Using scintillometry to assess reference evapotranspiration methods and their impact on the water balance of olive groves

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Abstract

Reference evapotranspiration (ET_0) is widely used for irrigation scheduling, to promote the efficient use of water resources, the sustainability of agro-ecosystem productivity, as well as to manage water quality and other environmental concerns. As suggested by ASCE-EWRI and FAO, standard Penman-Monteith methods are generally applied for the accurate estimations of ET_0, from hourly to daily scale. In the absence of detailed meteorological information several simplified equations, using a limited number of variables, have been alternatively proposed. In this paper, the performance of different reference evapotranspiration methods, at hourly (Penman-Monteith, Pristley-Taylor, Makkink and Turc) and daily scale (Penman-Monteith, Blaney and Criddle, Hargreaves, Pristley-Taylor, Makkink and Turc), was initially evaluated based on scintillometer measurements collected during six month, in 2005, in an experimental plot maintained under "reference" conditions (alfalfa crop).

The daily values of ET_0 obtained with the examined methodologies were then used as input in FAO-56 agro-hydrological model, in order to evaluate, for an olive grove in a Mediterranean environment, the errors associated to simulated actual evapotranspiration.

Experiments were carried out in South West of Sicily, in an area where olive groves are the major crop. The comparison between estimated and measured fluxes confirmed that FAO-56 Penman-Monteith (PM) standardized equation is characterized by the lowest mean bias error (-0.15 mmd^{-1} and 0.06 mmd^{-1} using daily or hourly data respectively)

However, the analysis also evidenced that the Pristley-Taylor equation can be considered a valid alternative for the accurate estimation of ET_0, charaterized by a mean bias error of 0.35 mmd^{-1} and 0.43 mmd^{-1} using daily or hourly data respectively

The application of the FAO-56 water balance model, evidenced how, on the investigated olive groves the best estimations of actual evapotranspiration are associated to the Pristley-Taylor ET_0 equation, confirming that the approach has to be considered a valid alternative to Penman-Monteith ET_0.

Key-words: Scintillometer; Evapotranspiration; Mediterranean climate; Micrometeorology.

Introduction

Evapotranspiration (ET) is one of the most important components of the hydrological cycle, and its modelling is crucial for a wide range of applications, including water resource management in agriculture.

Among the factors affecting ET processes, the atmospheric forcing plays a fundamental role since it characterizes the upper boundary layer. Commonly, ET is estimated by separating the effects of meteorological conditions from the nature of crop surface and the soil water availability (Doorenbos and Pruitt, 1977). For this reason, the concept of reference evapotranspiration, ET_0, has been introduced to represent the atmospheric water demand, regardless of crop type, when water availability is not a limiting factor (Allen et al. 1998).

Between the various standard reference surfaces (i.e., grass, alfalfa and pan), the Environmental and Water Resources Institute of American Society of Civil Engineering (ASCE-EWRI) proposed to refer to a short crop similar to clipped and cool-season grass or to a tall crop similar to full-cover alfalfa (ASCE-EWRI, 2005).

A number of methods have been proposed to estimate ET_0, which can be schematically divided in the following categories: (1) combined energy-mass balance methods (e.g., Penman 1948, Monteith 1965); (2) radiation-based methods (e.g., Priestley and Taylor 1972); (3) temperature-based methods (e.g., Blaney and Criddle, 1950); (4) mass transfer-based methods (e.g. Trabert, 1896, WMO, 1966, Mahringer, 1970); (5) pan evaporation-based models (Liu et al., 2004). The distinction of these methodologies is generally based on the number of atmospheric variables used as input, like air temperature, wind speed, air relative humidity and solar or net radiation. Commonly, the Penman-Monteith (PM) equation has been adopted as standard method to estimate ET_0, because it combines the energy and mass balances and accounts for the fundamental physical principles. Due to its incorporation of the physical processes, the Food and Agriculture Organization, FAO (Allen et al. 1998) and later on also the ASCE-EWRI (ASCE-EWRI, 2005) detailed the procedures to compute ET_0 according to the PM equation. However, although these procedures are very reliable, they need a number of meteorological variables (including wind speed and air relative humidity) that may not be available or not at the required time step. Therefore, several simplified semi-empirical methods requiring a lower number of climatic variables have been proposed under different environmental conditions. These methods generally use solar radiation and/or air temperature data only, and their applicability is usually limited to climate conditions that are similar to those where they were developed (Jensen and Haise, 1963).

Several review's papers of these methods, including PM equation have been recently published (Kumar et. al., 2012; Valipour and Eslamian, 2014; Valipour, 2015a,b). Among the radiation-based methods, the Priestley and Taylor (1972) and the Makkink (1957) equations, have been extensively and successfully used at hourly time step, even for remote sensing-based applications aimed at ET_0 estimate (De Bruin et al., 2010; Cammalleri and Ciraolo, 2013; Valipour, 2015c,d,e). Moreover, several studies have been carried out in order to propose comparisons between simplified approaches and more robust methods, like the PM in its different formulations, usually assumed as the reference (Todorovic et al., 2013; Valiantzas, 2013; Valipour, 2014a,b,c; Djaman et al., 2015; Valipour, 2015f). Despite the PM equation being usually considered as a reliable reference of the 'true' ET_0, it should be noticed that only a limited number of papers have been focusing on the comparisons between estimated and measured ET_0, mainly due to the lack of reliable in-situ measurements

When considering simplified formulations, it is imperative that such formulations should be routinely tested with field observations.

Other concerns are related to the limited number of full weather stations in various regions of their world as well as the location, sometimes not optimal.. It is well-known, in fact, that air temperature and relative humidity measured on rather dry surfaces can differ significantly from well-watered fields of the same area, leading to an overestimation of ET_0 due to unreliable estimations of actual water vapor deficit. This is an additional reason why in the Mediterranean environments, the PM-based ET_0 estimations obtained by using meteorological data from common weather stations, have to be tested with field measurements.

The first objective of this study is to assess the performances of seven equations to estimate ET_0 at different time steps (i.e., hourly and daily), by contrasting the estimates against laser scintillometer surface flux measurements collected over a well-watered alfalfa (*Medicago sativa* L.) field characterized by semiarid climate and dry summer seasons. The considered methods include the PM equation in the versions suggested by FAO 56 and ASCE-EWRI, as well as some simplified approaches, such as the Priestley and Taylor (1972), the Makkink (1957), the Turc (1961), the Blaney-Criddle (1950) and the Hargreaves-Samani (1985) relationships.

Secondly, the values of daily ET_0 obtained with the different methodologies were used as input in the FAO 56 agro-hydrological model, in order to quantify the impacts of the different formulations on the actual evapotranspiration simulated for an olive grove in a typical Mediterranean environment.

