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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Mass and surface energy balance approaches for monitoring water stress in vineyards

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Abstract

Tree crops are representing one of most widespread agricultural systems in Mediterranean regions, thus contributing in a substantial way to the economy and productivity of primary sectors of the countries interested. Besides the aspects concerning their economical relevance, tree crops like vineyards, olive and orange orchards are also typical elements of the Mediterranean landscape, and their ecological role has been recently revitalised in consideration of their function as carbon sinks for the Kyoto agreement.
The environmental and economical sustainability of these agricultural systems in arid and semi-arid zones has to cope with the availability and management of water resources for irrigation. During recent years there has been a substantial progress in understanding the evolution of evapotranspiration processes in cropping systems, and detailed models and measurement techniques have been set-up for describing the mass and energy exchanges in the soil-plant-atmosphere continuum. However, due to the complexity of rooting systems and aerial parts further steps are needed for a full comprehension of hydrological processes in tree crop systems, with special regard to water stress conditions.
Within the research project P.R.I.N. 2008 "*Assessment of mass and energy fluxes for the irrigation management of Mediterranean tree crops*" different techniques for measuring evapotranspiration fluxes in tree crops will be developed and tested, from innovative methodologies based on remote sensing observations to in-situ observations (xylem-flow measurements and micro-meteorology). These data-sets have be interpreted by means of physical approaches, with a modelling perspective of the observed processes.

Keywords: surface energy balance; tree-crops; water stress modelling

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1. Introduction

The general decreasing trends for water supply in Mediterranean regions make essential to understand the water relations in the primary sector; in Southern Italy, tree crops – olive, orange and vineyards- represent one of the most relevant components in the agricultural economy, as well as in the exploitation of water resources. Therefore, the first step toward proper management of scarce water resources in these regions requires accurately estimating the spatio-temporal variability of crop water exchanges with the atmosphere through evapotranspiration process (ET) and the management of irrigation applications under water stress conditions.

Deterministic water balance models, that have embedded specific codes for root water uptake simulation, have been intensively used in the past years to evaluate crop water stress in homogeneous canopies, such as herbaceous crops. Technical advances include more rigorous treatment of multidimensional soil water flow models and temporal patterns of root water uptake. However, in tree crop systems, showing horizontal heterogeneity, the complexity of parameters needed to describe multidimensional root water uptake represents a severe constraint for the application of the modelling approaches. Conversely, the effective limitations of accuracy of 1-D approach vs. 2- or 3-D are not quantified. Experimental evaluations are still needed to assess the suitability of one-dimensional modelling approach based on the solution of Richards' equation for water flow in the soil-plant-atmosphere continuum to heterogeneous canopies and complex root geometry systems under irrigated condition, as in the case of the tree-crops considered in this research.

In a similar way, radiometric observations of canopy temperature have been implemented in simple water stress indicators or more complex surface energy balance models. However, the latter approaches have found limited applications in tree-crops; in the case of water balance models, the root water uptaking models need to be correctly implemented for taking into account the complexity of root systems. Secondly, measuring and modelling the evapotranspiration of tree crops either at the plant or at the plot scale is still an issue of debating. A major reason is the sparse canopy condition which determines an important but variable source of evaporation from the soil surface, i.e. measurements by Lascano et al. [1] and Heilman et al. [2] in vineyards showed that soil evaporation can account as much as 60-70% of evapotranspiration. Thus, in tree crops we need to evaluate separately the evaporation flux from the soil and the canopy transpiration in order to achieve a reasonable accuracy in the evaluation of crop water requirements. Previous studies about soil-water relations in tree crops have mainly shown that differences in soil water regimes induce differences in leaf water potential and stomatal conductance [3] or transpiration [4]. In such cases, single-source energy balance models like SEBAL or SEBS are not the most appropriate ones.

In this research work, two distinct water and surface energy balance modeling approaches have been applied and tested in two vineyard case-studies:

- the model SWAP [5], widely used for simulating the water flow in the soil-vegetation-atmosphere continuum; the algorithm is based on an extended form of Richard's equation with the inclusion of a sink term to describe water uptaking by roots. From the soil water flow simulation it is possible to estimate the vertical distribution of soil water potential and hence the different terms of the water balance including the actual rate of evaporation and canopy transpiration;
- the two-sources energy balance model TSEB [6], by using image and point-based measurements of radiometric temperature of soil and canopy composites.

