the corn field between 28 April and 4 September 2008 and from 16 May until 29 August 2009, measuring continuously except on rainy days.

Detailed studies have shown how the eddy covariance technique underestimates turbulent fluxes, a finding that has been attributed to many different factors (Massman and Lee, 2002). Twine et al. (2000) compared different energy-balance closures; EC measurement of H and LE fluxes can be adjusted for closure, maintaining the Bowen ratio or forcing closure, assuming that H is accurately measured and solving LE as a residual to the energy balance equation ($\mathrm{LE} = R_n - H - G$). Brotzge and Crawford (2003) suggested residual LE closure as the best eddy covariance approach because the Bowen ratio technique tends to underestimate LE under highly evaporative conditions. We therefore calculated daily ET values by forcing closure of the energy balance using the residual-LE closure method, and an average closure of 80% was obtained.

2.3.2 Weighing lysimeter

Wheat ET was measured by a weighing lysimeter located in the center of the plot. The surface dimensions of the lysimeter tank are $2 \times 3\,\mathrm{m}^2$ and the depth is 1.5 m. It is supported by a counter-weighted platform scale capable of detecting changes in weight of about 0.1 kg (equivalent to 0.02 mm water depth over the lysimeter surface). The lysimeter weight was sensed by a load cell (model TSF-P, Epel Industrial S.A., Alcala Guadaira, Spain) connected to a Datalogger CR10X (Campbell Scientific) and set to measure semi-hourly ET. The outputs were obtained as the average of 120 readings taken every 2 s over a 4-min period centered at the respective sampling times, so that fluctuations in weight due to wind friction on the lysimeter surface were smoothed (Berengena and Gavilán, 2005). Only measured ET from rainless days were used for

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comparison purposes. During the data-acquisition period (17 January to 25 June 2009) the lysimeter was drained twice (DOY 42 and 76), on neither of which days its measurements were used. Table 4 presents a summary of the validation sites.

2.3.3 Soil water content

Soil water content was calculated as the difference between wet and dry weight of soil samples taken at intervals of 9–19 days throughout the wheat and corn-growing season. Four randomly distributed samples were taken each measurement day. The samples were taken at a depth of 120 cm and were extracted as 30 cm-deep layers. The direct weight of these samples represented the wet weight. The samples were placed in an oven at 105 °C for two days to obtain the dry weight.

3 Results

3.1 ET estimation using field radiometry data

Daily measured ET fluxes were first compared with daily estimated ET using the hand-held radiometer measurements to assess the basal crop coefficient. Fig. 2 shows daily estimated ET from the model and daily measured ET in corn (2008) using the eddy covariance system, and wheat (2009) using the weighing lysimeter.

The performance of the model was measured using the root mean square difference (RMSD) between estimated and measured ET values and the coefficient of determination. RMSD values of 0.79 and 0.67 mm d^{-1} were obtained for corn and wheat respectively. These values are slightly higher than those presented by other authors in earlier studies of the same herbaceous crops. Er-Raki et al. (2007) and González-Dugo et al. (2009) found differences close to 0.5 mm d^{-1}. The poorer performance found here does not appear to be significant and could be explained by differences in meteorological data quality and/or management practices. The model showed a trend

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to overestimate daily ET of 8 and 11% in corn and wheat respectively. A higher dispersion can be observed in corn for low ET values, suggesting the possibility that at the beginning of the growing cycle, when lower ground-crop cover tends to be lower, field-measured SAVI was less representative of average values for the area covering the flux tower footprint than those measured for higher coverage. This problem was not encountered with wheat, where six radiometric measurements were taken over the lysimeter area (plot size 6 m^2) The coefficients of determination (r^2) were of 0.92 for both crops, slightly higher than the good correlations presented by other authors for herbaceous and woody crops, including corn, $r^2 = 0.70$ (González-Dugo et al., 2009), wheat, $r^2 = 0.64$–0.86 (Er-Raki et al., 2007) and vines, $r^2 = 0.86$ (Campos et al., 2010). The soil water-content measurements were used to validate the water balance employed in the calculation of K_e and K_s. This may be regarded as an alternative validation of the complete ET computing procedure. Fig. 3 shows the comparison between the model-estimated root-zone water deficit and the real deficit obtained from soil samples, where good agreement exists between the estimated and measured deficit. The trend of the estimated deficit matches the measured data reasonably well, irrespective of whether or not particular corrrespond to the general behavior of the model.