Theoretical background

Two main crops have been traditionally considered as the reference crop, i.e. grass and alfalfa. The former, referring to a type of grass similar, in terms of physiological and structural characteristics, to perennial ryegrass (*Lolium perenne* L.) or tall fescue (*Festuca arundinacea Schreb*) has been preferred by researchers. However, alfalfa has been also used to describe reference evapotranspiration thanks to its similarity in terms of leaf area index, roughness and physical characteristics to many other common agronomic crops . In order to ensure "standard conditions", whatever is the reference crop, it is necessary to apply suitable agronomic management practices

According to Allen et al. (1998), reference evapotranspiration (ET_0) is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground".

Based on the model developed by Penman (1948), later adapted by Monteith (1965), reference evapotranspiration, ET_0 (mm h^{-1}), can be expressed as:

$$\mathrm{ET}_0 = \frac{0.408\Delta\left(R_{n,\mathrm{sw}} - R_{n,\mathrm{lw}} - G_0\right) + \gamma \frac{C_n}{T_a} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + C_d u_2\right)} \qquad (1)$$

where $R_{n,\mathrm{sw}}$, $R_{n,\mathrm{lw}}$ and G_0 (MJ m^{-2} h^{-1}) are the short-wave and long-wave net radiations and soil heat flux, respectively, T_a (K) is the air temperature at 2 m height, u_2 (m s^{-1}) is the wind speed at 2 m height, e_s and e_a (kPa) are the saturation and actual vapor pressure, respectively, Δ (kPa K^{-1}) is the slope of vapor pressure curve, γ (kPa K^{-1}) is psychrometric constant and, finally, C_n and C_d are two coefficients depending on the reference surface.

The standardized procedures proposed by FAO 56 (Allen et al. 1998) and ASCE-EWRI (2005) use in both cases eq. 1, even if they differ in the way to quantify the soil heat flux and the coefficients C_n and C_d. In this paper, ET_0 values computed by using the FAO 56 procedure were named PM-FAO, whereas those computed with ASCE-EWRI method, for short canopy, were defined as PM-ASCE

The short-wave net radiation, $R_{n,\mathrm{sw}}$ (MJ m^{-2} h^{-1}), can be evaluated as:

$$R_{n,\mathrm{sw}} = (1-\alpha)R_s \qquad (2)$$

where R_s (MJ m^{-2} h^{-1}) is the incoming solar radiation and α is the surface albedo, assumed equal to 0.23 for reference crop.

The long-wave net radiation, $R_{n,\mathrm{lw}}$ (MJ m^{-2} h^{-1}), can be computed according to the formulation based on the Stefan-Boltzmann's law:

$$R_{n,\mathrm{lw}} = \sigma T_a^4 \left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad (3)$$

where σ is the Stefan-Boltzmann constant (2.04 × 10^{-10} MJ m^{-2} K^{-4} h^{-1}) and R_{so} (MJ m^{-2} h^{-1}) is the clear-sly solar radiation. The correction term for cloudiness (second factor in brackets) has to be constrained to assume always values higher than 0 ($R_s/R_{s0} > 0.26$).

The dependence of e_s, Δ and γ on T_a can be expressed according to the following relationships:

$$e_s = 0.611\exp\frac{17.27(T_a - 273)}{T_a - 35.7} \quad (4)$$

$$\Delta = 4098\frac{e_s}{(T_a - 35.7)^2} \quad (5)$$

$$\gamma = 0.0675\left(\frac{T_a - 0.0065q}{T_a}\right)^{5.256} \quad (6)$$

where q (m) is the elevation above the sea level. Additionally, once e_s is known, the actual vapor pressure, depending on the air relative humidity, RH (%), is:

$$e_a = e_s\frac{\mathrm{RH}}{100} \quad (7)$$

At daily time step soil heat flux G_0 was ignored because it is relatively small for a fully vegetated grass or alfalfa reference surface. On hourly time step, the magnitude of G_0 of a full covered grass surface can be computed as a fraction of R_n (sum of $R_{n,\mathrm{sw}}$ and $R_{n,\mathrm{lw}}$), whose value differs for night-hours ($R_n \leq 0$) and day-hours ($R_n > 0$) respectively. Particularly FAO 56 assumes G_0 equal to $0.04R_n$ and $0.2R_n$ for night-hours and day-hours, respectively, whereas in ASCE-EWRI the two fractions of R_n were fixed equal to 0.1 for day-hours and 0.5 for night hours.

With reference to the dimensionless coefficients of eq. 1, both FAO 56 and ASCE-EWRI proposed a value of 37 for C_n regardless of the time, Regarding the parameter C_d a constant value of 0.34 is used by by FAO 56, whereas ASCE-EWRI use a nighttime value for C_d of 0.96 and a value of 0.24 during the daytime. It is interesting to notice that the two procedures adopted the same value of C_n, but different values of C_d. The latter, as reported by FAO 56, is a consequence of the constant surface resistance, that was assumed equal to 70 s m^{-1} during the whole day. On the contrary, in ASCE-EWRI the differences can be ascribed to the surface resistance, assumed equal to 30, and 200 s m^{-1} for day-time and night-time respectively.

Priestley and Taylor (1972), P&T, proposed a simplification of PM model, valid for extensive wet surface under minimum advection, for which the effects of aerodynamic component can be considered negligible if compared to the radiation component. According to these Authors, ET_0 can be estimated as:

$$\mathrm{ET}_{0-\mathrm{P\&T}} = 1.26\frac{\Delta}{\Delta+\gamma}\frac{\left(R_n - G_0\right)}{\lambda} \tag{8}$$

Several studies (Castellví et al., 2001; Pereira, 2004; Baldocchi and Xu, 2007) have highlighted how the coefficient of 1.26 initially proposed, could be different and vary from 1.08 and to more than 1.60 due to the advectivity of the environment (Villalobos et al., 2002).

The Makkink (1957) formulation, later on resumed by de Bruin (1987), aims to provide reliable estimations of ET_0, by only using R_s and T_a observations. This method can be seen as a further simplification of the P&T equation, where R_n is replaced with R_s and the empirical coefficient is conveniently redefined. Following this approach, ET_0 can be estimated as:

$$\mathrm{ET}_{0\text{-}\mathrm{MAK}} = 0.61\frac{\Delta}{\Delta+\gamma}R_s \tag{9}$$

Turc (1961) proposed an empirical approach to estimate ET_0 which is commonly used under humid conditions.

$$\mathrm{ET}_{0\text{-}\mathrm{TURC}} = a_T\,0.013\frac{\left(T_a\right)}{\left(T_a+15\right)}\frac{\left(23.8856R_s+50\right)}{\lambda} \tag{10}$$

Trajković and Stojnić (2007) found that the reliability of Turc method strongly depends on wind speed, with overestimation under low wind speeds and underestimation during windy periods.

All these methods can be applied at hourly or daily time steps. On the contrary, the approaches proposed by Blaney and Criddle (Allen and Pruitt, 1991) and Hargreaves-Samani (1985) can be used only at daily temporal scale.

