The use of high-resolution weighing lysimeters to improve estimates of soil evaporation in drip-irrigated olive orchards

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Keywords: soil evaporation, olive orchard, surface resistance, weighing lysimeter

Abstract

Soil surface resistance increase quickly during the first three days after irrigation or rain event. By explicitly incorporating surface resistance in simple equations, daily total evaporation estimation of a drip-irrigated olive grove was significantly improved. This increase in soil surface resistance could explain why observed cumulative soil evaporation is higher in locations with lower irradiance. In these locations surface resistance increased more slowly during the first days after irrigation.

INTRODUCTION

As in many natural ecosystems in the semi-arid region of the Mediterranean, vegetation in olive orchards does not completely cover the underlying ground surface. Any land surface with a sparse overstory has at least two significant sources of heat and water vapour: the canopy itself and the soil. These two component surfaces are often very different in their control of water and heat fluxes; both need to be accounted for when calculating a flux from the land surface as a whole, and consider their interactions (Lund and Soegaard, 2003).

Soil evaporation accounts for between 30 and 80% of the total evapotranspiration of the crop in Mediterranean climate (Bonachela *et al.*, 1999). This is due to the low canopy density of trees causing a reduced vegetation cover and low foliar area index. Modern olive orchards are usually drip-irrigated, with 200-300 trees/ha and ground cover of 40-50 %, while traditional rainfed olive orchards in Spain have typically around 100 trees/ha.

Measurements of evaporation from the bare soil are generally made using weighing microlysimeters (Daamen *et al.*, 1993). First objective of this study was to design and develop nine weighing lysimeters to allow direct measurement of soil evaporation. The main advantage of this method is that the larger size of these lysimeters minimises many of the errors associated with the use of traditional microlysimeters, such

as the boundary to water flow imposed at the base, and the conduction of heat through the microlysimeter casing. Also, this method provides an accurate and in-continuous measurement of evaporation.

The most commonly used model to predict evaporation from bare soil is based on the Ritchie (1972) approach, which considers evaporation to occur in two distinct phases. This is an empirical model which has been adapted to olive orchards by Bonachela *et al.* (1999). Some authors pointed out that those models should be used with caution for soil beneath trees as tree patterns and tree crop species play a role. Empirical testing of the model for different situations would be laborious and costly due to the diversity of cropping systems. Therefore, the development of a more mechanistic approach (e.g. Shuttleworth and Wallace model (1985) with appropriate surface resistance parameterisation) is recommended. These mechanistic models are based on the original Penman-Monteith equation. Therefore, the second objective, and major goal of this study, was to estimate soil surface resistance by inverting the Penman-Monteith equation using the measured soil evaporation with developed lysimeters. This allowed us to test weather the key assumption in the Ritchie approach (i.e. surface resistance during evaporation phase is equal zero) is valid.

MATERIALS AND METHODS

The study was carried out under field conditions in an olive tree orchard of 0.5 ha, planted with 35-year-old olive trees at a spacing of 5m × 5m, and located at CSIC experimental farm La Hampa (Coria del Rio, Sevilla). Nine weighing lysimeters were installed at different orientations around a single olive tree (Fig. 1). Each lysimeter (0.55 × 0.55 × 0.25 m) was made of perspex, a material with a very low thermal conductivity to avoid the conduction of heat through the lysimeter casing. Changes in weight were measured using three 50 kg capacity load cells per lysimeter, and each one was equipped with four thermistors and two soil moisture sensors, which allowed us to estimate soil heat flux. Resolution achieved by our lysimeters was 0.01 mm. Aerodynamic resistance was determined from the energy balance of a pair of adjacent sensors, heated and unheated, placed flush with the soil surface, using the McInnes *et al.* approach (1994). Also, one psychrometer, two anemometers, one net radiometer and 23 PAR sensors were placed on the lysimeters or nearby, to measure temperature, humidity, wind speed, net radiation and PAR respectively. Measurements were taken every 10 seconds and 10 minutes averages were stored in a Campbell CR21x logger. Irrigation was applied using 4 l h⁻¹ drippers.