3.2 Satellite scale ET assessment

TM and ETM+ sensors were used to derive the SAVI index as periodic input to the FAO56 model. The comparison between daily estimated and measured ET is shown in Fig. 4. An RMSD of 1 $mm\,d^{-1}$ was obtained for corn during this second season. Both RMSD and the 9% overestimation are similar to 2008 corn season values. The computed SAVI represented an average of 7.4 ha, discounting field-border pixels, and taking into account the variability within the field. An RMSD of 0.47 $mm\,d^{-1}$ and $r^2 = 0.91$ was obtained for wheat using satellite inputs. The model showed a tendency to overestimate ET by four percent. The comparison between modeled root-zone water deficit values and measured values on this scale is shown in Fig. 5. The reasonable agreement in Fig. 5 indicates that the model estimates the root-zone water deficit under

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both rain-fed and irrigated conditions. However the model's estimation ability is better under non-irrigated conditions, a simpler situation where the possibility of mismatches between model input and actual amounts of irrigated water may represent a source of error.

3.3 Water stress monitoring of crops

A further step in irrigation water management is the monitoring and control of crop water stress, essential to guarantee high yields under water scarce situations. It is also required in deficit irrigation systems and to improve fruit or grain quality in certain crops. The degree of water stress can be approximated by following the development of modeled K_s coefficients. Only satellite-based campaigns have been used for this analysis, due to the better representativity of SAVI values provided by these sensors. According to FAO-56 methodology, K_s values lower than unity indicates that the crop is suffering water stress. Fig. 6 shows the stress and basal crop coefficients for wheat and corn throughout the growing season. Two periods of water stress can be observed in Fig. 6a for irrigated corn. A mild one occurred between 18 and 20 May 2009, close to the end of the rapid growth stage and two days before the start of irrigation. According to the growth dynamic followed by the crop, represented by K_{cb} curve in Fig. 6a, and the reasonably good tolerance of corn plant to soil water stress during this stage (Doorembos and Kassam, 1979), it had no consequences for the final yield. During the reproductive stage, the most critical period, enough water was available for the plant, but a second period of water stress was observed during the late season, 15 days before harvest. This was the consequence of a common management practice in this area, where most local farmers apply the final irrigation 15 to 20 days before the grain ripens, in order to save water and given the relative tolerance of the crop to water stress during maturity (Doorembos and Kassam, 1989). However, this dry period was too prolonged and probably contributed to a reduction in yield that in this particular field was around 20% lower than the 12 500 $kg\,ha^{-1}$ local average (CAP 2009).

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The water stress for wheat affected the entire grain-filling stage, Fig. 6b, corresponding to Zadoks stages 7–9 (Zadoks et al., 1974). A lack of water at these stages is known to have a significant effect on grain filling, resulting in lower yields (Rawson and Gómez, 2000). In this case, the harvested yield of 2100 kg ha^{-1} was 28% lower than the figure provided by regional agriculture statistics for wheat (CAP, 2009) in this area, a result that could be explained by the observed stress. The cumulative soil water content during the winter was not enough to satisfy the evapotranspiration demand of the final two months of the growing season. The 200 mm of water applied during the month of May would have satisfied the water requirement of the crop and helped to increase the yield.

4 Conclusions

The results of daily ET obtained for both crops using crop coefficients calculated using field and satellite derived remote vegetation indices were generally consistent with measurements. The modeled results compared well with both ET measurement systems, EC and lysimeter, showing average overestimates of 8%. The model was also capable of tracing a soil water deficit curve in agreement with point measurements of soil moisture.

The use of satellite-borne sensors permitted low-cost, large-scale acquisition of distributed vegetation indices, without any loss of accuracy in final ET estimation, thus avoiding problems of representative field measurements for low plant ground coverage. The extension of the method to larger areas using satellite inputs is hindered by the need for a daily water balance that requires accurate soil and irrigation information, which is difficult to gather on a large scale. However, Diaz et al. (2009) have proposed a simplification of water balance calculating a synthetic crop coefficient that accounts for the main effects of rain and irrigation soil wetting on ET that could permit an upscaling of this model, reducing its data requirements.

