Improvement of FAO-56 model to estimate transpiration fluxes of drought tolerant crops under soil water deficit: An application for olive groves

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Abstract

Agro-hydrological models are considered an economic and simple tool to quantify 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, due to the high number of required variables, simplified models have been proposed to quantify crop water consumes.

The main aim of the paper is to propose an amendment of FAO-56 spreadsheet program in order 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 to the revised model, resulting significantly higher than the corresponding values obtained with the original version.

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 semi-arid 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, Agnese et al., 2013), 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.

FAO Irrigation and Drainage Paper 56 (Allen et al., 1998) provides a comprehensive description of the widely accepted Penman-Monteith method to estimate reference evapotranspiration from standard weather data and also an affordable procedure to compute actual crop evapotranspiration under standard and non-standard (stressed) conditions. A first amendment of the algorithm, was recently proposed by Rallo et al. (2012) for arboreal crops in order 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, more related 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 and in particular on the partition of the components of crop evapotranspiration in semiarid areas, a few studies have been considering 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 linearly dependent on the soil water depletion, in the range between a certain critical value and the wilting point. Actually, 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 also that crop water stress conditions occur for soil matric potentials lower than -0.40 MPa. Moreover, it was showed that the reduction of actual transpiration becomes severe only under extreme water deficit conditions.

The main objective of the paper is to propose an amendment of FAO-56 original spreadsheet program and to assess its suitability to simulate 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 between 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 (*MSWP*) are used to evaluate the ability of simulated stress coefficients to explain the actual crop water stress conditions.

Overview on FAO-56 dual approach model and critical analysis

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:

$$D_i = D_{i-1} - (P_i - RO_i) - I_i + ET_{c,i} + DP_i \qquad (1)$$

where D_i [mm] and D_{i-1} [mm] are the root zone depletions at the end of day i and i-1 respectively, P_i (mm) is the precipitation, RO_i the surface runoff, $ET_{c,i}$ [mm] is the actual evapotranspiration and DP_i [mm] is the 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:

$$TAW = 1000\left(SWC_{fc} - SWC_{wp}\right)Z_r \qquad (2)$$

where SWC_{fc} [cm^3 cm^{-3}] and SWC_{wp} [cm^3 cm^{-3}] are the soil water contents at field capacity and wilting point respectively and Z_r [m] is the depth of the root system.

In absence of water stress (potential condition), the crop potential evapotranspiration ET_c is obtained 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 FAO 56 paper, splits the single K_c factor in 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 to a reduction factor, K_s, variable between 0 and 1. The reduction factor can be express by:

$$K_s = \frac{TAW - D_i}{TAW - RAW} \qquad (3)$$

where *RAW* [mm] is the readily available water, that can be obtained multiplying *TAW* to 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 *RAW* ($D_i > RAW$), the reduction coefficient K_s is lower than 1, whereas for $D_i \leq RAW$ results K_s=1. Values of *p*, valid for different crops, are proposed in the original publication (Allen at al., 1998). Considering that the term *p* depends of 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 maximum. Dryer the soil surface, 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 considered proportional to the amount of water in the soil top layer, or:

$$K_e = MIN \begin{Bmatrix} K_r * \left(K_{c\_\max} - K_{cb} \right) \\ \\ f_{ew} * K_{c\_\max} \end{Bmatrix} \qquad (4)$$

where K_r is a 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} is the maximum value of K_c following rain or irrigation; K_{c_max} represents an upper limit of evapotranspiration fluxes from any cropped surface, whereas the term 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:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \qquad (5)$$

where $D_{e,i-1}$ is cumulative depth of evaporation (depletion) from the soil surface layer at the end of (i-1)th day [mm], *TEW* [mm] is the 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 $TEW = 1000(SWC_{fc} - 0.5SWC_{wp})Z_e$, where Z_e is usually assumed equal to 0.10-0.15 m. On the other hand, *REW* can be estimated according to soil texture (Allen et al., 1998).