According to Blaney-Criddle method, reference evapotranspiration is:

$$\mathrm{ET}_{0-\mathrm{B\&C}} = a\frac{\Delta}{\Delta+\gamma}R_s - b \tag{11}$$

where R_s (MJ m^{-2} d^{-1}) is the daily solar radiation, a and b are correction coefficients.

When solar radiation, relative humidity and/or wind data are not available, ET_0 can be computed by means of Hargreaves-Samani model:

$$\mathrm{ET}_{0-HAR} = 0.0023\left(\frac{T_{\max} - T_{\min}}{2} + 17.8\right)\sqrt{T_{\max} - T_{\min}}\,\frac{R_a}{2.45} \quad (12)$$

where T_{max} (°C) and T_{min} (°C) are maximum and minimum daily air temperature, and R_a (MJ m^{-2} d^{-1}) is the extra-terrestrial solar radiation.

It is interesting to notice how the different proposed methodologies require a diverse number of meteorological variables, decreasing when passing from PM-based to radiation-based to temperature-based equations, as summarized in Table 1.

Table 1 here

ET_0 estimations based on the mentioned models have been initially compared, using classical statistical descriptors, with scintillometer measurements collected over a standard crop surface (alfalfa).

Daily ET_0 values obtained with the different procedures, were finally used as input data in FAO 56 agro-hydrological model (Allen et al., 1998), in order to evaluate the corresponding effects on actual ET estimated for an olive grove.

According to the dual crop coefficient approach, actual evapotranspiration, *ET,* can be evaluated as:

$$ET = T + E = (K_{cb}K_s + K_e)ET_0 = K_{c,adj}ET_0 \quad (13)$$

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 soil water content, *SWC,* and K_e describes the evaporation component from wet soil, following rain or irrigation (Allen and Pereira, 2009).

The values of K_s can be computed as:

$$K_s = \frac{TAW - D_i}{TAW - RAW} \qquad \text{for } D_i > \mathrm{RAW} \quad (14a)$$

$$K_s = 1 \qquad \text{for } D_i \leq \mathrm{RAW} \quad (14b)$$

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, being p evaluated as:

$$p = p_{table} + 0.04(ET_0 - 5) \quad (15)$$

Values of p_{table} for different crops were suggested by Allen at al. (1998). For the investigated system, p_{table} was set equal to 0.55.

The evaporation coefficient, K_e, can be also derived following the methodology described in the original publication requiring, however, measurements of soil water contents in the topsoil.

In absence of water stress (K_s=1 and negligible soil evaporation), K_{adj} returns to the standard crop coefficient K_c, as defined in the "single" approach (Doorenbos and Pruitt, 1977; Allen et al., 1998). Although values of K_c and K_{cb} for some crops can be found in the literature (Allen and Pereira, 2009), the proper local estimation of these coefficients for the examined olive groves was performed based on direct measurements (Minacapilli et al., 2009; Cammalleri et al., 2013a). In particular, K_{cb} and K_s were obtained by simultaneous measurements of evapotranspiration, crop transpiration and soil water content. The stress coefficient K_s was computed by eq. (14), in which:

$$D_i = 1000 * \left(SWC_{fc} - SWC_{r,i}\right) * Z_r \quad (16)$$

$$TAW = 1000 * \left(SWC_{fc} - SWC_{wp}\right) * Z_r \quad (17)$$

where SWC_{fc} and SWC_{wp} are the soil field capacity and wilting point, whereas Z_r is the rooting depth.

Materials and Methods

Description of the study area and experimental layout

The research was carried out from May to August 2005, in a commercial farm located near the town of Castelvetrano, Sicily (37º38'46" N, 12º51'10" W), characterized by an average elevation of about 120 m above sea level. By following the USDA classification, soil can be classified as silty clay loam with average clay, silt and sand contents of about 24, 16 and 60%, respectively (Cammalleri et al. 2013b).

Crops on the farm are those typical of the Mediterranean environment, including olive, grapes and citrus. Olives, generally planted with an average density of about 250 trees per hectare, represent the main orchard crop in the area.

Experiments were carried out over a field of alfalfa (*Medicago sativa* L.) during the stationary phase of crop biological cycle, by monitoring all the components of the surface energy balance with a scintillometer station.

The crop was sown in the first decade of March 2005, with a sowing rate of 20 kg ha^{-1} and, according to the agronomic guidelines for hay crops, it was periodically cut down (every 7-10 days) in order to maintain the canopy at an uniform height of approximately 12-15 cm.

The field was maintained under reference standard conditions (Allen et al., 1998). A sprinkler irrigation system was used to ensure an adequate crop water availability, avoiding soil water deficit conditions. In order to evaluate the crop water availability, the preliminary hydraulic characterization of the soil was carried out with standard laboratory procedures on undisturbed soil samples collected at different depths (0-100 cm).

The classical evaporation technique allowed determination of the soil water retention curve, that was mathematically described according to the van Genucthen equation (van Genuchten, 1980).

Soil water retention curves were determined on twenty undisturbed soil samples, 0.08 m diameter and 0.05 m height, collected along 1 m vertical soil profile. Hanging water column apparatus and pressure plate apparatus (Burke et al., 1986), were used to evaluate soil water contents corresponding to soil matric potential values ranging from −0.05 to −153 m. The van Genuchten model (van Genuchten, 1980) was used to fit experimental data; the water retention curve parameters were obtained by means of the retention code, RETC (van Genuchten et al., 1992).

The soil water contents dynamics were monitored every 10 cm, from the soil surface to 120 cm depth, by using a Diviner 2000 Sentek FDR (Frequency Domain Reflectometry) probe, after the preliminary calibration of the sensor (Provenzano et al., 2015; Rallo and Provenzano, 2015). Measurements were carried out every week, as well as before and after each irrigation event. Values of soil water contents (*SWC*) measured at the different depths were then averaged in order to determine, for each measurement day, a single value representative of the soil layer from where the root water uptake mainly occurs.

Irrigation was scheduled according to the average soil matric potential in the root zone indirectly estimated based on the soil water retention curve and measured soil water contents. Matric potentials were in particular maintained always higher than -80 kPa, to avoid crop water deficit conditions during the whole investigated period (Homaee et al., 2002). In this way it was possible to account for the precipitation of the period. Total irrigation depth provided during the experiments was equal to 122 mm, distributed in two equal events provided on 9th and 15th August.

Standard meteorological variables were acquired hourly, by a weather station belonging to Sicilian Agrometeorological Information Service (SIAS, http://www.sias.regione.sicilia.it). The area is characterized by the typical Mediterranean climate, with moderate rainfall during autumn and winter, and high air temperature with scarce precipitation in summer.