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Analysis of trends in the stress coefficient derived from the water balance provided valuable information about the use of water in both crops along the growing season, helped to quantify the incidence of water stress during individual growth stages and provided insights into its relationship with final yields under both rainfed and irrigated conditions.

This methodology can be used to perform water stress analyses and to decide when and how much to irrigate. The combination of remote sensing-derived basal crop coefficients with the FAO methodology could be an important tool for estimating water requirements and improve water management at irrigation-scheme and basin scales.

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Table 1. Crop parameter used for deriving the crop coefficients and computing the water balance following the procedure described in FAO Irrigation and Drainage Paper No. 56 (Allen et al., 1998).

Parameter	Corn 2008	Corn 2009	Wheat 2009
Maximum crop height (m)	2.6	2.6	0.92
Maximum effective root depth (m)	1.35	1.35	1.25
Minimun effective root depth (m)	0.4	0.4	0.4
$SAVI_{max}$	0.65	0.65	0.7
$SAVI_{min}$	0.07	0.07	0.09
Maximum effective root coefficient[a]	1.11	1.13	1.06
Ground cover fraction for K_{cbmax}	80	80	80

[a] Typical values adjusted for local relative humidity and wind speed.

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Table 2. Soil Parameters used for computing the water balance following the procedure described in Allen et al. (1998), being θ_{FC} the soil water content at field capacity, θ_{WP} the soil water content at wilting point, Z_e the depth of soil surface evaporation layer, REW the readily evaporable water and TEW the total evaporable water.

Parameter	Θ_{FC}($m^3\,m^{-3}$)	Θ_{WP}($m^3\,m^{-3}$)	Z_e (m)	REW (mm)	TEW (mm)
Corn (2008–2009)	0.255	0.09	0.1	10	24
Wheat (2009)	0.23	0.085	0.1	10	24

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Table 3. Sensors and dates used for monitoring corn and wheat fields during 2008 and 2009 growing season.

Corn				Wheat			
2008 growing season		2009 growing season		2009 growing season		2009 growing season	
DOY	Sensor*	DOY	Sensor	DOY	Sensor*	DOY	Sensor
91	ASD	67	ETM+off (L7)	43	ASD	11	TM (L5)
105	ASD	99	ETM+off (L7)	56	ASD	43	TM (L5)
115	ASD	123	TM (L5)	71	ASD	67	ETM+off (L7)
143	ASD	147	ETM+off (L7)	78	ASD	99	ETM+off (L7)
158	ASD	163	ETM+off (L7)	96	ASD	123	TM (L5)
169	ASD	171	TM (L5)	113	ASD	147	ETM+off (L7)
185	ASD	203	TM (L5)	125	ASD	163	ETM+off (L7)
200	ASD	219	TM (L5)	139	ASD	171	TM (L5)
217	ASD	227	ETM+off (L7)	175	ASD		
233	ASD	235	TM (L5)	178	ASD		
261	ASD	243	ETM+off (L7)	184	ASD		

* ASD = Field measurements with a hand-held radiometer ASD-FieldSpec.

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Table 4. Summary of the model validation fields including location, crop, growing season, remote sensors type and validation system.

Location	Crop	Year	Remote sensor type	Validation system
Hornachuelos	Corn	2008	Field radiometer	Eddy covariance
Hornachuelos	Corn	2009	Satellite sensor	Eddy covariance
Córdoba	Wheat	2009	Field radiometer	Lysimeter
Córdoba	Wheat	2009	Satellite sensor	Lysimeter

