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Determining irrigation needs of sorghum from two-source energy balance and radiometric temperatures

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Abstract

Estimates of surface actual evapotranspiration (ET) can assist in predicting crop water requirements. An alternative to the traditional crop-coefficient methods are the energy balance models. The objective of this research was to show how surface temperature observations can be used, together with a two-source energy balance model, to determine crop water use throughout the different phenological stages of a crop grown. Radiometric temperatures were collected in a sorghum (*Sorghum bicolor*) field as part of an experimental campaign carried out in Barrax, Spain, during the 2010 summer growing season. Performance of the Simplified Two-Source Energy Balance (STSEB) model was evaluated by comparison of estimated ET with values measured on a weighing lysimeter. Errors of $\pm 0.14\,\mathrm{mm\,h^{-1}}$ and $\pm 1.0\,\mathrm{mm\,d^{-1}}$ were obtained at hourly and daily scales, respectively. Accumulated crop water use during the campaign resulted 500 mm versus the total 524 mm measured by the lysimeter. It is then shown that thermal radiometry can provide precise crop water necessities and is a promising tool for irrigation management.

1 Introduction

Understanding the surface actual evapotranspiration (ET) is essential for managers responsible for planning and managing water resources, especially in arid and semi-arid regions where crop water demand generally exceeds precipitation and irrigation from surface and/or groundwater resources is then required to meet the deficit. This is particularly sensitive in areas where water usage is regulated due to ecological protection programs, limited resources, or competitive demand (Piccinni et al., 2009).

Increasing demand for sustainable production of biofuels such as ethanol is currently driving intense research and discussion. Even though these technologies still face some important technical and economic challenges, energetic crops are expected to become a relevant energy source in the near future (Álvarez et al., 2010). Different crops have been explored experimentally and commercially, such as maize or sorghum.

Production of energetic crops involves changes in land uses that might compromise the water conservation strategies. This is of utmost importance in regions such as Castilla-La Mancha in central Spain, where determining crop water requirements specific to each crop is key in providing growers with information to select which crops to grow and determine the timing and quantity of irrigation events throughout the growing season (Montoro et al., 2010).

Actual evapotranspiration varies regionally and seasonally according to weather conditions. The use of on-site meteorological data and crop coefficients enables the determination of crop water use. However, generic crop coefficients will not fulfill the need for precise irrigation applications, and specific crop coefficients need to be developed (López-Urrea et al., 2009a, b, c). This can be a limitation for providing spatially distributed regional ET information. Remote sensing has long been recognized as a feasible means to achieve this goal. The basis of remote sensing techniques is to determine ET as a residual of the land surface Energy Balance Equation (EBE), using the surface temperature as a key input (e.g. Bastiaanssen et al., 1998; Su, 2002).

The utility of the crop surface temperature to detect crop water stress (Pinter et al., 2003; Gardner et al., 1992; Jackson et al., 1981), and the EBE to estimate daily evapotranspiration, has been already demonstrated (Hatfield et al., 1983; Kustas and Norman, 1996; Pinter et al., 2003; Gavilan and Berengena, 2007). Some authors such as Faver et al. (1989) or Choudhury and Idso (1985) used canopy temperature together with the Penman-Monteith equation to estimate crop ET. These authors reported high correlation between lysimeter ET and modeled ET from sorghum and wheat for selected days. Similar results were also found by Hatfield et al. (1983) and Jackson et al. (1983) but now focusing on a particular time of day. More recently, Bashir et al. (2008) used the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), together with Landsat/ETM+ and MODIS images to estimate ET of a large irrigated sorghum area. Comparison with ET calculated using the water balance approach, for 4 selected days, showed an average absolute error around $0.9\,\mathrm{mm\,d^{-1}}$. However, SEBAL requires heterogeneity in surface moisture conditions

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and is not applicable to small crop fields. These and some other problems have been pointed out due to difficulties in quantification of aerodynamic resistances, especially under partial fraction cover conditions (Hall et al., 1992). Two-Source Energy Balance models solved many of these limitations by allowing the estimation of soil and canopy contributions to the total energy fluxes, including evapotranspiration (Norman et al., 1995; Li et al., 2005).

One of the objectives of this paper is to show the potential of the Simplified Two-Source Energy Balance model (STSEB) (Sánchez et al., 2008, 2009), together with radiometric surface temperature measurements, to determine accurate ET values under a variety of fraction cover conditions. In this work we focus on a forage sorghum field located in "Las Tiesas" experimental site in Barrax, Spain. A field campaign was carried out in the summer growing season of 2010 with the aim of studying water balance techniques and water necessities of energetic crops. A weighing lysimeter was placed in this site to register sorghum ET values, and two Infrared Thermal radiometers (IRT) were installed to measure surface temperatures.

The second objective of this study is to present this method as a simple and feasible technique to determine short and long-term crop water use from thermal infrared radiometry and ancillary meteorological data, under clear and cloudy sky conditions, and covering all stages of the crop development.

This paper is organized as follows. Information related to the study site, experimental set-up, and measured variables and parameters, is presented in Sect. 2. A summary of the main equations and aspects of the STSEB approach is given in Sect. 3. Section 4 shows the analysis of the measured radiometric temperatures and the estimated surface energy fluxes in the sorghum field. Modeled values of hourly and daily ET, together with the comparison with lysimeter ET measurements, are included in this Section. Finally, main conclusions are given in Sect. 5.

