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Crop coefficients from METRIC and SIMDualKc models for discontinuous woody crops. A remote sensing application to a super intensive olive grove

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Abstract: The estimation of crop water requirements is conventionally based on the use of reference evapotranspiration and crop coefficients which are tabulated for a wide range of crops cultivated in standard conditions. In orchards, planting density and geometry, vegetation height and canopy architecture can be highly variable and the tabulated crop coefficients require adjustment to the specific conditions. Thus, the estimation of crop coefficients based on the physical characteristics of the vegetation might be particularly useful. Satellite-based surface energy balance models like METRIC™ (Mapping EvapoTranspiration at high Resolution using Internalized Calibration) have been successfully applied to estimate and map evapotranspiration (ET) and derive crop coefficients. In anisotropic canopies as in olive orchards, some adjustments in METRIC application related to the estimation of vegetation temperature and of momentum roughness length must be considered. In a different approach, the SIMDualKc model performs the soil water balance simulation with estimation of the actual crop ET using the dual crop coefficient procedure from FAO 56 and incorporating improvements regarding soil evaporation calculation and the use of a density coefficient to deal with incomplete cover crops. In the current study, the METRIC model was applied to Landsat images to produce estimates of ET and further derive crop coefficients for different stages of the growing season in a super intensive olive orchard in Southern Portugal. Similarly, ET modelling was performed and crop coefficients were obtained with the SIMDualKc model. Crop coefficients derived from both models were compared against each other and with values tabulated and in the literature.

Keywords: Density coefficient, Dual crop coefficients, Remote sensing, Incomplete cover canopies, Surface energy balance

1. INTRODUCTION

In the last decade, traditional orchards (with less than 100 trees ha^{-1}) have been replaced by highly productive irrigated ones (Orgaz et al., 2006; Testi et al., 2006), with very high density and hedgerow type (up to 2000 trees ha^{-1}). In Portugal, this intensification is particularly important in the southern regions, where the Mediterranean climate prevails. An accurate estimation of crop water requirements, i.e., crop evapotranspiration, ET_c, in these highly intensive orchards is important to optimize water management.

A conventionally accepted approach for the estimation of crop ET is the FAO-56 method where the grass reference evapotranspiration is multiplied by a crop coefficient, K_c (Allen et al., 1998), thus associating the climatic demand with the plant response. Crop coefficients can follow either a single or dual approach. In the single approach both crop transpiration and soil evaporation are integrated into an average K_c; in the dual approach K_c consists of a basal crop coefficient (K_{cb}), representing primarily the plant transpiration component of ET_c, and a soil evaporation coefficient (K_e). The dual K_c approach is more suitable for crops having partial ground cover, where evaporation from non-shaded soil is important, especially when only a fraction of soil surface is wetted by irrigation (Allen et al., 2005a), as in olive groves. Nevertheless this approach involves some complexity as it requires knowledge of the soil evaporable characteristics, of ground cover conditions, and of the energy available for soil evaporation (Allen et al., 1998, 2005a; Paço et al., 2012; Rosa et al., 2012a).

Although standard K_c are defined and tabulated for a wide range of agricultural crops, including horticultural and tree crops (Allen et al., 1998; Allen and Pereira, 2009) and can be transferable to different regions and climates, their adjustment for local conditions might be necessary due to differences in planting density and geometry, vegetation height, and canopy architecture. The estimation of K_c based on the physical characteristics of the vegetation might then be useful to improve the estimation of ET. The value of K_c is smaller when plant density is small. Thus, a density coefficient (K_d) has been developed to be used in the computation of K_c and K_{cb} (Allen and Pereira, 2009). K_d can be estimated as a function of the fraction of ground covered by vegetation (Allen and Pereira, 2009):

$$K_d = \min(1, M_L f_{c\,eff}, f_{c\,eff}^{(1/(1+h))}) \qquad (1)$$

where $f_{c\,eff}$ is the effective fraction of ground covered or shaded by vegetation near solar noon, M_L is a multiplier on $f_{c\,eff}$ describing the effect of canopy density on shading and on maximum relative ET per fraction of ground shaded, and h (m) is the mean height of the vegetation.

The SIMDualKc water balance model (Rosa et al., 2012a) applies the dual coefficient approach, thus computing daily the soil evaporation (E_s) and plant transpiration (T_p). E_s is computed through a daily water balance of the soil surface layer, while the computation of T_p results from a soil water balance of the entire root zone. This SIMDualKc model considers the computation of K_{cb} for crops that do not completely cover the ground and adopts the extensions proposed by Allen et al. (2005a) and Allen and Pereira (2009).This model has been successfully applied to estimate ET and assess K_c of a wide range of vegetation types, including orchards and vineyards (Paço et al., 2012; Rosa et al., 2012b; Fandiño et al., 2013).

An alternative approach to obtain K_c is to use remote sensing data and tools, which have advantage in spatial accuracy because allowing to obtain information for each pixel of a satellite image. Satellite-based surface energy balance models have been successfully applied to estimate and map ET and derive K_c. The METRIC^{tm}, Mapping EvapoTranspiration at high Resolution using Internalized Calibration (Allen et al., 2007b), is one of such models. METRIC^{tm} has been used over an extensive range of vegetation types and applications, mostly focusing annual crops, but also in olive orchards (e.g., Allen et al., 2007a; Pôças et al., 2013; Santos et al., 2012). METRIC^{tm} estimates the ET flux as a "residual" of the surface energy balance at the time of satellite overpass. The model allows obtaining ETrF, which is a crop coefficient relative to alfalfa reference ET (ET_r), which is adopted in METRIC – Allen et al., 2005b. ETrF is defined as the ratio of ET for each pixel to ET_r computed from weather data. By computing a crop coefficient based on the estimated ET, it allows to directly integrate factors related with orchard architecture and agricultural practices and conditions.

The present study aims at providing information on crop coefficients and evapotranspiration for a super intensive olive grove by considering the physical characteristics of the vegetation, i.e., crop density and height. Specific goals include the computation of K_c and K_{cb} with the SIMDualKc model and the METRIC algorithm, and comparing K_c results obtained by both models.