Soil evaporation was modelled following the method of Ritchie, which considers evaporation occur in two distinct phases,

$$\Sigma E_{s1} = \sum_{t=0}^{t_1} E_{s0} = U \quad (1)$$

$$\Sigma E_{s2} = \alpha \sqrt{(t - t_1)} \quad (2)$$

where E_{s1} and E_{s2} are the cumulative amounts of soil evaporation in the first (equation 1) and second drying phase (equation 2). In the first one evaporation proceeds at the potential rate E_{s0} , which can be calculated from the Penman-Monteith equation assuming

surface resistance equal to zero, until the total amount of water evaporated is U . In the second one, soil evaporation declines as a function of time and α , a constant which is assumed to be a function of soil diffusivity.

The standard Penman-Monteith equation is given by,

$$E_s = \frac{\Delta(R_n - G) + \rho C_p [e_s - e_a] / r_a}{\Delta + \gamma(1 + r_s / r_a)} \quad (3)$$

where Δ is the slope of the saturation vapour pressure-temperature curve at the mean temperature, R_n is the net radiation, G is the soil heat flux, ρC_p is the volumetric heat capacity, e_s is the saturated vapour pressure at air temperature, e_a is the air vapour pressure, γ is the psychrometric constant, r_a is the aerodynamic resistance, and r_s is the soil surface resistance. Surface resistance of the soil surface was estimated inverting equation 3, as we measured all the other variables.

RESULTS

Solar radiation reaching the ground surface underneath the trees in an olive orchard is very heterogeneous. Lysimeters in outer locations, further away from tree trunk (see Fig. 1), received more radiation than inner ones. We expect a correlation between incoming radiation and soil evaporation, and Figure 2 shows that in our case this relationship was negative. The four lysimeters closer to the tree trunk received down to half the radiation of the outer ones, and their accumulative evaporation in a 9-day period was up to 15 % higher than those. This fact was also correlated with soil moisture sensors at 2.5 cm of soil surface. Inner lysimeters showed larger soil water depletion (around $0.01 \text{ m}^3 \text{ m}^{-3}$) than outer ones, especially after the third day of evaporation.

Figure 3 shows the average E_s of the eight lysimeters average for a nine-day drying cycle. Potential evapotranspiration was determined with the FAO56 Penman-Monteith equation (Allen *et al.*, 1998), and shows a value for the studied period of around 5 mm day⁻¹. Most of the soil evaporation took place during the first two days, and then evaporation rate decreased rapidly down to values of 0.5 mm day⁻¹. Dashed line represents results for the Ritchie model. The first two days fall into the energy limiting stage of the model, meanwhile, from the third day onwards, soil evaporation occurs in the falling rate stage. There is a good agreement between data and model estimates of E_s for the whole period, except for the second day in the energy limiting stage when evaporation was overestimated.

To estimate r_s we inverted the Penman-Monteith equation. Values of r_s changed during the day, depending on soil drying and fluctuating atmospheric conditions. To simplify the application of the model, we obtained a daily average value of r_s . For the first three days we obtained values of 89.4 sm^{-1} , 556.9 sm^{-1} , and 824.1 sm^{-1} respectively, showing the progressive increase of this resistance which increased more than 6 times from the first day to the second. Figure 4 shows the application of the Penman-Monteith equation with surface resistance estimates as inputs. Model matches daily fluctuation of evaporation. The Penman-Monteith model was then applied to the whole period, and a

good agreement was obtained with observed evaporation on the second day, thereby improving the results of the Ritchie model (Fig. 3).

DISCUSSION

The negative relationship of accumulated soil evaporation with radiation contrasts with what is expected and with the results from Bonachela *et al.* (1999) in an olive orchard. They found a positive relationship with incoming radiation, but in their case most of the evaporation took place during the first three days of the drying cycle, and later on, as in our case, readings from locations with lower incoming radiation showed higher values of soil evaporation.

