Improvement of FAO-56 Model to Estimate Transpiration Fluxes of Drought Tolerant Crops under Soil Water Deficit: Application for Olive Groves

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Abstract: Agro-hydrological models are considered an economic and simple tool for quantifying crop water requirements. In the last two decades, agro-hydrological physically based models have been developed to simulate mass and energy exchange processes in the soil-plant-atmosphere system. Although very reliable, because of the high number of required variables, simplified models have been proposed to quantify crop water consumes. The main aim of this paper is to propose an amendment of the Food and Agricultural Organization (FAO) of the United Nations FAO-56 spreadsheet program to introduce a more realistic shape of the stress function, valid for mature olive orchards (*Olea europaea* L.). The modified model is successively validated by means of the comparison between measured and simulated soil water contents and actual transpiration fluxes. These outputs are finally compared with those obtained with the original version of the model. Experiments also allowed assessing the ability of simulated crop water stress coefficients to explain the actual water stress conditions evaluated on the basis of measured relative transpirations and midday stem water potentials. The results show that the modified model significantly improves the estimation of actual crop transpiration fluxes and soil water contents under soil water deficit conditions, according to the RMSEs associated with the revised model, resulting in significantly higher than the corresponding values obtained with the original version. **DOI: 10.1061/(ASCE)IR.1943-4774.0000693.** *© 2014 American Society of Civil Engineers.*

Author keywords: FAO-56 agro-hydrological model; Water stress function; Water uptake ability; Table olive orchards; Midday stem water potential; Relative transpiration.

Introduction

The quantification of crop water requirements of irrigated land is crucial in the Mediterranean regions characterized by semiarid conditions, where water scarcity and increasing competition for water resources are pressurizing farmers to adopt different water-saving techniques and strategies, which may range from a simple periodic estimation of the soil water balance terms to a precise assessment of temporal and spatial distribution of water exchange within the soil–plant–atmosphere continuum (Provenzano et al. 2013).

The knowledge of actual transpiration fluxes can allow the correct estimation of crop water requirements and to dispose of irrigation management strategies aimed to increase water use efficiency. Physically based and stochastic hydrological models, although very reliable, in relation to the high number of variables and the complex computational analysis required (Laio et al. 2001), cannot often be applied. The use of simplified models, considering a simple water bucket approach, may therefore represent a useful and simple tool for irrigation scheduling.

The Food and Agricultural Organization (FAO) of the United Nations Irrigation and Drainage Paper 56 (Allen et al. 1998) provides a comprehensive description of the widely accepted Penman-Monteith method for estimating reference evapotranspiration from standard weather data, and an affordable procedure for computing actual crop evapotranspiration under standard and nonstandard (stressed) conditions. A first amendment of the algorithm was recently proposed by Rallo et al. (2012) for arboreal crops, to allow irrigation scheduling under soil water deficit conditions; with this modification the eco-physiological factor, affected by the crop stress, was separated from the management allowed depletion (MAD) term, which is related more to the farmer choices and dependent on aleatory variables like the economic factors.

Even if several studies have been carried out (Fernández et al. 2001; Testi et al. 2004; Ezzahar et al. 2007; Er-Raki et al. 2008; Cammalleri et al. 2013) on the evaluation of olive water consumptions, particularly on the partition of the components of crop evapotranspiration in semiarid areas, very few studies have considered the eco-physiological processes influencing the kinetic of root water uptake. This missing feature represents a limitation of the available version of the model that schematizes the crop water uptake by means of a transpiration reduction function in which the stress coefficient, K_s, is assumed to be linearly dependent on the soil water depletion, in the range between a certain critical value and the wilting point. In actuality, the shape of K_s depends on eco-physiological processes like plant resistance/tolerance/avoidance to water stress and soil water availability in the root zone. For xerophytes crops like olives, Rallo and Provenzano (2013) recognized a convex shape of the K_s relationship, and that crop water stress conditions occur for soil matric potentials lower than −0.40 MPa.

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Note. This manuscript was submitted on April 3, 2013; approved on November 18, 2013; published online on January 6, 2014. Discussion period open until June 6, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, © ASCE, ISSN 0733-9437/A4014001(8)/$25.00.

Moreover, it was shown that the reduction of actual transpiration becomes severe only under extreme water deficit conditions.

The main objective of this paper is to propose an amendment to the original FAO-56 spreadsheet program and to assess its suitability for simulating the table olive (*Olea europaea* L.) water requirement under soil water deficit conditions. In particular, a more realistic shape of the water stress function, valid for the considered crop, is introduced into the model in place of the original liner function; the validation is firstly carried out through the comparison of measured and simulated soil water contents (SWCs) and actual transpiration fluxes (T_a). Outputs of the amended model are then compared with those obtained with the original version. Finally, the measured relative transpirations and midday stem water potentials (MSWPs) are used to evaluate the ability of simulated stress coefficients to explain the actual crop water stress conditions.

Overview of FAO-56 Dual Approach Model and Critical Analysis

The FAO-56 model evaluates the root zone depletion at a daily time step with a water balance model based on a simple tipping bucket approach

$$D_i = D_{i-1} - (P_i - \mathrm{RO}_i) - I_i + \mathrm{ET}_{c,i} + DP_i \tag{1}$$

where D_i (mm) and D_{i-1} (mm) = root zone depletions at the end of day, i and $i-1$, respectively; P_i (mm) = precipitation; RO_i = surface runoff; $\mathrm{ET}_{c,i}$ (mm) = actual evapotranspiration; and DP_i (mm) = deep percolation of water moving out of the root zone.

