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Estimation and partitioning of actual daily evapotranspiration at an intensive olive grove using the STSEB model based on remote sensing

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A R T I C L E I N F O

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A B S T R A C T

This study is based on the application of an existing simplified two-source energy balance (STSEB) model, using medium-resolution satellite imagery (Landsat) to estimate instantaneous (at the satellite overpass time) and daily actual crop evapotranspiration (ET_a) over an intensive olive grove. Daily values were obtained by the use of the evaporative fraction method and corrected for latent heat, available energy, and evaporative fraction biases (beta-factor correction). Model estimates were compared to ground-based measurements. Heat flux densities (eddy covariance method) were recorded, and five Landsat images at approximately monthly intervals were used, covering our study site in 2011. Comparison with ground measurements showed a maximum difference of -0.6 mm day^{-1} before, and 0.2 mm day^{-1} after beta-factor correction for the main plot.

The experimental site consisted of a main plot exposed to deficit irrigation, and two small subplots where—during a limited period of time (six weeks)—one was temporarily not irrigated, and the other well-irrigated for reference. One Landsat image was available for this limited period of time.

Additionally, the STSEB algorithm was tested for partitioning evapotranspiration into its evaporation and transpiration components. Evaporation estimated from the STSEB model was compared with evaporation estimated from a model adjusted from local lysimeter measurements. Transpiration data obtained from calibrated sap flow measurements were, after local calibration, also compared to model estimates. Model results agreed with the measured data, showing) under- and overestimation for transpiration and evaporation, respectively.

1. Introduction

Over the last decade, more and more traditional olive orchards (< 100 trees ha^{-1}) have been replaced by intensive to super-intensive ones (> 2000 trees ha^{-1}), especially in the South of Portugal with Mediterranean climate conditions. This development demands improved water management and optimised irrigation practices in terms of quantifying olive water requirements. This study aims to estimate actual evapotranspiration (ET_a) and its contributing parts of canopy transpiration (LE_v) and soil water evaporation (LE_s), as the latter is often seen as water loss for irrigated crops. An existing simplified two-source energy balance model (STSEB) based on Norman et al. (1995) and further simplified by Sánchez et al. (2008b) has been, in combination with satellite imagery, tested for separately estimating LE_s and LE_v on a daily basis.

To estimate the amount of water transferred to the atmosphere from different crops, various estimation approaches have been developed, in general using implicitly (or explicitly) the leaf surface conductance (bulk stomatal and leaf boundary layer). Due to the difficulty in obtaining this variable for every crop in any water status condition, simple semi-empirical models have been used to calculate ET_a for decades. The principle is based on the reference evapotranspiration (ET_0) estimated from on-site collected meteorological data, which then is multiplied by a crop coefficient, obtaining ET_m ($k_c = ET_m/ET_0$) and finally by a stress coefficient ($k_s = ET_a/ET_m$). In a well-known group of guidelines (FAO Irrigation and Drainage Paper 56), Allen et al. (1998) proposed

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estimating ET_0 based on the Penman-Montheith equation, which incorporates aerodynamic and physiological parameters of a previously defined reference grass to retrieve k_c and k_s coefficients.

An alternative approach to obtain ET_a and its contributing parts, LE_v and LE_s, was adopted from the energy balance equation (Eq. (A.1)). A distinction is drawn between one- and two-source models, to account for the different heat transfers from the soil surface and the plant canopy. One-source models assume one surface temperature and aerodynamic resistance for the zone of soil and vegetation cover while the two-source models identify soil and vegetation layers as separate sources of heat flux.

To date, many studies have been carried out over annual crops or uniform land covers (Tasumi et al., 2005; Agam et al., 2010; Hoffmann et al., 2016; Timmermans et al., 2007), and many studies have dealt with heterogeneous ground cover (Bastiaanssen et al., 1998; Colaizzi et al., 2016; Roerink et al., 2000), and only recently with tree crops (e.g. olive orchards; Cammalleri et al., 2012; Pôças et al., 2014; Ortega-Farías and López-Olivari, 2012).

Due to the accessibility of satellite data, remote sensing based estimations of ET_a (Sun et al., 2012; Peng et al., 2012; Minacapilli et al., 2016), combined with energy balance models (Du et al., 2013; Ruhoff et al., 2013), became more and more attractive, especially because only a few additional meteorological variables (e.g., air temperature, wind speed, global solar radiation) are needed, being regularly measured at meteorological stations. Yang et al. (2015a) made a comparison between three two-source remote sensing evapotranspiration models, where two of them were two-source energy balance models (TSEB) and the third was the MOD16 ET_a algorithm (algorithm according to Norman et al., 1995 and Nishida et al., 2003b,a). Results showed that MOD16 failed to reproduce spatial ET_a patterns over particularly dry environments, while the TSEB model was in agreement with the ET_a measurements.