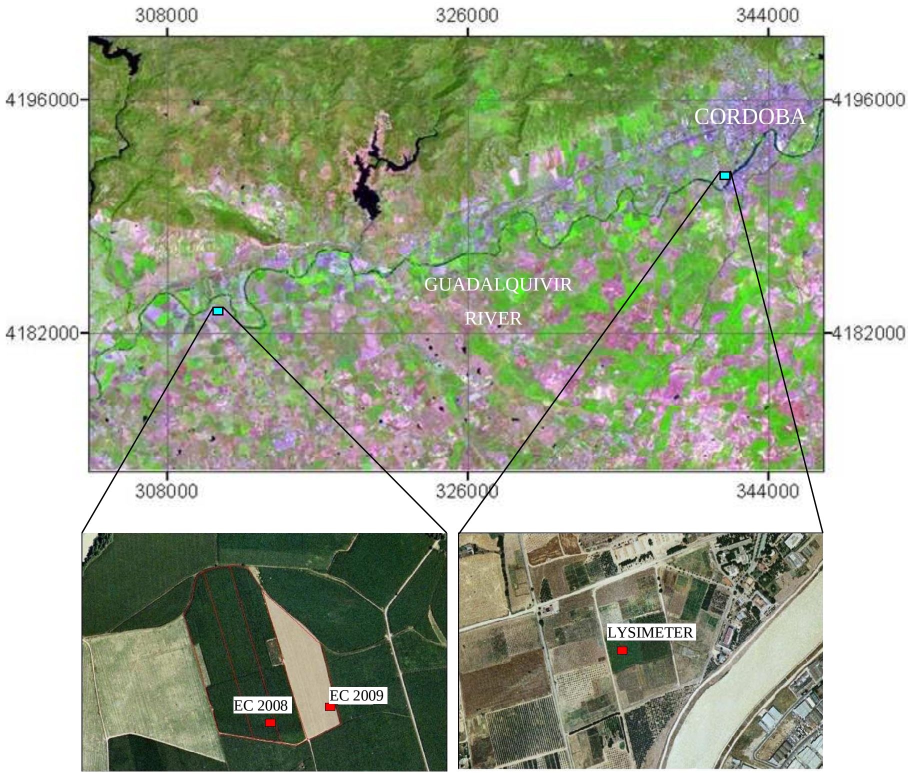

Fig. 1. (5-4-3) composite of the Landsat TM-5 image (3 May 2009; DOY 123) and a high resolution ortho-photography (2004) showing the fields that contained the eddy covariance flux stations (2008 and 2009) and the weighing lysimeter (2009).

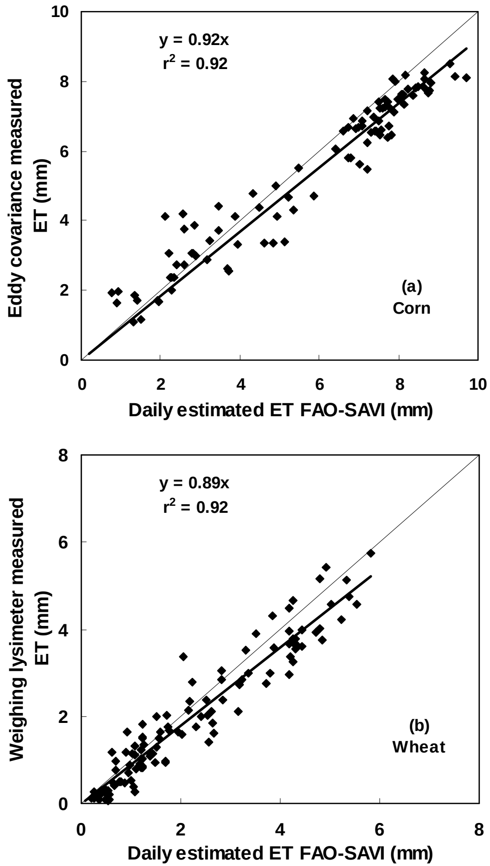

Fig. 2. Daily measured and estimated ET and measured for corn (2008) **(a)** and wheat (2009) **(b)** using a radiometer-estimated K_{cb}. The thin solid diagonal line represents the 1:1 line, while the dark line segment represents the linear regression through the points.

