Seasonal dynamics and operational monitoring of hedgerow olive tree transpiration in response to applied water

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Abstract

We used 2012 sap-flow measurements to assess the seasonal dynamics of daily plant transpiration (ET_c) in a high-density olive orchard (*Olea europaea* L. 'Arbequina') with a well-watered (HI) control treatment A, to supply 100% of the crop water needs, and a moderately watered (MI) treatment B, which replaced 70% of crop needs. We then tested the hypothesis of indirectly monitoring olive ET_c from readily available vegetation index (VI) and ground-based plant water stress indicators. In the process, we used the FAO56 dual crop coefficient (K_c) approach. For the HI olive trees, we defined K_{cb} as the basal transpiration coefficient, and we related K_{cb} to the remotely sensed soil-adjusted vegetation index (SAVI) through a K_{cb}-SAVI functional relationship. For the MI treatment, we defined the actual transpiration ET_c as the product of K_{cb} and the stress reduction coefficient K_s, and we correlated K_s with MI midday stem water potential (ψ_{st}) values through a K_s-ψ functional relationship. Operational monitoring of ET_c was then implemented with the relationship $ET_c = K_{cb}(SAVI) \times K_s(\psi) \times ET_0$ derived from the FAO56 approach and validated, taking as inputs collected SAVI and ψ_{st} data reporting to year 2011. Low validation error (6%) and high goodness-of-fit of prediction were observed (R^2=0.94, RSME=0.2 mm day^{-1}, P=0.0015), allowing us to consider that, under field conditions, it is possible to predict ET_c values for our hedgerow olive orchards if SAVI and water potential (ψ_{st}) values are known.

Keywords: SAVI, stem water potential, sap flow, vegetation index, 'Arbequina', Alentejo

INTRODUCTION

Operational tools for precise quantification of actual ET_c under field conditions are important, and their development requires appropriate correction of the standard and tabulated potential K_{cb} crop coefficient values (Allen et al., 1998), by adopting a stress coefficient (K_s) to obtain the actual K_c as the product $K_s \times K_{cb}$. The conundrum is the setting of K_s to adjust for stress effects.

Transpiration of olive trees is mainly controlled by canopy conductance, as derived with the model of Orgaz et al. (2007). Nevertheless, the main challenge in such models remains the integration of the effect of water stress. For operational applications, the K_{cb} approach has been linearly related to remotely sensed vegetation indices (VI) such as the normalized difference vegetation index (NDVI) or the soil-adjusted vegetation index (SAVI) (Huete, 1988; Pôças et al., 2015). On the ground, field monitoring of crop water stress has been achieved with the development of plant-based measurement methods such as sap flow (Green et al., 2003) and leaf water potential (Moriana et al., 2012).

In this study, we hypothesized that directly relating readily available VI of well-watered olive trees to ground-based plant water-stress indicators might provide indirect assessment of the actual transpiration and water requirements of olive orchards. In this context, the objectives of this paper were: (1) to determine the transpiration dynamics and

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related crop transpiration coefficients of a hedgerow olive orchard in southern Portugal during the course of the summer under two (well-watered and moderate) irrigation regimes, (2) to validate whether treatment A-derived K_{cb} is from a well-watered treatment, by comparing field-derived sap-flow ET_c values to ET_c values obtained with the Penman-Monteith (PM) model incorporating values from the Orgaz et al. (2007) daily mean conductance (g_c) model, (3) to analyze the dynamics and derive K_{cb}-SAVI and K_s-ψ_{st} relationships, and (4) to assess the feasibility of integrating those relationships into the FAO56 model, and of using SAVI and ψ_{st} measurements as inputs to monitor hedgerow olive tree transpiration in southern Alentejo.

MATERIAL AND METHODS

Study site

The experiments were conducted during 2011 and 2012 in a commercial hedgerow olive orchard near Évora in southern Alentejo, Portugal (38°24’47.03”N 7°43’38.36”W; altitude 75 m a.s.l.). The orchard was established with 6-year-old ‘Arbequina’ trees in grids of 3.75×1.35 m (1976 trees ha^{-1}) in a north-south orientation, and in a sandy loam Eutric Cambisoil (WRB, 2006). Climate in the region is typically Mediterranean, and summer and year-round ET_0 were 506 and 1212.8 mm, respectively, for the two irrigation seasons.

