Highlights

> Eddy covariance and sap-flow techniques allow a better comprehension of the combined roles of actual crop transpiration and soil evaporation.

>For the investigated crop, when the availability of soil water content decreases under a threshold value (≈ 0.16 m^3 m^{-3}) for a long period, the plant transpiration is only driven by soil water content.

>For the investigated crop, the "seasonal" crop coefficients suggested by the FAO-56 using both "single" and "dual" approach were experimentally confirmed.

> In absence of direct measurements of actual transpiration, a suitable stress descriptor can be evaluated from values of soil water content in the root zone.

Combined use of eddy covariance and sap flow techniques for partition of ET fluxes and water stress assessment in an irrigated olive orchard

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ABSTRACT

Correct estimation of crop actual transpiration plays a key-role in precision irrigation scheduling, since crop growth and yield are associated to the water passing through the crop.

Objective of the work was to assess how the combined use of micro-meteorological techniques (eddy covariance, *EC*) and physiological measurements (sap-flow, *SF*) allows a better comprehension of the processes involving in the Soil-Plant-Atmosphere continuum.

To this aim, an experimental dataset of actual evapotranspiration, plant transpiration, and soil water content measurements was collected in an olive orchard during the midseason phenological period of 2009 and 2010.

It was demonstrated that the joint use of *EC* and *SF* techniques is effective to evaluate the components of actual evapotranspiration in an olive orchard characterized by sparse vegetation and a significant fraction of exposed bare soil.

The availability of simultaneous soil water content measurements allowed to estimate the crop coefficients and to assess a simple crop water stress index, depending on actual transpiration, that can be evaluated even in absence of direct measurements of actual transpiration.

The crop coefficients experimentally determined resulted very similar to those previously evaluated; in particular, in absence of water stress, a seasonal average value of about 0.65 was obtained for the “single” crop coefficient, whereas values of a 0.34 and 0.41 were observed under limited water availability in the root zone.

The comparison between the values of crop water stress index evaluated during the investigated periods evidenced systematically lower values (less crop water stress) in the first year compared to the second, according to the general trend of soil waters content in the root zone.

Further researches are however necessary to extent the experimental dataset to periods characterized by values of soil evaporation higher than those observed, in order to verify the crop coefficients even under different conditions than those investigated.

1. INTRODUCTION

In the last decade, observations of physical processes developing in the Soil-Plant-Atmosphere (SPA) continuum become fundamental for agricultural water management, especially in arid and semi-arid ecosystems (Noy-Meir, 1973), where water is a limiting factor of the production, and the application of precision irrigation represents an appropriate management strategy. The development of precision irrigation aimed to reduce irrigation plays a major role in Mediterranean countries, where the reduction of water availability in the last 20 years has been observed (UNEP/MAP-PlanBleu, 2009).

At present, studies on the dynamic of trees transpiration (*T*), field evapotranspiration (*ET*) and soil water content (*SWC*) in areas characterized by sparse drought-resistant crops like olives groves, represent one of the most appealing challenges of agro-hydrological researches. In this context, particular relevance assumes the partition of actual *ET* in crop transpiration (*T*) and soil evaporation (*E*), because only the first term is essentially related to the crop water requirement and stress condition (Jackson et al., 1981). This interest is enhanced by the large variability in both space and time of these two components (Kemp et al., 1997; Smith et al., 1995).

The assessment of actual olive evapotranspiration, *ET*, and its partitioning, can be achieved with different methodologies. Whole actual evapotranspiration is commonly obtained using micro-meteorological techniques, i.e. by measuring the total water vapour fluxes with the Eddy Covariance (*EC*) technique, representing at present the best known and widely accepted methodology (Verstraeten et al., 2009).

The role of soil evaporation in sparse vegetated areas can be relevant, particularly when the fraction of exposed soil is predominant (Heilman et al., 1994; Savage et al., 2000). This means that under this condition, *EC* technique could not be able to recognize the effective crop water use, because of the relatively high contribute of soil evaporation.

In general, to separate *ET* in *T* and *E*, additional measurements of *T* or *E* are requested. Approaches based on tracking stable isotope in the water vapour fluxes, have been recently proposed to detect the source of fluxes (soil or vegetation) at field scale (Ferretti et al., 2003; Wang et al., 2010; Williams et al., 2004).

Alternatively, measurements of soil evaporation or plant transpiration can be carried out with microlysimeter (Martìnez-Cob and Faci, 2010) and sap-flox sensors (Rousseaux et al., 2009) respectively. The latter represents a commonly used technique to monitor the sole transpiration term at the scale of single plant. Considering that the temporal delay induced by the effect of tree capacitance can be assumed negligible at daily scale, the methodology allows reliable estimations of T fluxes, aiming to derive variables that can be directly related to the plant water status. However, multiple sources of uncertainty could be detected when processing sap flow observations (Allen et al., 2011), including inaccuracy in detection trunk geometry and sap wood depth, significant effect of trunk capacitance (Motisi et al., 2012) and/or the wood response to probe implantation (Clearwater et al., 1999).

Up-scaling transpiration fluxes from plant to field scale is complicated by the spatial heterogeneity of vegetation characteristics (Schaeffer et al., 2000); it is therefore necessary to know crop-specific parameters like leaf area index or sapwood surface (Oishi et al., 2008; Soegaard and Boegh, 1995).

In absence of direct measurements, separate evaluation of E and T fluxes can also be obtained with agro-hydrological models; in fact several surface-vegetation-atmosphere-transfer (SVAT) models allow to determine the temporal dynamic of E and T using various schematizations of the physical processes; these models however, require a high number of soil and crop parameters (Cammalleri et al., 2010a; Crow et al., 2008; Minacapilli et al., 2008; Minacapilli et al., 2009, Rallo et al., 2012).

A simplified way to deal with actual ET components is the “dual approach” method suggested by Allen et al. (1998), in which soil evaporation and potential plant transpiration are estimated by multiplying reference evapotranspiration ET_0, respectively to a soil evaporation coefficient (K_e) and a basal crop coefficient (K_{cb}). Despite this approach is affected by theoretical limitations, it can be considered acceptable for practical applications.

The main objective of the paper is to assess if the joint use of *EC* and *SF* techniques is effective to partition the whole actual evapotranspiration in *T* and *E*, in an olive orchard characterized by sparse vegetation and a significant fraction of exposed bare soil. Moreover, under the examined environmental conditions, experimental values of crop coefficients, as defined by Allen et al. (1998), are determined. The dynamic of a crop water stress index (Jackson et al., 1981), evaluated according to measured actual transpiration, was finally investigated.

2. MATERIALS AND METHODS

2.1 Site description

The experimental study area, showed in Fig. 1, is mainly cultivated with olive orchard (*cv.* "*Nocellara del Belice*") and has an extension of about 13 ha. The site is located in the South-West of Sicily (Italy), about 5 km far from the town of Castelvetrano (37.6494" N, 12.8492" E, 123 m a.s.l.) and it is characterized by a flat landscape and a rather homogeneous soil type.

Within the study field the plants, having a height of about 3.5 m, are spaced according to a regular grid 5 × 8 m (density of 250 plants/ha); the average fraction cover is about 0.35.

The climate of the area is typically Mediterranean, characterized by moderate rainfall during autumn and winter and quite high air temperatures and low precipitation in summer. Fig. 2 shows the daily and cumulative rainfall distributions registered, from June to December 2009 and 2010, by SIAS (*Servizio Informativo Agrometeorologico Siciliano*) in a meteorological station located about 500 m apart from the study area. The meteorological station also allows to monitor solar radiation, wind speed, air temperature and relative humidity.

Irrigation water is supplied by a drip irrigation system (four 8 l h^{-1} emitter/plant). Irrigation volumes, decided by the farmer according to the ordinary management practised in the area, resulted quite different in the two years, as detailed in Table 1.