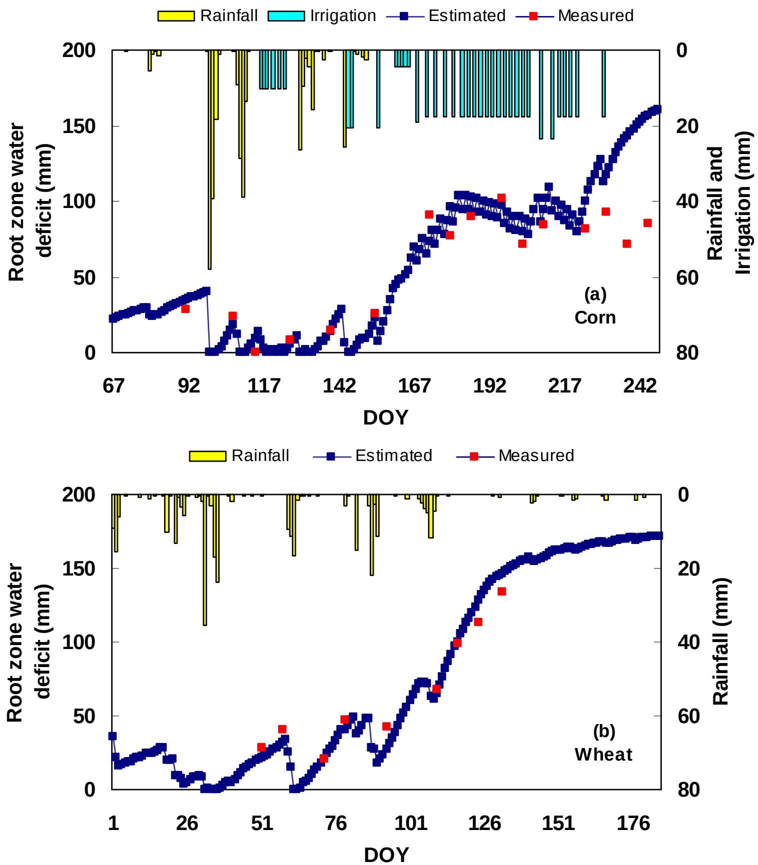

Fig. 3. Daily measured and estimated root zone water deficit for corn (2008) **(a)** and wheat (2009) **(b)** using a radiometer-estimated K_{cb}

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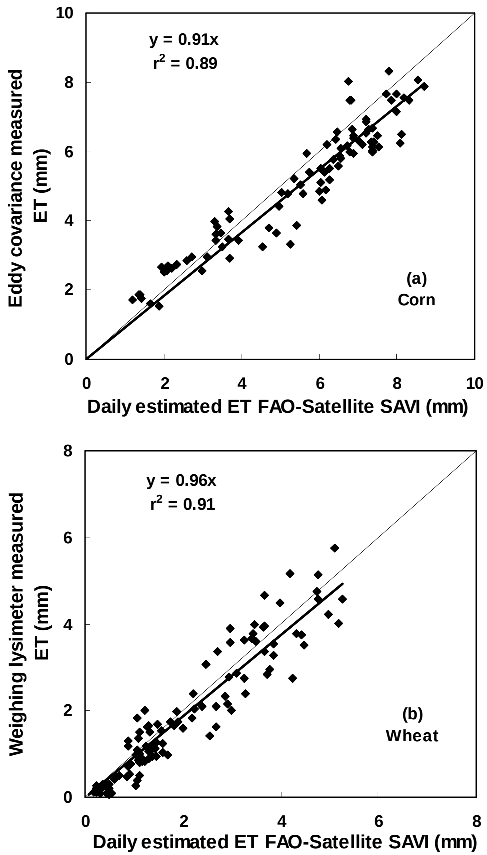

Fig. 4. Daily measured and estimated ET for corn (2009) **(a)** and wheat (2009) **(b)** using a satellite-estimated K_{cb}. The thin solid diagonal line represents the 1:1 line, while the dark line segment represents the linear regression through the points.