The domain of the depletion function, D_i, is between 0, which occurs when the soil is at the field capacity, and a maximum value, corresponding to the total plant available water (TAW) (mm), obtained as follows:

$$\mathrm{TAW} = 1{,}000(\mathrm{SWC}_{fc} - \mathrm{SWC}_{wp})Z_r \tag{2}$$

where SWC_{fc} ($\mathrm{cm^3\,cm^{-3}}$) and SWC_{wp} ($\mathrm{cm^3\,cm^{-3}}$) = soil water contents at field capacity and wilting point, respectively; and Z_r (m) = depth of the root system.

In the absence of water stress (potential condition), the crop potential evapotranspiration ET_c is obtained by multiplying the dual crop coefficients ($K_{cb} + K_e$) and the Penman-Monteith reference evapotranspiration rate, ET_0 (Allen et al. 1998). In particular, the *dual crop coefficients approach*, as explained in the FAO-56 paper, splits the single K_c factor into two separate terms: a basal crop coefficient, K_{cb}, considering the plant transpiration, and a soil evaporation coefficient, K_e.

When water represents a limiting condition, the basal crop coefficients, K_{cb}, has to be multiplied by a reduction factor, K_s, variable between 0 and 1. The reduction factor can be expressed as

$$K_s = \frac{\mathrm{TAW} - D_i}{\mathrm{TAW} - \mathrm{RAW}} \tag{3}$$

where RAW (mm) = readily available water that can be obtained by multiplying TAW with a depletion coefficient, p, taking into account the resistance of crop to water stress. In particular, when water stored in the root zone is lower than $\mathrm{RAW}(D_i > \mathrm{RAW})$, the reduction coefficient K_s is lower than 1, whereas for $D_i \leq \mathrm{RAW}$ results in $K_s = 1$. Values of p, valid for different crops, are proposed in the original publication (Allen et al. 1998). Considering that the term p depends on the atmospheric evaporative demand, a function for adjusting p for ET_c is suggested (van Diepen et al. 1988).

The soil evaporation coefficient, K_e, describes the evaporation component of ET_c. When the topsoil is wet, i.e., after a rainfall or an irrigation event, K_e is at its maximum. The dryer the soil surface, the lower is K_e, with a value equal to zero when the water content of soil surface is equal to SWC_{wp}. When the topsoil dries out, less and less water is available for evaporation; the soil evaporation reduction can be therefore be considered proportional to the amount of water in the soil top layer, or

$$K_e = \mathrm{MIN}\begin{bmatrix} K_r \times (K_{c\_\max} - K_{cb}) \\ f_{ew} \times K_{c\_\max} \end{bmatrix} \tag{4}$$

where K_r = dimensionless evaporation reduction coefficient depending on the cumulative depth of water evaporated from the topsoil; f_{ew} is the fraction of the soil that is both exposed and wetted, i.e., the fraction of soil surface from which most evaporation occurs; and $K_{c\_\max}$ = maximum value of K_c following rain or irrigation. $K_{c\_\max}$ represents an upper limit of evapotranspiration fluxes from any cropped surface, whereas f_{ew} depends on vegetation fraction cover and irrigation system, the latter influencing the wetted area.

The evaporation decreases in proportion to the amount of water in the surface soil layer

$$K_r = \frac{\mathrm{TEW} - D_{e,i-1}}{\mathrm{TEW} - \mathrm{REW}} \tag{5}$$

where $D_{e,i-1}$ = cumulative depth of evaporation (depletion) from the soil surface layer at the end of $(i-1)$th day (mm); TEW (mm) = total evaporable water from an effective depth Z_e of soil surface subject to drying; and REW (mm) is the readily evaporable water, representing the maximum depth of water that can evaporate from the topsoil layer without restrictions. When TEW is unknown, it can be estimated as $\mathrm{TEW} = 1{,}000(\mathrm{SWC}_{fc} - 0.5\mathrm{SWC}_{wp})Z_e$, where Z_e is usually assumed to be equal to 0.10–0.15 m. In contrast, REW can be estimated according to soil texture (Allen et al. 1998).

Bucket models are very sensitive to the rooting depth parameter, Z_r, directly influencing the ability of the plant to extract water. Errors in its determinations generate an incorrect estimation of soil water stress coefficient and, as indicated by Er-Raki et al. (2008), the values of simulated evapotranspiration increase with increasing Z_r. In fact, higher Z_r causes increments of TAW within the root zone and, according to Eq. (3), leads to higher K_s values.

Materials and Methods

Investigations were carried out during irrigation seasons 2009, 2010, and 2011 (from April 15, DOY 105 to September 30, DOY 273) in the Tenute Rocchetta experimental farm, located in Castelvetrano, Sicily (UTM EST: 310050, NORD: 4168561). The farm, with an extension of approximately 13 ha, is mostly cultivated with table olive grove (*Olea europaea* L., var. Nocellara del Belice), representing the main crop in the surrounding area. The experimental plot is characterized by 17-year-old olive trees, planted on a regular grid of 8 m × 5 m (250 plants/ha); the mean canopy height is approximately 3.7 m and the average fraction of vegetation cover is approximately 0.35. Irrigation is practiced by means of pipelines with on-line emitters installed along the plant rows. Each plant was irrigated with four 8-l/h emitters. Soil textural class, according to USDA classification, is silty clay loam.