2 Study site and materials

This study was conducted during the summer of 2010 in the “Las Tiesas” farm, located between Barrax and Albacete (Central Spain). Its geographical coordinates are: longitude 2°5′ W, latitude 39°14′ N, and its altitude is 695 m above sea level) (Fig. 1a). The climate is semi-arid, Temperate Mediterranean with 320 mm of annual rainfall, mostly concentrated in the spring and fall. Average mean, maximum and minimum temperatures are: 13.7, 24.0 and 4.5 °C, respectively. For a more detailed description of the climate of the area see López-Urrea et al. (2006).

The soil is classified as Petrocalcic Calcixerepts (Soil Survey Staff, 2006). Average soil depth of the experimental plot was 40 cm, and is limited by the development of a more or less fragmented petrocalcic horizon. Texture is silty-clay-loam, with 13.4% sand, 48.9% silt and 37.7% clay, with a basic pH. The soil is low in organic matter and in nitrogen, and has a high content of active limestone and potassium.

To determine actual forage sorghum (*Sorghum bicolor* (*L*) Moench cv. H-133) ET, a weighing lysimeter was used (Fig. 1b). To schedule irrigation ET_c values were calculated from daily mass loss minus drainage loss and the mass added from irrigations and/or rainfall. In the lysimeter lost water was replaced, maintaining non-limiting soil water content. The lysimeter is located in the center of a 100 m × 100 m plot, where sorghum sowed on 27 May in 2010 (DOY 147) in rows (N-S orientated) of 35-cm spacing. Plant population was 21 plants m^{-2}. Plant samples from three separate areas were obtained periodically to measure crop development. Leaf area index (LAI), fractional vegetation cover (P_v), and crop height (h) were measured from the three samples. Sorghum reached a maximum crop height of nearly 5 m, a maximum LAI of 11 $m^2\,m^{-2}$, and the final harvest dry matter was over 3 kg m^{-2}. Field harvest was on 23 September in 2010 (DOY 265).

The whole plot has a permanent sprinkler irrigation system with sprinklers placed on a grid of 15 × 12.5 m that provide a precipitation rate of 8.6 mm h^{-1}. The lysimeter container is 2.7 m long, 2.3 m wide and 1.7 m deep, with an approximate total weight of

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14.5 Mg. Efforts were made to keep the crop inside the lysimeter at the same growth rate and plant population (21 plants m^{-2}) as the crop outside to minimize edge effects. The lysimeter soil-containing tank sits on a system of scales with a counterweight that offsets the dead weight of the soil and the tank. The de-multiplication factor of the system is 1000:1. A steel load cell (model SB2, Epelsa[1] Ind., S.L.) is connected to the system of balances. The scales beams allow measurements of ET in the lysimeter with a resolution of 0.04 mm equivalent water depth. The sample frequency was 1 s, and a reading was registered by a datalogger (CR10X, Campbell Scientific Ltd., Logan, Utah, USA) every 15 min. Additional information about the technical features of the lysimeter may be found in López-Urrea et al. (2006). The lysimeter readings were checked daily to identify individual readings that were not explained by natural processes of water input and loss. Data losses occurred during irrigation and precipitation events, weight and calibration verifications, and once, when the soil inside the lysimeter tank was cultivated. The resulting data was compiled to obtain the measurement of sorghum ET.

Starting on 19 June (DOY 174), radiometric surface temperature was measured, using an Apogee SI-211 thermal Infrared Radiometer (IRT). This radiometer has a broad thermal band (6–14 µm) with an accuracy of ±0.3 °C, and 28° field of view. It was placed at a height of 2 m above the canopy level at anytime, looking at the surface with nadir view (Fig. 1c, d). Sky brightness temperature was measured by a second 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. The calibration was done using a blackbody source (Model Land P80P). The calibration encompassed a wide range of temperatures (−5 to 50 °C), exceeding those experienced in the field. Unfortunately, measure of surface temperature failed after 9 September (DOY 249), reducing our study period to 75 days.

Solar irradiance (model CM14, Kipp & Zonen Delft, Holland) and incoming long-wave radiance (model CG2, Kipp & Zonen Delft, Holland), wind speed (model A100R, Vector Instruments Ltd., UK), air temperature and relative humidity (model MP100, Campbell Scientific, Logan, UT) were measured 2 m above local terrain at an adjacent weather

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station placed over an irrigated fescue grass surface. Reference evapotranspiration, ET_o, was also determined using the FAO56 Penman-Monteith method (Allen et al., 1998).

1Trade and company names are given for the benefit of the reader and imply no endorsement by the authors.

3 Model description

The net energy balance of the soil-canopy-atmosphere system 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 ($W\,m^{-2}$), λET is the latent heat flux ($W\,m^{-2}$), and G is the soil heat flux ($W\,m^{-2}$). Some other minor terms such as photosynthesis, advection or canopy storage have been neglected in Eq. (1). The effective radiometric surface temperature in the same system, T_R (K), can be obtained as a weighted composite of the soil temperature, T_s (K), and the canopy temperature, T_c (K):

$$T_R = \left[\frac{P_v(\theta)\varepsilon_c T_c^4 + (1 - P_v(\theta))\varepsilon_s T_s^4}{\varepsilon} \right]^{1/4} \tag{2}$$

where ε_c, and ε_s, are the canopy and soil emissivities, respectively, ε is the effective surface emissivity, and $P_v(\theta)$ is the fractional vegetation cover for the viewing angle θ.