Irrigation treatments

Two plots of 450 trees were selected for the experiments and subjected to one of two irrigation treatments: a control treatment A, in which trees were irrigated to replace 100% of daily crop water need (HI), and a moderate (MI) deficit irrigation treatment B to provide approximately 70% of the water applied to treatment A. Treatments A and B were serviced by 2.3 and 1.6 L h^{-1} emitters, respectively, spaced 0.75 m apart in the row. Irrigation scheduling and time of water delivery to trees were the same for both treatments. Crop water needs for treatment A were calculated based on the crop coefficient approach of Allen et al. (1998). Totals of 296 and 206 mm water were applied to treatments A and B in 2012 for an equivalent amount of 251 and 207 mm in 2011 (1 June to 30 September).

Field measurements

Predawn leaf (ψ_{pd}; MPa) and stem (ψ_{st}; MPa) water potentials were measured from late May to early September with a pressure chamber (PMS Instruments, Corvallis, WA, USA). Leaf area index (LAI) measurements were taken periodically with a ceptometer (Accupar-LP80, Decagon Devices Inc., Pullman, WA, USA). Sap flow (SF) in treatments A and B was monitored continuously from late May to early September using the compensation heat pulse (CHP) method (Green et al., 2003) and used to obtain olive transpiration.

Tool description

With data from year 2011, we calibrated the Orgaz g_c equation (Orgaz et al., 2007) to our olive orchard conditions, to obtain the following g_c equation (mm s^{-1}) for our olive orchard:

$$g_c = \frac{QR_{sp}}{10^3 D}(2.43T_d - 0.87) \tag{1}$$

where Q (dimensionless) is the fraction of intercepted photosynthetically active radiation (PAR), R_{sp} (W m^{-2}) is the mean daytime PAR irradiance, D (kPa) is the mean daytime vapor pressure deficit, and T_d (°C) is the mean daytime temperature. Subsequently, we determined g_c and ET_c for our orchard conditions in 2011 and 2012 by inputting the g_c values into the Penman-Monteith (PM) equation (Monteith and Moss, 1977). We also compared our observed (SF-based) ET_c outputs with the simulated (PM-based) ET_c values. Agreement between 2012 simulated (PM-based) and observed (SF-based) ET_c outputs was then analyzed using the root-mean square error (RMSE) and the Willmott index of agreement (IA) (Willmott, 1982).

Remotely sensed spectral band data from moderate resolution imaging spectrometer (MODIS; http://reverb.echo.nasa.gov/reverb/) sensors provided data for calculation of SAVI values (Huete, 1988). The FAO56 model (Allen et al., 1998) was used to predict olive tree transpiration, where ET_c is described as:

$$ET_c = K_{cb}\,K_s\,ET_0 \tag{2}$$

where seasonal values of K_{cb}, the unstressed plant transpiration coefficient, are the ratio of ET_c from treatment A daily SF-based values to ET_0. They were further correlated with canopy reflectance-derived SAVI to obtain a functional K_{cb}-SAVI relationship, subsequently used in the following equation to predict K_{cb} from known values of SAVI. We followed a similar approach to predict values of the stress reduction coefficient K_s. In this case, we correlated K_s with midday stem water potential (ψ_{st}) values obtained from the stress treatment B to provide us with a K_s-PWSI functional relationship able to predict K_s from known values of ψ_{st}. Operational monitoring and validation of ET_c were then accomplished with the following final relationship:

$$ET_c = K_{cb}(SAVI)\,K_s(\psi)\,ET_0 \tag{3}$$

RESULTS AND DISCUSSION

Dynamics of ET_c and plant water status

The results of g_c estimated from our calibrated Equation 1 were included in the Penman-Monteith equation to obtain the PM-based ET_c for 2011. We then assessed whether the PM-based ET_c values were related to unstressed SF-based ET_c from treatment A field data. The PM-based ET_c showed good agreement with ET_c field values, with $R^2=0.96$, RMSE=0.4 mm day^{-1}, $p<0.01$, and regression coefficient b close to 1.0 (data not shown). Such results confirm that treatment A was obtained under non-limiting conditions. Figure 1 plots 2012 predicted PM- and SF-based transpiration in treatments A and B and applied water.