Standard meteorological data (incoming short-wave solar radiation, air temperature, air humidity, wind speed, and rainfall) were collected hourly by Servizio Informativo Agrometeorologico Siciliano (SIAS) with standard equipment installed approximately 500 m apart from the experimental field. Net radiation R and its

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components were measured with a four-component net radiatiometer (NR01, Hukseflux, Manorville, New York). According to ASCE-EWRI, the standardized Penman-Monteith method (ASCE-EWRI 2005) was used to calculate atmospheric water demand.

A preliminary investigation on the root spatial distribution was carried out to identify the soil volume within which the highest root density is localized and where most water uptake processes occur. A more detailed description of the soil physical properties and the root distribution is presented and discussed in Rallo and Provenzano (2013).

Irrigation scheduling followed the ordinary management practiced in the surrounding area. The total irrigation depth provided by the farmer was equal to 80 mm in 2009, 33 mm in 2010, and 150 mm in 2011.

Soil and Crop Water Status Measurements

During the investigation periods, soil water contents were measured with time domain reflectometry (TDR) (TDR100, Campbell Scientific, Logan, UT) and frequency domain reflectometry (FDR) (Diviner 2000, Sentek, Stepney, Australia) probes. On the basis of the results of Rallo and Provenzano (2013), the soil volume in which most of the root absorption occurs has been considered to install the soil moisture probes and to dispose of a representative measure of the average SWC in the entire system (Xiloyannis et al. 2012). In particular, the soil volume in which 80% of the roots are localized can be assumed as a parallelepiped with a length equal to the tree spacing (5.0 m), a width of 1.5 m, and a depth of 0.75 m. Referring to this soil volume, spatial and temporal variability of soil water contents was monitored, from the soil surface to a depth of 100 cm, using a FDR probe. Five access tubes were installed along two parallel directions: the first below the irrigation pipeline, at distances of 1.0, 2.0, and 2.5 m from the plant, and the second along a parallel direction, at a distance of 0.5 m from the first and approximately 1.0 and 2.5 m from the plant. In this way it was possible to take into account the spatial variability of soil water content after irrigation. Additional measurements of soil water contents were carried out using nine TDR probes connected to a multiplexer. The probes, having a length of 20 cm, were installed below the irrigation pipeline, at the same distances as the FDR access tubes, but the opposite side of the plant, in layers at 10–30, 35–55, and 60–80 cm. Values of soil water contents measured with FDR and TDR systems were then averaged to determine, for each measurement day, a single value of SWC representative of the soil layer where most of the root absorption takes place.

Transpiration fluxes were monitored on three consecutive trees, selected within the field according to their trunk diameter, so that they can be considered representative of the grove, using standard sap flow sensors (thermal dissipation probes) (Granier 1987). For each plant, two probes were installed on the north side of the trunk and then insulated to avoid the direct sun exposure. The measurements acquired by the two sensors were then averaged. The central plant was the same in which SWCs were measured.

Daily values of actual transpiration were obtained by integrating the sap flux, under the hypothesis of neglecting the tree capacitance. Daily transpiration depth ($\mathrm{mm\,d^{-1}}$) was obtained by dividing the daily flux ($\mathrm{l\,d^{-1}}$) for the pertinence area of the plant, equal to 40 $\mathrm{m^2}$. Then, to evaluate a representative value of the stand transpiration referred to the entire field, it was necessary to up-scale the plant fluxes by considering, as a proximal variable, the ratio between the average leaf area index, $\mathrm{LAI}(\mathrm{m^2\,m^{-2}})$, measured in field, and the average value, $\mathrm{LAI}_p(\mathrm{m^2\,m^{-2}})$, measured on the plants in which sap fluxes were monitored.

In the same trees selected for transpiration measurements, midday stem water potentials (MSWP) were measured in 2009 and 2011 by using a pressure chamber (Scholander et al. 1965), according to the protocol proposed by Turner (1988).

Amendment to the FAO-56 Model and Parameterization of Soil and Crop

The FAO-56 model has been applied (1) in its original form and (2) in its amended version, in which the stress function, the threshold value of the soil water content below which water stress occurs, SWC^*, and the minimum seasonal value of soil water content recognized in the field, $\mathrm{SWC_{min}}$, were experimentally determined.

In the first case, the model parameter p was assumed to be equal to 0.65, as indicated in Table 22 of the original paper, corresponding for the investigated soil to $\mathrm{SWC}^* = 0.20$, whereas SWC_{fc} and SWC_{wp} were considered equal to 0.33 and 0.13, determined according to the soil water retention curve for matric potentials of −0.33 and −1.50 MPa, respectively.

In the second case, to consider a more realistic water stress response of olive crops, the original function, as implemented in the model, was modified according to the relationship proposed by Steduto et al. (2009), in which K_s is a function of the relative depletion, D_{rel}

$$K_s = 1 - \frac{e^{D_{\mathrm{rel}} f_s} - 1}{e^{f_s} - 1} \tag{6}$$

where f_s = fitting parameter characterizing the shape of the stress function. The value of f_s was assumed to be equal to 2.89 as experimentally determined by Rallo and Provenzano (2013).

Relative depletion can be determined as

$$D_{\mathrm{rel}} = \frac{\mathrm{SWC}^* - \mathrm{SWC}}{\mathrm{SWC}^* - \mathrm{SWC_{min}}} \tag{7}$$

in the domain of soil water contents determining stress conditions for the crop ($\mathrm{SWC_{min}} < \mathrm{SWC} < \mathrm{SWC}^*$).

