Agricultural and Forest Meteorology 256–257 (2018) 159–178

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Analysis of evapotranspiration components of a rainfed olive orchard during three contrasting years in a semi-arid climate

Chebbi W.[a,b,*], Boulet G.[b], Le Dantec V.[b], Lili Chabaane Z.[a], Fanise P.[b], Mougenot B.[b], Ayari H.[b]

[a] Université de Carthage/LR17AGR01 (GREEN-TEAM). INAT, Institut National Agronomique de Tunisie, 43, Avenue Charles Nicolle 1082, Tunis, Tunisia
[b] CESBIO, Université de Toulouse, (CNES/CNRS/IRD/UPS), 18, Av Edouard Belin, 31401 Toulouse, France

ARTICLE INFO

Keywords:
Eddy covariance
Sap flow
Evapotranspiration
Partitioning
Water stress
Rainfed olive

ABSTRACT

Evapotranspiration is one of the most important fluxes of the water budget in semi-arid areas. The estimation of actual crop transpiration is a major issue in those regions due to its remarkable impacts on the precision of irrigation scheduling, crop growth and yield. Rainfed olive trees are adapted to the southern part of the Mediterranean basin even though they are vulnerable to an increased number of drought spells that might occur under current climate change scenarios. This present paper studies both water and energy exchanges over a rainfed olive grove in semi-arid conditions. The hydrological functioning of sparse olive trees is difficult to characterize because of its low LAI. To better understand water exchanges within the Soil–Plant–Atmosphere continuum and better evaluate the evapotranspiration and its components, we combine data arising from eddy covariance, soil water content measurements and the sap flow method. First, we check the consistency of the evapotranspiration partitioning and water balance over three contrasted years: one wet and two dry. Total evapotranspiration (ET) from eddy covariance method compares well with the sum of the evaporation (E) generated from the surface soil moisture measurements and the transpiration derived from the sap flow method. The top meter soil water balance corresponds roughly to ET during the wet year but for the dry years there is an evidence of extraction by roots below the first meter of soil. Inter-annual variations of the transpiration and associated water stress levels are analyzed by the combined use of different types of eco-physiological (sap flow) as well as remotely sensed variables that can be monitored through proxi-detection (albedo, surface temperature, surface soil moisture). The amount and timing of vegetation stress are consistent throughout the various indicators. Consequently, this consistent set of data can be used to constrain a SVAT land-surface model capable of representing the various features of the water and energy budget for this specific land cover.

1. Introduction

Olive orchards are a key agro-system for the economy in the semi-arid regions of the Mediterranean basin, which are known for their irregular rainfall, high evaporative demand and frequent water shortages. In Tunisia, olive yards cover 1.8 million hectares with 65 million olive trees representing nearly 79% of the total tree-covered area and 34% of arable land ("Observatoire National de l'Agriculture," 2017,"Patrimoine et répartition - Office National de l'Huile de Tunisie," 2017).

Because of their physiological and morphological properties, olive trees can survive under semi-arid conditions. They are efficient for preventing soil erosion and desertification, in addition to their important role in improving the soil carbon balance. When external conditions are not favorable, like high temperature or drought, olive trees are able to balance water inflows and outflows by minimizing the loss of water from the surface to the atmosphere and maximizing root extraction (Fernández et al., 1997; Fernández and Moreno, 1999). Moreno et al. (1996) compare the water use efficiencies of irrigated and rainfed olive yards under the same climatic conditions. They show through heat pulse velocity sensors (inserted in one root of the tree) that rainfed olive trees transpire less than irrigated olive trees and can extract water through deep roots, whereas irrigated olive trees rely only on shallow roots. After a heavy rainfall, an olive tree that has not been irrigated for 3 months increases its transpiration by 40% without reaching transpiration rates of an irrigated tree in similar pedo-climatic conditions and decreases its transpiration quickly after a few days. This behavior proves that the olive tree carries out a conservation strategy in soil-water use. The roots in a rainfed orchard are mostly located at the surface near the trunk and grow deeper further away from the trunk (Fernández et al., 1991). The inter row spacing is adjusted to explore the maximum volume of soil in such systems (Fernández et al., 1991).