A displaced-beam laser scintillometer (DBLS) installed in the field provided observations aimed at estimating the surface energy balance terms allowing the evaluation of sensible heat, H, net radiation, R_n, and soil heat, G, fluxes. Similarly to many others micro-meteorological techniques (i.e., bowen ratio, surface renewal), scintillometry provides observations of ET as the residual term of the surface energy budget equation, as:

$$ET = \frac{R_n - G_0 - H}{\lambda} \qquad (18)$$

Respect to other systems such as lysimeters, the distinct advantage of scintillometry is the ability to derive surface energy balance terms over a long transect scaling from some ten of meters to several kilometers. A detailed description of the DBLS used in the investigation, as well as the related theory has been reported in appendix A.

Results

Firstly, the results of soil hydraulic characterization were analyzed in order to determine the water availability in alfalfa field. Fig. 1 shows the soil matric potentials as a function of soil water contents obtained at the different depths. According to the limited differences observed with depths, a single equation was used to fit the experimental data.

Figure 1 here

Soil water content at field capacity (soil matric potential of -33 kPa) was equal to 0.42 $cm^3\ cm^{-3}$, whereas at matric potential of -80 kPa, corresponding to the threshold of *SWC* below which crop water stress occurs (Homaee et al., 2002; Kirkham, 2014), the soil water content was 0.18 $cm^3\ cm^{-3}$.

In order to check that standard conditions in alfalfa field occurred during the period of investigation, the temporal variability of soil water status was monitored, from the soil surface to a depth of 120 cm, using a Frequency Domain Reflectometry (FDR) probe.

Fig. 2 shows the temporal dynamic of daily precipitation *P* and irrigation *I*, shortwave radiation, R_s, average air temperature, *T*, vapor pressure deficit, *VPD* and crop evapotranspiration obtained with the scintillometer. The temporal dynamic of soil water content along the investigated profile (0-120 cm) is also shown in the lowest panel. Unfortunately, the scintillometric acquisitions were not continuous due to various technical problems causing the malfunctioning of the instrument, and were limited to a total of 22 complete days. However, it has to be highlighted that all the variables were registered with a time step of 15 minutes, composed of more than 2200 records.

Figure 2 here

The analysis of the climatic variables (Short wave radiation, Air temperature and Vapor pressure deficit) showed R_s values around 300 W m^{-2} d^{-1}, with a slightly decreasing trend from May to August. Occasional reductions of solar radiation occurred during cloudy days or rain events. On the contrary, the trend of average daily temperatures and the corresponding VPD values slowly increased over time.

Precipitation and irrigations events maintained the soil (on average along the whole depth) at sufficiently wet conditions, to avoid limitations on crop transpiration.

This is demonstrated by the analysis of temporal evolution of *SWC* along the investigated soil profile (Fig. 2 - panel d). In fact, the minimum *SWC* in the layer 25-75 cm ranged between 0.10 and 0.14 cm^3 cm^{-3} due to the higher active root density charactering the layer, in the layers 0-25 cm and 75-100 cm, soil water contents resulted around 0.25 cm^3 cm^{-3} over the whole period. This was due to the negligible contributes of soil evaporation in the top layer and root water uptake in the lower layer. However, in the period before the 9th of August when the first irrigation event occurred, the average *SWC* along the vertical profile decreased from 0.24 cm^3 cm^{-3} to 0.18 cm^3 cm^{-3}, a range of values characterizing absence of water stress conditions.

Daily ET_0 obtained by means of scintillometer measurements ranged between 3.2 mm d^{-1} and 6.0 mm d^{-1}, as a consequence of the combined effects of climatic variables such as solar radiation, vapor pressure deficit and, only marginally, wind speed (data not shown).

At the begin of the experiment (around mid of May), despite the optimal water availability in the soil (around 0.24 m^3 m^{-3}), the observed values of ET_0 were not very high and around 4 mm d^{-1}; this fact can be explained by the relatively low *VPD* and air temperatures (low atmospheric demand). From the end of May to the end of June, ET_0 increased to 5.5 mm d^{-1} thus showing that the alfalfa was fully developed in a soil characterized by an average water content of about 0.21 $m^3 m^{-3}$, and responding to the atmospheric demand. In July, slight reductions of ET_0 values were observed, as a consequence of the progressive decline of water availability along the soil profile, in which *SWC* reached the threshold value of about 0.18 $m^3 m^{-3}$ (first week of August). During the second decade of August, despite the two irrigations events contributing to increase water availability in the root zone, only a slightly increase of ET_0 was observed. This circumstance can be explained by the contemporary reduction of the forcing factors (*VPD*, *T* and R_s).

For each reference evapotranspiration equation, Fig. 3 illustrates the cross comparison between measured and estimated ET_0 at a daily time step. As can be observed, all the investigated equations showed a certain dispersion around the 1:1 line, the highest accuracy in terms of determination coefficient, R^2, and root mean squares difference, (RMSD) was associated with the two methods based on PM equation. These two approaches, applied at daily time step, gave practically identical values, as shown in Fig. 3a. The negative R^2 values, observed when HAR and TURC methods are applied, are a consequence of setting equal to zero the intercept of the considered regression (estimated vs measured ET_0).

Figure 3 here

Because a statistical analysis based only on R^2 and RMSD can be misleading, a more exhaustive comparison between measured and estimated daily ET_0 values was carried out according to the Mean Absolute Difference (MAD), Slope of the regression equation, Relative Error (RE), Mean Bias Error (MBE), and the scores, (T), obtained using the statistical T-test, whose values are specified in Table 2.

These statistical descriptors confirmed the highest accuracy of PM methods also in terms of MAD, Slope of the regression equation, RE, MBE and T. However, the P&T and MAK equation are characterized by higher R^2, but slopes of regression equation different from 1.0 which suggests some bias that could be removed by a site-specific calibration procedure.

Table 2 here

A similar comparison was carried out at hourly time step and at daily scale obtained by aggregating the resulting hourly ET_0 values.. Of course, in these comparisons the B&C and HAR equations were not examined, because their application was originally proposed only for a daily time step. Fig. 4 shows the comparisons between measured and estimated ET_0 at hourly time-step, whose related statistical indicators are summarized in table 3 (hourly data). As can be observed from the analysis of statistical indices a better performance can be associated with the PM-FAO56 equation. However, comparing daily and hourly simulations the use of an hourly time step instead of daily did not improve the performances of tested. In fact the higher values of R^2 obtained by the statistical comparison (see Table 3) can be only ascribe to the higher magnitude values and data-population of measured and estimated ET_0 values at hourly scale.

Figure 4 here

Table 3 here

Finally, daily ET_0 values obtained by the different equations, were used as input in FAO-56 agro-hydrological model in order to assess the impact that the different equations have on actual evapotranspiration estimated for an olive grove (ET).

ET values estimated by considering $ET_{0\text{-}PM\text{-}FAO}$ as input, were assumed as the benchmark, accounting for the results of a previous model validation carried out in the same soil-plant-atmosphere system (Rallo et al., 2012; Rallo et al., 2014).