Fig. 1 shows the water stress function, as implemented in the spreadsheet program.

The shape of the considered function evidences that the water stress model is convex and demonstrates that water stress becomes

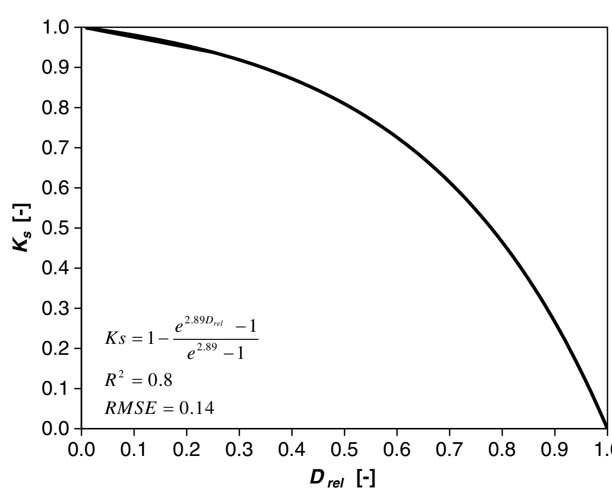

Fig. 1. Water stress functions for table olive orchards, as implemented in spreadsheet

more and more severe at decreasing soil water status (D_{rel} tending to 1); therefore, the reduction of actual transpiration is critical only for the most extreme water stress conditions. Moreover, the modified crop water stress function allows smoothing the unrealistic angular point indicating, in the K_s linear relationship, the passage from no-water stress to water stress conditions.

Under the investigated conditions, SWC* and SWC_{min} were assumed to correspond to a matric potential of −0.4 MPa, representing the threshold soil water status separating a condition of negligible water stress (relative transpiration is approximately equal to 1) from a condition in which relative transpiration decreases with soil water content (Rallo and Provenzano 2013).

In contrast, $SWC_{min} = 0.07\ m^3\ m^{-3}$, lower than the measured wilting point of 0.13 $m^3\ m^{-3}$, represents the minimum soil water content measured during the investigated seasons. The choice to consider SWC_{min} as the minimum seasonal value of soil water content recognized in the field and not the soil wilting point, as traditionally used for most crops, followed the suggestion of Ratliff et al. (1983) and, more recently, of Pellegrino et al. (2006). This assumption allows one to consider the strong ability of olive trees to extract water from the soil even below the soil wilting point and, consequently, a more coherent evaluation of the crop water availability (Lacape et al. 1998).

The depth of the root system, Z_r, was assumed to be equal to 0.75 m, as obtained on the basis of the measured root distribution, corresponding to the soil layer within which 80% of roots were encountered (Martin and Moffat 1999).

The average value of basal crop coefficient, in the mid- and late-stage seasons, was considered equal to 0.60, as recommended by Allen et al. (1998) and recently verified in the same experimental field (Minacapilli et al. 2009; Cammalleri et al. 2013).

Simulations were run during the three years of investigation, from DOY 105 to DOY 273. For all of the investigated periods, SWC_{fc} equal to 0.33 $m^3\ m^{-3}$ was considered as the initial condition, as a consequence of the copious precipitation that occurred in the decade before mid-April each year.

The values of the simulations variables, used as input for the original and modified models, are showed in Table 1.

Performance of the Models

The performance of the models was evaluated using the root mean square error (RMSE) and the mean bias error (MBE), defined as follows:

$$\text{RMSE} = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N} d_i^2\right)} \tag{8}$$

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N} d_i \tag{9}$$

where N = number of measured data, and d_i = difference between predicted and measured values (Kennedy and Neville 1986).

An additional student t-test was applied, as proposed by Kennedy and Neville (1986)

$$t = \sqrt{\frac{(N-1)\text{MBE}^2}{\text{RMSE}^2 - \text{MBE}^2}} \tag{10}$$

To determine whether the differences between measured and simulated soil water contents are statistically significant, the absolute value of the calculated t must be less than the critical t value (t_{crit}) for a fixed significance level. In this analysis, a significance level of $\alpha = 0.05$ was assumed.

Results and Discussion

Figs. 2(a–c) show the temporal dynamics of measured SWCs during the investigation periods 2009, 2010 and 2011; and Figs. 2(d–f) shows the estimated potential crop transpiration (dashed line), T_c, and the measured actual transpiration, T_a, in the same time intervals. In addition, Fig. 2 displays the corresponding simulation results obtained by considering the original (light line) and the modified (bold line) versions of the model. The top of the figure also shows the water supplies (precipitation and irrigation).

Table 1. Values of Variables Used for Simulations Carried Out with Original and Modified FAO 56 Model

