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Research Paper

A simple and alternative approach based on reference evapotranspiration and leaf area index for estimating tree transpiration in semi-arid regions

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ABSTRACT

The present work aims to develop a simple approach relating normalized daily sap flow (liters per unit of leaf area) and daily reference evapotranspiration (ET_0) (mm/day). Two methods (FAO-Penman-Monteith (FAO-PM) and Hargreaves-Samani (HARG)) of the calculation of ET_0 were tested in order to examine their impact on the established relationships. The data sets used for developing this approach are taken over well irrigated orchards from three experimental sites (olive trees, cv. "*Olea europaea L.*", olive trees, cv. "*Arbequino*" and citrus trees cv. "*Clementine Afourar*") conducted in the Tensift region around Marrakech (center of Morocco) and one experimental site (pecan orchard, cv. "*Carya illinoinensis, Wangenh. K. Koch*") conducted in the Yaqui Valley, northwest of Mexico).

The results showed that the normalized daily sap flow was linearly correlated with ET_0 (mm per day) calculated by FAO-PM method. The coefficient of determination (R^2) and the slope of this linear regression varied between 0.71 and 0.97 and between 0.30 and 0.35, respectively, depending on the type of orchards. For HARG method, the relationship between both terms is also linear but with more discrepancy ($R^2 = 0.7$). This was somehow expected since this method is known to underestimate ET_0 values in the semi-arid areas. Afterward, the validation of the developed linear relationship was performed over an olive orchard ("*Olea europaea L.*") where the measurements of sap flow were available for another cropping season (2004). The scatter plot between the normalized measured and estimated sap flow based on FAO-PM method reveals a very good agreement (slope = 1, and RMSE = 0.14 L/m^2 leaf area). However, for the estimation of normalized sap flow based on HARG method, the correlation is relatively more scattered (slope = 0.95, and RMSE = 0.35 L/m^2 leaf area). A further validation was performed using the measurements of evapotranspiration (ET) by eddy correlation system and the results showed that the correlation between normalized measured ET and estimated normalized sap flow is best when using FAO-PM method (RMSE = 0.33 L/m^2 leaf area) for estimating ET_0 than when using HARG method (RMSE = 0.51 L/m^2 leaf area).

Finally, the performance of the developed approach was compared to the traditional dual crop coefficient scheme for estimating plant transpiration. Cross-comparison of these two approaches with the measurements data gave satisfactory results with an average value of RMSE equal to about 0.37 mm/day for both approaches.

1. Introduction

Water availability is a major limitation for crop production in arid and semi-arid regions. Accurate estimation of crop water need constitutes a very important part of irrigation system planning

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and designing. Good irrigation management requires an accurate quantification of plant water consumption equivalent to the transpiration. The most accurate method for determining plant transpiration (T) directly is the measurements of sap flow (Kool et al., 2014). Several techniques have been developed to measure sap flow, and can be classified principally into three general groups: heat pulse (Burgess et al., 2001), heat balance (Sakuratani, 1981), and thermal dissipation techniques (Granier, 1987). A literature review with advantages and challenges of these techniques can be found in detail in Allen et al. (2011) and Er-Raki et al. (2013). The most challenge of these techniques is the scaling-up of the measurements from the stem and/or branch to the tree and after to the orchard level transpiration (Jones, 2004). The scaling-up procedure with its experimental protocol depends mainly on the characteristics of the stand (Smith and Allen, 1996; Oren et al., 1999; Rana et al., 2005; Er-Raki et al., 2010a). Among these procedures, the relationship between sap flow measurements and different morphological parameters of the crop such as leaf area index (LAI), stem diameter and surface area is extensively used (Smith and Allen, 1996; Valancogne, 1996; Rana et al., 2005; Er-Raki et al., 2009). However, these methods are not accurate enough, expensive, difficult, destructive and very time-consuming (Steppe et al., 2010; Allen et al., 2011; Kool et al., 2014).

Sap flow rates are largely controlled by physiology and anatomy of the species (Smith and Allen, 1996). Also, transpiration is influenced by climate conditions such as humidity, solar radiation, saturation vapor pressure deficit (Oren et al., 1999; Pataki et al., 2000) and therefore reference evapotranspiration (ET_0) (Er-Raki et al., 2009), that integrates all meteorological factors. Thus, changes in sap flow can occur without changes in stomatal aperture. Sap flow rates can vary between trees due to the difference in tree size and LAI, but a similar sensitivity to environmental conditions and to water status can occur (Eastham and Gray, 1998). Several works (e.g. Fernández et al., 2001; Nicolas et al., 2005; Pereira et al., 2006; Er-Raki et al., 2009) found that sap flow measurements in each tree, was linearly related to ET_0. It also has been shown that under the same ET_0 conditions, the sap flow of irrigated trees is a positive function of the total LAI (Hatton et al., 1998; Pereira et al., 2006). To eliminate the effect of canopy size on the sap flow rates, it is clear to divide by LAI and then sap flow is solely controlled by climate demand (ET_0). In this context, Pereira et al. (2006) have obtained a linear relationship between normalized sap flow (liters per unit leaf area) and ET_0 (mm) for many irrigated trees (apple, olives, grapevines, kiwifruit and an isolated walnut). The slope of this relationship is about 0.349, which corresponds to the inverse of the hypothetical leaf area of the reference grass surface, i.e., $2.88^{-1} = 0.347$. This can indicate that the normalized sap flow based on LAI is very similar notwithstanding of the plant canopy size, and equal to the normalized ET_0 (per unit of grass leaf area).