Fig. 5a (upper panels) shows the results of the water balance simulations. As can be observed, all the different ET_0 methods seem to reproduce similar patterns of simulated actual evapotranspiration with differences mainly observed in the peaks. Since the FAO-56 agro-hydrological model is a widely used tool to schedule irrigation on the base of simulated soil water contents, the latter were also compared using all the different ET_0 methods. As can be observed in Fig. 5b (lower panels) a significant variability was recognized in terms of soil water content that certainly affect the scheduling of irrigations. In fact, assuming as time threshold value for scheduling irrigation a soil water content value of 0.2 m^3m^{-3} some differences can be realized comparing the various scenarios plotted in Fig.5b. Particularly, using as input ET_0 values obtained using PM, P&T and MAK equations, similar patterns of soil water content were obtained with a resulting first irrigation identified around the end of the first decade of June. Differently, using TURC, HAR and B&C equations for ET_0 estimation, the first irrigation should be applied at the begin of June. Also in terms of number of scheduled irrigations the scenarios that can be deduced analyzing the trends of Fig. 5b appear sometimes more different, as for the B&C case which seems to suggest four date for irrigations instead of two.

Figure 5 here

Final discussion and conclusions

In the research, the performance of different methods to estimate ET_0 was tested in a typical Mediterranean environment during spring-summer 2005, based on the comparison with scintillometric measurements carried out on alfalfa reference crop. The need for this kind of investigation arises from the consideration that in semi-arid environments, full weather datasets required by PM based equations are often lacking, so that alternative and simplified approaches characterized by a limited number of input variables, are required.

Experiments confirmed that PM-FAO56 formulation represents the best approach to estimate ET_0 at both hourly and daily time steps. Moreover, in the examined environment, when full weather datasets are not available, satisfactory estimations of daily ET_0 can be obtained by using P&T and MAK equations. The latter can be improved after a site-specific calibration.

The results suggested that: i) no systematic overestimations of ET_0 were caused by the suboptimal location of standard weather station used to acquire the data; ii) the aerodynamic terms caused slight differences between observed and estimated ET_0 obtained with the different methods, whereas solar radiation had the major effects in the process. These considerations allows confirmation that PM-based methods are able to reproduce fairly well evapotranspiration processes in the investigated area and under the examined conditions. However, the small discrepancy observed between measured and estimated ET_0 (PM-methods) can be ascribed to possible differences between theoretical and actual reference surface conditions, as well as to presumable measurement errors and of course not to the failure of the theoretical approach. For similar regions in terms of climate, landscape and dominant crops, the P&T and MAK equations can be considered reliable alternatives to the PM-based approaches, after site-specific parameter optimization when a full weather dataset is not available,.

To assess the different approaches to estimate ET_0, a functional evaluation was carried out by using FAO-56 agro-hydrological model with input ET_0 values obtained from all the methods evaluated here. The simpler P&T equation gave the best estimation of actual evapotranspiration, confirming again that this method is a valid alternative to the PM-FAO56 method.

Finally, the use of scintillometry for validation purpose allowed the acquisition of reliable observations at hourly (or shorter) time step, as well as to field-average data that are only slightly affected by heterogeneity caused by field management practices.

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APPENDIX A

Scintillometer measurements of evapotranspiration

Scintillometry provides estimations of *ET* as residual term of the surface energy balance equation, as:

$$ET = \frac{R_n - G_0 - H}{\lambda} \tag{A1}$$

where H (MJ m^{-2} h^{-1}) is the sensible heat flux observed by the scintillometer and λ is the latent heat of vaporization (≈ 2.45 MJ kg^{-1}), whereas R_n and G_0 can be measured with common instruments, i.e. net radiometers and flux plates.

Scintillometry retrieves H on the base of the optical distortion of a light beam caused by turbulence in the atmosphere. DBLS measures the scintillations over two close parallel path beams produced by a transmitter at the wavelength, λ_s, of 670 nm, and recorded by a receiver placed at a certain distance, R (m).

The theory of DBLS can be found in Thiermann and Grassl (1992) which demonstrated that the covariance of the logarithm of the amplitude of the received radiation is given by:

$$B_{12} = 0.124 C_n^2 K^{7/6} R^{11/6} f_B\left(\frac{l_0}{\sqrt{\lambda_s R}}, \frac{d_i}{\sqrt{\lambda_s R}}, \frac{D}{\sqrt{\lambda_s R}}\right) \qquad \text{(A2)}$$

where K is the optical wave number (equal to $2\pi/\lambda_s$), C_n^2 is the structure parameter of the refractive index of air ($m^{-2/3}$) and f_B describes the decrease of B_{12} with increasing of l_0 (inner length), d_i (separation between the two sources) and D (diameter of the two detectors) (m). The Eq. (A2) allows computation of variance of a single beam (B_{11} and B_{22}) simply by assuming $d_i = 0$. For given d_i and D, the ratio $r_{12} = B_{12}/(B_{11}B_{22})^{1/2}$ is a sole function of l_0, so r_{12} yields directly l_0. Afterwards, C_n^2 can be derived from Eq. (A2) for known l_0 and B_{11} (or B_{22}).

The so-called "structure parameter of temperature", C_T^2 (K $m^{-2/3}$), and the "dissipation rate of the kinetic energy of the turbulence", ε ($m^2 s^{-3}$), can be calculated from C_n^2 and l_0 with:

$$C_T^2 = \left(\frac{T_a^2}{b_a P}\right)^2 C_n^2 \qquad \text{(A3a)}$$

$$\varepsilon = \nu^3 \left(\frac{7.4}{l_0}\right)^4 \qquad \text{(A3b)}$$

where b_a is the refractive index coefficient for air at 670 nm, equal to 0.789×10^{-3} K kPa^{-1}, P is the air pressure (kPa) and ν is the air viscosity ($m^2 s^{-1}$).

H fluxes are computed from C_T^2 and ε using the Monin-Obukhov Similarity Theory (MOST). MOST defines H as:

$$H = \rho c_p u_* T_* \qquad \text{(A4)}$$

where u_* (m s^{-1}) is the friction velocity and T_* (K) is temperature scale. Both u_* and T_* can be computed using dimensionless functions. In our experiment the formulation proposed by Hartogensis (2006) for unstable conditions has been used:

$$\varepsilon k z (u_*^{-3}) = \left(1 - 15.1\frac{z}{L}\right)^{-1/3} - \frac{z}{L} - 0.16 \qquad \text{(A5a)}$$

$$\frac{C_T^2 z^{2/3}}{T_*^2} = 4.9\left(1 - 6.1\frac{z}{L}\right)^{-2/3} \qquad \text{(A5b)}$$

and the relationships proposed by Thiermann and Grassl (1992) for stable conditions:

$$C_T^2 (0.41 z)^{2/3} T_*^2 = 4\beta\left(1 + 7\frac{z}{L} + 20\left(\frac{z}{L}\right)^2\right)^{1/3} \qquad \text{(A6a)}$$

$$\varepsilon 0.41 z(u_*^{-3}) = \left(1 + 4\frac{z}{L} + 16\left(\frac{z}{L}\right)^2\right)^{-1/2} \quad \text{(A6b)}$$

where z is the height of the instrument above the zero plane displacement (m), β is the Obukhov-Corrsin constant (0.86), and L is the Obukhov length (m), equal to:

$$L = -\frac{\rho c_p T_a u_*^3}{kgH} \quad \text{(A7)}$$

The relationships (A4)-(A7) allow deriving H fluxes by means of an iterative procedure for both stable and unstable conditions.