Traditional laboratory methods were used to evaluate soil hydraulic properties of undisturbed soil cores, representative of four different depths (0, 30, 60 and 100 cm) of a soil profile. At each depth two soil samples 0.05 m height and 0.08 m diameter were collected in order to determine some points of the water retention curve, in the range of matric potential between –0.05 and -153 m. Hanging water column apparatus was used to evaluate soil water contents corresponding to matric potential values ranging from -0.05 m to -1.5 m; pressure plate apparatus with sieved soil samples 0.05 m diameter and 0.01 m height, was used to measure soil water contents corresponding to soil matric potentials of -3.37 m, -10.2 m, -30.6 m and -153.0 m. For each undisturbed soil sample, dry bulk density was also determined. Soil texture was measured by the hydrometer method. Soil textural class, according to USDA classification, is classified as silty clay loam; average clay, silt and sand contents resulted equal to 24, 16 and 60% respectively.

The average water retention curve obtained along the soil profile was then used to determine soil water contents at field capacity, SWC_{fc}, and wilting point, SWC_{wp}, whose value resulted equal to 0.32 m^3m^{-3} and 0.08 m^3m^{-3}.

2.2 Micrometeorological fluxes measurements

Energy balance and evapotranspiration measurements were performed using the Eddy Correlation (*EC*) method (Rosenberg *et al.*, 1983; Kaimal and Finnigan, 1994; Stull, 1988), that is widely accepted as the reference methodology to observe the atmospheric turbulence in the surface boundary layer. Using *EC*, it is possible to derive the sensible heat flux, H (W m^{-2}), as:

$$H = \rho c_p \sigma_{wT} \tag{1}$$

where ρ (g m^{-3}) is the air density, c_p (J g^{-1} K^{-1}) is the air specific heat capacity at constant pressure and σ_{wT} (m s^{-1} K) is the covariance between vertical wind speed and air temperature.

Similarly, the vertical flux of water vapour content, *i.e.*, the latent heat flux, $\lambda * ET$ (W m^{-2}), can be expressed as:

$$\lambda ET = \lambda \sigma_{wq} \tag{2}$$

where λ (J g^{-1}) is the latent heat of vaporization and σ_{wq} (g m^{-2} s^{-1}) is the covariance between the vertical wind speed and the water vapour density.

The auxiliary experimental set-up is also constituted by net radiometer, to measure net radiation, R_n, and self-calibrated flux plates, to measure soil heat flux, G_0.

The energy balance closure can be tested considering the closure ratio, CR, evaluated as:

$$CR = \frac{(H + \lambda ET)}{(R_n - G_0)} \tag{3}$$

This ratio, as suggested by Prueger et al. (2005), has to be computed only from the subset of data for which R_n is higher than 100 W m^{-2}. For the following analysis, the surface balance closure was forced according to the procedure proposed by Twine et al. (2000), in order to keep constant the observed Bowen ratio between the sensible and latent heat fluxes.

In the centre of the experimental area (Fig. 1) an *EC* tower has been installed. The system allows to obtain high frequency measurements of the three wind components and the H_2O and CO_2 concentrations by means of a three dimensional sonic anemometer (CSAT3-3D, Campbell Scientific Inc.) and an infrared open-path gas analyzer (LI7500, Li-cor Biosciences Inc.), respectively. Both the instruments were installed at an elevation of 7 m above the ground; the sample frequency for the raw data was equal to 20 Hz.

The auxiliary experimental set-up is represented by a low frequency (30-min), 4-components net radiometer (CNR-1 Kipp & Zonen) located at an elevation of 8.5 m and two self-calibrated flux plates (HFP01SC, Hukseflux) placed respectively in the exposed and shadowed bare soil, at a depth of about 0.1 m. All the data (high and low frequency) were stored in a CR5000 data logger (Campbell Scientific Inc.) equipped with a PCMCIA memory card.

EC footprint was computed with the model proposed by Kormann and Meixner (2000), based on the analytical solution of the two-dimensional advection-diffusion equation for non-neutral stratifications. Fig. 1 shows the footprint, represented by the source area encompassing the 90% of the observed fluxes, obtained using the daytime predominant wind conditions (average speed of 3.1 m s^{-1} and direction of 140°). Finally the 30-min fluxes data were aggregated at daily scale and latent heat fluxes, acquired in W m^{-2}, were then transformed in actual evapotranspiration values, *ET* (mm d^{-1}).

2.3 Sap flow and soil water content measurements

The Heat Dissipation Technique, *HDT*, (Granier, 1985) allows to obtain the sap velocity by measuring difference of temperature between a heated and an unheated needle inserted radially into the sap wood. Therefore, the probe measures the heat dissipation in the sapwood, increasing with the sap flow. When the sap velocity is minimal, the temperature difference ($\Delta\tau$) between the two sensors is maximal ($\Delta\tau_{max}$); for practical purposes, $\Delta\tau_{max}$ is assumed to correspond to the zero flow condition.

This approach allows the estimation of sap velocity, v (cm min^{-1}), by using the empirical relationships proposed by Granier (1985):

$$v = 0.714\left(\frac{\Delta\tau_{max} - \Delta\tau}{\Delta\tau}\right)^{1.231} \qquad (4)$$

Sap fluxes, q (cm^3 min^{-1}), can be evaluated multiplying the sap flow velocity for the cross-sectional area of conducting sapwood, S (cm^2):

$$q = v\, S \qquad (5)$$

Hourly measurements of sap velocity were acquired on three olive trees by using, for each of them, two standard thermal dissipation probes (SFS2 TypM-M; UP GmbH) installed into the trunk, at a height of about 0.4 m from the ground level. According to the footprint analysis, the position of the trees was chosen inside the area where the “relative normalized contribution” to flux was estimated near to the maximum (Fig. 1). Moreover, the three plants were selected according to their trunk diameter, so that they can be considered representative of entire experimental plot.

In all the trees, both the sap flow probes were installed on the north side of the trunk and then insulated, to avoid the direct sun exposure.

At the end of the experiments, the sapwood area was determined by a colorimetric method, on a total of six wood carrots extracted with a Pressler gimlet on the same three trees, in between each couple of the sap flow needles. The conductive section was identified by adding methyl-orange to the carrot, in order to enhance the difference between the sapwood and the heartwood. Each image of colored wood carrot was then analyzed with software Image-Pro Plus 6.0 to recognize the sapwood depth.

Temporal variability of soil water content (*SWC*) was continuously monitored around the same trees where sap flow sensors were installed, by using a time domain reflectometry system (TDR-100; Campbell Scientific Inc.). A number of 12 probes, 20 cm length, were installed along four soil profiles, to explore SWC in the layers 10-30, 30-60 and 50-80 cm. Unfortunatelly it was not possible to install TDR probes in the evaporative layer, due to the incoherent topsoil (0-10 cm). The planimetric position of the sensors, showed in fig. 1, was chosen in order to consider the spatial variability of *SWC* after irrigation. Acquisition time step was set up to 3 hours in the period from June to September of each year.

The data acquired by each probe were then aggregated to a daily time scale and the arithmetic mean value for the entire root zone was finally evaluated.

2.4 Data analysis and pre-processing

For both the monitored years, the micro-meteorological data and the measurements of plant and soil water status were pre-processed in order to create a daily database of reference evapotranspiration, ET_0, actual evapotranspiration, *ET*, plant transpiration, *T*, and soil water content, *SWC*.

For each of the two years (2009 and 2010) it was possible to dispose of a significant dataset of simultaneous measurements of *EC*, *T* and *SWC* during the midseason phenological period (from the first decade of June, corresponding to the “initial fruit development” stage to the first decade of September, corresponding to the “maturity” stage) for a total of 90 days.

