Agricultural Water Management 191 (2017) 138–152

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Three years of monitoring evapotranspiration components and crop and stress coefficients in a deficit irrigated intensive olive orchard

Nuno Conceição[a,*], Luca Tezza[b], Melanie Häusler[c], Sónia Lourenço[a,e], Carlos A. Pacheco[d], M. Isabel Ferreira[a,e]

[a] *Linking Landscape, Environment, Agriculture and Food (LEAF), Instituto Superior de Agronomia (ISA), Universidade de Lisboa (ULisboa), Tapada da Ajuda, 1349-017, Lisboa, Portugal*
[b] *CIRVE, Interdepartmental Centre for Research in Viticulture and Enology, University of Padova, Padova, Italy*
[c] *Centro de Estudos Florestais (CEF), Instituto Superior de Agronomia (ISA), Universidade de Lisboa (ULisboa), Portugal*
[d] *Departamento dos Recursos Naturais, Ambiente e Território (DRAT), Instituto Superior de Agronomia (ISA), Universidade de Lisboa (ULisboa), Portugal*
[e] *Departamento de Ciências e Engenharia de Biossistemas (DCEB), Instituto Superior de Agronomia (ISA), Universidade de Lisboa (ULisboa), Portugal*

ARTICLE INFO

Article history:
Received 30 November 2016
Received in revised form 21 May 2017
Accepted 30 May 2017

Keywords:
Olea europaea
Drought
Eddy covariance
Sap flow
Mediterranean
Portugal

ABSTRACT

A long-term experiment was conducted to study water use of olive trees in a six-year-old, deficit irrigated, intensive olive orchard (‘Arbequina’) in one of the driest regions of Southern Portugal. Woody agricultural crops are regularly cultivated with some water stress to maintain an equilibrium between the vegetative and reproductive cycles, to improve production quality and, when irrigated, to save water. To achieve a precise irrigation scheduling it is necessary to quantify water use reduction due to water stress. This study reports results from spring 2010 to autumn 2012, and encompasses a hydrological drought occurred in 2012. A long-term seasonal time series of transpiration (Tr), was obtained by combining data on evapotranspiration (ET) measured with the eddy covariance method, soil evaporation measured with microlysimeters and sap flow measured with a heat dissipation method. For the years 2010 and 2011, with normal precipitation, Tr varied between 2 and 4 mm/day, in the summer. In 2012, due to the winter drought, soil water content did not reach field capacity during the wet season and an important reduction in Tr was observed ranging from 1 to 2 mm/day during summer. Predawn leaf water potential (Ψ_{pd}) was selected as plant water status indicator, because these olive trees showed near-isohydric behaviour. A function relating Ψ_{pd} to the correspondent stress coefficient (Ks) was used to decompose Tr/ETo into the basal crop coefficient (Kcb) and the Ks. The first, during the summer period, oscillated around 0.4 for years with precipitation close to average, while Ks estimated from Ψ_{pd} decreased between 1.0 in early June to about 0.83 before first autumn rain. However, these Ks values did not explain the important reduction observed in Tr during the 2012 severe drought. Measured Kcb values were compared to the ones modelled using approaches based on density factor. The derived Kcb values for summer were lower than those observed.

1. Introduction

The increasing demand for crops with low environmental impact, high nutritional value and standard quality calls for improved knowledge on crop water relations. Olive trees are of recognized high nutritional and socio-economic importance and are cultivated in the Mediterranean basin since the antiquity. In Portugal, the consumption of olive oil per capita was 7.8 kg in 2013 which represents an increment of + 5.7% relatively to 2012; in 2014, the area for table olives was 8 800 ha with a production of 17.4 Mkg of olives and, for oil, 343 600 ha, producing 438.0 Mkg of olives (2012/2013 average is 526.1 Mkg) that originated about 66.5 ML of olive oil (INE, 2015). Following a recent trend in production increase, olive tree plantations represent now in Portugal an area of 53% of total woody agricultural crops, with 1.3% and 52% for table olives and oil respectively, being wine grapes the second most representative woody crop with 27% of the area, on the same basis (INE, 2015).