2. MATERIAL AND METHODS

2.1 Study area

The study area is located in a commercial super intensive olive grove (1.35 m x 3.75 m, 1975 trees ha^{-1}, total area of 78 ha), near Viana do Alentejo, (38º24'N, 7º 43' W, 143 m a.s.l.) Southern Portugal (Fig. 1). Climate is of Mediterranean type, with an average annual rainfall between 600 and 800 mm, mainly concentrated in the winter period, and an average monthly temperature ranging from 9.6 ^oC in January and 24.1 ^oC in August. Winds predominantly blow from the quadrant between N and W directions. The olive cultivar was *Olea europea* cv Arbequina. The olive grove was irrigated by the evening almost daily during spring and summer with a drip system (emitters with 0.75 m spacing and discharge of 2.3 L min^{-1}). The wetted area was around 23% and the fraction of ground covered by the vegetation was $f_c \approx 0.35$. Tree height was around 3.5 m. The soil is sandy loam, with a water content of 0.24 [cm^{-3} cm^{-3}] at field capacity (θ_{FC}) and 0.12 [cm^{-3} cm^{-3}] at wilting point (θ_{WP}). In 2012, the grove was affected by an heavy frost from 20th to 25th

February, which caused a strong leaf fall and obliged to apply a heavy pruning. This affected the fraction of ground cover and was accounted for in the modelling process.

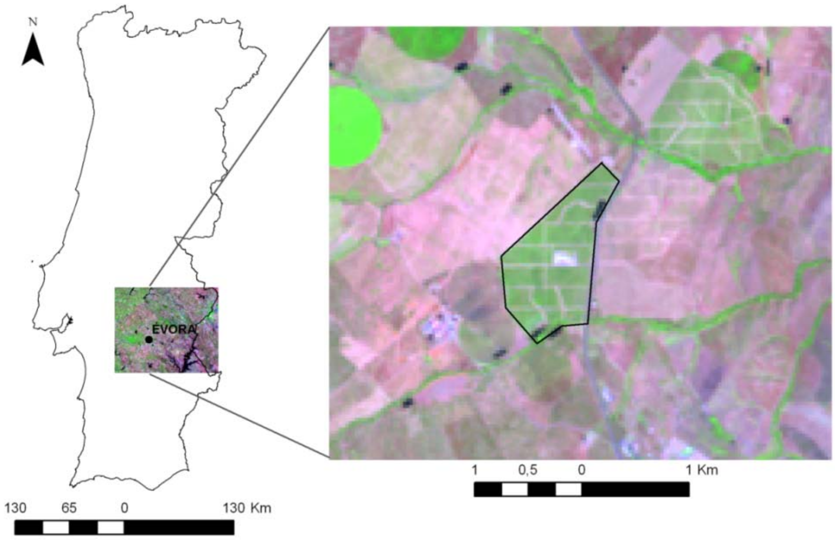


Fig. 1.Location of the study area in Évora (Southern Portugal), with the identification of the super intensive olive grove in the Landsat image (scene 203/033; RGB combination 5:4:3).

2.2 Field data

Data obtained from ground-based measurements were used to validate information from simulation models. Plant transpiration was assessed using sap flow measurements by the *Granier* method (Granier, 1985) from DOY (day of year) 134/2011 to 366/2012. A set of six sensors was distributed by seriated trees, according to trunk diameter class frequency. Natural gradients were corrected using data from non-heated sensors during long periods. Soil evaporation (E_s) was measured with six microlysimeters (Daamen et al., 1993) distributed by three representative areas.

ET measurements were performed by the eddy covariance (EC) micrometeorological technique using a three-dimensional sonic anemometer and a krypton hygrometer (Models CSAT3 and KH20, Campbell Scientific, Inc., Logan, UT, USA), from end of July until end of August in 2011 and from the mid June until the end of August in 2012.The sensors were placed at a measurement height of 4.8m. EC raw data (H, sensible heat flux density, and λE, latent heat flux density) were collected at a 10 Hz frequency and further analysed for correction following Foken et al. (2011). Given the non-flat terrain conditions, raw data were submitted to a coordinate rotation using the Double Rotation method (Kaimal and Finnigan, 1994). The spatial representativeness of the measurements was examined through a footprint analysis (Schuepp et al., 1990). Soil heat flux (G) was measured using eight soil heat flux plates (Peltier modules sealed 20 V, 4.4 A, 40 x 40 x 3.9 mm, RS Components, Spain) distributed in the tree row and between rows at a depth of 2 cm. Net radiation (R_n) was measured with a net radiometer (Model, NR-LITE, Campbell Scientific, Inc., Logan, Utah, USA). Surface energy balance evaluation provided an energy balance equation closure error of 10%, determined for daily values by linear regression forced to origin ($R_n - G = 0.91\ (\lambda E + H)$, $R^2 = 0.87$). Data from days with wind from the NE direction were discarded given the proximity of a building (200 m) in that direction. All other directions were considered valid, providing that over 88 to 96% of the fluxes were coming from the region of interest, as determined by the footprint analysis. For specific modelling purposes, data was further serialized by quality labels, according to fetch conditions.

The EC technique was used for a short period while the sap flow measurements were performed for a longer one, allowing the extension of the data series as described in Paço et al. (2012). ET obtained with the EC technique (ET_{ec}) subtracted of soil evaporation (E_s) simulated with SIMDualKc (E_{ssim}) were mathematically related to *Granier* sap flow data in order to calibrate these data and obtaining extended series of calibrated sap flow transpiration (T_{sf}). In previous studies (e.g., Silva et al., 2008) the *Granier* sap flow method was found to underestimate transpiration, especially for high flux densities; therefore the original calibration of the method was verified. The best mathematical relationships found were $ET_{ec}–E_{sim}$ = $0.48e^{1.14SF}$ (R^2 = 0.46; n=13) and ET_{ec}-E_{ssim} = $0.34e^{1.72SF}$ (R^2 = 0.61; n=28) for the first and the second year, respectively, where SF [mm d^{-1}] is sap flow obtained with the *Granier* method.

Irrigation data were provided by the farming owners "Olivais do Sul" or were locally measured with a tipping-bucket raingauge (ARG100, Environmental Measurements Ltd., Sunderland, UK).