* Corresponding author at: Université de Carthage/LR17AGR01 (GREEN-TEAM). INAT, Institut National Agronomique de Tunisie, 43, Avenue Charles Nicolle 1082, Tunis, Tunisia.
E-mail address: chebbiwafa@outlook.fr (W. Chebbi).

https://doi.org/10.1016/j.agrformet.2018.02.020
Received 21 July 2017; Received in revised form 4 January 2018; Accepted 16 February 2018
0168-1923/

Connor et al. (2014) explain how the row spacing affects the root density, water use and yield by combining model simulations of the response of olive trees yields to irradiation for different row spacing values. As a short term response to drought, the olive trees suffering from water stress can limit the relative water content of leaves, the photorespiration and the stomatal conductance (by closing the stomata) (Boussadia et al., 2008). During long drought periods, olive trees reduce their photosynthesis and thus their productivity (Ben Ahmed et al., 2007). When olive trees are exposed to severe drought, the roots reduce the efficiency of water transport through cavitation or suberification (Tataranni et al., 2015).

Despite the fact that olive trees are adapted to the past frequency of drought spells, they could be vulnerable to future climate changes if droughts are becoming more intense or more frequent. These severe weather conditions could threaten the resilience capabilities of the trees, alter soil moisture levels, biomass production and affect negatively fruit productivity in such water controlled systems. For instance, the region of Kairouan suffered from a substantial water deficit from 1998 to 2003 which led to a significant drop in the olive production by 95% in rainfed orchards. The average olive production of the previous 10 years was 837 tons while it was 75 tons in the year 2001 (Gargouri et al., 2008). To predict the quantities of olives produced in 2130, Viola et al. (2013) test the impact of future climate scenarios on the annual yield in olives by incorporating carbon assimilation during the development stage and by taking into consideration the effects of the vegetation water stress on the allocation of biomass. According to their study, the average yield of olive could decrease from 2.7 tons per hectare ($t\,ha^{-1}$) in 2010 to 1.9 $t\,ha^{-1}$ in 2130 as a result of reduction in rainfall (30%), in actual evapotranspiration (28%) and in carbon uptake throughout the growing season (27%). Similarly, Gómez-Rico et al. (2007) show that the fruit yield of a rainfed orchard is already four times smaller than that of an irrigated olive orchard. Hence, the relationship between the olive fruit size and ET (or water stress) is roughly linear (Bustan et al., 2015). A better comprehension of the underlying plant mechanism to resist to drought is therefore required so that we can study the influence of climate changes on these systems. Soil-Vegetation-Atmosphere Transfer (SVAT) models act as tools to simulate scenarios of energy and mass fluxes, in addition to their individual turbulent, radiative, conductive and water transfer components, and the stomatal control on transpiration (Boulet et al., 2000). Besides, when the projection of future climate is produced, they allow to explore past and future scenarios like more intense and longer drought periods and higher CO_2 concentration (Calvet et al., 2008), to study the year-to-year variability of water and energy balances in response to different climate conditions (Calvet et al., 1998) and to understand their partitioning: 1- into plant transpiration (T) and soil evaporation (E) and 2- into turbulent heat fluxes and available energy at the dry down scale. However, SVAT models require an important number of parameters and continuous meteorological data as inputs to replicate the plant functioning and its response to water stress. SVAT models also fail to reproduce the complex interaction of all the mechanisms governing soil evaporation. For example, when the top soil layer becomes dry during the second stage of evaporation, the water vapor transfers are not represented in SVAT models, especially when they occur in a very thin layer compared to the vertical discretization of the soil (Kuchment and Singh, 2009). Several physiological processes are also not accurately prescribed in most SVAT model schemes and are difficult to characterize. This is particularly true for the stomatal behavior (Arora, 2002), the energy storage in the trunk (Michiles et al., 2008), the cavitation of xylem conduits (Tognetti et al., 1996) and the root hydraulic lift (Caldwell et al., 1998). Neither of the experimental methods nor the modelling techniques discussed above are perfect; therefore a complete dataset is required to represent the inter-annual variability and the water and the energy balances components as well as to check the model ability to represent them.