The system used in this study case is the optical energy balance measurement system (OEBMS1, Scintec AG - Germany), which includes a displaced beam small aperture scintillometer (SLS20, Scintec AG - Germany) to H fluxes, a two component (total incoming and outgoing) pyrradiometer (model 8111, Schenk GmbH - Germany), and three soil heat plates (HFP01SC, Hukseflux - The Netherlands).

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Figures and Tables

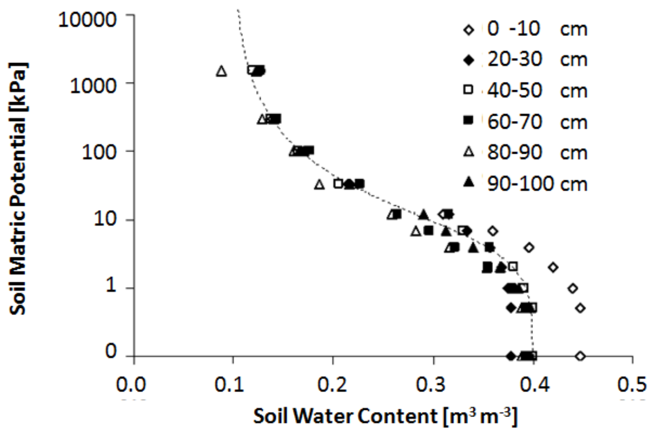

Fig. 1 - Soil water retention data obtained at the different depths. Dotted line represents the van Genuchten fitting model

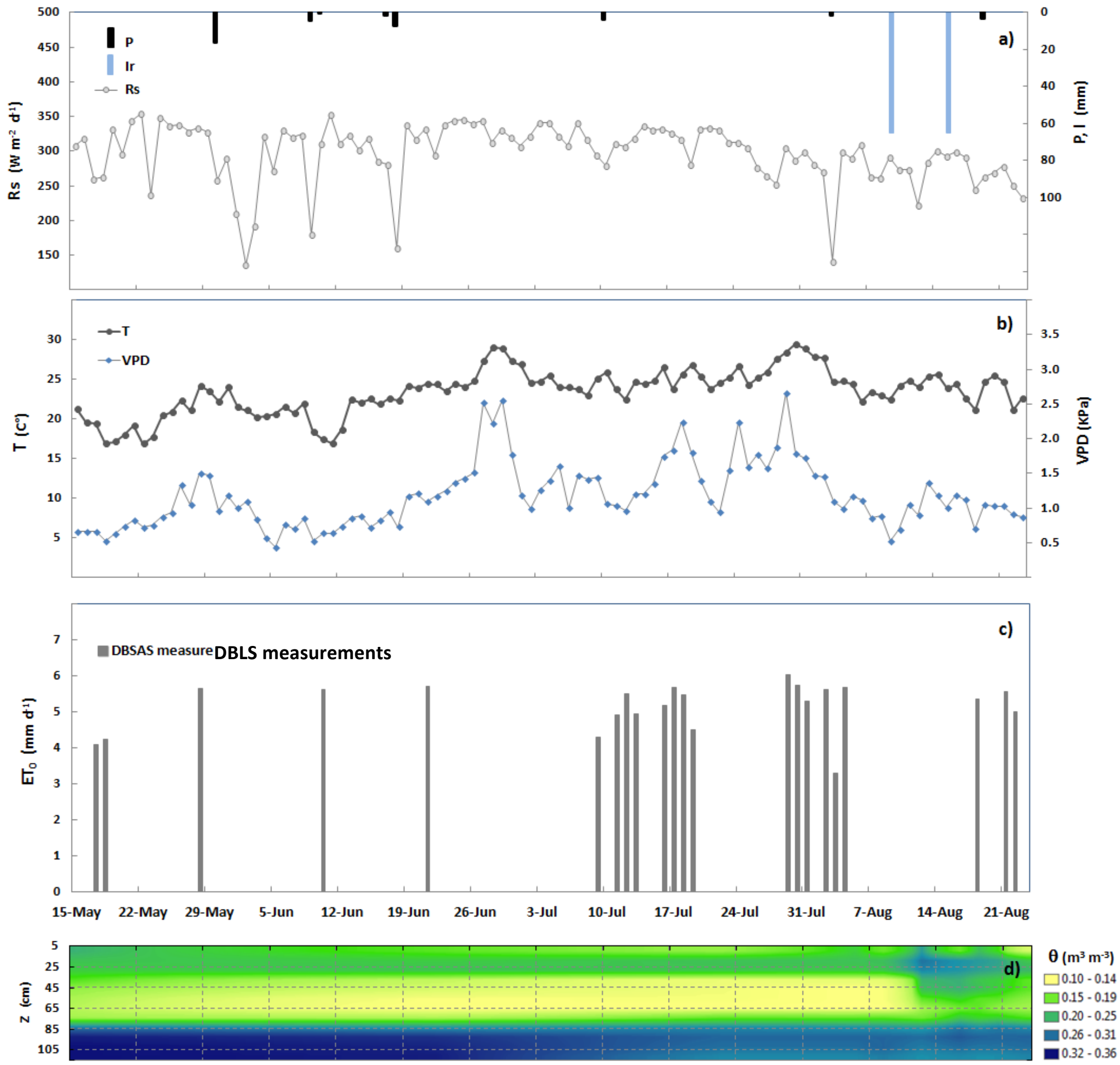

Fig. 2 a,d – Main variables measured at daily scale: a) Shortwave radiation, R_s, Precipitation, P and Irrigation, I; b) Mean air temperature, T and Vapor Pressure Deficit, VPD; c) Observed Evapotranspiration (DBLS scintillometer), ET_0; d) Dynamic of Soil water content, SWC