Hourly temperatures of shaded and sunlit soil were measured by infrared sensors (Apogee, Model SI-111). An infrared sensor placed above the canopy continuously recorded the canopy temperatures. Additionally, thermal-infrared images, collected using an infrared camera (thermCam Model SC640, Flir), were obtained for 30 trees distributed in the olive grove in several dates aiming at adjusting the canopy temperatures recorded with the IR sensor to values representative of all the trees in the orchard.

2.3 Satellite data and ancillary data

METRIC was applied to several Landsat5 TM and Landsat7 ETM+ images (path203/row033) from the year 2011: January 31st, March 20th, April 5th, May 23rd, June 24th, July 26th, August 27th, September 12th, October 6th, and October 30th; and from the year 2012: February 11th, April 15th, July 20th, August 21st, September 6th, and October 8th. Images had L1T processing level (geometric and terrain correction).

A digital elevation model was used to correct the surface temperature according to the differences in elevation and to produce slope and aspect maps required in METRIC to estimate solar radiation (Allen et al., 2006). A land cover map, obtained from CORINE Land Cover 2006 (scale 1/100,000), was used to support estimation of the momentum roughness length used in calculating convective heat transfer.

Meteorological data, including wind speed, air temperature (maximum and minimum), solar radiation, precipitation, and relative humidity, were collected at the Viana do Alentejo weather station (Latitude 38º 21' 42'' N, longitude 08º 07' 29'' W, and elevation 138m). All weather data were subjected to quality control following the procedures recommended by Allen et al. (2005). Wind speed, air temperature, solar radiation, and relative humidity data were used to estimate the alfalfa reference evapotranspiration ETr using the ASCE procedure (Allen et al., 2005) as well as the grass reference ET_o (Allen et al., 1998) used with the SIMDualKc model. Precipitation data were used to perform the soil water balance of the upper soil layer for days preceding satellite overpass days to assess ET conditions for bare soil.

2.4 SIMDualKc and METRIC models

SIMDualKc model calibration was performed for 2011 field data and 2012 data were used for model validation. Field data sets consisted of: (i) ET obtained with the EC technique (ET_{ec}); (ii) SF data (calibrated against ET_{ec} subtracted of $E_{s\,sim}$); and (iii) E_s data measured with microlysimeters.

The density coefficient (K_d) was computed for the actual fraction of ground cover ($f_{c\,eff}$) and accounting for the reduction caused by frost in 2012. The K_{cb} values were computed from the density factor with a M_L value of 1.7 (Eq. 1). Potential K_{cb} values considered were K_{cb_ini} = 0.7, K_{cb_mid} = 0.8 and K_{cb_end} = 0.7 according to Allen and Pereira (2009). A p value of 0.4 was adopted.

The calibration and validation methodologies were adapted from that described by Popova and Pereira (2011) and Rosa et al. (2012b). The model fitting analysis was also the same as described by these authors; it comprised a regression forced to the origin relating observed and model predicted values, a set of indicators of residual estimation errors (RMSE = root mean square error, E_{max} = maximum absolute error, AAE =average absolute error and ARE = average relative error) and two statistical agreement indicators (EF = modelling efficiency, d_{IA} = index of agreement).

The METRIC ET algorithm is based upon the energy balance at the land surface. The latent heat flux (λE), which is readily converted to instantaneous ET, is calculated by subtracting G and H from Rn. A scaled reference ET is used to translate instantaneous ET to longer periods, e.g. to daily periods (Allen et al., 2007b). This scaling coefficient is the fraction ETrF, defined before. The ETrF is readily converted to K_c by using the k_{ratio}= 1.2, which is the average value for the ratio between the alfalfa and grass reference ET (Allen et al., 1998; Allen et al., 2007b). In crops like olives, having stomatal control characteristics different from those of most agricultural crops, it might be needed to adjust these scaling coefficients (ETrF or K_c) during the mid-season period (Allen et al., 1998). As the stomatal conductance in olive trees respond seasonally, with stomata closing under conditions of high evaporative demand, and diurnally, with stomata open wider in the morning than in the afternoon (Fernández et al., 1997; Moriana et al., 2002), for the images of the summer period (when temperatures are higher and relative humidity is low) the translation of instantaneous ET into daily ET was based on an evaporation fraction providing an adjustment for daily ET and daily ETrF.

The METRIC is a one-source model, which considers soil and vegetation as a sole source. It uses two “anchor points for calibration” – “cold pixel” and “hot pixel” – to define the limit conditions for the energy balance over the study area, as described by Allen et al. (2007b). In incomplete woody canopies, the estimation of H may be biased by uncertainties in the definition of the momentum roughness length (Z_{om}) and by the mixture and shading effects on the surface temperature and on the near-surface temperature gradient, dT; moreover, the estimation of pixel temperature may be biased by the soil and shadow effects (Allen et al., 2007b; Santos et al., 2012). Thus, some adjustments related with the estimation of vegetation temperature in tall canopies and the estimation of momentum roughness length and sensible heat flux for tall vegetation were considered.

Regarding Z_{om}, its estimation in METRIC is done for each pixel according to the land cover type or amount of vegetation. For tall vegetation, such as in orchards, the Z_{om} increases with the orchard/stand density until that a threshold density is reached, which brings the zero plane displacement up nearer to the top of the canopy, thereby reducing roughness when density increases above that threshold (Allen et al., 2012). To account for such effects, METRIC estimates Z_{om} for agricultural orchards using a Perrier (1982) function which considers the leaf area index (LAI) and the crop height (h), as described in Allen et al. (2012).This function was applied by Santos et al. (2012) with good results for Z_{om} estimation in an application of METRIC to olive orchards in Spain.