The meteorological data collected by SIAS were used as an auxiliary independent information to estimate the atmospheric evaporative demand in the study area. Reference crop evapotranspiration, ET_0 (mm d^{-1}), was determined according to the FAO-56 procedure (Allen et al., 1998), on the basis of the following Penman Monteith equation:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0,34U_2)} \qquad (6)$$

where Δ [kPa °C^{-1}] is the slope of saturation vapour pressure curve, $e_s(T)$ [KPa] is the saturation vapour pressure at air temperature, R_n [MJ m^{-2} d^{-1}] is the net radiation, G [MJ m^{-2} d^{-1}] is the soil heat flux, $(e_s\text{-}e_a)$ [kPa] is the vapour pressure deficit, γ [kPa °C^{-1}] is the psychometric constant at air temperature T_a [°C] and U_2 [m s^{-1}] is the wind speed measured at 2 m from the soil surface.

EC measurements were pre-processed and the accuracy of balance closure was verified considering the closure ratio, *CR* evaluated with eq. 3, that resulted equal to 0.90 and 0.92 respectively for 2009 and 2010, as can be observed in Fig. 3.

Sap fluxes, q (cm^3 min^{-1}), computed by eq. (5), allowed to determine the daily volume of water consumed by a single plant assuming negligible, at the daily time interval, the effect of the tree capacitance (Motisi et al., 2012). The daily stand transpiration of a plant, T_{plant}, can thus be evaluated dividing this water volume for the plant pertinence area, A_p equal to 40 m^2. In order to evaluate a representative value of the stand transpiration referred to the entire field, T, it was necessary to up-scale T_{plant}, by considering, as a proximal variable, the ratio between the average Leaf Area Index, LAI (m^2 m^{-2}), measured in field, and the corresponding value obtained on the single plant, LAI_p (m^2 m^{-2}), in which sap fluxes were monitored:

$$T = T_{plant} \frac{LAI}{LAI_p} \qquad (7)$$

The values of LAI and LAI_p were estimated from in-situ observations, collected with a hand-held optic sensor (Villalobos et al., 1995) even if it has been recently demonstrated that, in absence of direct measurements, high resolution remote sensing images can be used (Cammalleri et al., 2010b). For the examined conditions LAI resulted about to 0.89, whereas LAI_p was about 1.27.

Crop coefficients were evaluated according to the FAO-56 procedure (Allen et al., 1998), in which actual evapotranspiration, *ET*, can be evaluated as:

$$ET = T + E = (K_{cb}K_s + K_e)ET_0 = K_{c,adj}ET_0 \quad (8)$$

where K_{cb} is the basal crop coefficient obtained when the soil surface is dry, but transpiration occurs at potential rate, K_s is a dimensionless stress coefficient dependent on *SWC* and K_e describes the evaporation component from wet soil, following rain or irrigation (Allen and Pereira, 2009). The sum $K_{cb}K_s$+K_e represents the so called "dual" crop coefficent, $K_{c,adj}$.

According to the FAO-56 procedure, K_s has been computed as:

$$K_s = \frac{TAW - D_i}{TAW - RAW} \qquad \text{for } D_i > \text{RAW} \quad (9)$$

$$K_s = 1 \qquad \text{for } D_i \leq \text{RAW} \quad (10)$$

where *TAW* (mm) is the total available water, D_i (mm) is the amount of daily water depleted out from root zone during the i-th day, and *RAW* (mm) is the readily available water. The latter can be evaluated as a fraction, *p*, of *TAW*. As indicated in FAO-56 procedure, *p* can be determined as:

$$p = p_{table} + 0.04(5 - ET_0) \quad (11)$$

Values of p_{table} for different crops are suggested by Allen at al. (1998). For the investigated case, p_{table} was set equal to 0.6.

The evaporation coefficient, K_e, can be also derived following the procedure described in Allen et al., (1998), requiring, however, to measure soil water contents in the topsoil.

When water stress is absent, (K_s=1), and soil evaporation is negligible, K_{cb}+K_e returns to the standard crop coefficient K_c, as described in the "single" approach (Doorenbos and Pruitt, 1977; Allen et al., 1998), commonly used to compute the potential evapotranspiration, ET_p, as:

$$ET_p = K_c ET_0 \quad (12)$$

Although values of K_c and K_{cb} for some crops can be found in the literature (Allen and Pereira, 2009) a correct estimation of these coefficients requires a local evaluation based on direct measurements.

In this study K_{cb} and K_s coefficients were obtained combining the experimental measurements of *ET* and *T* with the values of soil water content in the root zone, SWC_r. The stress factor K_s was computed from eq. (9), in which:

$$D_i = 1000 * \left(SWC_{fc} - SWC_{r,i}\right) * Z_r \quad (13)$$

$$TAW = 1000 * \left(SWC_{fc} - SWC_{wp}\right) * Z_r \quad (14)$$

Using the measurements of transpiration, *T*, once evaluated K_s, the experimental values of K_{cb} were computed as:

$$K_{cb} = \frac{T}{K_s ET_0} \quad (15)$$

Due to the absence of *SWC* measurements in the topsoil (0-10 cm) the experimental evaluation of K_e was not possible; thus K_e was derived from eq. (8) as a residual term:

$$K_e = \frac{ET - T}{ET_0} \quad (16)$$

Then the "single" crop coefficient was computed as:

$$K_c = K_{cb} + K_e \quad (17)$$

Finally, the crop water stress condition during the investigated periods was described according to a crop water stress index, *CWSI* (Jackson et al., 1981) determined as:

$$CWSI = 1 - \frac{T}{T_p} = 1 - \frac{T}{K_{cb} ET_0} \quad (18)$$

3 RESULTS AND DISCUSSION

For each investigated period, the temporal dynamic of collected data was preliminarily analysed in order to detect the main differences between the single components of the whole evapotranspiration fluxes.

For the 2009 season, Fig. 4a shows the temporal dynamic of evapotranspiration *ET*, plant transpiration, *T*, soil evaporation, *E*, as well as atmospheric demand, ET_0, rainfall, *P* and the amount of irrigation, *I*. For the same period, Fig. 4b shows the average soil water content in the root zone (SWC_r, 30-100 cm) and in the upper soil layer (SWC_u, 10-30 cm).

In absence of direct measurements of surface soil evaporation and under the hypothesis to consider negligible the daily tree capacitance (Motisi et al., 2012), the term *E*, was estimated as difference between *ET* and *T* measurements.

The analysis of Fig. 4 evidences an average seasonal value of *T* of 2.3 mm d^{-1}; similar values were obtained by Rousseax et *al.* (2009), during summer season, for an olive grove characterized by a canopy cover of 23%.

A detailed analysis of Fig. 4 evidences that *ET* and *T* fluxes tendencially decrease from beginning of June (initial fruit development stage) to September (maturity stage), according to the general trends of reference evapotranspiration and soil water contents.

High values of *ET* (from 3 to 4 mm d^{-1}) and *T* (from 2 to 3 mm d^{-1}) were in fact observed during the period between DOY 160 (second decade of June) and DOY 170, when soil water contents in the root zone (SWC_r) and in the upper layer (SWC_u) were, on average, 0.22 and 0.10 respectively; during the initial period, even soil evaporation, *E*, resulted high, with pick values greater than 1 mm d^{-1}. This circumstance is in agreement to the high SWC_u values, despite these data were collected in the layer 10-30 cm and not in the topsoil (0-10 cm).

After the second decade of June (DOY 180-210) *ET* values resulted slightly higher than *T* and the consequent low soil evaporation (about 0.4 mm d^{-1}) is supported by the low SWC_u (about 0.05 m^3

m^{-3}). In the following period (DOY 210-230), the lack of *EC* measurements did not allow to evaluate soil evaporation, so that only a general reduction of *T* can be observed.