Buckets 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 determine 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 *Ks* 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 experimental farm “Tenute Rocchetta”, located in Castelvetrano (Sicily, UTM EST: 310050, NORD: 4168561). The farm, with an extension of about 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 years old olive trees, planted on a regular grid of 8 x 5 m (250 plants/ha); the mean canopy height is about 3.7 m and the average fraction of vegetation cover is about 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 USDA classification, is silty clay loam.

Standard meteorological data (incoming short-wave solar radiation, air temperature, air humidity, wind speed and rainfall) were hourly collected by SIAS (Servizio Informativo Agrometeorologico Siciliano), with standard equipments installed about 500 m apart from the experimental field. Net radiation *R* and its components were measured with a 4-component net radiatiometer (NR01, Hukeseflux). According to ASCE-ESRI, the standardized Penman-Monteith method (Allen at et al., 2008) was used to calculate atmospheric water demand.

A preliminary investigation on the root spatial distribution was carried out in order to identify the soil volume within which the highest root density is localized and where most of 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 practised 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 the 2011.

Soil and crop water status measurements

During the investigation periods, soil water contents were measured with Time Domain Reflectometry (TDR 100, Campbell Inc.) and Frequency Domain Reflectometry (FDR, Diviner 2000, Sentek) probes. On the basis of the results of Rallo and Provenzano (2013), the soil volume in which most of the root absorption occurs have been considered, in order 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 where 80% of 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 m, 2.0 m and 2.5 m from the plant and the second along a parallel direction, at a distance of 0.50 m from the first and about 1.0 m and 2.50 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 of the FDR access tubes, but opposite side of the plant, in the layer 10-30 cm, 35-55 cm and 60-80 cm. Values of soil water contents measured with FDR and TDR systems were then averaged in order 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 to neglect the tree capacitance. Daily transpiration depth [mm d^{-1}] was obtained dividing the daily flux [l d^{-1}] for the pertinence area of the plant, equal to 40 m^2. Then, in order 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, *LAI* (m^2 m^{-2}), measured in field, and the average value, LAI_p (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 e Jarvis (1982).

Amendment of the FAO-56 model and parameterization of soil and crop

FAO 56 model has been applied i) in the original form and ii) 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, SWC_{min}, were experimentally determined.

In the first case, the model parameter p was assumed equal to 0.65, as indicated in table 22 of the original paper, corresponding for the investigated soil to $SWC^*=0.20$, 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 MPa and -1.50 MPa respectively.

In the second case, in order 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}:

$$Ks = 1 - \frac{e^{D_{rel}\, f_s} - 1}{e^{f_s} - 1} \qquad (6)$$

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

Relative depletion can be determined as:

$$D_{rel} = \frac{SWC^* - SWC}{SWC^* - SWC_{\min}} \qquad (7)$$

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

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

Figure 1 – Water stress functions for table olive orchards, as implemented in the spreadsheet

The shape of the considered function evidences that the water stress models is convex and demonstrates that water stress becomes 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} was assumed to correspond to a matric potential of -0.4 MPa representing the thresholds 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).

On the other side, 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 allowed 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 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 et al., 1999).

The average value of basal crop coefficient, in the mid and late stage seasons, was considered equal to 0.60, as recommended from 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 investigated years, from DOY 105 to DOY 273. For all the investigated periods, SWC_{fc} equal to 0.33 m^3 m^{-3} was considered as initial condition, as a consequence of the copious precipitation occurred in the decade antecedent mid of April each year.

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

Tab. 1 –Values of the variables used for the simulations carried out with the original and modified FAO 56 model.

Performance of the models

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

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

$$MBE = \frac{1}{N}\sum_{i=1}^{N} d_i \qquad (9)$$

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

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

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

To determine if 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 α=0.05 was assumed.

Results and discussion

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

As can be observed, compared to the original version, the amended model, provides better estimation in terms of either actual transpiration fluxes and soil water contents.

The statistical comparison, express in term of *RMSE* and *MBE* associated to *SWC* and T_a simulated by modified and original models are presented in table 2.