In this work, a Simplified version of a Two-Source configuration of the Energy Balance (STSEB) (Sánchez et al., 2008) was used. According to this approach, the addition between the soil and canopy contributions (values per unit area of component) to the total sensible heat flux, H_s and H_c, respectively, are weighted by their respective partial areas as follows:

$$H = P_v H_c + (1 - P_v) H_s \tag{3}$$

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where P_v (without a view angle argument) refers to the fraction cover at nadir view (i.e. $\theta = 0^o$). In Eq. (3), H_s and H_c are expressed as:

$$H_c = \rho C_p \frac{T_c - T_a}{r_a^h} \tag{4a}$$

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

where ρC_p is the volumetric heat capacity of air ($\mathrm{J\,K^{-1}\,m^{-3}}$), T_a is the air temperature at a reference height (K), r_a^h is the aerodynamic resistance to heat transfer between the canopy and the reference height at which the atmospheric data are measured ($\mathrm{m\,s^{-1}}$), r_a^a is the aerodynamic resistance to heat transfer between the point $z_{0M} + d$ (z_{0M}: canopy roughness length for momentum, d: displacement height) and the reference height ($\mathrm{m\,s^{-1}}$), r_a^s is the aerodynamic resistance to heat flow in the boundary layer immediately above the soil surface ($\mathrm{m\,s^{-1}}$). A summary of the expressions to estimate these resistances can be seen in Sánchez et al. (2008). Equations (4a) and (4b) are taken from the parallel configuration of the TSEB model (Norman et al., 1995; Li et al., 2005), modified to take into account the distinction between r_a^h and r_a^a.

The partitioning of the net radiation flux, R_n, between the soil and canopy is proposed as follows:

$$R_n = P_v R_{nc} + (1 - P_v) R_{ns} \tag{5}$$

where R_{nc} and R_{ns} are the contributions (values per unit area of component) of the canopy and soil, respectively, to the total net radiation flux. They are estimated by establishing a balance between the long-wave and the short-wave radiation separately for each component:

$$R_{nc} = (1 - \alpha_c) S + \varepsilon_c L_{sky} - \varepsilon_c \sigma T_c^4 \tag{6}$$

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$$R_{ns} = (1-\alpha_s)S + \varepsilon_s L_{sky} - \varepsilon_s \sigma T_s^4 \quad (7)$$

where S is the solar global radiation ($W\,m^{-2}$), α_s and α_c are soil and canopy albedos, respectively, σ is the Stefan-Boltzmann constant, and L_{sky} is the incident long-wave radiation ($W\,m^{-2}$).

A similar expression is used to combine the soil and canopy contributions, λET_s and λET_c, respectively, to the total latent heat flux:

$$\lambda ET = P_v \lambda ET_c + (1-P_v)\lambda ET_s \quad (8)$$

According to this framework, a complete and independent energy balance between the atmosphere and each component of the surface is established, from the assumption that all the fluxes act vertically. In this way, the component fluxes to the total latent heat flux can be written as:

$$\lambda ET_c = R_{nc} - H_c \quad (9)$$

$$\lambda ET_s = R_{ns} - H_s - \frac{G}{(1-P_v)} \quad (10)$$

Finally, G can be estimated as a fraction (C_G) of the soil contribution to the net radiation (Choudhury et al., 1987):

$$G = C_G(1-P_v)R_{ns} \quad (11)$$

where C_G can vary in a range of 0.2–0.5 depending on the soil type and moisture.

4 Results

4.1 Radiometric temperatures

Growth cycle of the sorghum plants was captured by interpolation from the periodic measurements taken over the course of the experiment. A third order regression equation was used for the canopy height (Fig. 2a). For the fraction cover, measured values

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also fitted a third order equation for $P_v < 1$, whereas a constant value of $P_v = 1$ was assumed from DOY 200 to the end of the experiment (Fig. 2b). Under these conditions of full vegetation coverage the two-source scheme becomes a single-source approach, with the vegetation as the only component exchanging energy with the atmosphere. Then, $T_R = T_c$ in Eq. (2), and transpiration is responsible of the total ET of the crop system. Also, differences between T_c and T_a are less than 1 °C for non-stressed canopies, which yields minor values for the sensible heat flux. Under these conditions λET becomes the dominant flux in the right term of Eq. (1). Since soil temperature measurements were not available in this study, for partial cover conditions we assumed $T_c \sim T_a$ and T_s was inferred from Eq. (2) together with the measured T_R values.

Apogee IRT measurements were corrected for emissivity and atmospheric effect using the radiative transfer equation adapted to ground measurements (Sánchez et al., 2008). Values of $\varepsilon_c = 0.985 \pm 0.011$ and $\varepsilon_s = 0.960 \pm 0.013$ were used for this study (Rubio et al., 2003). Effective emissivity, ε, was calculated following the method proposed by Valor and Caselles (1996) (see Fig. 2b). The downwelling long-wave radiance, required for the atmospheric correction, was determined from the IRT values registered by the second Apogee pointing to the sky (Rubio, 1998). Thanks to the wide field of view of the Apogee radiometers, and the deployment configuration, sampled values of T_R, and estimated values of T_s, weighted for the sunlit and shaded portions of the two components.