A relevant contribution of soil evaporation can be detected after DOY 233 (E =1.33 mm d^{-1}), due to the rainfall event, wetting the entire extension of the topsoil surface. Furthermore, the limited irrigation volume did not produce any significant effect in SWC_r and accordingly the dynamic of crop transpiration did not change.

Table 2, for each decades of the considered period, shows the mean values of *SWC*, K_s, ET_0, *ET*, *T*, *E*, as well as crop coefficients K_{cb}, K_e, K_c and $K_{c,adj}$ and finally T/ET_0, E/ET_0 and T/T_p ratios.

The average values of decadal crop coefficients, as well as T/ET_0 and E/ET_0 ratios, cannot be directly related to a single factor, depending on the combined effects of ET_0 and *SWC*.

Moreover, similarly to what described by Rousseax et *al.* (2009), decadal values of T/ET_0 and E/ET_0 show low variability as evidenced by the corresponding values of the standard deviations. On the contrary a high variability of the T/T_p ratio can be observed.

The average seasonal crop coefficients resulted very similar to those suggested by Allen et al. (1998) and also experimentally determined by other Authors (Villalobos et al., 2000; Testi et al., 2004), with seasonal actual transpiration equal to 34% of reference evapotranspiration.

The same data analysis was replied for 2010, as shown in Fig. 5. As can be observed, measured *ET* and *T* fluxes tend to decrease from the begin (June) to the end (September) of the observation period, even if all fluxes resulted lower than those evaluated in 2009.

Average values of $ET \approx 3$ mm d^{-1} and $T \approx 2$ mm d^{-1} were observed between DOY 160 and DOY 170, when the average soil water content in the root zone (SWC_r) and in the upper surface (SWC_u) were approximately 0.16 m^3 m^{-3} and 0.11 m^3 m^{-3} respectively. In the following period (DOY 180-235) *ET* values resulted generally slightly higher than *T* and the consequent low soil evaporation (about 0.3 mm d^{-1}) is confirmed by values of SWC_u of about 0.08 m^3 m^{-3}. Despite the irrigation volume (30 mm) in DOY 206 increased SWC_r, no significant influence on *ET* an *T* was observed, probably due to the limited atmospheric water demand during the days after irrigation.

In the following period (DOY 235-245) even if T values decrease with the same tendency previously observed, actual evapotranspiration tends to increase as a consequence of the high atmospheric demand ($ET_0 \approx 7$ mm d^{-1}) from DOY 236 to DOY 240.

Finally, after the rainfall event recorded during DOY 245, a significantly higher soil evaporation can be detected.

The decadal mean values of SWC, K_s, ET_0, ET, T, E, as well as crop coefficients K_{cb}, K_e, K_c and $K_{c,adj}$, T/ET_0, E/ET_0 and T/T_p obtained for 2010 are summarized in Table 3. As can be observed, even in 2010 the values of K_e, K_c and K_{cb} resulted very similar to those evaluated in 2009.

On the contrary, in 2010 the decadal transpiration values resulted significantly lower than 2009 and strongly dependent on the K_s stress coefficients evaluated according to the soil depletion (Fig. 6).

For the investigated crop, this circumstance suggests that when the availability of soil water content decreases under a threshold value ($\approx$ 0.16 m^3 m^{-3}) for a long period, the plant transpiration is driven by only the SWC in the root zone. The seasonal average value of T/ET_0 obtained in 2010 shows that the transpiration was on average equal to 27% of reference evapotranspiration.

Finally, as observed for 2009 the seasonal crop coefficients, computed as averages over the entire period, resulted very similar to those suggested by Allen et al. (1998) and confirmed by other Authors (Villalobos et al., 2000; Testi et al., 2004). Particularly the average value of K_{cb}, K_e and K_c resulted not significantly different during both the considered years. The experiments confirmed that "seasonal" K_c coefficients for the investigated crop can be assumed equal to 0.65, as proposed by Allen et al. (1998).

Moreover it is interesting to notice that again the ratio T/T_p at decadal scale is more variable than T/ET_0 and E/ET_0 values as a consequence of the higher variability of K_s. For this reason the crop water stress descriptor was chosen dependent on T/T_p.

Figure 7a,b shows the temporal dynamic of $CWSI$ and soil water content in the root zone, SWC_r in 2009 and 2010.

The comparison between the values of *CWSI* obtained during the investigated periods evidences generally lower values (less water stress) in the first year compared to the second, with seasonal average values of 0.32 and 0.53 for 2009 and 2010, respectively.

Differences of *CWSI* can be justified by the different soil water contents in the root zone, SWC_r, particularly in the first decade of June (DOY 160-170) and after the second decade of August (DOY 220-230).

The absence of water stress (*CWSI* =0), evident at the beginning of June 2009, is certainly consequent to the high cumulative rainfall observed during two months antecedent the investigated period (see Fig. 2), producing a significant water storage in the soil.

Differently, in 2010 the lower cumulative rainfall antecedent the observation period and the consequent lower SWC_r compared to 2009, determined conditions of crop water stress (*CWSI* > 0) since the beginning of the investigated period. The higher initial water availability seems to reflect the minor extension of crop water stress observed in 2009 compared to 2010.

In absence of measurements of actual transpiration, a simplified crop water stress index, *CSWI**, can be evaluated after substituting in eq. 18 the values of actual transpiration, *T**, indirectly estimated as $K_{cb}K_sET_0$, obtaining:

$$CWSI^* = 1 - K_s \qquad (19)$$

Eq. 19 requires only the knowledge of K_s, that can be estimated as a function the soil water depletion D_i. According to eq. 8, D_i can be obtained from direct measurements of *SWC* or by following the simplified soil water balance approach proposed in the FAO-56 procedure.

Figure 8 shows the comparison between the decadal values of *CSWI* and *CSWI** for both the considered years. As can be observed the decadal indexes evaluated with measured actual transpirations (eq. 18) resulted very similar to those calculated according to K_s (eq. 19). In absence of direct measurements of actual transpiration, a suitable stress descriptor can be therefore evaluated from measured or estimated values of soil water content in the root zone.

CONCLUSIONS

The research assessed how the joint measurements of eddy covariance and sap-flow techniques allow a better comprehension of the combined roles of actual crop transpiration and soil evaporation in a typical Mediterranean olive orchard, where the problem of evapotraspiration fluxes partitioning is quite complex.

An experimental dataset of *ET* and *T* measurements, collected from June to September 2009 and 2010, has been analysed. In absence of direct measurements of soil evaporation, the *ET* and *T* measurements, coupled with simultaneous measurements of soil water contents, ensured the correct partition of evapotranspiration fluxes.

In both the investigated years *ET* and *T* fluxes resulted very similar during dry periods, due to the negligible contribute of soil evaporation; on the other hands the differences became relevant only for a few days after rainfall events. *ET* fluxes measured in 2009 resulted generally higher than those recognized in 2010, as a consequence of higher *SWC* observed in 2009. Moreover, the different soil water status between the two years evidenced that when the availability of soil water content decreases under a threshold value (≈ 0.16 $m^3\ m^{-3}$) for a long period, the plant transpiration is only driven by the soil water content.

The experimental dataset allowed to assess decadal values of crop coefficients evaluated according to the “single” and the “dual” approaches suggested by the FAO-56 procedure. Average seasonal crop coefficients resulted practically the same in both the investigated years and similar to those suggested by other Authors.

The temporal dynamic of *CWSI*, computed using direct measurements of *T*, was analyzed and the observed differences during the examined periods were related to the soil water content in the root zone. In fact, the systematically lower values of *CWSI* (less water stress) in the first year reflects the corresponding generally higher soil water content in the root zone.