LAI is conventionally computed in METRIC using the soil adjusted vegetation index (SAVI) and h (Allen et al., 2007b; 2012). However, as the traditional equation used in METRIC underestimated the LAI values for the studied olive grove, LAI estimates were adjusted according to information collected in the field and SAVI data taking into consideration the range of LAI values obtained by Diaz-Espejo et al. (2012) for a hedgerow olive orchard in Spain whose characteristics are similar to the ones of the study area. Thus:

$$LAI_{j,i} = LAI_{max}*((SAVI_{j,i} – SAVI_{min,i})/(SAVI_{max,i} – SAVI_{min,i}))+ 0.01 \quad (2)$$

where $LAI_{i,j}$ is the LAI for each pixel and date, LAI_{max} is the maximum LAI based on Diaz-Espejo et al.(2012) LAI values obtained in specific periods of the year for a fully irrigated hedgerow olive orchard, $SAVI_{i,j}$ is the SAVI for each pixel and date, and $SAVI_{min}$ and $SAVI_{max}$ are respectively the minimum and maximum values of SAVI in each date for the olive orchard under study. Following this adjustment, and considering the crop height data collected in the field, the relationship h=3.5 LAI was adopted.

The surface temperature observed by a satellite integrates a mixture of temperatures of sunlit and shaded canopy surfaces along with sunlit and shaded soil surfaces. Thereby, the computation of radiometric temperature for tall vegetation can be expressed as a three-source condition (Kjaersgaard and Allen, 2009):

$$T_s = f_cT_c + f_{shadow}T_{shadow} + f_{sunlit}T_{sunlit} \quad (3)$$

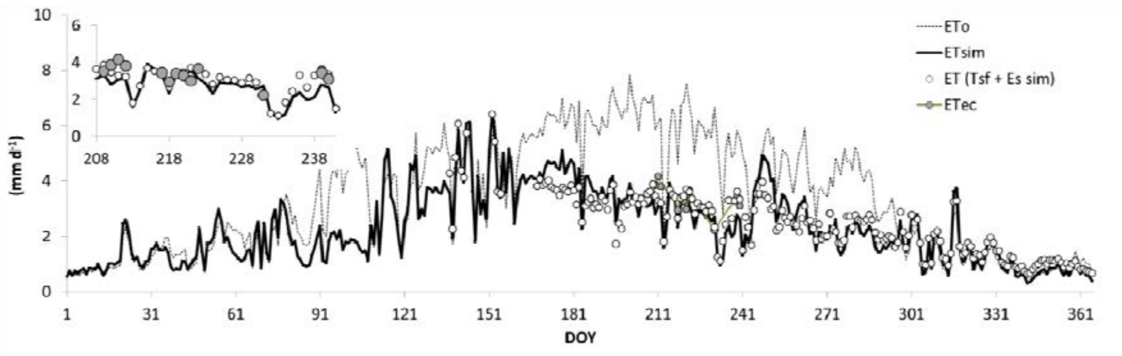
where f_c, f_{shadow} and f_{sunlit} correspond to the relative fraction of ground covered by vegetation, shadow and sunlit ground surface, respectively, when viewed from nadir, so that $f_c+f_{shadow}+f_{sunlit}=1$. T_c, T_{shadow} and T_{sunlit} correspond to the temperature of the canopy, the shaded ground surface and the sunlit ground surface, respectively. As the sunlit canopies are the primary source of energy exchange, the effective temperature for tall canopies can be estimated by solving equation (3) for T_c. The T_{shadow} and T_{sunlit} are estimated as a function of the temperatures for the hot and cold pixels, and the temperature of the wet bulb (Kjaersgaard and Allen, 2009). The estimation of the relative fraction of vegetation cover (f_c) for the olive orchard was based on the Normalised Difference Vegetation Index (NDVI).The fractions of shaded ground and of sunlit ground surface were estimated according to Kjaersgaard and Allen (2009).

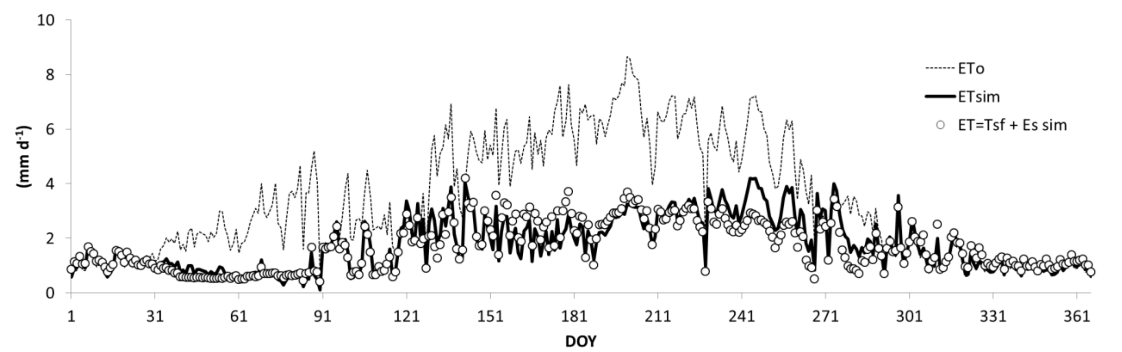
Further details of METRIC algorithm are given by Allen et al.(2007b; 2012). The software ERDAS IMAGINE v.2010 (Leica Geosystems) was used for the METRIC algorithm application.

3. RESULTS AND DISCUSSION

3.1 SIMDualKc results

SIMDualKc estimations of ET (ET_{sim}) were compared with ET obtained from the EC technique (ET_{ec}) as shown in Fig. 2. ET_{ec} varied between 2.2 and 4.2 mm d^{-1} in 2011 (July-August, n = 13) and between 0.4 and 3.5 mm d^{-1}, in 2012 (June-August, n = 28). For the same time interval, ET_{sim} ranged between 2.3 and 3.5 mm d^{-1} and 1 and 3.5 mm d^{-1}, respectively, showing a very similar range in 2012, with the same maximum. In 2011, for the period with available SF data, simulated ET_{sim} and T_{sim} agree well with field derived data (ET = T_{sf} + E_{ssim} and T_{sf}). ET_{sim} for 2012 was in average 1.8 mm d^{-1} and ET = T_{sf} + E_{ssim} was 1.7 mm d^{-1}, showing also a good agreement, although some discrepancy is observed for the maximum values of transpiration.