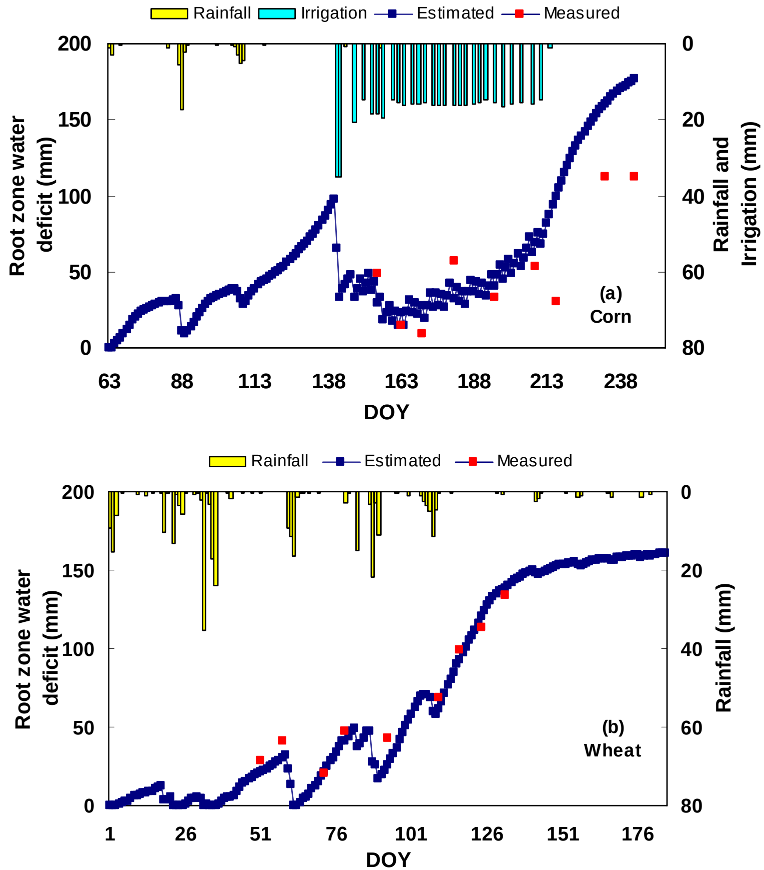

Fig. 5. Daily measured and estimated root zone water deficit for corn (2009) **(a)** and wheat (2009) **(b)** using a satellite-estimated K_{cb}

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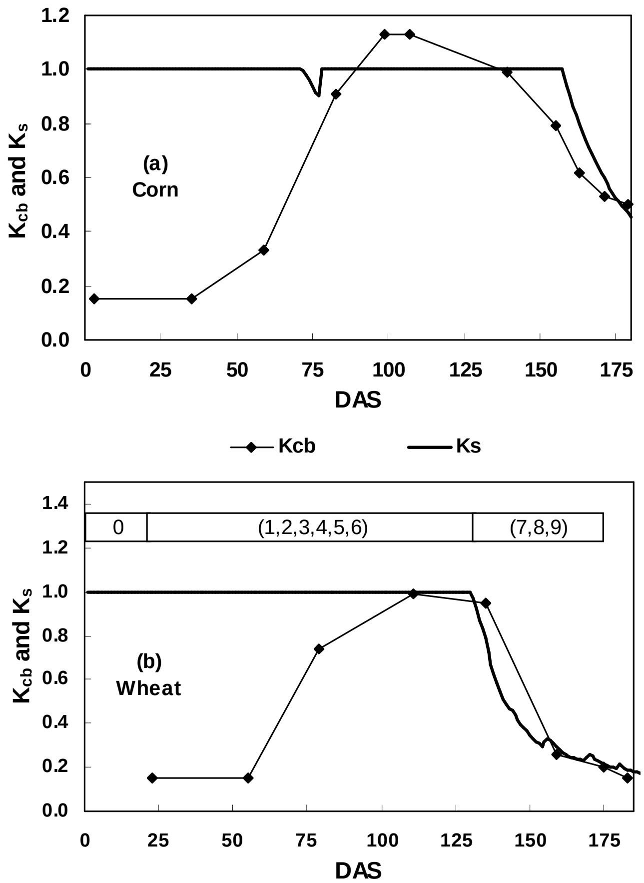

Fig. 6. Satellite-estimated basal crop coefficient and stress coefficient for corn (2009) **(a)** and wheat (2009) **(b)**. The figure “b” also shows the Zadoks stages for wheat.

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