Fig. 2a-i - Temporal dynamic of observed and simulated *SWCs* and T_a fluxes during 2009, 2010 and 2011. Potential transpiration fluxes and total water supplies are also shown

Tab. 2 – *RMSEs* and *MBEs* associated to *SWC* and actual T_a simulated with the original and modified models

A substantial agreement between measured average soil water contents in the root zone and the corresponding values, simulated with the revised model, is generally observed, with a root mean square error variable 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* variable 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 fig. 2d-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 if considering all 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, due to 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 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 of July and end of August 2010 (*RMSE*=0.78 mm), could be due to the neglected contribute to transpiration of the water stored in the tree. After any input of water in the soil, in fact, even the modified model does not consider the water redistribution processes occurring in the soil, as well as the tree capacitance effect, taking into account the increasing water stored in the leaves, branches and trunk of the tree. Anyway, contribution of the tree capacitance on transpiration fluxes needs a more specific investigation, in order to further improve the FAO-56 model framework. In addition, the result could be also due to the circumstance that after a prolonged drought period, it is possible that trees activate the portion of the root system placed outside the soil volume where soil moisture was actually monitored.

On the other hands, if comparing the original and the revised version of the model characterized of average *RMSE* values (all the data) equal to 1.40 mm and 0.54 mm respectively (table 2), it is evident that for both the simulations the predicted transpiration fluxes are coincident 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 were generally higher than the corresponding measured, the values of actual transpiration resulted systematically lower.

Table 3 shows the statistical comparison in terms of Student-t test. As can be observed, differences between measured *SWC* and T_a values and the corresponding estimated by the revised model are statistically not significant (α=0.05) in 2009 and 2011, while 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.

Tab. 3 – Student-t related to T_a and *SWC* obtained with the original and modified model. The corresponding critical t-values are also shown

Fig. 3a-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 predicted 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 to the original model, the modified version estimates quite well the cumulative crop water consumes during the examined periods.

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

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 evidenced that, assuming the depletion fraction *p*, as computed on the basis of experimental SWC^* and SWC_{min}, without modifying the stress function, slightly improve the estimation of soil water contents and actual transpiration fluxes compared to the original version of the model (data not showed), due to the increased total available water and to the reduced slope of the stress function. This results indicated that the impact on simulated variables (*SWC* and T_a) is mainly due to the shape of the stress function, more than the choice of SWC^* and SWC_{min}.

In order to assess the ability of simulated crop water stress coefficient to explain the actual water stress conditions, fig. 4a-c shows the temporal dynamic of measured relative transpirations and simulated K_s values obtained with the original (light line) 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.

Fig. 4a-f - Temporal dynamic of measured relative transpiration, T_a T_c^{-1}, and simulated water stress coefficient, K_s, during 2009, 2010 and 2011. Measured midday stem water potential (MSWP) and total water supply are also shown

As can be observed, both the models determines a quick increasing of the relative transpiration immediately after irrigations, similarly to what observed for actual transpiration. Even in this case the modified model allows to better explain the dynamic of relative transpiration, showing a convex curve reflecting the marked tendency of the $K_s(SWC)$ relationship. Conversely, the stress coefficient simulated by the original model systematically underestimates the relative transpiration with an opposite tendency, certainly due to the misrepresentation of the stress function. Additionally, if the amended model allows determining 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 it can be evidenced that the water stress coefficients follow the general seasonal trend observed for midday stem water potentials.

Fig. 5a-b illustrates 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 can be observed in the figure, K_s values estimated with the modified model are characterized by a lower variability compared to those evaluated with the original FAO 56 model; furthermore, for the revised model, the fitted regression allows to explain the variance of the considered *MSWP* data set.

Fig. 5a-b - Relationships between water stress coefficient, K_s, and midday stem water potential, *MSWP*, in the original (left) and modified (right) FAO 56 model

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

Conclusions

In the paper, an improvement of 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 contents and actual transpiration fluxes measured during the three irrigation seasons 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 dataset of midday stem water potentials measured in the field.

