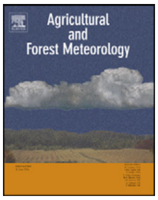
Agricultural and Forest Meteorology 171–172 (2013) 93–103

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

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



Modelling canopy conductance and transpiration of fruit trees in Mediterranean areas: A simplified approach

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ARTICLE INFO

Article history:
Received 20 March 2012
Received in revised form 5 October 2012
Accepted 18 November 2012

Keywords:
Sap-flow
Irrigation
Citrus
Olive
Walnut
Apple
Apricot
Peach
Pistachio

ABSTRACT

Improving current approaches to quantify the transpiration of fruit trees is needed for water allocation purposes and to enhance the precision of water applications under full and deficit irrigation. Given that transpiration of tree crops is mainly modulated by canopy conductance (G_c) and vapour pressure deficits, we developed a functional model of tree transpiration by quantifying an average daily G_c based on radiation use efficiency and CO_2 assimilation. For model calibration, an extensive experimental dataset of tree transpiration (E_p) was collected in many of the main temperate fruit tree species, namely, apricot, apple, citrus, olive, peach, pistachio, and walnut, all under non-limiting water conditions, in different orchards in Spain and California (USA). In all species, E_p was assessed by measuring sap flux with the Compensation Heat Pulse method for several months, and a transpiration coefficient (K_t) was calculated as the ratio of measured E_p to the reference evapotranspiration. For three deciduous species (apricot, peach and walnut) K_t showed maximum values close to 1, a value which stayed more or less constant throughout the summer in peach and walnut. The maximum K_t values were measured in pistachio (1.14) while they only reached 0.35 in olive and citrus trees. In the latter two species, K_t varied seasonally between 0.2 and 0.6 depending on the weather. The average G_c in July was high for apple, walnut, peach and pistachio (range 0.240–0.365 mol m^{-2} s^{-1}) and low for olive and orange (range 0.074–0.100 mol m^{-2} s^{-1}). The calibrated model outputs were compared against measured E_p data, suggesting the satisfactory performance of a functional model for E_p calculation that should improve the precision of current empirical approaches followed to compute fruit tree water requirements.

1. Introduction

The estimation of evapotranspiration (ET) and its components (evaporation from the soil surface, E_s and transpiration or plant evaporation, E_p) has been a key issue in hydrological studies (Nakayama, 2011; Wagner et al., 2011) and for improving irrigation management of agricultural crops (Evans and Sadler, 2008).

The most widely adopted method in agricultural water management for calculating ET is the one originally proposed by FAO (Doorenbos and Pruitt, 1977) that uses the product of two factors, the reference ET (ET_0) that models the ET of an hypothetical grass surface and a crop coefficient (K_c) that is proportional to crop ground cover and frequency of soil wetting. This method was later refined by Allen et al. (1998) through the development of a dual approach – crop coefficient, which separated K_c into a "basal" (crop) and a soil component – that *grosso modo* corresponds to separating E_p and E_s. However, in this case the basal crop coefficient includes E_p and some E_s when the soil is dry, which makes it almost impossible to check the validity of ET partitioning. The dual approach of Allen et al. (1998), was based on the original work of Wright (1982), which may be valid as an approximate engineering approach for ET estimation, but that may not be precise enough in many situations. Furthermore, the precise quantification of E_p is also important as it is related to canopy performance in terms of assimilation, and thus, productivity (Tanner and Sinclair, 1983). Also, evaluation of alternatives for water savings based on reduction/suppression of E_s, – an important issue that demands critical evaluation (Perry et al.,

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http://dx.doi.org/10.1016/j.agrformet.2012.11.010

2009) and that is currently a subject of debate (Gleick et al., 2011) – depends on our ability to estimate E_p.

Fruit trees are usually irrigated in the arid and semi-arid areas and represent a large demand for irrigation water, which is rising given the increasing world demand for fruits and the high water productivity of perennials as compared to that of many annual crops. On the other hand, the large investments required and high production costs make the optimal use of water critical for the sustainability of commercial orchards. In this case a precise estimation of transpiration under non limiting conditions is required to set the upper limit of irrigation requirements, and to adjust it to assess the opportunities of reducing transpiration via deficit irrigation (DI; Fereres and Soriano, 2007). In recent years the literature on DI has been abundant, although in many studies a given DI programme is compared to the commercial practice, but the actual differences in E_p between treatments are not assessed, precluding the estimation of transpiration reductions as compared to its maximum unstressed values (Lampinen et al., 2001; Ortuño et al., 2009; Pérez-Pastor et al., 2009). This clearly limits the applicability of many of these studies to conditions different from those of the original experiment.

The ET of fruit trees presents two distinct features as compared to that of annual crops; one is the large fraction of soil evaporation due to an incomplete ground cover that changes with plantation age and may be highly variable among orchards, but that seldom reach complete cover due to traffic and orchard management needs. The second is the tighter coupling of fruit tree canopies to the atmosphere due to the large roughness (Villalobos et al., 2000). The latter implies that transpiration will be mainly modulated by canopy conductance and vapour pressure deficit as opposed to short crops (including the reference grass surface), where transpiration is mostly dependent on solar radiation (Jarvis, 1985). Transferability of standard crop coefficients for fruit trees among different environmental and orchard management conditions is thus open to some question, and alternative approaches to quantify orchard ET need to be sought.