According to Kaniewski et al. (2012) survival mechanisms of the olive tree are not yet enough clarified. An improved knowledge of olive tree water relations is relevant not only for scientific purposes i.e. to better understand and simulate the physical and biological

---

[*] Corresponding author.
E-mail address: nuconceicao@isa.ulisboa.pt (N. Conceição).

http://dx.doi.org/10.1016/j.agwat.2017.05.011

processes involved, namely water use and survival strategies, but also for its immediate applicability to calibrate and validate evapotranspiration (ET) models, for which there is a possibility to obtain, for common uses, all input variables and parameters.

The models, always combining physical and empirical modules, can be single leaf (Monteith, 1965) or based on two or more compartments (e.g. Shuttleworth and Wallace, 1985) with data from ground level. However, these last usually require input data difficult to get outside the scope of research. Models can also use remote sensing data, such as one source energy balance models SEBAL (Bastiaanssen et al., 1998) and METRIC (Allen et al., 2007), two source energy balance models (e.g. Sánchez et al., 2008) and others still being developed and tested. Finally, a common approach includes the concept of crop coefficient (Kc). Doorenbos and Pruitt (1977) and Allen et al. (1998) are well known examples of compilation of Kc data, from a large collection of previous studies that used this approach for decades. The Kc model can be used in the one source form or single Kc approach (Doorenbos and Pruitt, 1977), with estimated maximum (crop) ET, $ET_c = Kc \times ETo$ where ETo is reference crop ET and where a stress coefficient (Ks) can be added (e.g. Ferreira and Valancogne, 1997) to obtain the actual estimated ET (ET_a). Another option is to use a two source form or dual Kc approach (Allen et al., 1998), where $ET_c = (Kcb \times Ks + Ke) \times ETo$, with Kcb basal crop coefficient, and Ke soil evaporation coefficient (= Es/ETo), being estimated actual transpiration (Tr_a) obtained as $Tr_a = Kcb \times Ks \times ETo$. This separation between the two components transpiration (Tr) and soil evaporation (Es) followed earlier works (e.g. Kanemasu et al., 1979; Wright, 1982).

Measurements of ET and its components are essential to obtain locally adjusted Kc, but measurements for woody crops are more difficult to obtain than for low crops (Ferreira et al., 2008; Allen and Pereira, 2009) and therefore they are scarce, especially for Mediterranean woody crops. These woody crops are usually cultivated with some level of water stress, therefore estimations must separate Kcb and Ks effects. Currently, another way to obtain Kc for large areas is using vegetation indexes (such as the normalized difference vegetation index) from remote sensing data, but this approach also needs measured Kc to validate a function relating measured Kc and vegetation indexes (Campos et al., 2010).

The difficulty to accurately measure ET and its components, for stands of woody plants (using micro-meteorological and hydrological methods) is well known and recognized (Rana and Katerji 2000; Testi et al., 2004; Williams et al., 2004; Ferreira et al., 2008) despite the advances in instrumentation and data acquisition systems, because of technical and/or methodological limitations of such methods, either physical (e.g. meteorological conditions) or biological (e.g. anatomical geometry and dynamics of stems and roots). Woody sparse canopies present increased difficulties mainly due to the complex architecture of roots and shoots (Ferreira et al., 2008).

The ET components, Tr and Es, have different dynamics on short time and seasonal time course (normally out of phase in woody Mediterranean ecosystems), Tr being usually the main component in ET from woody crops during summer, often estimated from sap flow measurements. Methods that allow measuring sap flow in stems, to infer Tr, can underestimate this component (Smith and Allen, 1996; Steppe et al., 2010; Wullschleger et al., 2011) namely when in use for long time (Moore et al., 2010) or due to other reasons not fully clarified (Wilson et al., 2001; Paço et al., 2004). In fact, there are studies reporting good absolute sap flow data in relation to reference methods (e.g. Berbigier et al., 1996) but many others show evidence that it is difficult to expect that the most common sap flow methods provide good absolute values in all circumstances, and mainly for high flows (Ferreira et al., 2008, 2012).