Compared to the original version, the modified model allows a better modelling of the root water uptake ability and consequently to predict quite well the soil water contents in the root zone, with differences generally not statistically significant (α=0.05). In fact, the assumption of the minimum soil water content measured in the field, in place of the traditionally used wilting point, allowed taking 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 of July to the end of August 2010 could be due to the soil volume explored by the roots and/or to the neglected contribute of the tree capacitance, related to the water stored in the leaves, branches and trunk of the tree. This aspect needs a more specific investigation in order to verify the possibility of a further improvement of FAO-56 model.

Acknowledgements

A special thanks to Dr. Pierluigi Crescimanno, manager of the farm “Tenute Rocchetta” hosting the experiments, for his great sensibility to any subject related to environmental safeguard.

Research was carried out in the frame of the projects PRIN 2010 co-financed by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) and FFR 2012-2013 granted by Università degli Studi di Palermo.

The contribution to the manuscript has to be shared between authors as following: Experimental set-up, data processing and final revision of the text have to be divided equally between Authors. Field data collection was cared by G. Rallo. Text was written by G. Rallo and G. Provenzano.

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Table 1
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Tab. 1 –Values of the variables used for the simulations carried out with the original and modified FAO 56 model.

Variables	Original model			Modified model		
	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 day of the year at time of planting, J_{plant} [-]	105	105	105	105	105	105
Number of day of the year at beginning of development period, J_{dev} [-]	135	135	135	135	135	135
Number of day of the year at beginning of midseason period, J_{mid} [-]	225	225	225	225	225	225
Number of day of the year at beginning of late season period, J_{late} [-]	285	285	285	285	285	285
Number of day 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* [m]	3.0	3.0	3.0	3.0	3.0	3.0
Minimum rooting depth, Z_r [m]	0.75	0.75	0.75	0.75	0.75	0.75
Maximum rooting depth, Z_r [m]	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

n.u.= not used in the simulations

Table 2
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Tab. 2 – *RMSEs* and *MBEs* associated to soil water contents and actual transpiration fluxes simulated with the modified and original models

	Year	Number of data (N)			Root Mean Sqare Error (RMSE)			Mean Bias Error (MBE)		
		Actual Transp.	FDR SWC	TDR SWC	Actual Transp.	FDR SWC	TDR SWC	Actual Transp.	FDR SWC	TDR SWC
		[-]	[-]	[-]	[mm]	[cm^3 cm^{-3}]	[cm^3 cm^{-3}]	[mm]	[cm^3 cm^{-3}]	[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

Table 3
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Tab. 3 – Student-t related to *T_a* and *SWC* obtained with the modified and original model. The corresponding critical *t* -values are also shown

	Year	Number of data (N)			Actual Transp.		FDR SWC		TDR SWC	
		Ta	FDR SWC	TDR SWC	*Student t*	*t_{crit} (a=0.05)*	*Student t*	*t_{crit} (a=0.05)*	*Student t*	*t_{crit} (a=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	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	0.7	1.98