It should be noticed here that both models have been mostly applied to herbaceous crops, and there are few studies concerning tree crops; thus the present study has a two-fold objective: a) testing the applicability to tree crops of the abovementioned models; b) assessing water stress conditions from models results. The accuracy of modeling output has been assessed from a comparison with eddy covariance data [7] and sap flow measurements.

2. Materials and methods

We have selected two typical areas for vine production in Southern Italy, with different soil and climatic conditions. In both cases, drip irrigation was available but not used during the observation periods.

The first campaign took place during the summer 2010 in the south-western part of Sicily, near Campobello di Mazara (Lat 37°35'; Long 12°38'); the vineyard had an extension of approx. 3 ha, variety Grillo, planted in 2003. The distance between the rows was 2.30 m; intra-row distance was 0.90 m (4831 plants/ha). At stationary growth phase canopy height was 1.50 m, with an average LAI value at plot scale of 0.8 m^2m^{-2}; the fractional vegetation cover was 0.36. From May 5th to Aug. 11th 2010 we monitored the plot by using the following instrumentations: a) sap flow (TDP probes); b) TDR probes for soil water content at different depths (10-30 cm, 35-55 cm and 60-80 cm); c) eddy covariance for energy fluxes (CSAT3 sonic and Licor 7500 gas analyser); d) infrared radiometers for surface temperature (Apogee infrared radiometers).

Soil texture was measured using the hydrometer method [8] and soil textural class, according USDA classification, is silty clay loam. Standard meteorological data (incoming short-wave solar radiation, air temperature, air humidity, wind speed and rainfall) were hourly collected by Pessl weather station installed inside the experimental field. Soil water retention curves were determined on four horizons by means of an inverse approach utilizing Hydrus-1d model [9] and TDR measurements.

The second campaign was organized in a Chardonnay vineyard located in northern Campania, in the Telesina Valley (Lat 42°12'; Long 14°37'); field extent and crop structure was similar to the previous one, with a slightly less developed canopy (LAI=0.7) compared to the previous site. Measurements took place from June to September 2012, where an eddy covariance system (CSAT3 sonic and Campbell EC150 analyser) was installed together with Apogee infrared radiometers pointing at the canopy and the soil surface.

Soil texture is clay loam according to USDA classification, after hydrometer analysys. Meteorological data (incoming short-wave solar radiation, air temperature, air humidity, wind speed and rainfall) were hourly collected by an automated weather station installed nearby the experimental field.

Soil water retention curves were determined using laboratory evaporation experiment, followed by the application of Wind method [10] to determine soil water retention and soil hydraulic conductivity. The method has also been enriched by using pressure plate apparatus [11] data measured on three undisturbed soil samples, 0.08 m diameter and 0.12 m height, collected at depth of 0-12 cm, 20-32 cm and 60-72 cm.

2.1. Theory

The water balance model used in this work is SWAP [12]. The movement of the water in the soil-plant system is described by Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right] - S_a(\psi) \tag{1}$$

SWAP routines solve Richards equation (eq. 1) with a numerical scheme in finite differences [13], allowing us to describe the fate of water in the soil. The model requires soil hydraulic functions described by analytical expressions of van Genuchten [14]. The upper boundary conditions are posed by potential fluxes of evaporation E and transpiration T, assuming a partitioning scheme based on the exponential extinction of net radiation with LAI; the pedological survey in both sites allows to assume the unit gradient hypothesis for the lower boundary (free drainage) and to determine the maximum soil depth.

TSEB model use a two-source approach for estimating latent heat flux, λE. The parallel model, also called two-source proposed by Norman et al. [6] considers the canopy and the ground as two separate system components. The scheme of the resistances in parallel allows to estimate a more correct λE in conditions of poor coverage of the soil (Norman et al., 2000). Kustas and Norman [15] (1999) have proposed a modification to the model that takes into account the contribution made by the individual components of temperature, soil and canopy. The calculation of the radiometric temperature becomes:

$$T_{RAD} = \left[f_c T_c^4 + (1 - f_c) T_s^4 \right]^{1/4} \qquad (2)$$

where fc represent the fraction cover. In TSEB, the sensible heat flux of the canopy Hc is estimated from the net radiation for the canopy component Rn,c and the Priestley-Taylor equation:

$$H_c = R_{n,c} \left[1 - \alpha_{PT} \frac{\Delta}{\Delta + \gamma} \right] \qquad (3)$$

Similarly to SWAP, also in this case the net radiation for the canopy component is calculated from LAI by using an exponential extinction-type approach In equation 3, Δ is the slope of the saturated vapour pressure-temperature curve, γ is thermodynamic psychrometric constant and αPT is the Priestley Taylor coefficient. Since the soil latent heat flux is derived as the residual term of the energy balance, the value of the parameter αPT is iteratively reduced until λEs is positive.