	Original model			Modified model		
Variables	2009	2010	2011	2009	2010	2011
Soil water content at field capacity, SWC_{fc} (m^3/m^3)	0.33	0.33	0.33	0.33	0.33	0.33
Soil water content at wilting point, SWC_{wp} (m^3/m^3)	0.13	0.13	0.13	n.u	n.u	n.u
Minimum soil water content, SWC_{min} (m^3/m^3)	n.u	n.u	n.u	0.07	0.07	0.07
Total available water, TAW (mm)	150	150	150	n.u	n.u	n.u
Depletion factor, p (%)	65	65	65	n.u	n.u	n.u
Total evaporable water, TEW (mm)	22.5	22.5	22.5	22.5	22.5	22.5
Readily evaporable water, REW (mm)	11.0	11.0	11.0	11.0	11.0	11.0
Fraction of soil surface wetted by irrigation, f_w	0.11	0.11	0.11	0.11	0.11	0.11
Number of days of the year at time of planting, J_{plant}	105	105	105	105	105	105
Number of days of the year at beginning of development period, J_{dev}	135	135	135	135	135	135
Number of days of the year at beginning of midseason period, J_{mid}	225	225	225	225	225	225
Number of days of the year at beginning of late season period, J_{late}	285	285	285	285	285	285
Number of days of the year at time of harvest or death, J_{harv}	375	375	375	375	375	375
Basal crop coefficient at initial season, $K_{cb\,ini}$	0.55	0.55	0.55	0.55	0.55	0.55
Basal crop coefficient at mid-season, $K_{cb\,mid}$	0.60	0.60	0.60	0.60	0.60	0.60
Basal crop coefficient at late-season, $K_{cb\,end}$	0.60	0.60	0.60	0.60	0.60	0.60
Maximum crop height, H	3.0	3.0	3.0	3.0	3.0	3.0
Minimum rooting depth, Z_r	0.75	0.75	0.75	0.75	0.75	0.75
Maximum rooting depth, Z_r	0.75	0.75	0.75	0.75	0.75	0.75
Midseason, average wind speed ($m\,s^{-1}$)	0.99	1.34	1.38	0.99	1.34	13.8
Midseason average, RH_{min} (%)	52.6	52.2	53.1	52.6	52.2	53.1

Note: n.u. = not used in the simulations.

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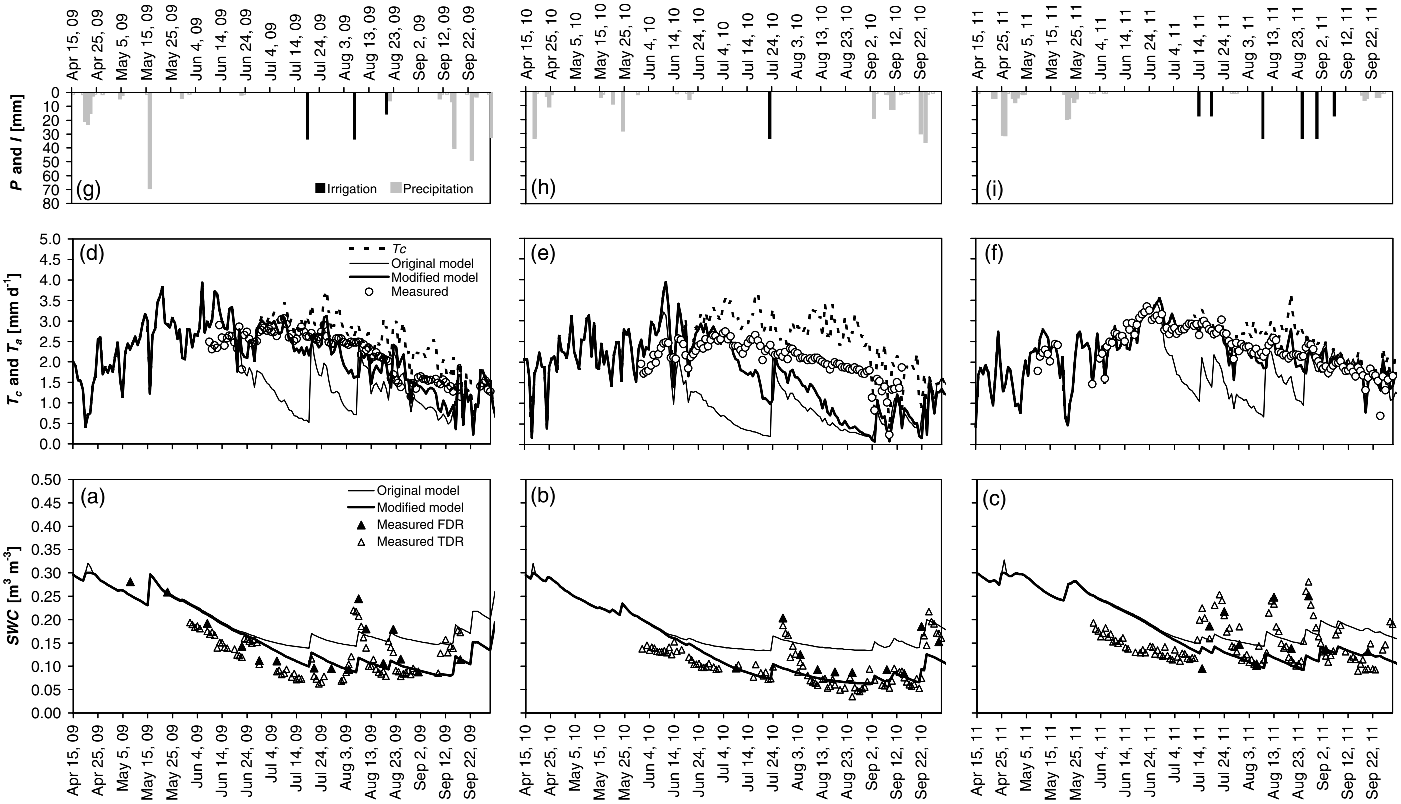

Fig. 2. (a–c) Temporal dynamic of observed and simulated soil water content; (d–f) potential and actual transpiration fluxes during 2009, 2010, and 2011; (g–i) total water supplies

Compared with the original version, the amended model provides better estimation in terms of either actual transpiration fluxes or soil water contents.