Figure 3 shows two examples of the diurnal evolution of the gradient T_R–T_a, one for intermediate vegetation cover when the soil component is still visible (DOY 185), and another for full cover conditions (DOY 236). Surface temperature was generally warmer than air temperature during the middle of the day. This difference was minimum for full vegetation cover conditions (<1 °C), and increased with the amount of soil exposed (Fig. 3). Irrigation was scheduled according to the water loss determined by the lysimeter throughout the growing season to ensure enough water availability for transpirational cooling, avoiding plant water-stress and then warming of the canopy temperature. At night, thermal inversion appeared and surface temperature was 2–3 °C cooler than air temperature. This difference was even higher for rainfall or irrigation events. These temperature gradients control the exchange of H between the surface and the atmosphere, adding or reducing energy to the available R_n.

4.2 Modelled ET

Surface temperature was used, together with registered solar radiation and down-welling long-wave radiation, to calculate R_n from Eqs. (5) and (6). Values 0.13 and 0.23 (Castrignanò et al., 1997) were used for the soil and canopy albedo, respectively, although possible changes in albedo are possible. Wind speed measurements from the adjacent weather station were used to calculate the aerodynamic resistances required in Eqs. (3) and (4). These resistances together with the surface and air temperature data yielded H results. A value of $C_G = 0.2$ was assumed in Eq. (9) to estimate G values.

Figure 4 shows hourly values of all flux components in Eq. (1). Note that, as a residual of the EBE, λET is principally controlled by R_n and modulated by H. For our study period most available energy was partitioned to λET. H was the dominant term for first weeks after planting, when the fraction cover was still very low, but unfortunately measure of T_R started on DOY 174 and data are not available for that period.

Values of latent heat flux were converted in ET values, dividing by the latent heat of vaporization, λ, and compared to ET water loss registered by the lysimeter. Figure 5 shows two examples of the diurnal evolution of these hourly ET values. STSEB estimations of ET matches the measured ET values under a wide range of vegetation cover fractions. Note that energy balance models yield ET values also under rainfall or irrigation conditions when the lysimeter measure is compromising.

Since night-time ET was generally negligible, hourly averages between 7 and 21 h were used for the quantitative test of the STSEB model. With this filtering we tried to avoid events such as irrigation (around midnight) or early morning dew. Rainfall events were also excluded from the hourly analysis. More than 1000 single observations were used for the comparison of the diurnal ET values (Fig. 6a). Besides the linear regression, the accuracy of prediction was quantified using the Root Mean Square Deviation (RMSD) between estimated and measured ET values. The systematic deviation was illustrated by the biased estimator (Bias), and the relative error by the Mean Absolute Percentage Difference (MAPD) (Willmott, 1982). STSEB model reproduced lysimeter hourly ET measurements with negligible systematic deviation, and a RMSD of 0.14 mm h^{-1}.

Beyond the performance of a model at an instantaneous scale, what is really important from the point of view of the irrigation planning or the water saving is the capacity of a model to predict daily ET values, and further cumulative water loss by evapotranspiration. Figure 7 shows the evolution of the daily ET values modelled and measured for the experiment duration. For a first stage, when the energy balance was still influenced by the exposed soil surrounding the sorghum plants, the average trend of daily ET was to increase with the vegetation fraction cover. Daily ET peaked by middle July, with values reaching 10 mm d^{-1}, and then decreased until beginning of September. Lowest daily ET values, close to 2 mm d^{-1}, were observed for some cloudy and rainy days by middle August. A total of 73 days were used for the quantitative comparison, with the only exclusion of rainy days with registered rainfall amounts over 5 mm. Modelled values underestimated 0.3 mm d^{-1} lysimeter daily ET measurements, with a RMSD of ±1.0 mm d^{-1} (Fig. 6b). A similar RMSD value of ±0.9 mm d^{-1} and underestimation of 6% was observed when daily ET values were calculated using the standard FAO56 methodology (Allen et al., 1998).

These results are in agreement with some recent works. For instances, Kato and Kamichika (2006) used a dual crop coefficient to estimate ET in a sorghum field. Comparison with Bowen Ratio energy balance method showed a RMSD value of 0.84 mm d^{-1}.

Figure 8 illustrates the growing season rainfall and irrigation along with the modelled and measured cumulative ET. For the 75-day period studied in this work a total ET of 524 mm was measured by the lysimeter, very close to the 500 mm estimated from the STSEB model together with sorghum radiometric temperatures as input. For the same period, the total rainfall registered was 33 mm, and a total irrigation of 506 mm was applied. Thus, cumulative ET predicted by the STSEB model underestimated 5% the lysimeter register.

These results illustrate the ability of surface temperature together with energy balance to predict both short-term and long-term ET rates, and then to determine crop water necessity and schedule crop irrigation. This study will be further completed with the application to other energetic crops such as sunflower and maize.