In the work of Pereira et al. (2006), ET_0 is calculated by using the FAO Penman–Monteith (FAO-PM) equation in order to develop this simple approach for estimating daily plant transpiration without any site specific calibration. However, the use of the FAO-PM equation requires the measurement of several climatic variables such as air temperature, relative humidity, solar radiation and wind speed (Allen et al., 1998, 2006). Unfortunately, there are a limited number of sites over the world (especially for developing countries) where complete meteorological stations are installed for routine measurements of these climatic variables. This lack of meteorological data leads to the development of simpler approaches to estimate ET_0 that require only air temperature which is the most available variable. Allen et al. (1998) proposed the use of the Hargreaves-Samani (HARG) equation (Hargreaves and Samani, 1985) as an alternative to estimate ET_0. In this regard, several studies have shown that this equation may provide reasonable estimates of ET_0 (Jensen et al., 1990; Hargreaves, 1994; Droogers and Allen, 2002; Dinpashoh, 2006; Er-Raki et al., 2010b).

In this context, the present study aims to estimate the daily plant transpiration of several orchards by using a simple approach which does not require a large number of input parameters that are not readily available. The proposed approach is based on the relationship between transpiration and ET_0. Herein, two methods are used to estimate ET_0: FAO-PM and HARG methods. As far as we know HARG method has never been tested before for this kind of study. Then, the performance of this proposed approach was compared to the traditional dual crop coefficient scheme for estimating plant transpiration. The advantage of this simple approach is to eliminate the effect of canopy size on the sap flow rates, and to make it only dependent on climate conditions without using a crop coefficient.

2. Materials and methods

2.1. Sites description and measurements

The data used for this research are taken from three experimental site operated in the Tensift region around Marrakech (centre of Morocco) and one experimental site in the Yaqui Valley (northwest of Mexico). The Tensift region is characterized by a semi-arid Mediterranean climate, i.e. the atmosphere is very dry, with an average relative humidity of 56%. The evaporative demand is very high [around 1600 mm/yr according to reference evapotranspiration estimates (Allen et al., 1998)], greatly exceeding the annual rainfall ranging from 190 to 250 mm year. Most of the precipitation falls during winter and spring, from the beginning of November until the end of April. Major irrigated vegetation types in the region include wheat, olive and orange. The irrigation uses either ground water or the water stored in the dams.

For the Yaqui Valley site, it is located in the Costa de Hermosillo which is the lower part of Sonora river watershed in northwest Mexico. This is mainly a flat agricultural area of 169,593 ha, where the annual and perennial crops occupy around 53,000 ha every year, irrigated using water from some 500 deep wells. The climate of the region is arid with an annual rainfall of around 200 mm. The rainy season is from July to September (with about 70% of the annual rainfall) and there is a very dry season with almost no rainfall from March to June. The mean daily temperature ranges from about 17 °C in January to 31 °C in summer (July-August), with sporadic frosts in the winter and temperatures that are frequently above 40 °C from the end of spring into summer.

Two data sets are from an experiment carried out during 2003 and 2004, in the Agdal olive (*Olea europaea L.*) orchard located in the Tensift region (31.601 N, 7.974 W). The experimental field is almost flat, planted with 240-year old olive trees, grown in an orchard of about 275 ha. The density of olive trees was about 225 trees per hectare, which corresponds to an area of about 45 m^2 occupied by each tree. Leaf Area Index (LAI) of the trees, where the sap flow measurements were taken, was measured using a LICOR 2000 plant canopy analyser, and was equal to about 2.5 m^2/m^2. The orchard was periodically surface-irrigated through level basin flood irrigation. Each tree is bordered by a small earthen levy that retains the irrigation water. Heat-pulse sap flow sensors (Heat Ratio Method, HRM, Burgess et al., 2001) were used to measure xylem sap flux on eight olive trees. In addition to sap flow measurements, total evapotranspiration (ET) was measured by eddy covariance system installed over the canopy. More details about the site description, the sap flow and eddy covariance measurements are given in Williams et al. (2004) and Er-Raki et al. (2008, 2009, 2010a).

One data set came from the study carried out during 2010, in the citrus orchard (*Afourar variety*) which was planted in July 2000. It is located approximately 30 km southwest of Marrakech city,