Figure 1
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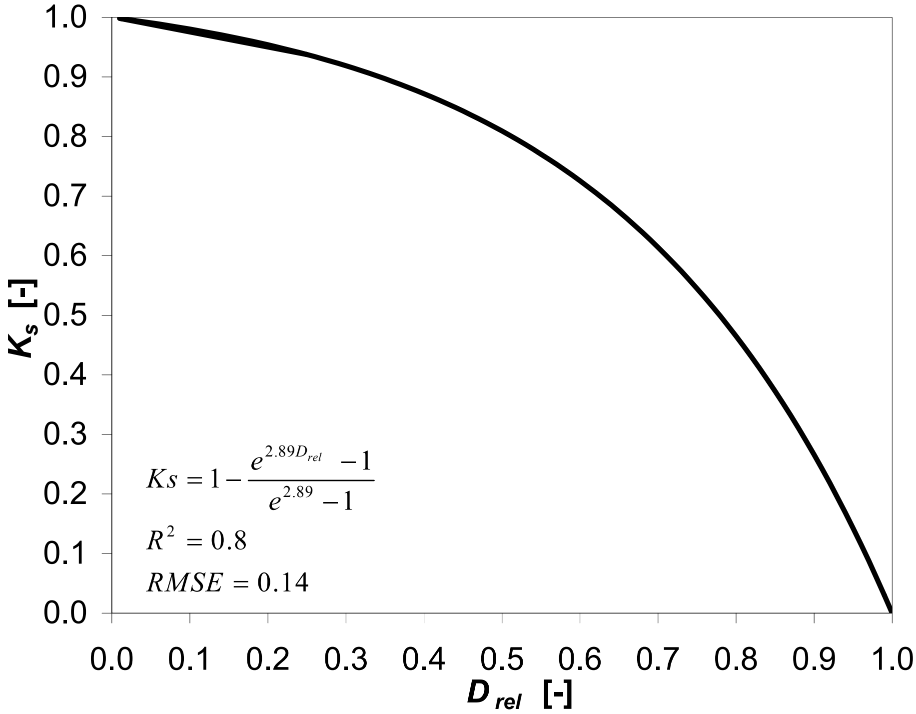

Figure 2
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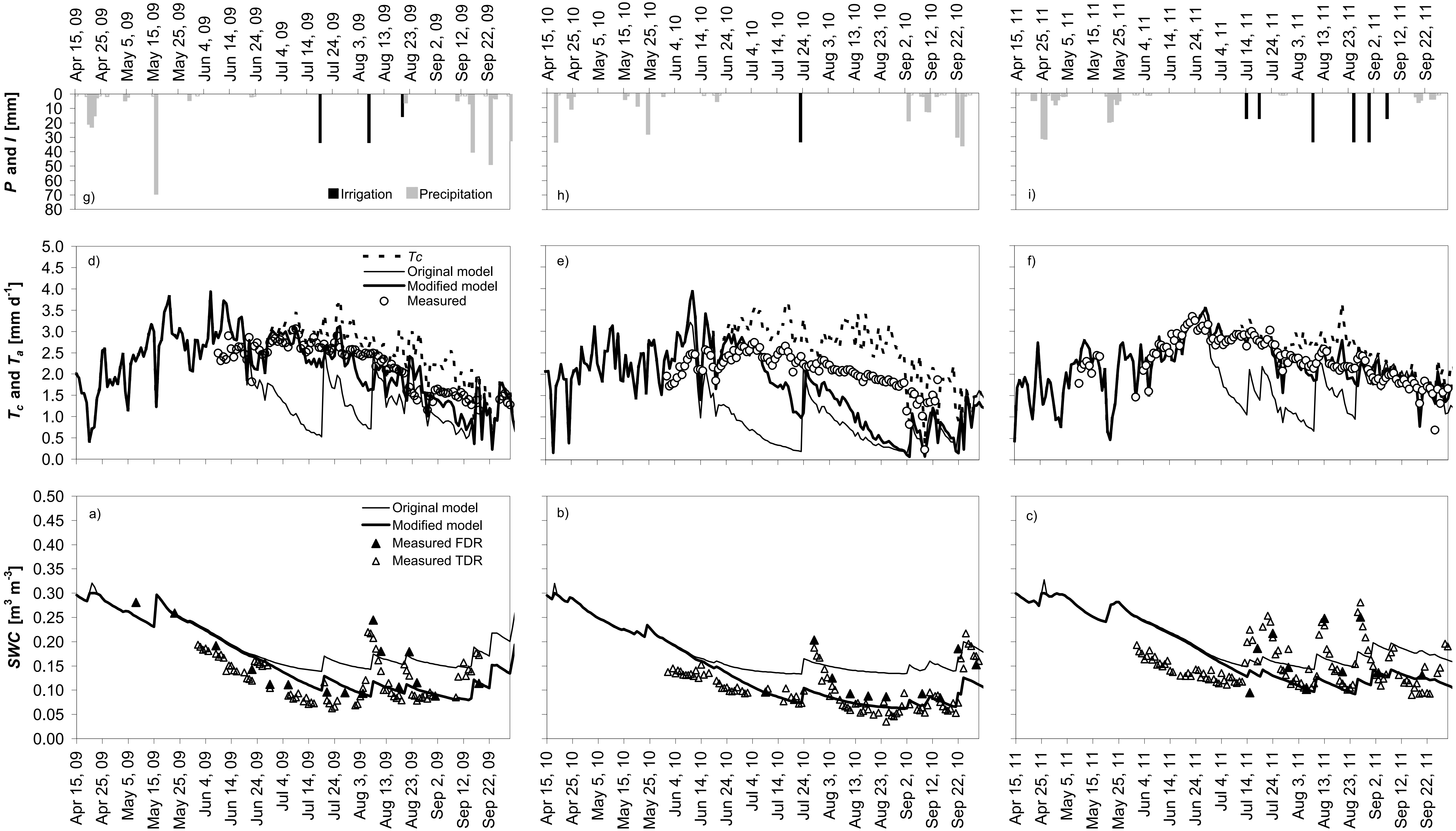