Models of transpiration have been developed for many species with a wide variation of physiological detail (e.g. Dekker et al., 2000, for a basic review). In general they are based on the calculation of canopy conductance which is often done by applying empirical models of leaf conductance (e.g. Jarvis, 1976) to canopies (Stewart, 1988). Another approach links leaf conductance to CO_2 assimilation using semi-empirical equations (e.g. Ball et al., 1987; Leuning, 1995). Overall, the complexity of many assimilation models (e.g. Farquhar et al., 1980) needed to calculate conductance preclude the wide use of approaches linking conductance to assimilation outside the academic environment.

In an attempt to simplify the requirements of the more complex models, Orgaz et al. (2007) proposed a synthetic approach for assessing the canopy conductance of olive trees based on the concept of Radiation-Use Efficiency (Monteith, 1977; Anderson et al., 2000) as a surrogate for the assimilation model. This simplified approach has been tested successfully for olives in different environments and cultivars (Rousseaux et al., 2009; Fernandes-Silva et al., 2010; Martínez-Cob and Faci, 2010; Martín-Vertedor et al., 2011), and thus could serve as the basis for empirical models in other fruit tree species.

The development of transpiration or canopy conductance models has been hindered by the lack of accurate, long-term transpiration data at the orchard scale. The measurement of transpiration can be performed by few methods, for example gas exchange chambers or bags (Dragoni et al., 2005; Pérez-Priego et al., 2010), but in trees it is often based on determining sap velocity using heat as a tracer. Among the different methods available for measuring sap flow the most common approach has been the heat dissipation technique (Granier, 1985) although recent studies indicate large potential errors depending on xylem thermal characteristics and tree size (Sevanto et al., 2009; Wullschleger et al., 2011). The Compensation Heat Pulse (CHP) method has been used successfully on many species (Swanson and Whitfield, 1981; Green et al., 2003), and it has shown better performance than other sap-flow methods (Steppe et al., 2010). A recent improvement in the methodology has overcome the problem of measuring low sap velocities with the CHP method (Testi and Villalobos, 2009). Records of sap velocity of different fruit tree species under a variety of conditions, are a prerequisite for the estimation of transpiration with sufficient accuracy as an input needed for the parameterization and experimental validation of transpiration models.

The objective of this study was to develop a generalized, simple transpiration model by: (a) collecting a comprehensive transpiration data set using the CHP method in orchards of the main fruit tree species, namely olive, citrus, peach, apple, pear, apricot, pistachio and walnut and (b) calibrating the conductance model of Orgaz et al. (2007) for the different species. This model is explicitly oriented to the calculation of tree crop water requirements for irrigation management, thus it was designed with functionality and low input requirements as its main features.

2. Materials and methods

2.1. Canopy conductance model

Starting with the leaf conductance model proposed by Ball et al. (1987) and Leuning (1995), that established the linear dependence of conductance on CO_2 assimilation (A), Orgaz et al. (2007) calculated canopy conductance (G_c) for olive trees as a function of tree intercepted radiation and vapour pressure deficit. This is based on the concept that canopy assimilation is proportional to radiation interception (Monteith, 1977) which was also underlying the foundation of the model of Anderson and Norman (Anderson et al., 2000). Here, we calculate canopy conductance for water vapour (G_c, $\mathrm{mol\,m^{-2}\,s^{-1}}$) as:

$$G_c = 1.6c\frac{\alpha Q R_{sp}}{(1+(D/D_0))C_s} \qquad (1)$$

where c is an empirical coefficient (dimensionless), α is the radiation use efficiency ($\mu\mathrm{mol\,CO_2\,\mu mol^{-1}}$), Q is the fraction of photosynthetically active radiation (PAR) intercepted by the canopy (dimensionless), R_{sp} is the average incident daily PAR ($\mu\mathrm{mol\,m^{-2}\,s^{-1}}$), D is vapour pressure deficit (kPa), D_0 (kPa) is an empirical coefficient related to the response of stomatal closure to D, C_s is the CO_2 concentration in the leaf boundary layer ($\mu\mathrm{mol\,mol^{-1}}$) and the coefficient 1.6 converts conductance for CO_2 to that of water vapour. Incorporating Eq. (1) in the "imposed" evaporation equation (Tan et al., 1978; McNaughton and Jarvis, 1983) leads to the following equation to calculate the average transpiration rate during the daytime (E_p, $\mathrm{mol\,m^{-2}\,s^{-1}}$):

$$E_p = 1.6c\frac{\alpha Q R_{sp}}{(1+(D/D_0))C_s}\frac{D}{P_a} \qquad (2)$$

where P_a is atmospheric pressure (kPa).

Eq. (1) might be re-arranged as follows:

$$\frac{QR_{sp}}{G_c} = \frac{C_s}{1.6c\alpha D_0}(D+D_0) = a + bD \qquad (3)$$

This equation indicates that if C_s and α are constant, the ratio of intercepted radiation and canopy conductance should be a linear function of D with an intercept of: $a = C_s\ 1.6^{-1}c^{-1}\alpha^{-1}$ which depends on radiation use efficiency, and a slope of $b = C_s 1.6^{-1}c^{-1}\alpha^{-1}D_0{}^{-1}$ which also depends on the parameter for response to D.