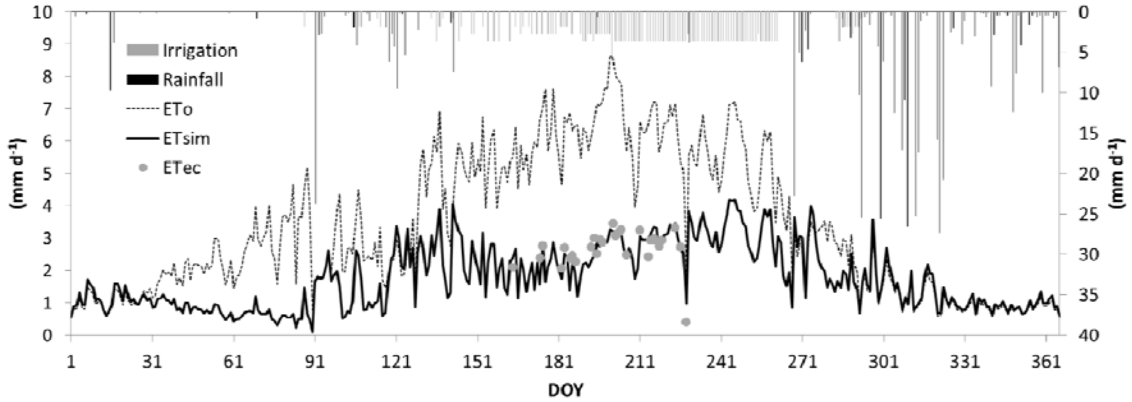
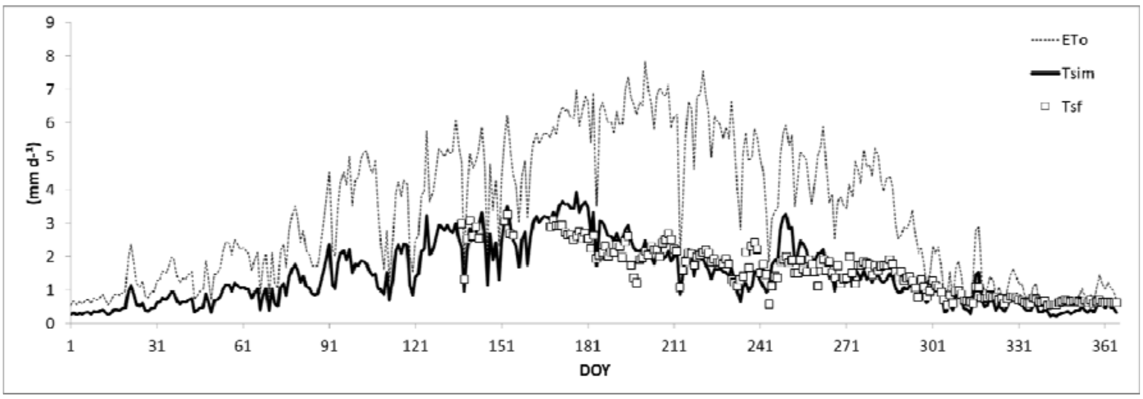


Fig. 2. Evapotranspiration modelled with SIMDualKc (ET_{sim}), ET derived from calibrated sap flow data (T_{sf}) and soil evaporation obtained with SIMDualKc (E_{ssim}), ET obtained with the eddy covariance technique (ET_{ec}) and grass reference evapotranspiration (ET_o) for 2011 (upper panel) and 2012 (middle and lower panels)

Table 1 shows results for model accuracy concerning SIMDualKc. In 2012, ET_{ec} and ET_{sim} were well correlated, with a determination coefficient of 0.75. The regression coefficient is close to 1.0, indicating a good performance of the model with only a slight overestimation of ET values. RMSE averages 0.31 mm d^{-1}, representing 12% of the mean measured daily ET_{ec}, for the dedicated period. AAE, is 0.25 mm $d^{-1}$and in relative terms (ARE) the error is close to 14%, corresponding to a maximum error of 0.71 mm d^{-1}. The modelling efficiency is above 0.70 and the index of agreement is close to 1 (0.95), both indicating a good agreement between measured and predicted values. In 2011, due to sensors malfunction and weather conditions, the number of days with valid ET_{ec} data measurements is smaller (n = 13) and, although data tend to show a good agreement with ET_{sim} (Fig. 2), the sample is not large enough to perform an adequate model accuracy analysis. A similar situation occurs with measured E_s for both years of the study (data not shown). SIMDualKc ET_{sim} results were also compared with data derived from SF measurements and evaporation simulated with SIMDualKc (ET (T_{sf} + E_{ssim})) (Fig. 2, upper and middle panel and Fig. 3).

Table 1. Goodness of fit indicators relative to SIMDualKc model.

2011	n	b	R^2	RMSE	EF	d_{IA}	E_{max}	AAE	ARE
ET = T_{sf} + E_{ssim}vsET_{sim}	209	1.04	0.89	0.46	0.86	0.97	1.37	0.34	15.20
T_{sf}vsT_{sim}	209	1.05	0.79	0.46	0.71	0.93	1.37	0.34	33.00
2012									
ET_{ec}vsET_{sim}	28	0.97	0.75	0.31	0.70	0.92	0.71	0.25	13.84
ET = T_{sf} + E_{ssim}vsET_{sim}	366	1.07	0.88	0.42	0.83	0.96	1.18	0.34	43.28
T_{sf}vsT_{sim}	366	1.08	0.81	0.42	0.73	0.93	1.18	0.34	81.10



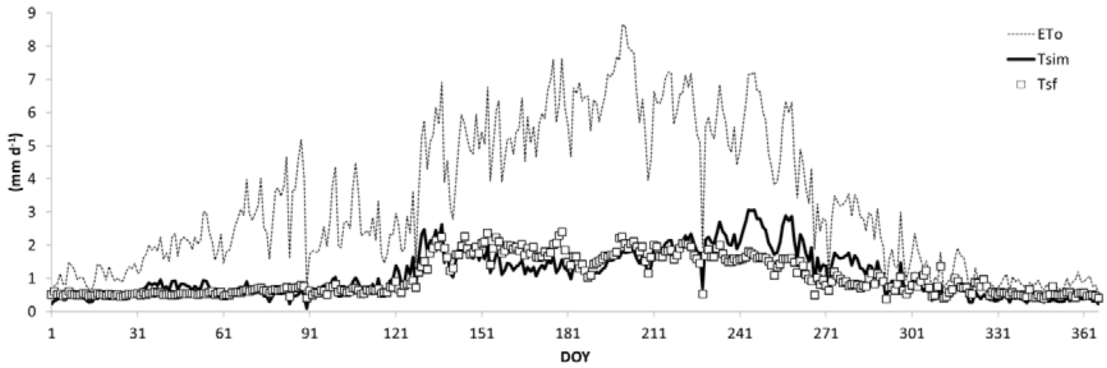


Fig. 3. Plant transpiration modelled with SIMDualKc (T_{sim}), calibrated transpiration derived from sap flow data (T_{sf}) and grass reference evapotranspiration (ET_o) for 2011 (upper panel) and 2012 (lower panel).