Finally, the decadal values of the simplified crop water stress index obtained with measured soil depletion, resulted quite similar to those derived from *T* measurements, demonstrating that, at this temporal scale, a suitable stress descriptor can be obtained using parameters derived by measured or estimated soil water contents.

Further experiments will be carried out in order to extent the experimental dataset to periods characterized by high values of soil evaporation, in order to verify the crop coefficients under different conditions than those investigated.

Acknowledgments

Contribution to the paper has to be shared between Authors as following: Field data collection and pre-processing were cared by G. Rallo and C. Cammalleri. All the AA. equally contributed to set-up the research, process the data and write the paper.

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ABSTRACT

Correct estimation of crop actual transpiration plays a key-role in precision irrigation scheduling, since crop growth and yield are associated to the water passing through the crop.

Objective of the work was to assess how the combined use of micro-meteorological techniques (eddy covariance, *EC*) and physiological measurements (sap-flow, *SF*) allows a better comprehension of the processes involving in the Soil-Plant-Atmosphere continuum.

To this aim, an experimental dataset of actual evapotranspiration, plant transpiration, and soil water content measurements was collected in an olive orchard during the midseason phenological period of 2009 and 2010.

It was demonstrated that the joint use of *EC* and *SF* techniques is effective to evaluate the components of actual evapotranspiration in an olive orchard characterized by sparse vegetation and a significant fraction of exposed bare soil.

The availability of simultaneous soil water content measurements allowed to estimate the crop coefficients and to assess a simple crop water stress index, depending on actual transpiration, that can be evaluated even in absence of direct measurements of actual transpiration.

The crop coefficients experimentally determined resulted very similar to those previously evaluated; in particular, in absence of water stress, a seasonal average value of about 0.65 was obtained for the “single” crop coefficient, whereas values of a 0.34 and 0.41 were observed under limited water availability in the root zone.

The comparison between the values of crop water stress index evaluated during the investigated periods evidenced systematically lower values (less crop water stress) in the first year compared to the second, according to the general trend of soil waters content in the root zone.

Further researches are however necessary to extent the experimental dataset to periods characterized by values of soil evaporation higher than those observed, in order to verify the crop coefficients even under different conditions than those investigated.