The Ritchie model predicted soil evaporation reliably from the third day, but it overestimated soil evaporation on the second day. This same result was obtained by Bonachela *et al.* (1999), and it can be attributed to the assumption that on the second day evaporation is still in its first stage, and its r_s is assumed to be zero. As our results demonstrate a six-fold increase in r_s was observed between the first and second day, and when we considered this in the Penman-Monteith model, it was possible to predict E_s correctly. The quick development of a thin dry soil layer with a high surface resistance, could also be the reason why more irradiated locations presented a lower cumulative E_s . Ham and Heilman (1991) calculated this dry layer to be around 2 to 12 mm thick. This layer reduces the capability of the soil moisture profile to recover during the nighttime, and could explain why lysimeters drying out slowly, i.e. those more affected by the shadow of the canopy, can achieve higher cumulative evaporation (van de Griend and Owe, 1994). Calculating r_s independently and its daily course is not straightforward if we want to apply the model. Currently, we are working on a method using surface temperature to estimate r_s remotely.

Acknowledgements

This research was supported by a Marie Curie European Reintegration Grant within the 6th European Community RTD Framework Programme. The authors wish to thank Bruce Main and Ignacio Girón for excellent technical assistance and field work.

Literature cited

- Allen R.G., Pereira L.S., Raes D. and Smith M. 1998. FAO irrigation and drainage paper n° 56. Crop evapotranspiration. FAO, Rome. 326 pp.
- Bonachela S., Orgaz F., Villalobos F.J. and Fereres E. 1999. Measurement and simulation of evaporation from soil in olive orchards. *Irrigation Science*, 18: 205-211.
- Daamen C.C., Simmonds L.P., Wallace J.S., Laryea K.B., Sivakumar M.V.K. 1993. Use of microlysimeters to measure evaporation from sandy soils. *Agricultural and Forest Meteorology*, 65: 159-173.

Ham J.M. and Heilman J.L. 1991. Aerodynamic and surface resistances affecting energy transport in a sparse crop. *Agricultural and Forest Meteorology*, 53: 267-284.

Lund M.R. and Soegaard H. 2003. Modelling of evaporation in a sparse millet crop using a two-source model including sensible heat advection within the canopy. *Journal of Hydrology*, 280: 124-144.

McInnes KJ, Heilman JL and Savage MJ, 1994. Aerodynamic conductances along a bare ridge-furrow tilled soil surface. *Agricultural and Forest Meteorology*, 68: 119-131.

Ritchie J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research*, 8: 1204-1213.

Suttleworth W.J., Wallace J.S. 1985. Evaporation from a sparse crops - an energy combination theory. *Quarterly Journal of the Royal Meteorological Society*, 111: 839-855.

Van de Griend A.A. and Owe M., 1994. Bare soil surface resistance to evaporation by vapor diffusion under semiarid conditions. *Water Resources Research*, 30: 181-188.

Figure 1. Schematic representation of the experimental set-up used. Meteorological sensor locations shown correspond to anemometers, psychrometer, net radiometer and heat plates to measure aerodynamic resistance.

Figure 2. Relationship between incoming radiation and cumulative soil evaporation after nine days. Open circles correspond to inner locations (close to the tree trunk), and closed circles to outer locations.

Figure 3. Daily soil evaporation values during a drying cycle in bare soil underneath an olive tree (close squares representing an eight-lysimeter average with standard deviation indicated by vertical bars). Also shown are simulated soil evaporation with Penman-Monteith and Ritchie models, and potential evapotranspiration.

Figure 4. Measured and modelled soil evaporation using Penman-Monteith equation and surface resistance estimated. Surface resistance increase from 89.4 s m^{-1} on day of year (DOY) 248 to 824.1 s m^{-1} on DOY 250.