Statistical indicators (Table 1) for model fitting show that, for the calibration year, observed and simulated data are well correlated (R^2 = 0.89 for ET and R^2 = 0.79 for transpiration, T_p) with regression coefficients slightly surpassing 1, indicating a very small overestimation by the model. Although the RMSE, E_{max} and AAE indicators return the same result for ET and T_p (0.46, 1.37 and 0.34, respectively), ARE is higher for T_p, indicating a twofold error in relative terms when comparing to ET. Modelling efficiency is higher for ET, but d_{IA} is comparable and very high, both for ET and T_p, showing an adequate performance of the model in the calibration phase.

In general, the validation procedure (2012 data) showed comparable or better results than those of calibration concerning model fitting indicators, with an exception for ARE. For validation, the model presents also a slight overestimation (b = 1.07 and 1.08, for ET and T_p, respectively) but RMSE and E_{max} are smaller. In general terms, model fitting was better for ET than for T_p, as for calibration and for validation.

The weaker points of field data reside: (i) on the calibration of Granier SF data against EC data and E_{ssim}, since the obtained calibration equations present some uncertainty for the region of higher transpiration values (small variations in SF can lead to large variations of $ET_{ec} - E_{ssim}$ in a range difficult to define); (ii) on the time interval used for calibration (periods without rainfall - since the krypton hygrometer used for water vapor fluctuations measurement could not get wet) which might not reflect the whole year conditions and ET extremes (e.g., large ET rates during the end of summer and beginning of autumn of 2012); (iii) the year-long series of E_s used either for calibration or validation of the SIMDualKc model are simulated by the model, therefore introducing some dependency in the variables despite this is partially overcome given that E_s is the smallest component of ET (the ratio of E_{ssim} to ET_{sim} is close to one third for the whole year periods), and that measured E_s data agree well with simulated data (although the sample considered is small, as discussed previously); however, the use of E_{ssim} allowed comparing simulated and measured T_p, that otherwise would not be possible since obtaining long-time series of E_s data is particularly difficult.

3.2 Application of METRIC algorithm to a discontinuous woody crop

To support the application of METRIC algorithm to the super intensive olive grove, results of several agronomic and biophysical parameters were compared with ground data and with values published in the literature.

The LAI data estimated by METRIC and data collected in the field were well correlated with R^2 of 0.81 (n=10) and a regression coefficient close to 1 (0.95), indicating a good agreement between measured and predicted values. The results obtained with METRIC for LAI ranged between 0.74 and 1.23 m^2m^{-2} in 2011 and between 0.62 and 0.96 m^2m^{-2} in 2012, with lower values occurring during winter and early spring. The lower LAI values for 2012 were due to the mentioned occurrence of a heavy frost during that winter, which highly affected the canopy condition and made it necessary a severe prune of the trees. Results for 2011 are in agreement with those reported by Diaz-Espejo et al. (2012) for a hedgerow olive grove in Spain with the same cultivar, similar orchard characteristics, and under regulated deficit irrigation, i.e., with management conditions not very different of those observed in the studied grove.

The average of Z_{om} values estimated by METRIC for the olive grove were 0.82 m in 2011 and 0.80 m in 2012, while the Z_{om}/h ratio was 0.24 in 2011 and 0.23 in 2012. These results are both within the values reported by Allen et al. (2012) for trees with a similar LAI to that observed in the studied olive grove. However, the Z_{om} and Z_{om}/h ratio estimated with METRIC are higher than those reported by other authors, 0.068h – 0.123h, for olive orchards with a lower number of trees, 70-250 trees ha^{-1} (Berni et al., 2009; Rallo and Provenzano, 2012; Santos et al., 2012). The higher Z_{om} values are likely due to the higher density in the super-intensive olive grove studied (1975 trees ha^{-1}) because the Perrier equation reflects the increase in Z_{om} when the stand density thickens up to a threshold (Allen et al., 2012).

Values estimated in METRIC for each one of the components of the temperature were compared with ground data. The differences for temperatures of shaded and sunlit ground surface were 3.6 K and 3.7 K, respectively, representing a mean bias of 1.23% and 1.20%, respectively. The differences for the temperature of the canopy were 4.9 K, thus a mean bias of 1.65%. Differences between soil (either shaded or sunlit) and canopy temperature were up to 20 K, which is also consistent with results of Sepulcre-Cantó et al. (2006) who pointed out the mixture of temperatures integrated in the surface temperature observed by the satellite. Such results show the importance of considering the three-source condition in the computation of surface temperature to obtain the canopy temperature.

Evapotranspiration obtained from both models (ET_{METRIC} and ET_{sim}) is presented in Figure 4 along with field data. With the SIMDualKc approach, K_c was multiplied by ET_o ($ET_{sim} = K_c\ ET_o$). In the METRIC approach, ET values obtained from the energy balance were adjusted to guarantee the comparability between results derived from both models. This adjustment was considered because the conversion of ETrF to K_c was performed considering an average K_{ratio} = 1.2 for the all set of dates studied. Thus, the crop coefficients derived from METRIC were further multiplied by ET_o in order to adjust ET ($ET_{METRIC} = K_{cMETRIC}\ ET_o$).