Figure 3
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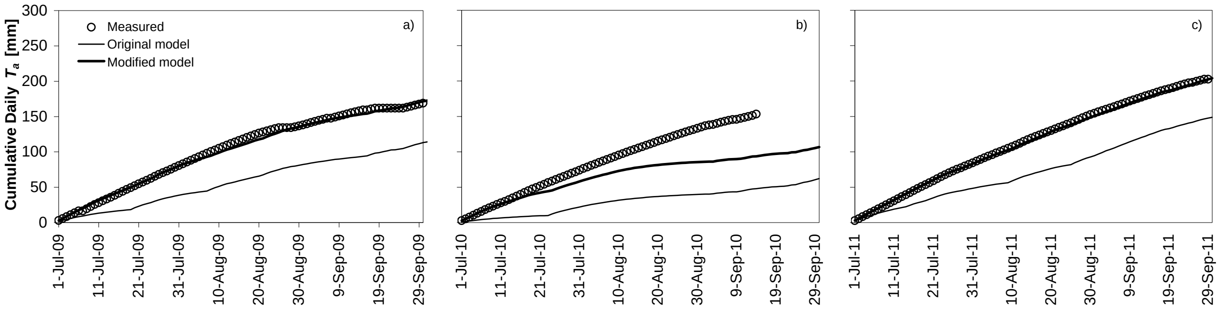