5 Conclusions

This work was motivated by an increasing production of energetic crops in semi-arid regions and the need to determine their water requirements. This study focused on the evaluation of a two-source energy model to estimate crop water necessities from radiometric temperature information in a forage sorghum field. Two IRT radiometers were used, together with meteorological data, to run the STSEB model. Measurements in a weighing lysimeter were used to test modelled ET values at both, hourly and daily scales. For a variety of P_{v} conditions, sorghum ET predictions were generally good, and even both very high and very low ET values were quite well predicted by the model. Average errors of 22 and 12% were obtained for hourly and daily ET values, respectively, and total cumulated ET for the study period was a 5% underestimated.

These results confirm STSEB model as an alternative to water balance techniques to determine short-term and long-term accurate actual evapotranspiration. The presented methodology could be then used to estimate ground-truth ET values, as an alternative to weighing lysimeters, required to determine irrigation needs or to calibrate crop coefficient based algorithms.

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References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration: guidelines for computing crop water requirements, in: Proceedings of the Irrigation and Drainage Paper No. 56, Food and Agricultural Organization, United Nations, Rome, 1998.

Alvarez, M. M., Pérez-Carrillo, E., and Serna-Saldívar, S. O.: Effect of decortication and protease treatment on the kinetics of liquefaction, saccharification, and ethanol production from sorghum, J. Chem. Technol. Biot., 85, 1122–1129, 2010.

Bashir, M. A., Hata, T., Tanakamaru, H., Abdelhadi, A. W., and Tada, A.: Satellite-based energy balance model to estimate seasonal evapotranspiration for irrigated sorghum: a case study from the Gezira scheme, Sudan, Hydrol. Earth Syst. Sci., 12, 1129–1139, doi:10.5194/hess-12-1129-2008, 2008.

Bastiaanssen, W. G. M., Menenti, M., Feddes, R. A., and Holtslag, A. A. M.: A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation, J. Hydrol., 212–213, 198–212, 1998.

Castrignanò, A., Di Bari, V., and Stelluti, M.: Evapotranspiration predictions of CERES-Sorghum model in Southern Italy, Eur. J. Agron., 6, 265–274, 1997.

Choudhury, B. J. and Idso, S. B.: Evaluating plant and canopy resistances of field grown wheat from concurrent diurnal observations of leaf water potential, stomatal resistance, canopy temperature, and evapotranspiration flux, Agric. For. Meteorol., 34, 67–76, 1985.

Choudhury, B. J., Idso, S. B., and Reginato, R. J.: Analysis of an empirical model for soil heat flux under a growing wheat crop for estimating evaporation by an infrared-temperature based energy balance equation, Agric. For. Meteorol., 39, 283–297, 1987.

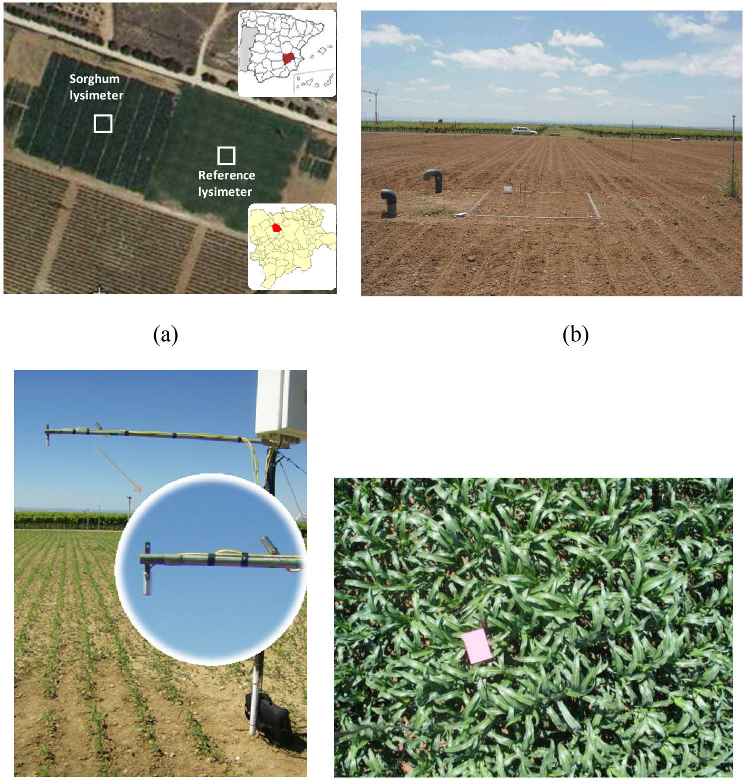
Faver, K. L. and O'toole, J. C.: Short-term estimation of sorghum evapotranspiration from canopy temperature, Agric. For. Meteorol, 48, 175–183, 1989.

Gardner, B. R., Nielsen, D. C., and Shock, C. C.: Infrared thermometry and the crop water-stress index:1. History, theory, and base-lines, J. Prod. Agric., 5(4), 462–466, 1992.