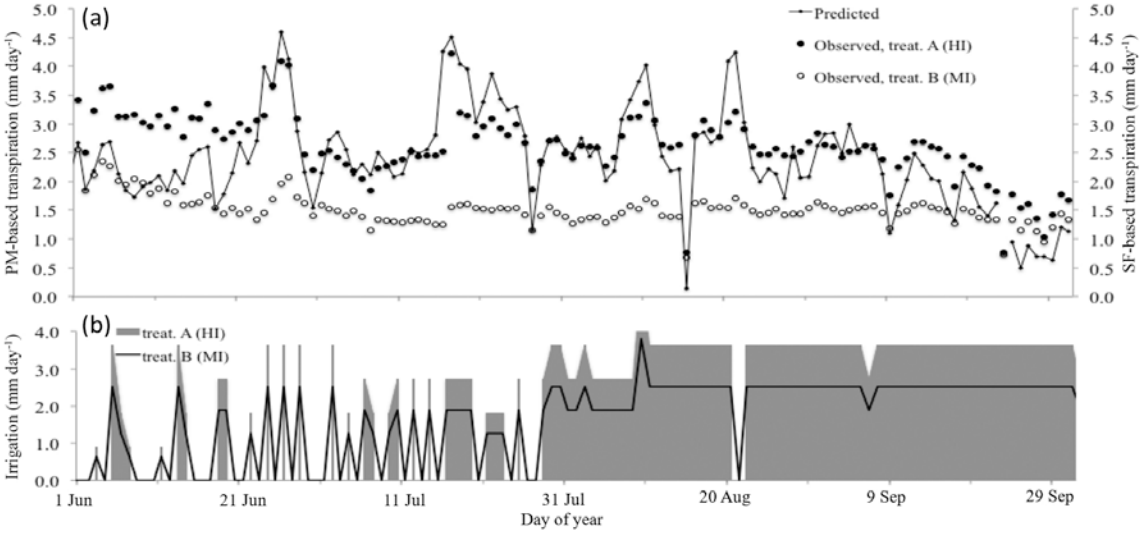

Figure 1. Seasonal course of predicted (PM-based) and observed (SF-based) transpiration rates (a), and applied irrigation to treatments A (HI) and B (MI) (b).

Statistical goodness-of-fit (IA=0.89; RSME=0.24 mm day^{-1}) also validated treatment A as irrigated under non-limiting conditions (well-watered, HI). For the period from 1 June to 30 September, treatment A total SF-based transpiration was 320.4 mm, while simulated PM-based transpiration was 306.3 mm. For the stress treatment B, SF-based transpiration was estimated as 185 mm, 87 mm short of treatment A.

Concurrent weather and water treatments had meaningful effects on 2012 plant-water relation parameters (Figure 2). Generally, midday stem water potential stayed stable and high until around 21 June (DOY 173) and decreased afterwards to its lowest values in mid-July (DOY 188), during late pit-hardening phase, when it reached its lowest value for the growing period, -1.9 MPa for treatment A and -2.8 MPa for treatment B. During late pit hardening, deficit was applied as convenient for this low-sensitive period to water stress (Moriana et al., 2012). Water application was enough in treatment A for ψ_{st} to generally stay higher than -1.5 MPa, showing the non-limiting condition of treatment A. In the MI treatment B, ψ_{st} values generally stayed below the -1.5 MPa threshold value from mid-June to the end of September (DOY 179-265). ψ_{st} values support the non-limiting condition of treatment A.

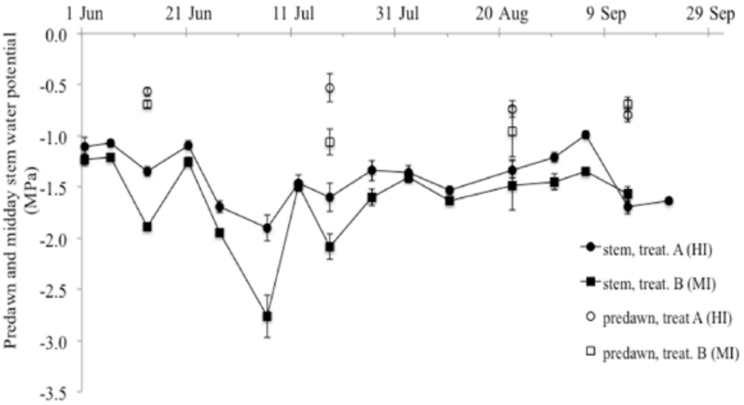

Figure 2. Seasonal course of predawn (ψ_{pd}) and midday stem water potential (ψ_{st}) of treatments A and B. Data points are means of measurements.

Transpiration coefficients, SAVI and PWSI relationships

Figure 3 shows the relationship between K_{cb} and SAVI values (R^2=0.79). The linear K_{cb} relationship was estimated with the aim of obtaining K_{cb} from VIs. For our olive orchard, estimating K_{cb} with SAVI gives b=1.73 and R^2=0.79.