Generally, TSEB models give reasonable results for ET_a, and are used for separately estimating LE_v and LE_s, which, based on remote sensing has not been tested yet, to its full extent. One reason might be that TSEB models tend to overestimate LE_s and underestimate LE_v (Colaizzi et al., 2014, 2016). Here, the STSEB model gives the opportunity to operate on a larger scale (e.g. field-scale), due to relatively few input variables, the use of standard meteorological data, and satellite imagery. Daily values of ET_a, LE_v, and LE_s were estimated using the Evaporative Fraction (EF) constant method. Correction factors (beta-factors), according to Van Niel et al. (2011), were tested to improve model estimations.

On this background, the objectives of this study were to:

i estimate instantaneous ET_a in discontinuous vegetation e.g., for an olive grove;
ii detect significant reductions in evapotranspiration due to the water status of the trees;
iii test the performance of the model for partitioning evapotranspiration into its contributing parts (transpiration and evaporation); and
iv evaluate the overall ground cover dynamics (effect of canopies and inter-row soil cover) affecting the use of satellite imagery.

On-site measurements of total ET_a, obtained with the eddy covariance (EC) method, and its contributing parts (LE_s and LE_v) were compared to the model estimates. Consequently, the sections highlighting the results of the research at hand, as well as the discussion of these results, are split in accordance with the aforementioned objectives.

2. Materials and methods

A detailed description of the experimental set-up, instrumentation and their specifications are given in Conceição et al. (2017).

2.1. Study site

This work is based on data obtained in an intensive olive grove in the southeast of Portugal, located in the region of Alentejo in 2011 (latitude: 38°1′15.90″ N, longitude: 8°10′44.50″ W, Datum WGS84, 97 m above sea level). In September 2004, a 10-ha olive grove (*cv. Arbequina*) with a tree spacing of 4.8 m, and a row spacing of 7 m was installed, where a continuous area of 434-ha was selected for taking measurements.

In 2010, the average height of the trees was 3.2 m, the average canopy projected area was 5.7 m^2, and the average leaf area index on a total area basis was 1.01 m^2 m^{-2}. Further biometric measurements were taken and are described in Häusler et al. (2014).

The climate in the region of Alentejo is temperate and is one of the Mediterranean types, Csa, characterized by mild and wet winters and very hot and dry summers (Köppen Geiger Classification Rubel and Kottek, 2010). The average annual rainfall is about 580 mm, with around 5% falling during summer time (http://www.ipma.pt/). The soil was classified as *Luvisol* (Food and Agriculture Organization of the United Nations (FAO), 2006) with a ApBtC profile.

The total olive orchard, with the exception of two subplots, during a limited stress period, was deficit-irrigated. Each tree row had a line of drippers spaced 0.75 m apart. The nominal flow for the deficit irrigation was 1.6 L h^{-1}, which corresponds to an irrigation flux density of 0.31 mm h^{-1}. During 2011 the deficit irrigation operated from 15 June to 26 September (103 days) with an average irrigation depth of 1.4 mm day^{-1}.

During six weeks, two subplots received different treatments. One received no water at all (Subplot 2) and the other was well-irrigated (Subplot 3; see also Section 2.2.3 and Conceição et al., 2017). Pre-dawn leaf water potential served to monitor and define the plant water status. According to Fernandes-Silva (2008) plants are in comfort between −0.4 MPa and −0.7 MPa. The observed values for the well-irrigated Subplot 3 were never below −0.5 MPa (Conceição et al., 2017). Trees with a pre-dawn leaf water potential of down to −0.5 MPa were therefore defined as being in comfort. Values below this point indicated water-stressed olive trees.

2.2. On-site measurements

2.2.1. Measurement of energy heat fluxes at the main plot

The installation of EC sensors allowed the measurement of the flux densities of latent heat flux density LE and sensible heat flux density H with a three-dimensional sonic anemometer and a krypton hygrometer (CSAT3-D and KH20, respectively, Campbell Scientific, USA), which were mounted on a metallic tower at the height of 4.5 m above ground and oriented into the dominant wind direction (Fig. 1). Raw fluxes (H and LE) were recorded by a data logger (CR10X, Campbell Scientific, USA), and 30 min averages were stored. Corrections for air density variations (WPL-correction, Webb et al., 1980), and oxygen cross sensitivity for krypton hygrometers (because of oxygen absorption, Tanner et al., 1993) were performed.

The net radiation R_n was measured with net radiometers (NR2 and NRlite, Kipp & Zonen, Netherlands) and the soil heat flux density G was recorded, using six heat flux plates (heat flux sensors HFP01 and HFT-3.1 manufactured by Hukseflux and Radiation and Energy Balance Systems, respectively) with known thermal conductivity. The heat flux plates were buried in the ground at a depth of 0.05 m, perpendicular to the flow direction. To quantify the heat stored in the soil layer between 0 and 0.05 m, copper-constantan thermocouples were used at 0.025 m soil depth (1/30 Hz, 10 min average). Further information about equipment and data processing, are described in Conceição et al. (2017).

A simplified footprint analysis (Schuepp et al., 1990) allowed the evaluation of the relative contribution of fluxes coming from different areas within the plot to the total measured flux. More than 85% of the