Gavilán, P. and Berengena, J.: Accuracy of the Bowen ratio-energy balance method for mea-

suring latent heat flux in a semiarid advective environment, Irrigation Sci., 25, 127–140, 2007.
Hall, F., Huemmrich, K., Goetz, S., Sellers, P., and Nickerson, J.: Satellite remote sensing of surface energy balance: Success, failures and unresolved issues in FIFE, J. Geophys. Res., 97, 19061–19089, 1992.
Hatfield, J. L., Perrier, A., and Jackson, R. D.: Estimation of evapo-transpiration at one time-of-day using remotely sensed surface temperatures, Agr. Water Manage., 7(1–3), 341–350, 1983.
Jackson, R. D., Idso, S. B., Reginato, R. J., and Pinter, P. J.: Canopy temperature as a crop water stress indicator, Water Resour. Res., 17, 1133–1138, 1981.
Jackson, R. D., Hatfield, J. L., Reginato, R. J., Idso, S. B., and Pinter, P. J.: Estimation of evapotranspiration from one time-of day measurements, Agric. Water Manage., 7, 351–362, 1983.
Kato, T. and Kamichika, M.: Determination of a crop coefficient for evapotranspiration in a sparse sorghum field, Irrig. Drain., 55, 165–175, 2006.
Kustas, W. P. and Norman, J. M.: Use of remote sensing for evapotranspiration monitoring over land surfaces, Hydrolog. Sci. J., 41(4), 495–516, 1996.
López-Urrea, R., Martín de Santa Olalla, F., Fabeiro, C., and Moratalla, A.: Testing evapotranspiration equations using lysimeter observations in a semiarid climate, Agric. Water Manage., 85, 15–26, 2006.
López-Urrea, R., Martín de Santa Olalla, F., Montoro, A., and López-Fuster, P.: Single and dual crop coefficients and water requirements for onion (Allium cepa L.) under semiarid conditions, Agric. Water Manage, 96(6), 1031–1036, 2009a.
López-Urrea, R., Montoro, A., López-Fuster, P., and Fereres, E.: Evapotranspiration and responses to irrigation of broccoli, Agric. Water Manage., 96(9), 1155–1161, 2009b.
López-Urrea, R., Montoro, A., González-Piqueras, J., López-Fuster, P., and Fereres, E.: Water use of spring wheat to raise water productivity, Agric Water Manage., 96, 1305–1310, 2009c.
Li, F., Kustas, W. P., Prueger, J. H., Neale, C. M. U., and Jackson, T. J.: Utility of Remote Sensing based two-source energy balance model Ander low and high vegetation cover conditions, J. Hydrometeorol., 6(6), 878–891, 2005.
Montoro, A., López-Fuster, P., and Fereres, E.: Improving on-farm water management through an irrigation scheduling service, Irrigation Sci., doi:10.1007/s00271-010-0235-3(online), 2010.

Marek, T. H., Schneider, A. D., Howell, T. A., and Ebeling, L. L.: Design and construction of large weighing monolithic lysimeters, Trans. ASAE, 31(2), 477–484, 1998.
Norman, J. M., Kustas, W., and Humes, K.: A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature, Agric. For. Meteorol, 77, 263–293, 1995.
Piccini, G., Ko, J., Marek, T., and Howell, T.: Determination of growth-stage-specific crop coefficient (k_c) of maize and sorghum, Agric. Water Manage., 96, 1698–1704, 2009.
Pinter, P. J., Hatfield, J. L., Shepers, J. S., Barnes, E. M., Moran, M. S, Daughtry, C. S. T., and Upchurch, D. R.: Remote sensing for crop management, Photogramm. Eng. Rem. S., 69(6), 647–664, 2003.
Rubio, E.: Optimising the remote sensing measurement of temperature and emissivity, Ph D. Thesis, University of Valencia, 272 pp., 1998.
Rubio, E., Caselles, V., Coll, C., Valor, E., and Sospedra, F.: Thermal infrared emissivities of natural surfaces: Improvements on the experimental set-up and new measurements, Int. J. Remote Sens., 20(24), 5379–5390, 2003.
Sánchez, J. M., Kustas, W. P., Caselles, V., and Anderson, M.: Modelling surface energy fluxes over maize using a two-source patch model and radiometric soil and canopy temperature observations, Remote Sens. Environ., 112, 1130–1143, 2008.
Sánchez, J. M., Caselles, V., Niclòs, R., Coll, C., and Kustas, W. P.: Estimating energy balance fluxes above a boreal forest from radiometric temperature observations, Agric. For. Meteorol., 149, 1037–1049, 2009.
Su, Z.: The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes, Hydrol. Earth Syst. Sci., 6, 85–100, doi:10.5194/hess-6-85-2002, 2002.
Valor, E. and Caselles, V.: Mapping Land Surface Emissivity from NDVI: Application to European, African, and South American Areas, Remote Sens. Environ., 57, 167–184, 1996.
Willmott, C. J.: Some comments on the evaluation of model performance, Bull. Am. Meteorol. Soc., 1309–1313, 1982.



(a) (b)

(c) (d)

Fig. 1. (a) Location of the experimental site. **(b)** Lysimeter placed in the center of the sorghum field (picture from DOY 147). **(c)** Experimental assembly of the two Apogee IRTs over the incipient sorghum (picture from DOY 172). **(d)** Nadir view of the developed sorghum (picture from DOY 196).