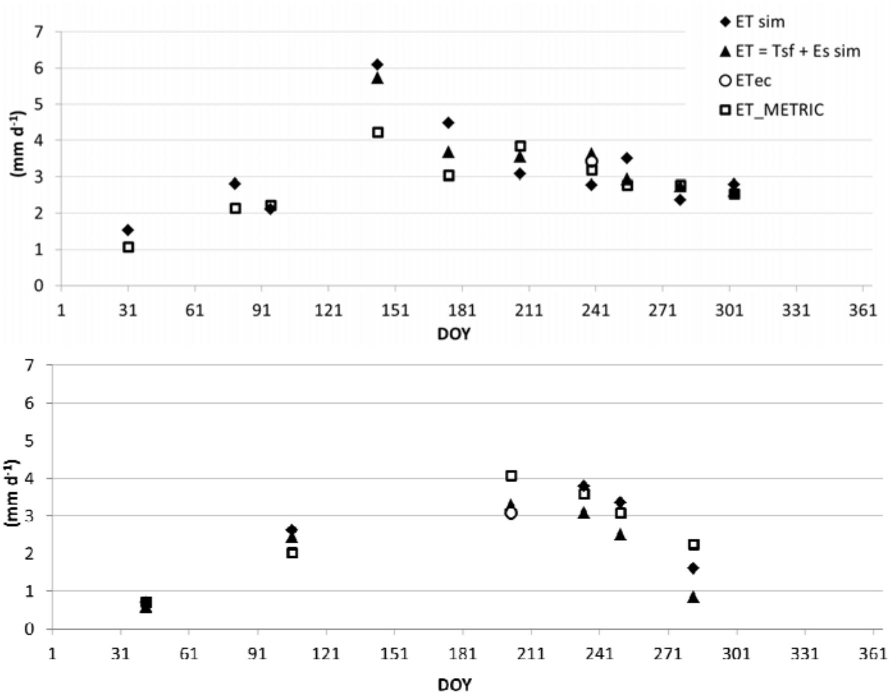


Fig. 4. Evapotranspiration modelled with SIMDualKc (ET_{sim}), ET derived from calibrated sap flow data and soil evaporation obtained with SIMDualKc ($ET=T_{sf}+E_{ssim}$), ET obtained with the eddy covariance technique (ET_{ec}) and evapotranspiration derived from METRIC(ET_{METRIC}) for 2011 (upper panel) and 2012 (lower panel).

The values of ET_{METRIC} ranged between 1.1 mm d^{-1} in January and 3.9 mm d^{-1} in July in 2011, and between 0.7 mm d^{-1} in February and 4.1 mm d^{-1} in July in 2012 (Fig. 4). The mean bias between ET_{METRIC} and

$T=T_{sf}+E_{ssim}$ is 14.9 % for the set of dates studied, excluding the DOY 282 from 2012, whose results were unacceptable and was considered an outlier indicating problems in the estimation of ET for this date.

For the year 2011, the mean bias between ET_{METRIC} and $ET=T_{sf}+E_{ssim}$ was 11% (corresponding to an absolute difference of 0.45 mm d^{-1}), with the larger difference (26%, representing an absolute difference of 1.5 mm d^{-1}) occurring for DOY 143 (May 23rd). This larger difference is most likely due to precipitation that occurred in the days prior to the satellite overpass, which increased the difficulty in the definition of the anchor points used to define the limit conditions for the energy balance. For the year 2012, the mean bias was larger, 21% (corresponding to an absolute difference of 0.49 mm d^{-1}). Nevertheless, for this year, the maximum absolute difference between ET_{METRIC} and $ET=T_{sf}+E_{ssim}$ was 0.81 mm d^{-1}. The larger mean bias in 2012 might be due to the changes in vegetation conditions following heavy frost and subsequent heavy pruning, which made more difficult the parameterization of the variables related with vegetation architecture in METRIC algorithm. As reported by Santos et al. (2012), the estimation of parameters like crop height and Z_{om} can have an important impact on the performance of METRIC application to incomplete woody canopies.

The mean biases obtained in the current study are within the range presented by Bastiaanssen et al. (2008) for comparing an evaporative fraction (latent heat/net available energy) derived from SEBAL (also a one-source model) and measured for several tree crops (absolute values between 2.5% and 24.6%). As discussed by those authors, such mean biases are acceptable as field measurements have also their own source of errors. Nevertheless, the overall discrepancies between ET_{METRIC} and $ET=T_{sf}+E_{ssim}$ can be due to the limitations in the application of one-source models, like METRIC, to crops with incomplete ground cover as discussed by Minacapilli et al.(2009) and Timmermans et al. (2007). Minacapilli et al. (2009) observed a slightly lower performance of SEBAL when compared with a two-source model (TSEB) for perennial tree crops in Italy (mean absolute differences of 0.14 mm d^{-1} with TSEB vs 0.55 mm d^{-1} using SEBAL). However, the data required to parameterize and apply TSEB are often not readily available.

3.3 Comparison of crop coefficients derived from SIMDualKc and METRIC

The crop coefficients computed with METRIC ($K_{cMETRIC}$), obtained from ETrF and the K_{ratio} = 1.2, ranged from 0.49 and 1.11 in 2011 and from 0.47 and 0.70 in 2012 (Fig. 5). 2012 values reflect the effects of frost and subsequent heavy pruning. Figure 5 also presents the crop coefficients obtained with SIMDualKc ($K_{cSimDualKc}$).