The statistical comparison, expressed in terms of RMSE and MBE associated with SWC and T_a, simulated by the modified and original models are presented in Table 2.

A substantial agreement between measured average soil water content in the root zone and the corresponding values, simulated with the revised model, is generally observed, with a root mean square error varying between 0.03 and 0.09.

Moreover, after a first simulation period in which the results of original and amended models are identical (absence of crop water stress), the original model determines a systematic overestimation of SWC, with RMSE varying between 0.05 and 0.10. The better estimation of minimum values of SWC obtained with the modified model is a consequence of considering SWC_{min} in place of SWC_{wp}, allowing a better modeling of the root water uptake ability, as actually recognized for olive trees.

As can be observed in Figs. 2(d–f), the seasonal trends of actual daily transpiration fluxes simulated with the modified model, in all the investigated periods, generally follow the observed values with RMSE, on average, equal to 0.54 mm when considering all of the data. Despite the reasonable global agreement, some local discrepancies can be observed in the periods immediately following irrigations (wetting events) in which peak values of T_a, resulting from the quick decrease of the depletion, are simulated. This evidence is corroborated by Liu and Luo (2010) and Peng et al. (2007), who observed that the dual approach of FAO-56 is appropriate for

Table 2. RMSEs and MBEs Associated with Soil Water Contents and Actual Transpiration Fluxes Simulated with Modified and Original Models

	Number of data (N)			Root mean square error (RMSE)			Mean bias error (MBE)		
Year	Actual transpiration	FDR SWC	TDR SWC	Actual transpiration (mm)	FDR SWC ($cm^3\ cm^{-3}$)	TDR SWC ($cm^3\ cm^{-3}$)	Actual transpiration (mm)	FDR SWC ($cm^3\ cm^{-3}$)	TDR SWC ($cm^3\ cm^{-3}$)
Original									
All data	381	43	337	1.02	0.06	0.08	0.64	−0.03	−0.04
2009	104	16	80	1.06	0.05	0.06	0.68	−0.03	−0.04
2010	125	11	118	1.25	0.04	0.06	0.93	−0.03	−0.05
2011	152	16	139	0.75	0.08	0.10	0.37	−0.04	−0.03
Modified									
All data	381	43	337	0.54	0.06	0.07	−0.14	−0.02	0.00
2009	104	16	80	0.44	0.04	0.04	−0.08	−0.01	0.01
2010	125	11	118	0.78	0.05	0.03	−0.37	−0.04	0.00
2011	152	16	139	0.30	0.07	0.09	0.01	−0.01	−0.01

simulating the total quantity of evapotranspiration, but inaccurate in simulating the peak values after precipitation or irrigation.

The highest differences between simulated (modified model) and measured actual transpiration fluxes, observed from mid-July and the end of August 2010 (RMSE = 0.78 mm), could be the result of the neglected contribution of transpiration of the water stored in the tree. After any input of water in the soil, even the modified model does not consider the water redistribution processes occurring in the soil, in addition to the tree capacitance effect, taking into account the increasing water stored in the leaves, branches, and trunk of the tree. Regardless, the contribution of the tree capacitance on transpiration fluxes needs a more thorough investigation to further improve the FAO-56 model framework. In addition, the result could possibly be the result of the circumstance that after a prolonged drought period, trees activate the portion of the root system placed outside the soil volume where soil moisture was actually monitored.

In contrast, if comparing the original and the revised version of the model characterized by average RMSE values (all of the data) equal to 1.40 and 0.54 mm, respectively (Table 2), it is evident that for both the simulations the predicted transpiration fluxes are coincidental during the first period of simulation (absence of crop water stress) and become quite different in the subsequent dry periods (Fig. 2). The quickest reductions of actual transpiration fluxes, visible for the original model, are a direct consequence of the adopted linear stress function, detecting a rapid reduction of the K_s coefficient since the initial phase of the crop water stress.

Moreover, during dry periods, despite simulated SWC_s being generally higher than the corresponding measured, the values of actual transpiration were systematically lower.

Table 3 shows the statistical comparison in terms of the student t-test. As can be observed, differences between measured SWC and T_a values and the corresponding estimation by the revised model are statistically not significant ($\alpha = 0.05$) in 2009 and 2011, whereas they are always significantly different when the original model is considered. According to this result, it is evident that the modified model considerably improves the estimation of soil water content and actual transpiration fluxes.

Figs. 3(a–c) shows, from the beginning of July to the end of September each year, the comparison between actual measured cumulative transpiration fluxes, together with the corresponding prediction by the original (light line) and amended (bold line) version of the model. As discussed, except that for a certain underestimation observable since the end of July 2010, compared with the original model, the modified version estimates quite well the cumulative crop water use during the examined periods.

The better performance of simulated transpiration fluxes obtained with the modified model is therefore consistent with the combined effects of the improved SWC estimation and the more adequate schematization of the stress function.

Additional simulations proved that, assuming the depletion fraction p as computed on the basis of experimental SWC^* and SWC_{min}, without modifying the stress function, slightly improved the estimation of soil water contents and actual transpiration fluxes compared with the original version of the model (data not shown), because of the increased total available water and to the reduced slope of the stress function. This result indicated that the effect on simulated variables (SWC and T_a) is primarily the result of the shape of the stress function, more than the choice of SWC^* and SWC_{min}.