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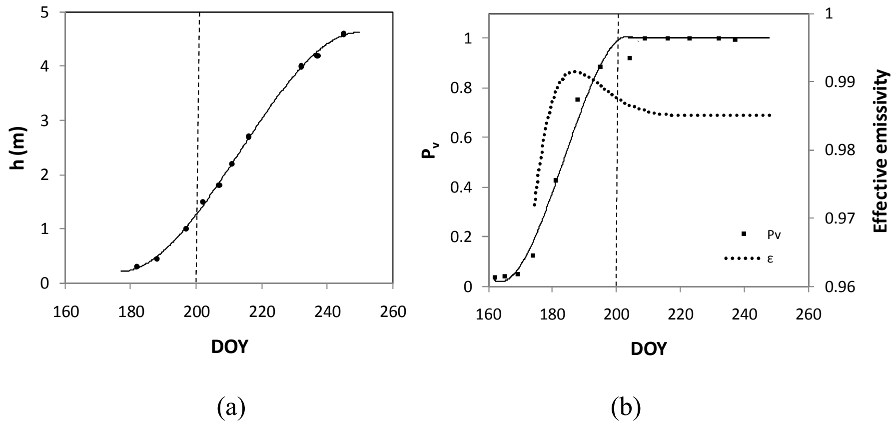

Fig. 2. **(a)** Evolution of the modelled sorghum height during the experiment (line) superposed to the field measurements (dots). **(b)** Evolution of the modelled P_v during the experiment (line) superposed to the field measurements (dots), together with the modelled effective emissivity.

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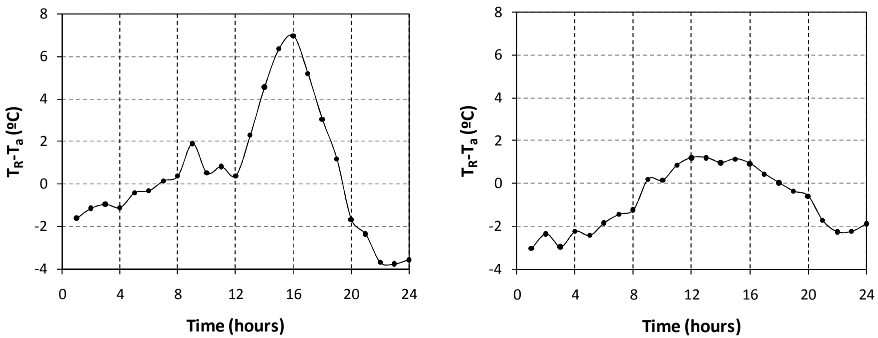

(a) (b)

Fig. 3. Diurnal evolution of the gradient between sorghum radiometric temperature and air temperature: **(a)** DOY 185, **(b)** DOY 236.

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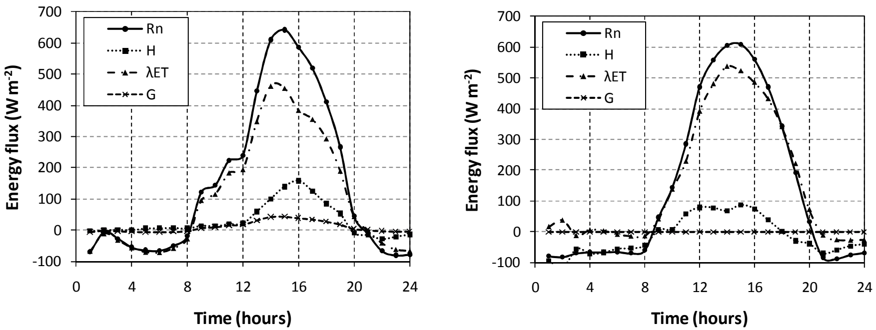

(a) (b)

Fig. 4. Diurnal evolution of the sorghum flux components of the energy balance equation: **(a)** DOY 185, **(b)** DOY 236.

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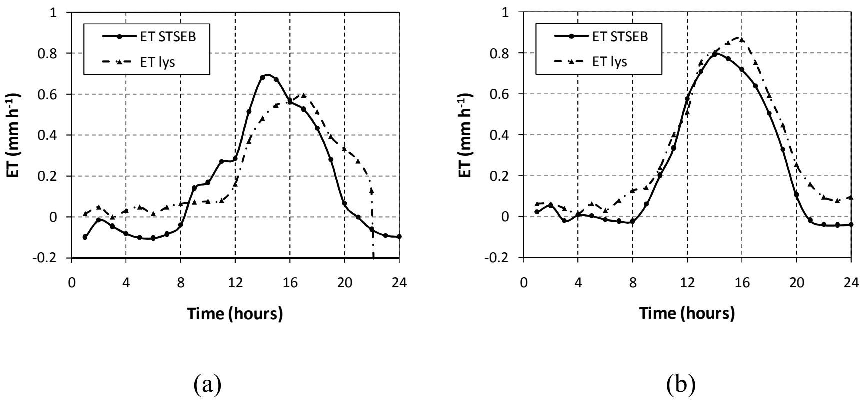

Fig. 5. Diurnal evolution of the estimated and measured sorghum ET: **(a)** DOY 185, **(b)** DOY 236.