Figure1

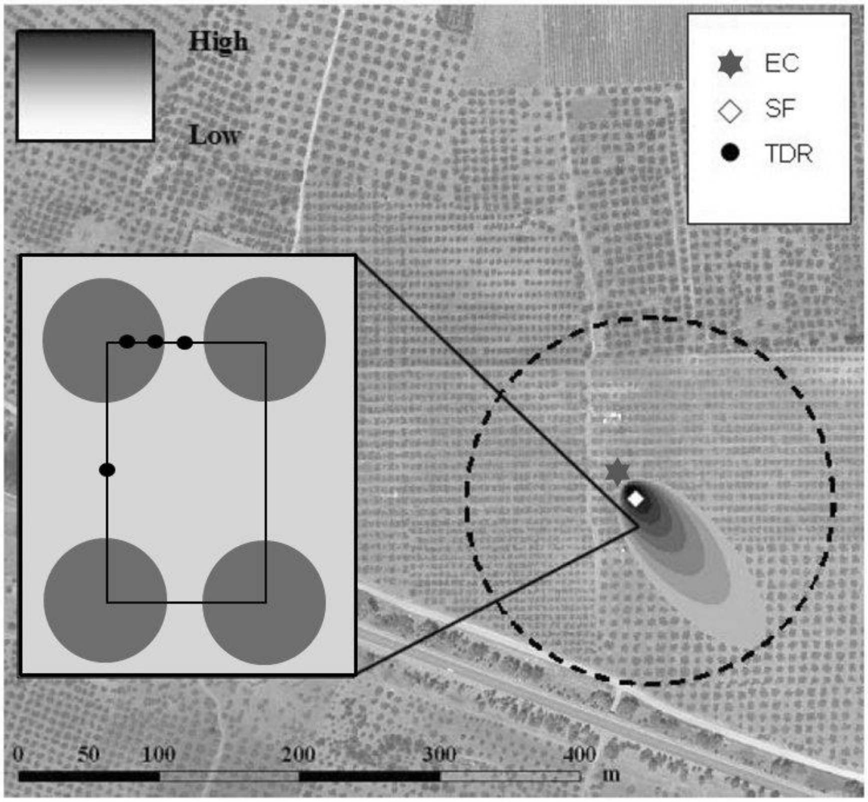

FIG.1

Figure2

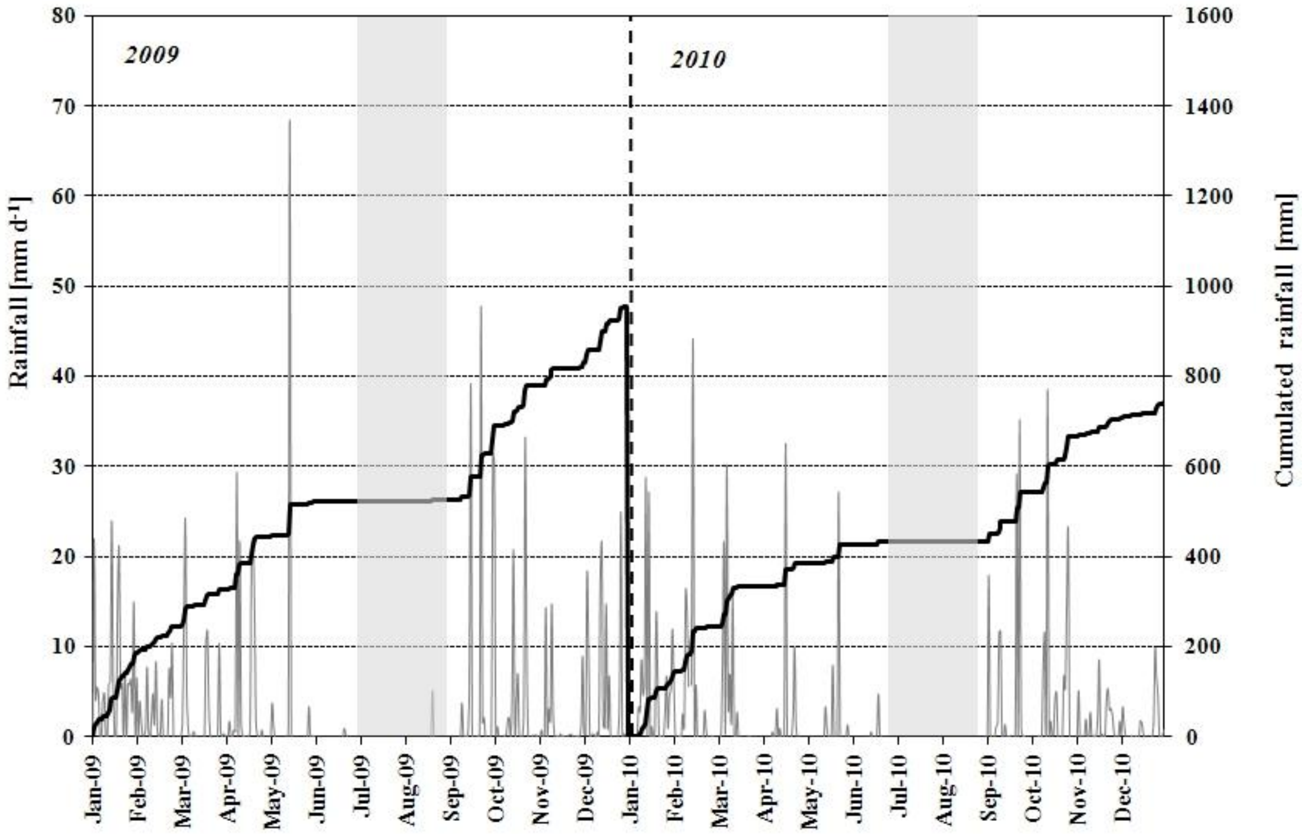

FIG.2

Figure3

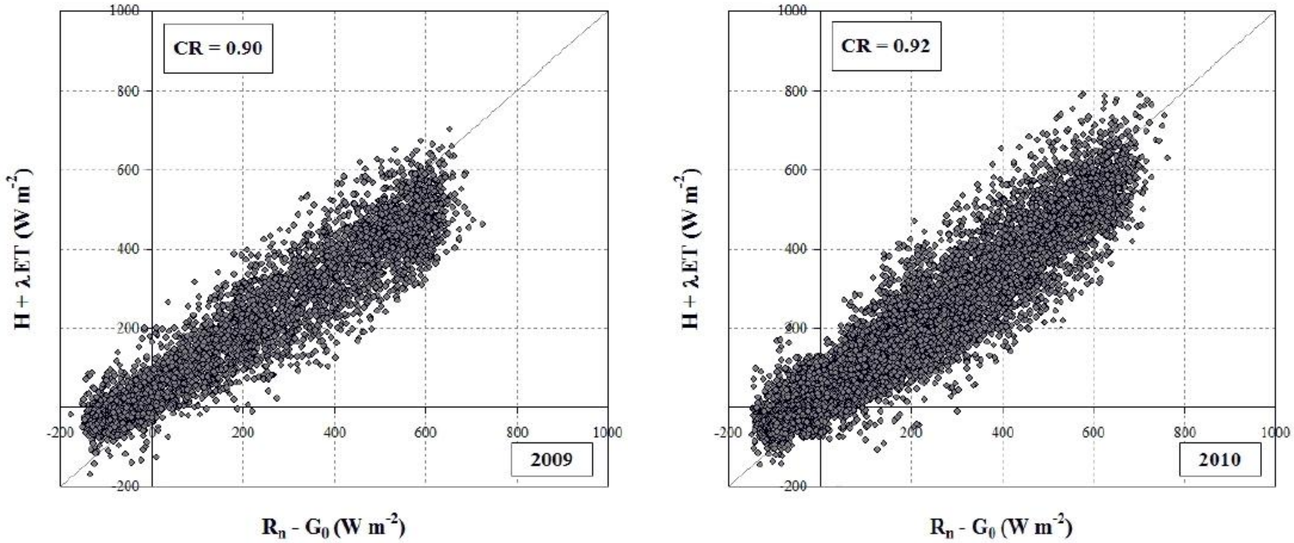

FIG.3

Figure4

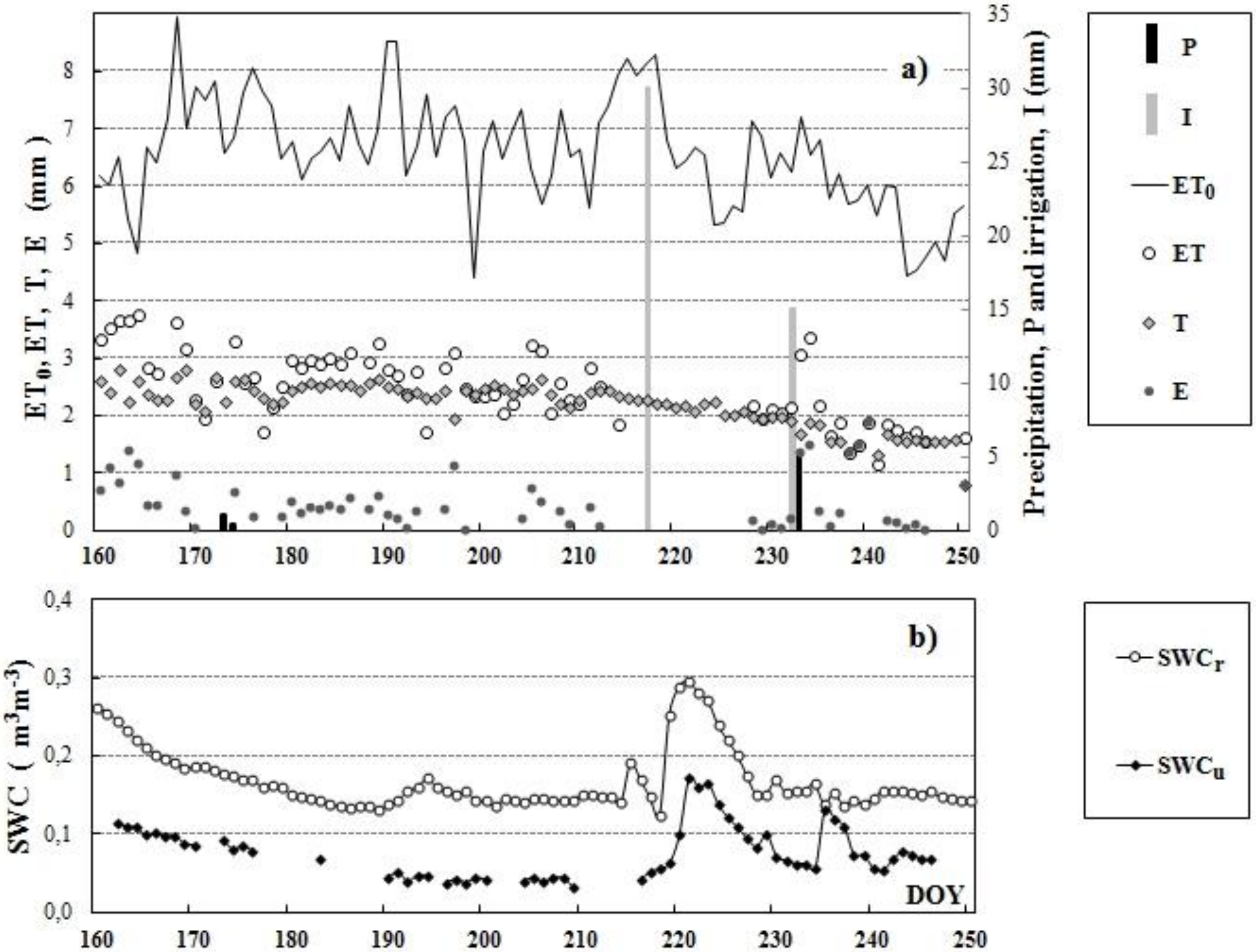

FIG.4

Figure5

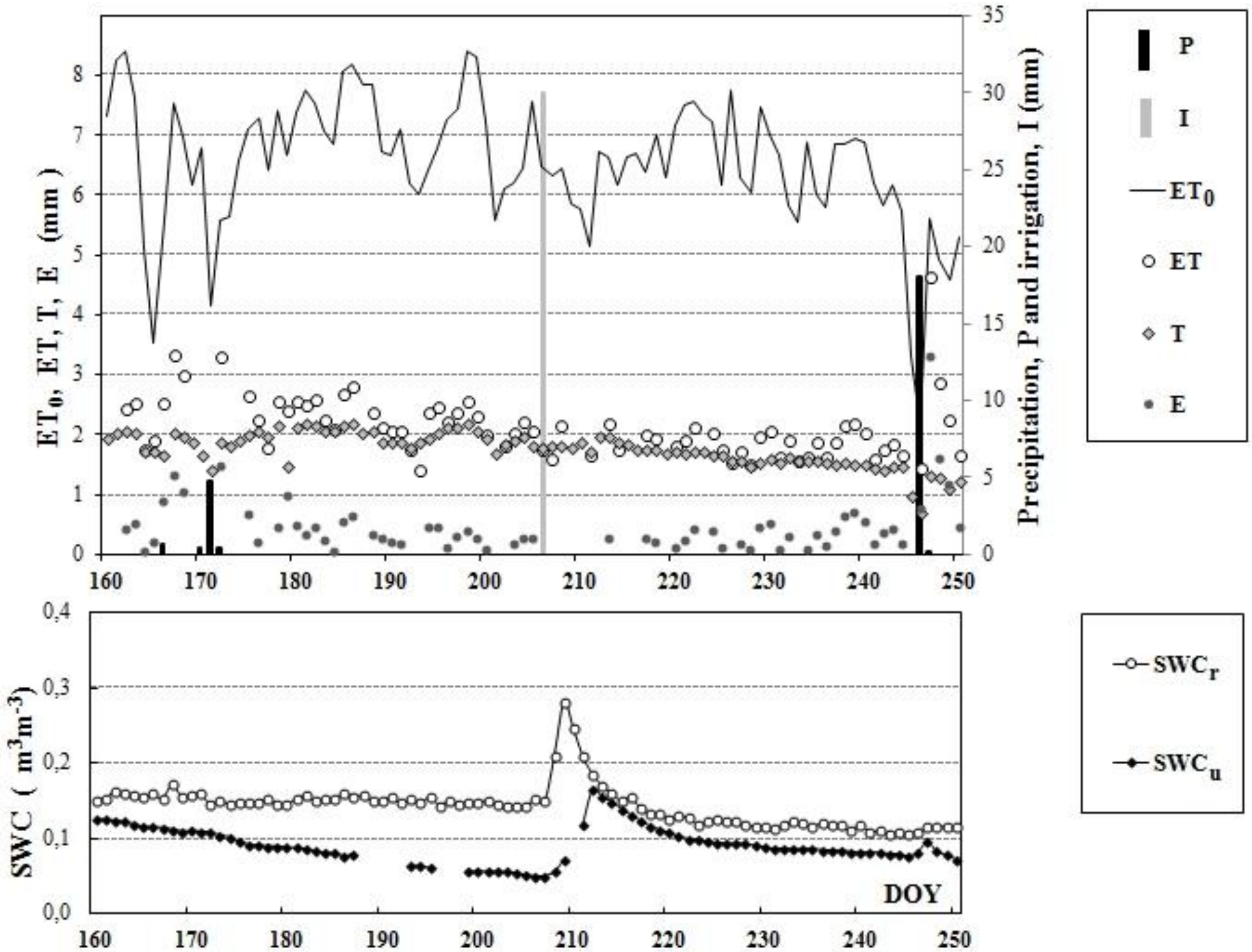

FIG.5

Figure6

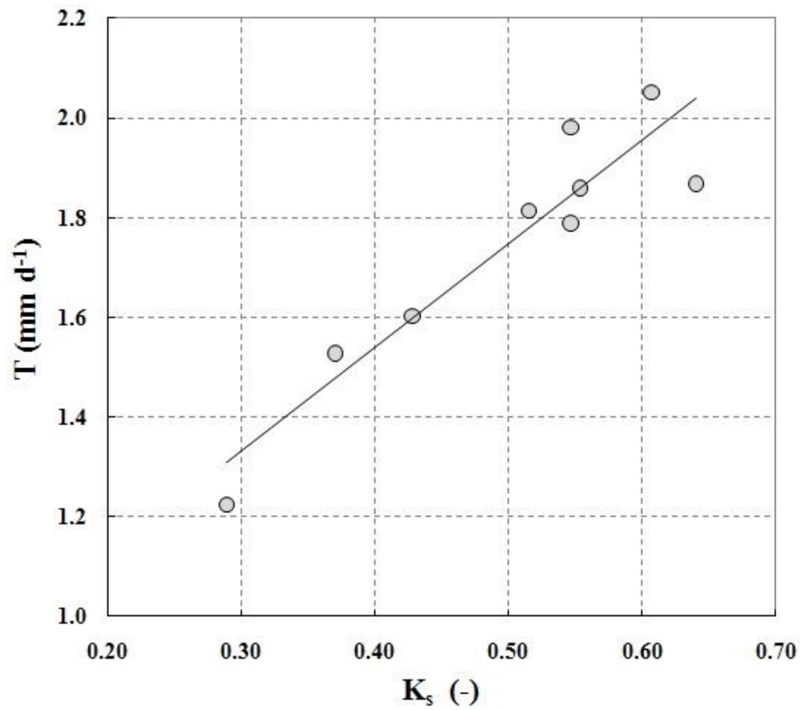

FIG.6

Figure7

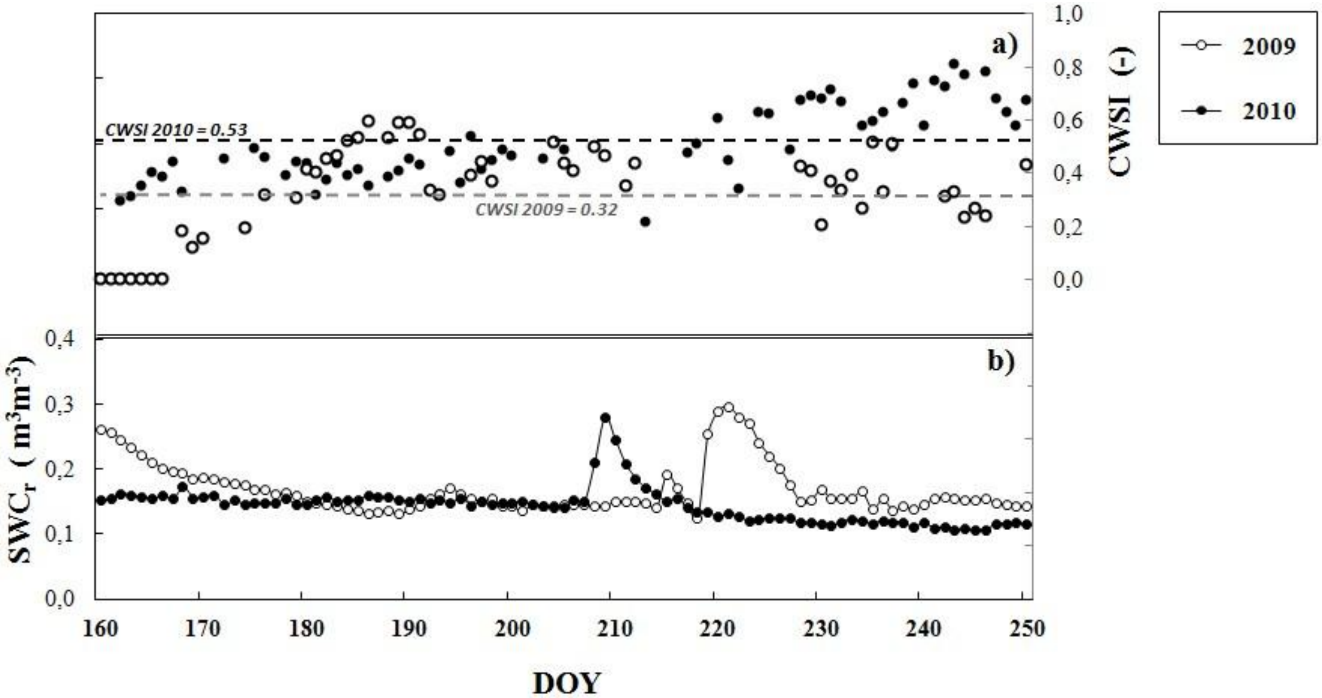

FIG.7

Figure8

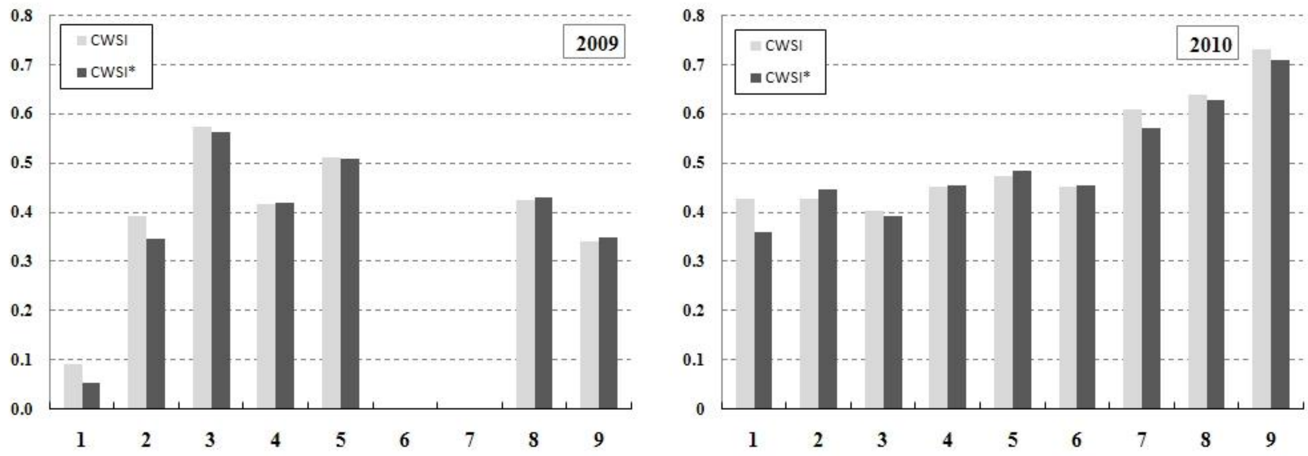

FIG.8

Figure Caption List

Fig. 1. Orthophoto of the experimental site, showing the location of Eddy Covariance system, *EC*, and Sap Flow sensors, *SF*; the filled area represents the footprint for the daytime predominant wind (average speed of 3.1 m s^{-1} with direction of 140°). The zoom emphasizes the locations of TDR probes.

Fig. 2 Daily and cumulative rainfall distributions registered from June to December 2009 and 2010.

Fig. 3. Analysis of the surface energy balance closure for the *EC* system. Scatterplot between (R_n - G_0) and ($H + \lambda ET$) measured with *EC* system in 2009 (left) and 2010 (right). Values of the Closure Ratio, *CR*, are also indicated.

Fig. 4. Temporal dynamic of the main hydrological variables observed from June to September 2009. Upper graphs (a) shows rainfall, *P*, irrigation, *I*, reference evapotranspiration, ET_0, actual evapotranspiration, *ET*, and its measured components. Lower graph (b) illustrates the average soil water content in the root zone, SWC_r, and in the upper soil layer, SWC_u.