To assess the ability of the simulated crop water stress coefficient to explain the actual water stress conditions, Figs. 4(a–c) shows the temporal dynamics of measured relative transpirations and simulated K_s values obtained with the original (light line)

Table 3. Student t-Test Related to T_a and SWC Obtained with Modified and Original Models and Corresponding Critical t-Values

Year	Number of data (N)			Actual transpiration		FDR SWC		TDR SWC	
	T_a	FDR SWC	TDR SWC	Student (t)	t_{crit} ($\alpha = 0.05$)	Student (t)	t_{crit} ($\alpha = 0.05$)	Student (t)	t_{crit} ($\alpha = 0.05$)
Original									
All data	381	43	337	15.57	1.97	4.12	2.02	11.94	1.97
2009	104	16	80	8.49	1.98	2.64	2.13	11.98	1.99
2010	125	11	118	12.4	1.98	3.00	2.23	21.38	1.98
2011	152	16	139	6.91	1.98	2.29	2.13	3.89	1.98
Modified									
All data	381	43	337	5.15	1.97	1.92	2.02	0.29	1.97
2009	104	16	80	1.81	1.98	0.96	2.13	1.72	1.99
2010	125	11	118	6.02	1.98	3.66	2.23	0.63	1.98
2011	152	16	139	0.53	1.98	0.36	2.13	0.70	1.98

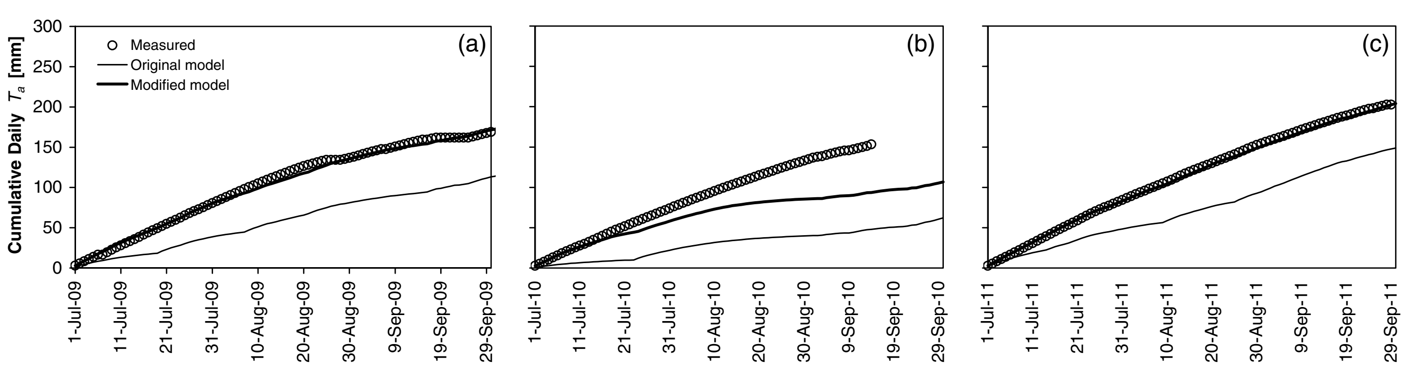

Fig. 3. Comparison between cumulative tree transpiration fluxes simulated by models for (a) 2009; (b) 2010; (c) 2011 seasons and corresponding measured values (white circles)

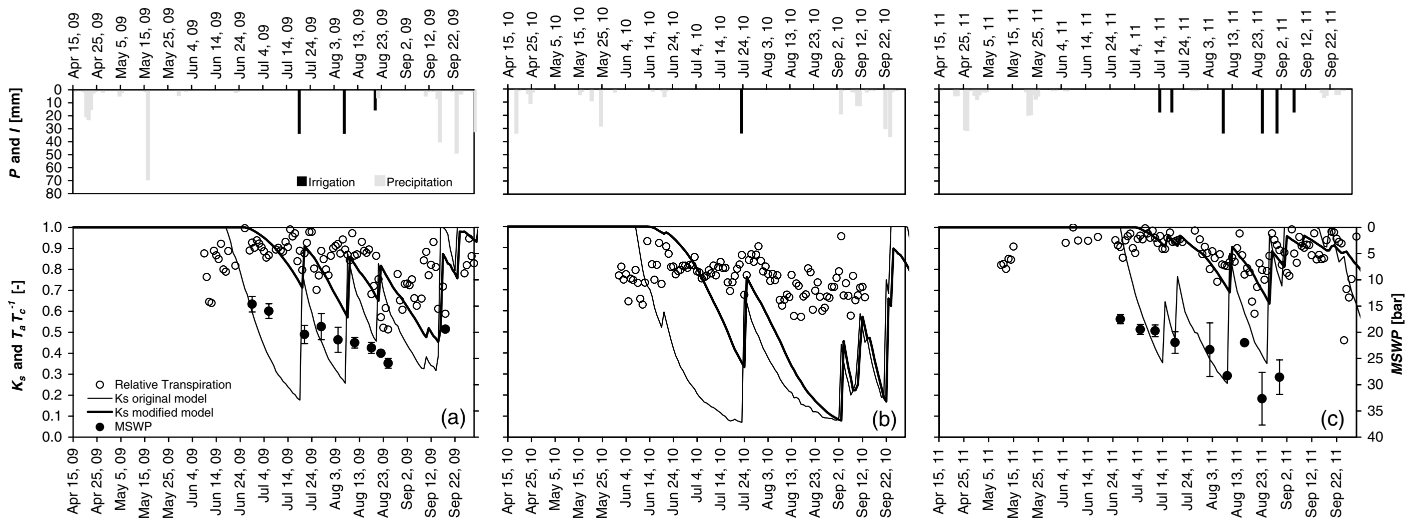

Fig. 4. Temporal dynamic of measured relative transpiration, $T_a T_c^{-1}$, and simulated water stress coefficient, K_s, during (a) 2009; (b) 2010; (c) 2011. Measured midday stem water potentials (MSWP) and total water supplies also shown