Figure 4

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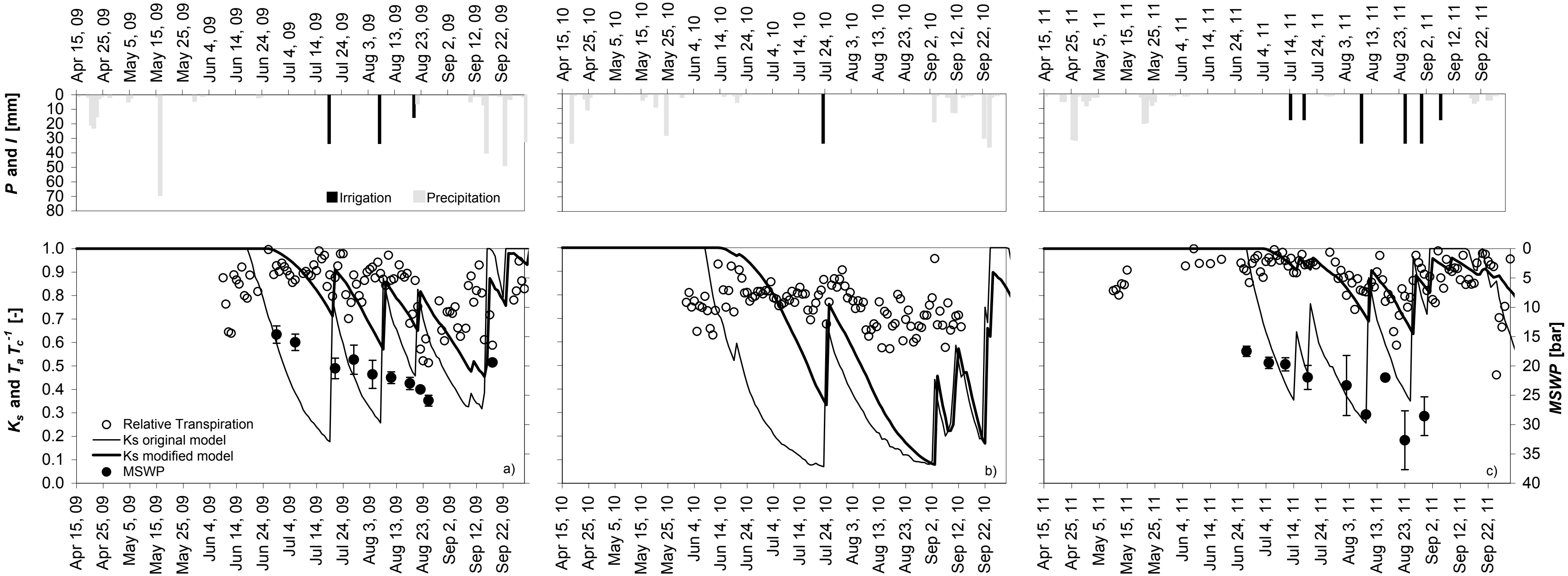

Figure 5
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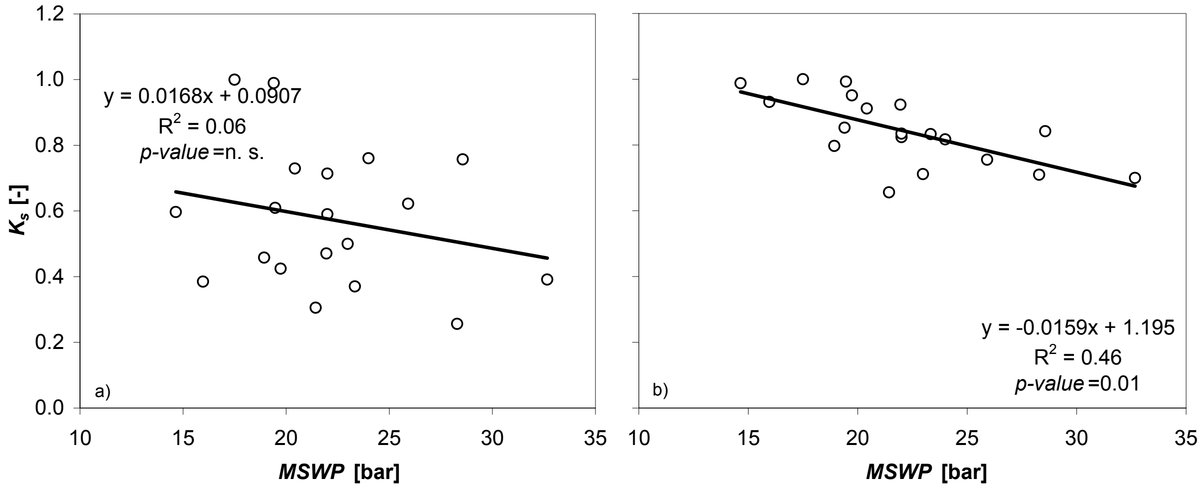

Figure Caption List

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

Fig. 2a-i - Temporal dynamic of observed and simulated soil water content and actual transpiration fluxes during 2009, 2010 and 2011. Potential transpiration and total water supplies are also shown

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

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

Fig. 5a-b - Relationships between water stress coefficient, K_s, and midday stem water potential, *MSWP*, in the original (left) and modified (right) model