To monitor the functioning of the olive tree, we need a good and suitable estimate of the transpiration (T). Hence, it is essential to determine the associated water budget components, such as deep drainage or the soil evaporation. E represents an important loss in sparse orchards (Boulet et al., 1997; Salvucci, 1997; Yamanaka and Yonetani, 1999) even through bare soils of semi-arid systems rarely evaporate at the potential rate except for a few days after precipitation.

Although the partitioning of ET between E and T is extremely important for understanding the hydrological cycle and for its modeling, (Reynolds et al., 2000), it is difficult to describe in these environments (Baldocchi et al., 2004) due to its high variability in space and time (Smith et al., 1995) and the difficulty to determine it accurately over such an heterogeneous area.

The estimation of transpiration of isolated trees can be achieved through three means: 1) by measuring T (Nicolas et al., 2005), 2) by measuring the ratio T/ET (Wang et al., 2010) or 3) by estimating E and ET through a residual analysis (Kelliher et al., 1992). Direct T estimates are obtained using the sap flow method (Granier, 1985), which is based on the sap flow heating dissipation by convection using sensors inserted into the tree trunk. The measured temperature difference between the heating source and the unheated sensor is directly proportional to the transpiration. The sap flow approach is praised for its efficiency to explore the relation between the root system and the canopy (sap circulation), its capacity to monitor transpiration continuously and on the long term for individual trees (Ben Aissa et al., 2009), its appropriateness for heterogeneous fields and its ability to describe physical and environmental controls on transpiration controls for individual branches or the whole tree. However, the sap flow requires the determination of the total sapwood area which often proves to be difficult and rather imprecise. The main limitation involves not only the scaling from the sensor to the tree, but also from the tree to the stand (Granier, 1987). Although transpiration chambers can determine directly the transpiration rate at the tree level, they are unable to represent the atmospheric conditions that prevail near the tree (Kölling et al., 2015). The chamber decreases the boundary layer and alters the water vapor in the confined volume. It is costly and also face a scaling-up problem (Kool et al., 2014). The ratio T/ET can be monitored through the isotopic method, but it is very expensive as well as difficult to implement (Williams et al., 2004). On the other hand, the flux-variance similarity partitioning proposed by Scanlon and Kustas (2010) consists in determining simultaneously the partitioning of water and carbon fluxes and requires only standard eddy covariance data. Hence, a continuous estimation of the vegetation water use efficiency (*WUE*) is required. The wide availability of eddy covariance data and the simplicity of the approach are the main benefits. Its efficiency is tested over isolated trees (i.e., Morgan Monroe State Forest) by Sulman et al. (2016) resulting in accurate values compared to the sub-canopy based method. The latter relies on comparing the eddy covariance data sampled from two different heights above the canopy to estimate the flux partitioning. Finally, we can deduce the transpiration rate from the estimates of the evapotranspiration and the soil evaporation. To do so, several methods of ET measurements and its components may be applied (Allen et al., 2011; Kool et al., 2014) such as lysimeter (Gebler et al., 2015), heat balance, isotope, chambers, eddy covariance (Baldocchi et al., 1988) and water balance method (Zeleke and Wade, 2012). E can be estimated by the soil weighting lysimeter (Scott et al., 2006), the soil heat pulse technique (Xiao et al., 2012) or the soil water budget method (Oren et al., 1998).

Nevertheless, the easiest solution to overcome the limitations of each method when applied separately is to combine two or more methods together. Thereupon, integrating the eddy covariance method with sap flow measurement aims to provide more robust estimates of E and T (Cammalleri et al., 2013). This method is applied over irrigated olive orchards (Er-Raki et al., 2009; Testi et al., 2004; Williams et al., 2004) showing promising results. For instance, Er-Raki et al. (2009) investigate irrigation practices by comparing localized drip and flooding irrigation techniques. They show that the combined use of sap