For the SAP flow measurements the method used is that of Granier [16] which is based on the heating of the trunk: a part of the heat is dispersed radially outward from the trunk, another part is dispersed along the trunk upwards and downwards, and finally a part is absorbed by the lymph and transported by it towards the leaves. The technique used for the estimation of transpiration is called SAP-FLOW, and allows to measure the transpiration rate through the flow xylem. This technology, long popular in arboriculture, is still applied in viticulture [17].

3. Results

For both experiments, during the observation period the ratio between actual ET and potential ET was very low, in spite of a observed consistent foliage vigor; indeed, no irrigation was applied by the grower. For Campobello di Mazara experiment, by analyzing our data, we found a substantial agreement of transpiration values (Fig.1) obtained by means of sap flow measurements Tsap (upscaled to field scale), the simulated values with soil water balance and root uptaking (Tswap) and the results of the energy balance model from infrared radiometers through TSEB (T(Ec) IR.

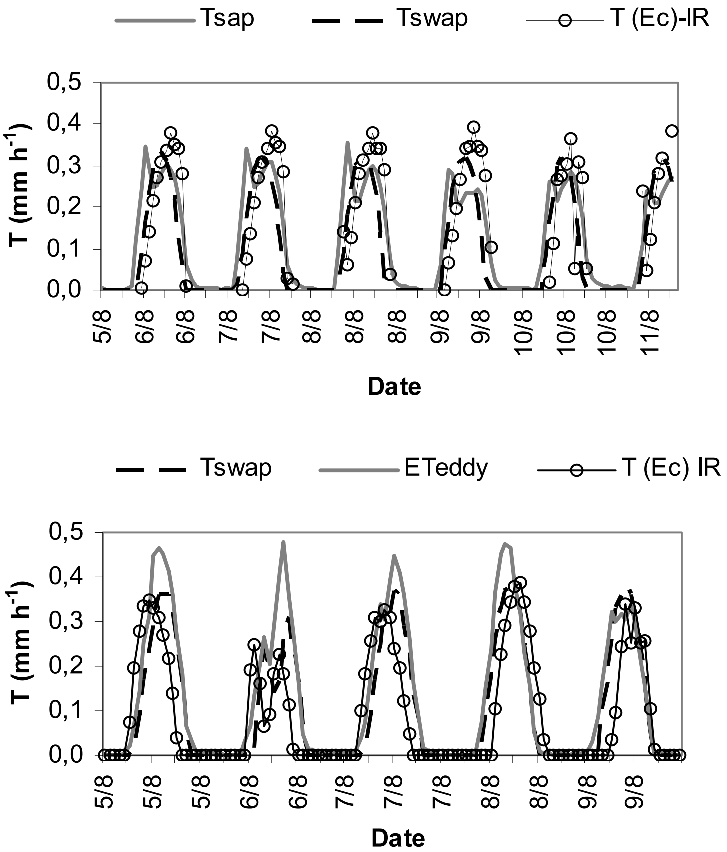

Fig. 1. Daily values of effective transpiration fluxes (T) calculated by sap-flow (Tsap), SWAP (Tswap and TSEB (T (Ec) – IR) for Campobello di Mazara 2010 (upper part) and Telesina Valley 2012 (lower part) experiments. Eddy covariance (ETeddy) measure total fluxes, thus representing effective evapotranspiration reference.

The plot in Fig.2 shows for Telesina Valley experiment daily values of fluxes. Similarly to the previous findings, the transpiration fluxes predicted both with SWAP and TSEB are very close to potential transpiration fluxes. During dry periods i.e. from July 14th to July 20th and from Aug. 15th to 23th (when no rainfall was recorded) the simulated fluxes, whatever the model used, are in perfect agreement with eddy covariance measurements. This means that for the vineyard investigated, almost the total of heat latent flux is represented by transpiration. The growing system used by farmers, often imposed by production regulations, tends to limit the size of vegetated part; this results in small canopies that can use the water held in the deep soil profile without suffering of stress, even without irrigation practices, despite the soil evaporation is absent. To investigate on the occurrence of water stress on the plants in a such decoupled system, one has to consider transpiration fluxes alone. This can be realized by calculating the maximum daily ratio between actual and potential transpiration values. Considering SWAP transpiration fluxes, Fig. 3 shows the occurrence of water stress only towards the last part of the observation period for Campobello di Mazara (Fig. 3(a)) and Telesina valley (Fig. 3(b)). Given the small value of LAI, the limited amount of water available in the soil was sufficient to sustain maximum transpiration flux until the first week of August, hence at full maturation and in proximity of harvest (Fig 3(b)). In Telesina valley experiment the plants doesn't show relevant stress condition, due to the occurrence of consistent rainfall events during the vegetation period.