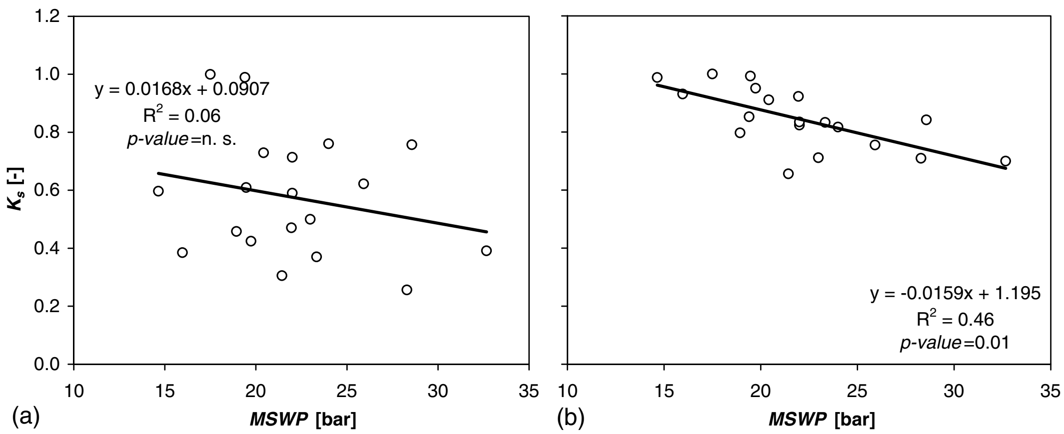

Fig. 5. Relationships between water stress coefficient, K_s, and midday stem water potential, MSWP, in (a) original; (b) modified models

and modified (bold line) model. Midday stem water potentials are also shown in the secondary axis, whereas total water supplies are presented at the top of the figure.

As observed, both models determine a quick increase of the relative transpiration immediately after irrigation, similarly to what was observed for actual transpiration. Even in this case the modified model allows one to better explain the dynamic of relative transpiration, showing a convex curve reflecting the marked tendency of the $K_s(\mathrm{SWC})$ relationship. Conversely, the stress coefficient simulated by the original model systematically underestimates the relative transpiration with an opposite tendency, certainly because of the misrepresentation of the stress function. Additionally, if the amended model allows one to determine K_s values not lower than 0.6, as observed in the field in terms of relative transpiration, with the unmodified model unrealistic lower K_s are displayed, with a minimum of about 0.1. In the same figure the water stress coefficients are observed to follow the general seasonal trend for midday stem water potentials.

Figs. 5(a and b) illustrate the predicted K_s values as a function of MSWPs, respectively, obtained when the original and the modified model are considered. The regression equations, characterized by $R^2 = 0.06$ and 0.46, respectively, are also shown. As observed in the figure, K_s values estimated with the modified model are characterized by a lower variability compared with those evaluated with the original FAO 56 model; furthermore, for the revised model, the fitted regression provides an explanation of the variance of the considered MSWP data set.

This result is in agreement with the relationship experimentally obtained in 2008 using independent measurements of relative transpiration and midday stem water potential (unpublished data), and indicates how the modified model is able to properly reproduce, for the investigated crop, the stress conditions as recognized in the field.

Conclusions

In this paper, an improvement of the FAO-56 spreadsheet program, aimed to consider a more realistic convex shape of the stress function for drought tolerant crops like olive trees, has been proposed and assessed.

The suitability of the amended agro-hydrological model was verified according to soil water content and actual transpiration fluxes measured during the three irrigation seasons of 2009, 2010, and 2011. At the same time, the ability of the model to simulate crop water stress coefficients was also verified on the basis of an independent data set of midday stem water potentials measured in the field.

Compared with the original version, the modified model allows a better modeling of the root water uptake ability and, consequently, can accurately predict the soil water content in the root zone, with differences generally not statistically significant ($\alpha = 0.05$). The assumption of the minimum soil water content measured in the field, in place of the traditionally used wilting point, allowed one to take into account the root ability of olive trees to extract water from the soil.

The amendment of the original model also permitted a considerable enhancement in the estimation of actual transpiration fluxes, as confirmed by the student *t*-test applied for the three investigated seasons. The better performance of simulated fluxes is consistent firstly with the combined effects of the more realistic schematization of the stress function, and secondly with the improved estimation of soil water content thresholds.

The underestimation of actual transpiration fluxes observed in the period from mid-July to the end of August 2010 could be the result of the soil volume explored by the roots and/or the neglected contribution of the tree capacitance, related to the water stored in the leaves, branches, and trunk of the tree. This aspect needs a more thorough investigation to verify the possibility of further improvement to the FAO-56 model.

Acknowledgments

A special thanks to Dr. Pierluigi Crescimanno, manager of the Tenute Rocchetta farm, which hosted the experiments, and for his great sensibility to any subject related to environmental safeguard. Research was carried out in the frame of the PRIN 2010 projects, co-financed by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) and FFR 2012–2013 granted by Università degli Studi di Palermo. Contributions to the manuscript were shared among the authors as follows: Experimental setup, data processing, and final revision of the text were divided equally among the authors; field data collection was handled by G. R.; and text was written by G. R. and G. P.

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