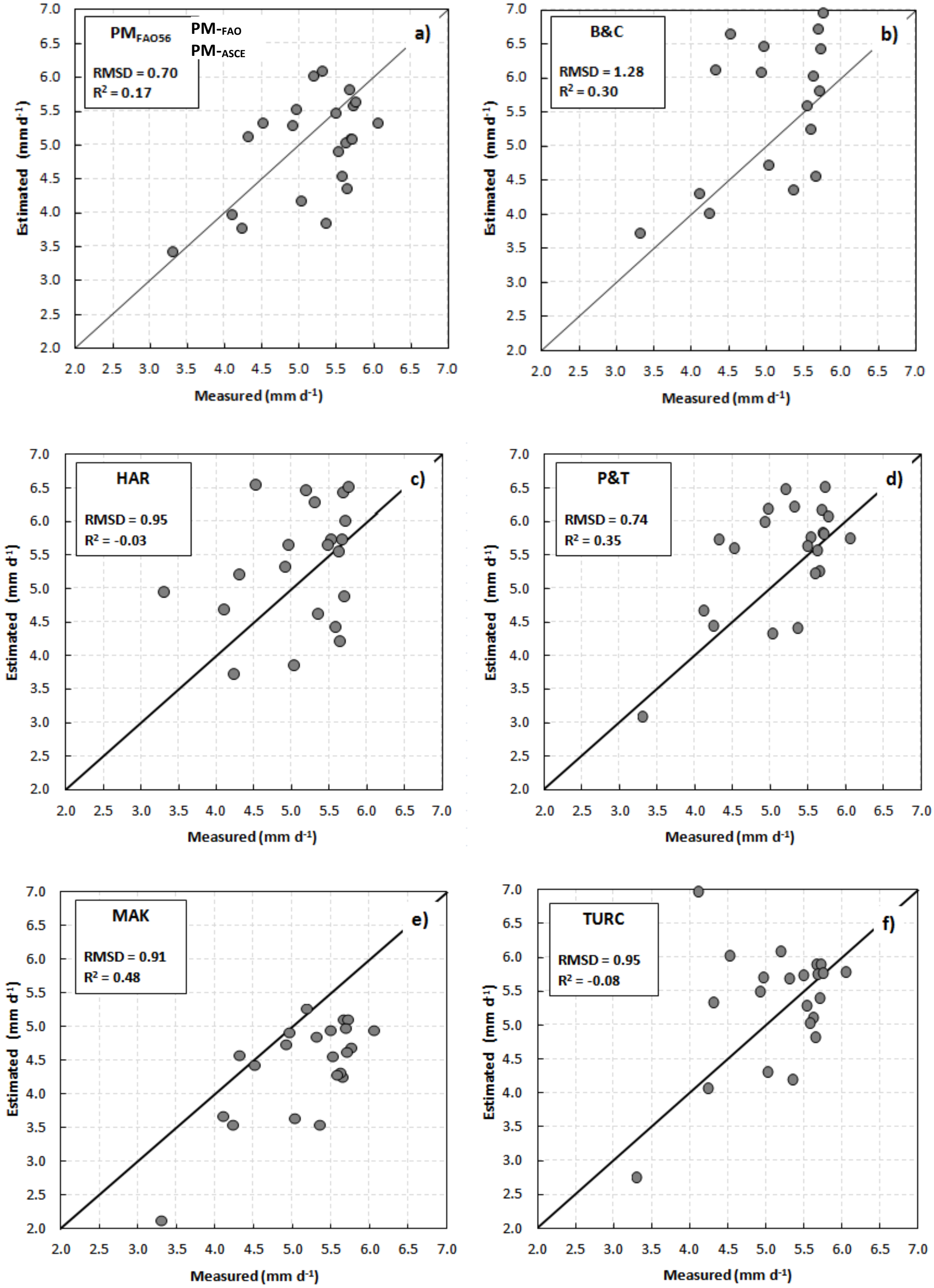

Fig. 3 – Measured vs. predicted daily evapotranspiration

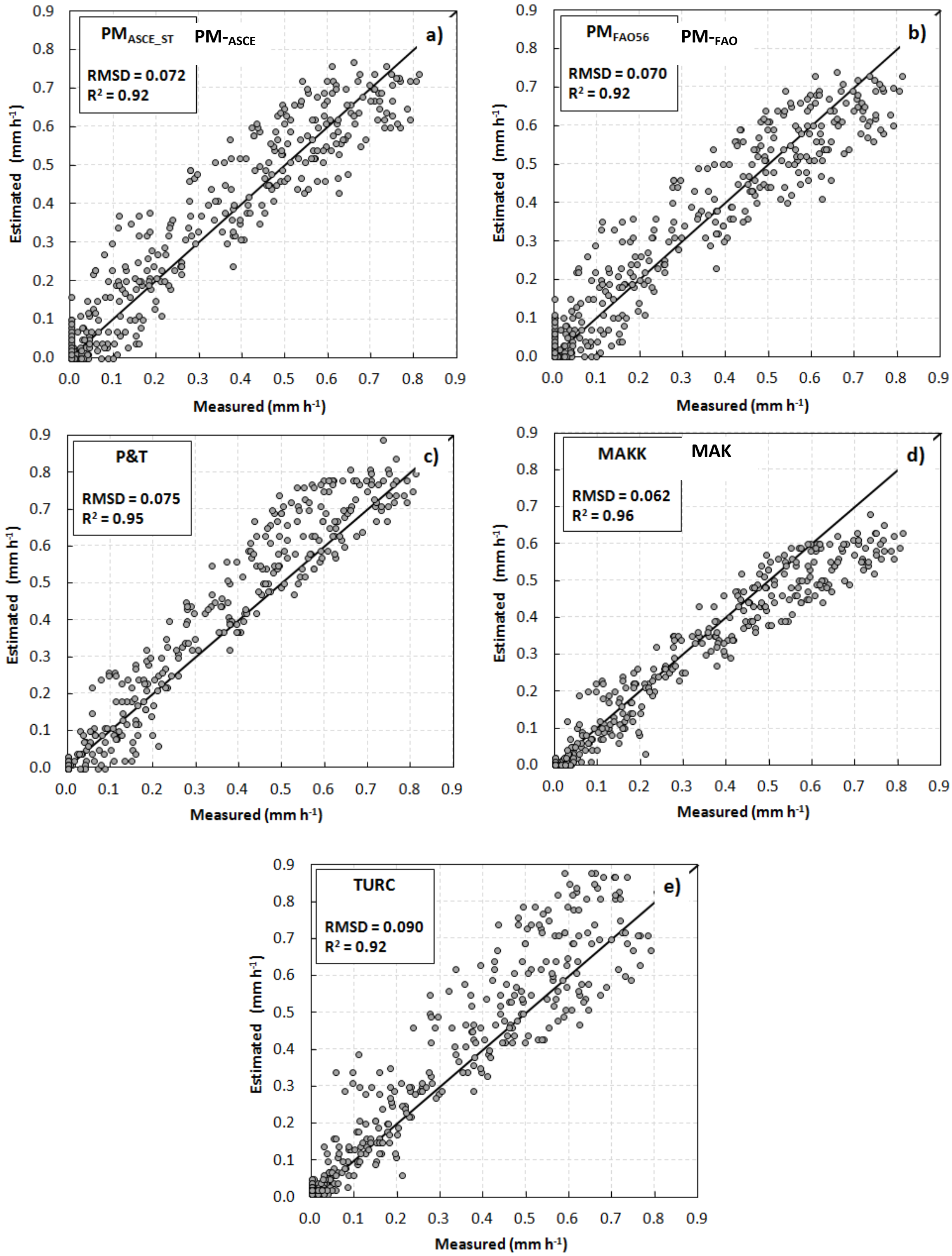

Fig. 4 – Measured vs. predicted hourly evapotranspiration

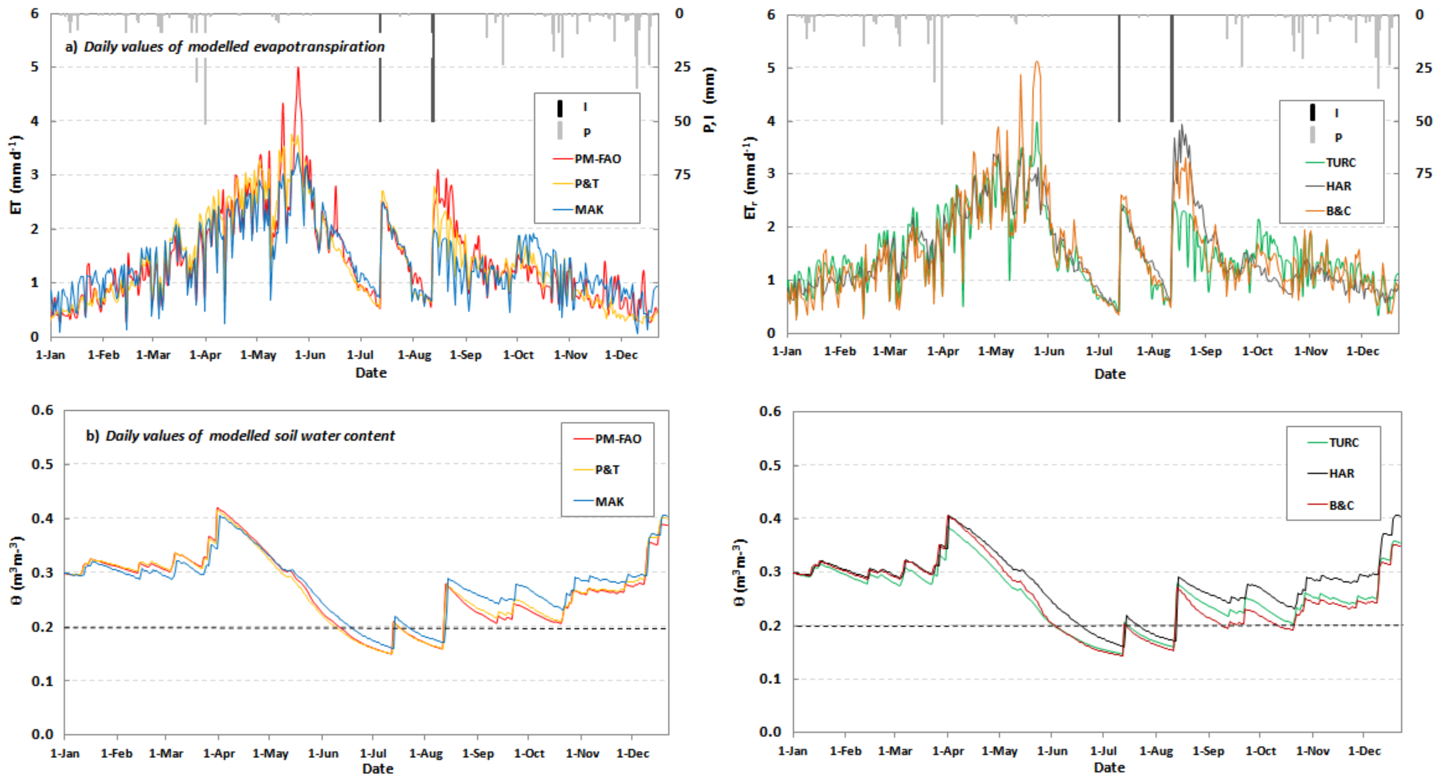

Fig. 5 – Dynamic of daily ~~and~~ actual evapotranspiration and soil water content obtained for olive groves by using the different methods to estimate ET_0

Table 1. Meteorological variables required by the different ET_0 computation methods

Method	Acronym	Time-step	R_s	T_a	RH	u
Penman-Monteith FAO56	PM_{FAO}	hourly/daily	×	×	×	×
Penman-Monteith ASCE	PM_{ASCE}	hourly/daily	×	×	×	×
Pristely & Taylor	P&T	hourly/daily	×	×	×	
Makkink	MAK	hourly/daily	×	×		
Turc	TURC	hourly/daily	×	×		
Blaney-Criddle	B&C	Daily	×	×	×	
Hargreaves	HAR	Daily		×		

Table 2 – Statistical indicators computed by comparing daily evapotranspiration obtained with the different methods (dependent variable) and observations (independent variable)

Methods	MAD (mm d^{-1})	RMSD (mm d^{-1})	Slope (-)	R^2 (-)	RE %	MBE (mm d^{-1})	T (-)
PM_{FAO}/PM_{ASCE}	**0.59**	**0.70**	**1.0**	**0.17**	**11.45**	**-0.15**	**0.355**
P&T	0.60	0.74	1.1	0.35	11.60	0.35	0.023