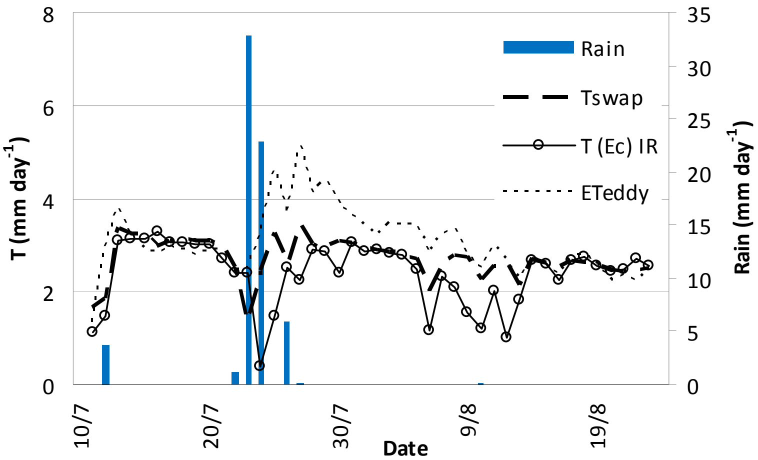

Fig. 2. Daily values of transpiration fluxes calculated by SWAP (Tswap) and TSEB (T (Ec) IR) for Telesina valley experiment.. Values of evapotranspiration fluxes measured by eddy covariance (ETeddy) are also given as reference.

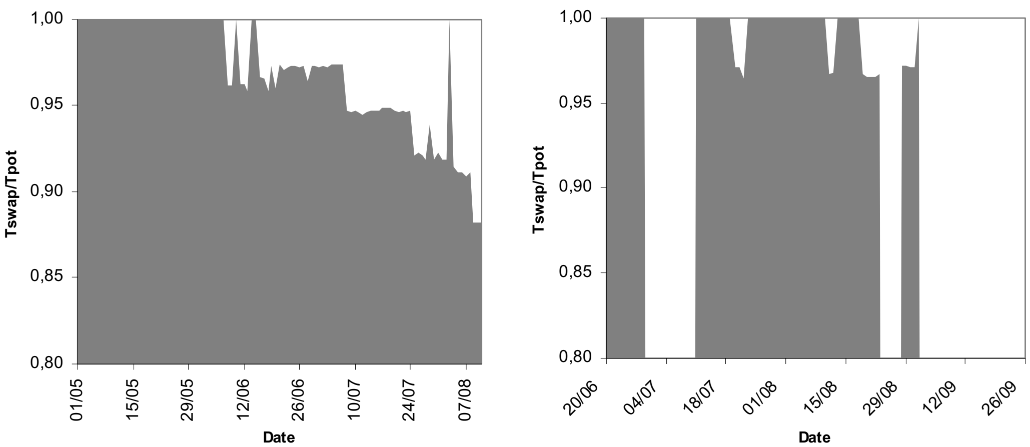

Fig. 3. Ratios between maximum daily effective transpiration fluxes calculated by SWAP and potential transpiration fluxes for Campobello di Mazara (a) and Telesina valley (b).

4. Concluding remarks

These results confirm the need for a separation of soil and canopy contributions to the evapotranspiration process for an adequate evaluation of crop water stress from both surface energy balance and soil water model approaches. The research has shown the usefulness of both dynamic water balance techniques and surface energy balance models to detect water stress in complex canopy-root systems such as vineyards. Considering the small value of LAI, the limited amount of water available in the soil was sufficient for Campobello di Mazara experiment the maximum transpiration of the canopy until the first week of August, hence at full maturation and in proximity of harvest. Simple bucket-type models of water balance or methods like CWSI from radiometric temperature would have been estimating a much higher stress than what was observed in the field, since the soil evaporation was practically zero. These results confirm the need for a separation of soil and canopy contributions to the evapotranspiration process for an adequate evaluation of crop water stress.

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