Fig. 5. Temporal dynamic of the main hydrological variables observed from June to September 2010. Upper graphs (a) shows rainfall, *P*, irrigation, *I*, reference evapotranspiration, ET_0, actual evapotranspiration, *ET*, and its measured components. Lower graph (b) illustrates the average soil water content in the root zone, SWC_r, and in the upper soil layer, SWC_u.

Fig. 6. Scatterplot between decadal measured actual transpiration, *T*, and crop stress coefficient, K_s, observed during 2010.

Fig. 7. Temporal dynamic of Crop Water Stress Index, *CWSI*, and soil water content in the root zone, SWC_r obtained in 2009 and 2010.

Fig. 8. Comparison between decadal *CWSI* and *CWSI** values for both years.

Table 1

Date	DOY	2009		2010	
		(m^3 ha^{-1})	(mm)*	(m^3 ha^{-1})	(mm)*
25/07	206	-	-	210	30
05/08	217	210	30	-	-
20/08	232	105	15	-	-

* Irrigation depths have been computed considering a wetted fraction area of 0.7.

Table 2

DOY Start	DOY End	SWC_r (m^3m^{-3})	SWC_s (-)	K_s (-)	ET_0 (mm d^{-1})	ET (mm d^{-1})	T (mm d^{-1})	E (mm d^{-1})	K_c (-)	K_{cb} (-)	K_e (-)	$K_{c,adj}$ (-)	T/ET_0 (-)	E/ET_0 (-)	T/T_p (-)
160	170	0.22	0.10	0.95	6.63	3.25	2.50	0.75	0.54	0.41	0.12	0.52	0.39	0.12	0.70
171	180	0.17	0.08	0.65	7.27	2.83	2.40	0.43	0.60	0.54	0.06	0.40	0.35	0.06	0.55
181	190	0.14	0.05	0.44	6.86	2.98	2.56	0.42	0.94	0.87	0.06	0.44	0.38	0.06	0.40
191	200	0.15	0.04	0.58	6.79	2.73	2.37	0.36	0.65	0.60	0.05	0.38	0.33	0.05	0.54
201	210	0.14	0.04	0.49	6.66	2.80	2.42	0.38	0.80	0.74	0.06	0.43	0.37	0.06	0.45