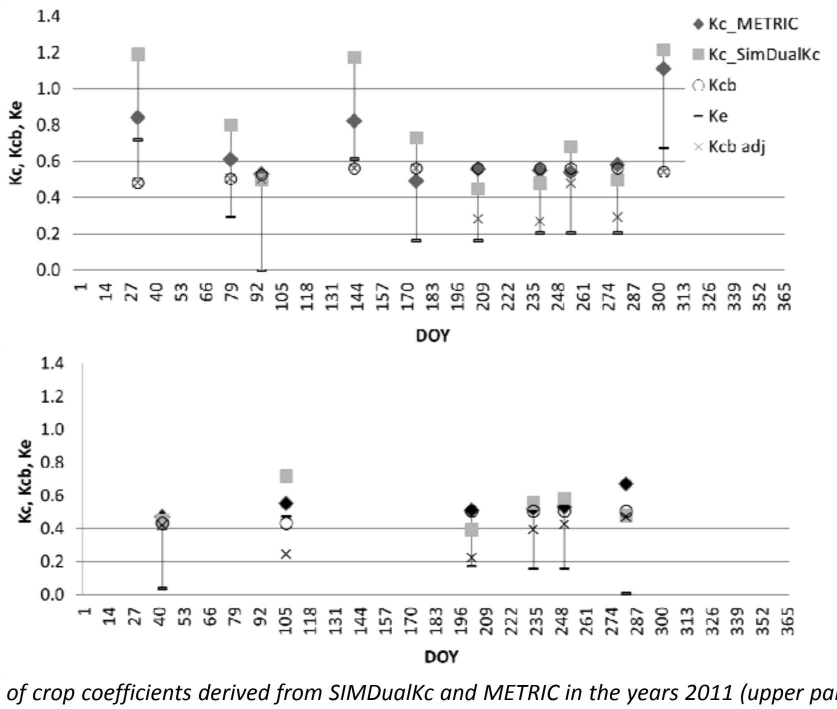


Fig. 5.Temporal evolution of crop coefficients derived from SIMDualKc and METRIC in the years 2011 (upper panel) and 2012 (lower pannel).

The $K_{cMETRIC}$ and $K_{cSimDualKc}$results for 2011 showed higher values during winter and autumn (Fig.6 upper panel), which are consistent with K_c values observed by Villalobos et al. (2000) in irrigated olive orchards in Spain. The higher K_c values during this period (image dates from January 31st – DOY 31 and October 30th - DOY 303), as well as in the May 23rd image (DOY 143), result from an increase in soil evaporation due to occurrence of precipitation, thus in higher K_e. In the other dates considered, as the precipitation decreased and the soil was less wet, particularly during the summer, K_e becomes very small and, despite K_{cb} is then high, K_c gets lower and less variable, around 0.6. These results are also consistent with the ones obtained by Testi et al. (2006) for a drip irrigated intensive olive orchard, where higher values (close to 1) occur in the wet season (autumn, winter and early spring) and decrease in the summer period. When comparing the K_c values obtained in this study with results obtained by Santos et al. (2012) for a rainfed olive orchard it was observed that: (i) K_c follow a similar pattern throughout the year; (ii) values are higher than those reported by Santos et al. (2012) due to irrigation and plant density (up to 200 vs 1975 trees.ha^{-1}). $K_{cMETRIC}$ are also not far from the K_c values for high density olive orchards published by Allen and Pereira (2009), which vary between 0.65 and 0.80 for K_{cini}, 0.70 – 0.75 for $K_{c\ mid}$, and 0.60 – 0.75 for $K_{c\ end}$, depending on the ground cover.

The lower K_c values obtained for 2012 (Fig. 5 lower panel), particularly the METRIC results, reflect the effects of heavy frost and pruning. Moreover, the precipitation occurrence in 2012 was much lower than in 2011, with 43.5 vs 177.9 mm. Comparing the results of 2011 and 2012 it is shown that: (i) the inter-annual variability in precipitation leads to variations in K_c, particularly during the winter and autumn seasons, i.e., during the wet season due to changes in K_e; (ii) crop management practices like pruning, that impact LAI and canopy architecture and condition, affect K_c through K_{cb},and (iii) other abiotic stresses such as severe frost also impact K_{cb} and K_c values.

The adjusted basal crop coefficients ($K_{cb\ adj}$) obtained with SIMDualKc for 2011 were 0.48 ($K_{cb\ adj\ ini}$), 0.56 ($K_{cb\ adj\ mid}$) and 0.46 ($K_{cb\ adj\ end}$). For the second year, those $K_{cb\ adj}$ values were 0.43, 0.50 and 0.41 respectively. For 2011, those values agreed well with those reported by Allen and Pereira (2009) for medium density olive groves (f_{ceff} = 0.5) and by Villalobos et al. (2000) (f_{ceff} =0.3-0.4). In 2012, differently, K_{cb} values were slightly lower as a result of differences in ground cover related to the mentioned reduction of the green active canopy. For days with METRIC information, when K_e is higher than 0.2, $K_{cMETRIC}$ tends to present larger differences regarding $K_{cSIMDualKc}$ (Fig. 5). Considering both years, mean K_{cadj}, K_{cb}, K_{cbadj} and K_e were 0.66 ($K_{cMETRIC}$), 0.68 ($K_{cSIMDualKc}$), 0.62, 0.42 and 0.27, respectively.

The average difference between $K_{cMETRIC}$ and $K_{cSimDualKc}$ was 20 %. The larger differences were observed for the image dates of January 31st (DOY 31, absolute difference = 0.35) and May 23rd (DOY 143, absolute difference = 0.36) from 2011 (Fig. 5 upper panel). In such dates, the occurrence of precipitation in the antecedent days made it more difficult to define the anchor points for METRIC algorithm application with consequences over the ET and subsequent K_c estimation. Probably, some change in METRIC application in to incomplete canopies for those type of weather conditions might be developed. Additionally, there are uncertainties associated to SIMDualKc parameterization, since there are no field data available for this period in 2011 to allow the comparison of the performance of the model. For the remaining days, the absolute differences were lower than 0.2.

4. CONCLUSIONS

The crop coefficient simulation procedure as a function of the fraction of ground cover and tree height as incorporated in SIMDualKc proved to be an adequate approach to a tall and incomplete cover crop. The possibility of simulating evapotranspiration components *per se*, contributed to a better understanding of crop functioning, mainly in relation to soil evaporation, which greatly varies along the year.The mean bias between ET obtained with remote sensing data and ET derived from field data was close to 15%, which is acceptable given the potential errors involved in both field and remote measurements, as well as in the simulation processes.

K_c values derived from both models showed a similar pattern, revealing good perspectives for the use of K_c derived from METRIC algorithm as inputs in models like SIMDualKc to improve the definition of K_c values considering the specificities of vegetation architecture in orchards. Nevertheless, further tests must be implemented, increasing the series of data available to improve the parameterization of both models.

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