Sap flow techniques allow to have cheap long term measurements of Tr but have to be compared and corrected using other methods, which are more expensive. Due to uncertainties with data from sap flow techniques and due to the limitations of using long term eddy covariance (EC), Ferreira et al. (2004, 2008) proposed and used a combination of methods to obtain high temporal resolution (daily or lower) and simultaneously long time-series of reliable values for Tr (months, few years), for large fields of woody crops. This was done by using, during short periods, simultaneous measurements of ET by the EC technique, used as a reference (Kustas, 1990) and measured or modelled Es data (local adjusted model from good quality direct measurements), to obtain ET − Es, plus trunk sap flow data (possibly under or overestimated). From all these, it is possible to get a relationship to correct trunk sap flow estimates (in relation to ET − Es), which in turn makes it possible to determine reliable absolute long term Tr data, as described in section 2.11.

Several researchers contributed to study olive water use and water relations. For instance, an early attempt to measure Tr during a vegetative cycle was done by Abdel-Rahman and El-Sharkawi (1974). They measured Tr (rapid weighing method) in order to quantify and understand the effects of irrigation (150 mm) under a desert climate zone with 150 mm annual rainfall (western desert in Egypt). On an orchard (15 years old trees 'Shimlali', spaced 7 × 7 m) plots were subjected to different irrigation methods and irrigation scheduling approaches (rainfed, winter surface irrigation, and summer surface and sub-surface irrigation). From some Tr daily courses they estimated seasonal monthly Tr for 14 months (November to January). However, they did not apply the ETo concept but studied the linear correlation between Tr and meteorological variables, underlining that these olive trees showed strong stomatal control.

Other studies were performed on olive showing that these trees have high water-use efficiency (Bacelar et al., 2007; Fernández, 2014). Using the compensation heat pulse method, Fernández et al. (2008, 2011) studied Tr for olive trees, in relation to many different aspects of water relations. The same team modelled Tr at leaf scale but none of those studies reports values for ET.

Villalobos et al. (2000) used the EC method to access ET and its components on a drip-irrigated olive tree orchard 'Picual' (trees with: 4 m height, 6 × 6; ground cover 40%; leaf area index (LAI) of 1.5 and 1.2 in May of 1996 and 1997, respectively), at Cordoba (Spain). From the 11th to the 30th June 1997, they measured convective heat fluxes (latent heat flux (LE) and sensible heat flux (H)) above the canopy (EC sensors at 5 m height, separation path of 0.3 m) and below the canopy (EC sensors at 0.4 m height, separation path of 0.13 m) that would correspond to ET and Es, respectively. Specific Tr measurements were not performed; Tr was calculated as Tr = ET − Es. For the three days with complete 24 h data (DOY 171, 172 and 173) daily ET, Es and T were on average 3.12 mm, 0.74 mm (24% of ET) and 2.38 mm, respectively.

Another experiment was carried out by the same team (Villalobos et al., 2000) in March-June 1996 (before the drip irrigation campaign started); they also measured ET by EC method which ranged from 2.0 to 5.5 mm/day, for ETo from 2.7 to 8.5 mm/day. Using those values, Kc × Ks would be from 0.65 to 0.74. They hypothesised that Es (for a wetted soil fraction of 0.05–0.1) would be between 0.5 and 1 mm day^{-1} and underline the importance of accurate Es values.

When estimating canopy conductance (inverting the Penman–Monteith model for the transpiration flux) Testi et al. (2006) used Tr data obtained as the difference between measured ET (EC method) and Es estimated from a model, as done in our work. By measuring ET from a young drip irrigated olive orchard of 'Arbequina' (3.5 × 7 m spacing, southern Spain), with EC method and soil water balance (from soil water measurements until 2.7 m depth), Testi et al. (2004) found a good agreement between ET from EC method and ET from soil water balance. From June 29 to