MAK	0.77	0.91	0.9	0.48	14.89	-0.73	0.000
TURC	0.66	0.95	1.0	-0.08	12.78	0.20	0.327
B&C	1.06	1.28	1.2	0.30	20.54	0.80	0.001
HAR	0.81	0.95	1.0	-0.03	15.70	0.29	0.162

Table 3 – Statistical indicators computed by comparing hourly and daily evapotranspiration obtained with the different methods (dependent variable) and observations (independent variable). Daily ET_0 estimations are evaluated by integrating hourly data

Methods	MAD		RMSD		Slope		R^2		RE		MBE		T	
	Hourly	*Daily*	*Hourly*	*Daily*	*Hourly*	*Daily*	*Hourly*	*Daily*	*Hourly*	*Daily*	*Hourly*	*Daily*		
	(mm h^{-1})	(mm d^{-1})	(mm h^{-1})	(mm d^{-1})	(-)	(-)	(mm h^{-1})	(mm d^{-1})	(-)	(-)	%	%	(-)	(-)
PM-ASCE	**0.05**	**0.61**	**0.07**	**0.73**	**1.0**	**1.0**	**0.01**	**0.27**	**0.92**	**0.24**	**23.98**	**11.86**	**0.004**	**0.066**
PM-FAO	**0.05**	**0.58**	**0.07**	**0.67**	**1.0**	**1.0**	**0.00**	**0.06**	**0.92**	**0.28**	**23.57**	**11.24**	**0.402**	**0.086**
P&T	0.05	0.63	0.07	0.78	1.1	1.1	0.02	0.43	0.95	0.42	24.65	12.30	0.000	0.006
MAK	0.04	0.65	0.06	0.79	0.9	0.9	-0.02	-0.59	0.96	0.49	18.02	12.65	0.000	0.000
TURC	0.06	1.13	0.09	1.38	1.1	1.2	0.04	0.98	0.92	0.46	27.10	21.99	0.000	0.000