211	220	0.18	0.10	0.56	7.38	-	2.33	-	-	0.69	-	-	0.39	-	-
221	230	0.22	0.09	0.61	6.17	-	2.09	-	-	0.49	-	-	0.30	-	-
231	240	0.15	0.08	0.57	6.28	2.66	1.79	0.87	0.58	0.50	0.08	0.36	0.28	0.08	0.49
241	250	0.15	0.07	0.65	5.22	1.72	1.49	0.23	0.48	0.43	0.04	0.33	0.29	0.04	0.60
Seasonal average				**0.61**					**0.65**	**0.59**	**0.06**	**0.41**	**0.34**	**0.07**	**0.53**
Standard deviation				*0.14*					*0.16*	*0.15*	*0.03*	*0.06*	*0.04*	*0.03*	*0.10*

Table 3

DOY Start	DOY End	SWC_r (m^3m^{-3})	SWC_s (-)	K_s (-)	ET_0 (mm d^{-1})	ET (mm d^{-1})	T (mm d^{-1})	E (mm d^{-1})	K_c (-)	K_{cb} (-)	K_e (-)	$K_{c,adj}$ (-)	T/ET_0 (-)	E/ET_0 (-)	T/T_p (-)
160	170	0.16	0.11	0.64	6.66	2.48	1.87	0.61	0.58	0.49	0.09	0.40	0.29	0.09	0.57
171	180	0.15	0.09	0.55	6.42	2.54	1.86	0.69	0.61	0.51	0.11	0.39	0.29	0.11	0.57
181	190	0.15	0.08	0.61	7.46	2.37	2.05	0.32	0.50	0.46	0.04	0.32	0.28	0.04	0.60
191	200	0.15	0.06	0.55	7.12	2.24	1.98	0.25	0.54	0.51	0.04	0.31	0.28	0.04	0.55
201	210	0.18	0.09	0.52	6.28	2.02	1.81	0.21	0.58	0.55	0.03	0.31	0.29	0.03	0.53
211	220	0.16	0.12	0.55	6.48	1.98	1.79	0.19	0.53	0.50	0.03	0.29	0.28	0.03	0.55
221	230	0.12	0.09	0.43	7.04	1.88	1.60	0.28	0.62	0.58	0.04	0.27	0.23	0.04	0.39
231	240	0.12	0.08	0.37	6.43	1.86	1.53	0.34	0.71	0.66	0.05	0.29	0.24	0.05	0.36
241	250	0.11	0.08	0.29	4.99	2.14	1.22	0.91	1.11	0.92	0.19	0.44	0.25	0.19	0.27
Seasonal average				**0.50**					**0.64**	**0.58**	**0.07**	**0.34**	**0.27**	**0.07**	**0.49**
Standard deviation				*0.11*					*0.19*	*0.14*	*0.05*	*0.06*	*0.02*	*0.05*	*0.12*

Table Caption List