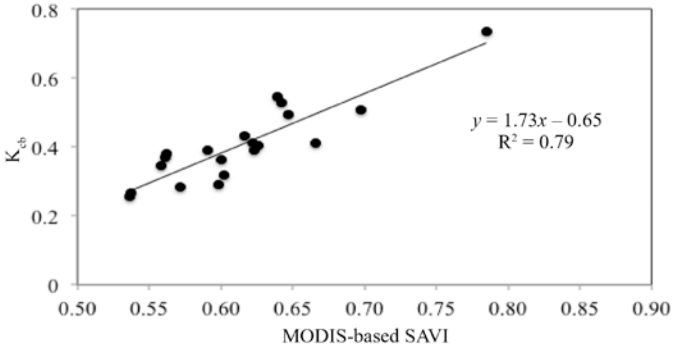

Figure 3. Relationship between K_{cb} from June to September and corresponding MODIS-based SAVI values. Regression parameters and function fitted to data are also reported.

The relationship in Figure 4 was estimated with the aim of obtaining K_s from ground-based treatment B midday stem water potential measurements. Values of K_s correlated well with ψ_{st} (R^2=0.79), showing ψ_{st} decreasing with K_s as water stress progresses.

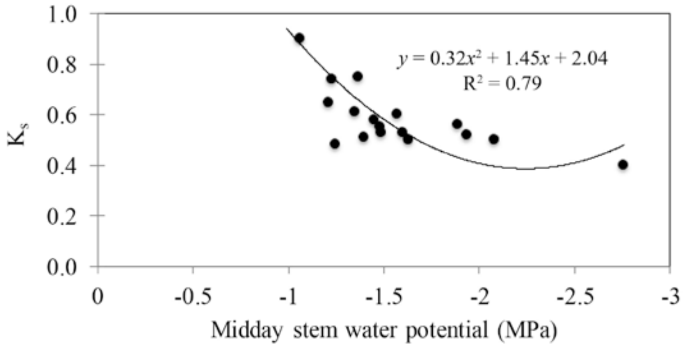

Figure 4. Relationship between mean K_s and midday stem water potential (ψ_{st}) for treatment B, showing regression parameters and function fitted to data (K_s-ψ_{st}).

The relationship shows that K_s values around 0.6 represent the threshold for well-irrigated olives, for a midday stem water potential of around -1.5 MPa. The K_{cb}-SAVI and K_s-ψ_{st} derived relationships in Figures 3 and 4, respectively, were used in FAO56 Equation 2 to derive the relationship in Equation 3. It was further used with data from year 2011 to monitor the course of ET_c and validate the derived relationship.

Monitoring ET_c with SAVI and PWSI

We validated our established FAO56 Equation 3 by comparing its results with field ET_c data collected from treatment B in 2011. The K_{cb}-SAVI and K_s-ψ_{st} functional relationships included in Equation 3 were implemented with the derived functions fitted to data and presented in Figures 3 and 4, respectively, and taking as inputs collected SAVI and ψ_{st} data from year 2011. Figure 5 displays the correlation between predicted and observed ET_c values, giving a high goodness-of-fit and low estimated error (R^2=0.94, RSMD=0.2 mm day^{-1}, P=0.0015). The good fit and low estimated error of 6% validate our model (Equation 3) and warrant its use for the purpose of this study, of trying to encompass ET_c of olives under mild water-stress conditions. Such facts encourage the use of Equation 3 for operational monitoring of ET_c of olive trees in response to SAVI-derived satellite data and ψ_{st} field-collected datasets.

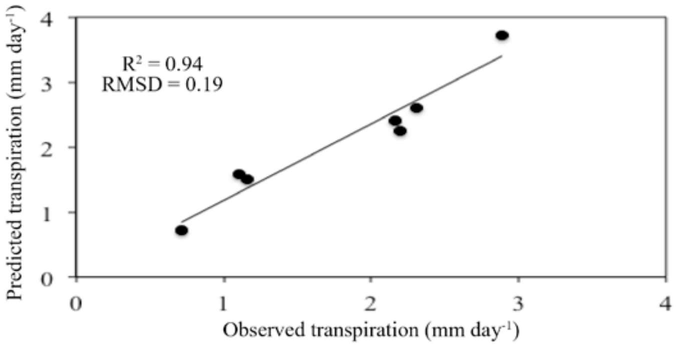

Figure 5. Relationship between predicted and observed olive tree transpiration in 2011. Predicted values were obtained from the K_{cb}-SAVI and K_s-ψ_{st} functional relationships presented in Figures 3 and 4, respectively.

CONCLUSIONS

Successful establishment of the K_{cb}-SAVI and K_s-ψ_{st} relationships made it possible to incorporate them into the dual FAO56 K_c-ET_0 approach by way of proposed Equation 3 and to obtain olive ET_c values for deficit irrigation treatment B. The approach adequately models actual olive transpiration. Further tests are desirable, however.

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