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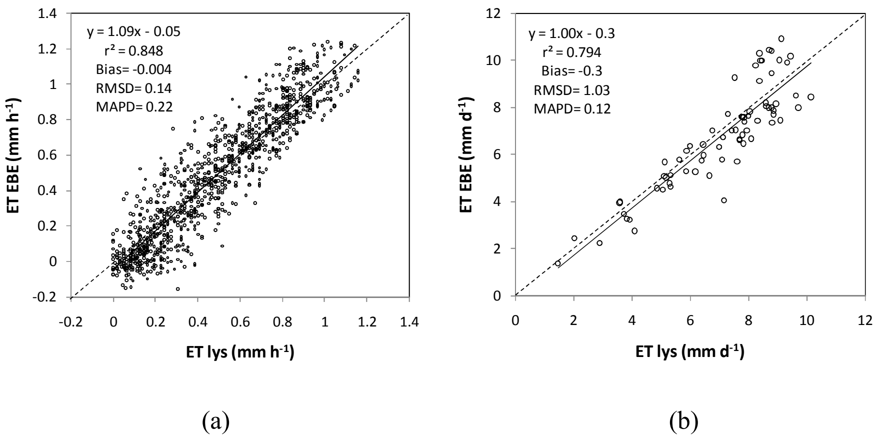

Fig. 6. Modelled (STSEB) versus measured (lys) sorghum evapotranspiration: **(a)** hourly values, **(b)** daily values. Results of the linear regression fit, together with the main statistics of the comparison (Bias, RMSD, and MAPD), are also included.

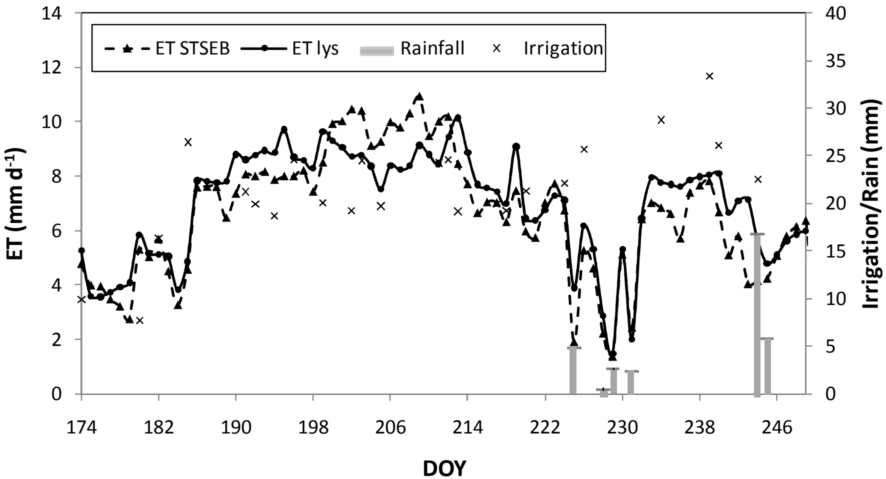

Fig. 7. Evolution of the sorghum daily ET values modelled (STSEB) and measured (lys) for the experiment duration. Rainfall and irrigation water quantities are also plotted.

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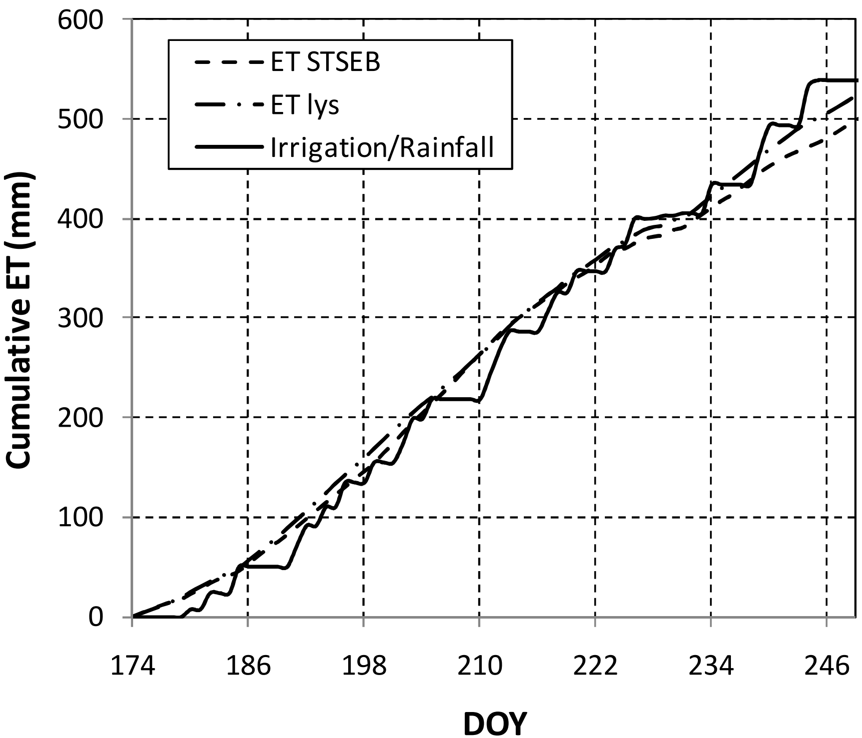

Fig. 8. Cumulative modelled (STSEB) and measured (lys) sorghum ET. Cumulative rainfall and irrigation applied is also plotted.

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