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.

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

73 shape of the K_s relationship and also that crop water stress conditions occur for soil matric
74 potentials lower than -0.40 MPa. Moreover, it was showed that the reduction of actual
75 transpiration becomes severe only under extreme water deficit conditions.
76 The main objective of the paper is to propose an amendment of FAO-56 original spreadsheet
77 program and to assess its suitability to simulate table olive (*Olea europaea* L.) water
78 requirement under soil water deficit conditions. In particular, a more realistic shape of the
79 water stress function, valid for the considered crop, is introduced into the model in place of
80 the original liner function; the validation is firstly carried out through the comparison between
81 measured and simulated soil water contents (*SWCs*) and actual transpiration fluxes (T_a).
82 Outputs of the amended model are then compared with those obtained with the original
83 version. Finally, the measured relative transpirations and midday stem water potentials
84 (*MSWP*) are used to evaluate the ability of simulated stress coefficients to explain the actual
85 crop water stress conditions.

Overview on FAO-56 dual approach model and critical analysis

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

89 $$D_i = D_{i-1} - (P_i - RO_i) - I_i + ET_{c,i} + DP_i$$

90 (1)

91 where D_i [mm] and D_{i-1} [mm] are the root zone depletions at the end of day i and $i-1$
92 respectively, P_i (mm) is the precipitation, RO_i the surface runoff, $ET_{c,i}$ [mm] is the actual
93 evapotranspiration and DP_i [mm] is the deep percolation of water moving out of the root
94 zone.

95 The domain of the depletion function, D_i, is between 0, which occurs when the soil is at the
96 field capacity, and a maximum value, corresponding to the total plant available water, *TAW*
97 [mm], obtained as:

98 $$TAW = 1000\left(SWC_{fc} - SWC_{wp}\right)Z_r$$ (2)

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

101 In absence of water stress (potential condition), the crop potential evapotranspiration ET_c is
102 obtained multiplying the dual crop coefficients ($K_{cb} + K_e$) and the Penman-Monteith reference
103 evapotranspiration rate, ET_0, (Allen et al., 1998). In particular the "dual crop coefficients
104 approach", as explained in FAO 56 paper, splits the single K_c factor in two separate terms, a

105 basal crop coefficient, K_{cb}, considering the plant transpiration and a soil evaporation
106 coefficient K_e.

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

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

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

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

$$K_e = MIN \left\{ \begin{array}{l} K_r * \left(K_{c\_max} - K_{cb} \right) \\ \\ f_{ew} * K_{c\_max} \end{array} \right\} \qquad (4)$$

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

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

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

133 where $D_{e,i-1}$ is cumulative depth of evaporation (depletion) from the soil surface layer at the

134 end of (i-1)th day [mm], *TEW* [mm] is the total evaporable water from an effective depth Z_e

135 of soil surface subject to drying, and *REW* [mm] is the readily evaporable water, representing

136 the maximum depth of water that can evaporate from the topsoil layer without restrictions.

137 When *TEW* is unknown, it can be estimated as *TEW* $=1000(SWC_{fc}- 0.5SWC_{wp})Z_e$, where Z_e is

138 usually assumed equal to 0.10-0.15 m. On the other hand, *REW* can be estimated according to

139 soil texture (Allen et al., 1998).

140 Buckets models are very sensitive to the rooting depth parameter, Z_r, directly influencing the

141 ability of the plant to extract water. Errors in its determinations determine an incorrect

142 estimation of soil water stress coefficient and, as indicated by Er-Raki et al. (2008), the values

143 of simulated evapotranspiration increase with increasing Z_r. In fact, higher Z_r causes

144 increments of *TAW* within the root zone and, according to eq. 3, leads to higher *Ks* values.

145

Materials and methods

147 Investigations were carried out during irrigation seasons 2009, 2010 and 2011 (from April 15,

148 DOY 105 to September 30, DOY 273) in the experimental farm "Tenute Rocchetta", located

149 in Castelvetrano (Sicily, UTM EST: 310050, NORD: 4168561). The farm, with an extension

150 of about 13 ha, is mostly cultivated with table olive grove (*Olea europaea* L., var. Nocellara

151 del Belice), representing the main crop in the surrounding area. The experimental plot is

152 characterized by 17 years old olive trees, planted on a regular grid of 8 x 5 m (250 plants/ha);

153 the mean canopy height is about 3.7 m and the average fraction of vegetation cover is about

154 0.35. Irrigation is practiced by means of pipelines with on line emitters installed along the

155 plant rows. Each plant was irrigated with four 8 l/h emitters. Soil textural class, according

156 USDA classification, is silty clay loam.

157 Standard meteorological data (incoming short-wave solar radiation, air temperature, air

158 humidity, wind speed and rainfall) were hourly collected by SIAS (Servizio Informativo

159 Agrometeorologico Siciliano), with standard equipments installed about 500 m apart from the

160 experimental field. Net radiation *R* and its components were measured with a 4-component

161 net radiatiometer (NR01, Hukeseflux). According to ASCE-ESRI, the standardized Penman-

162 Monteith method (Allen at et al., 2008) was used to calculate atmospheric water demand.

163 A preliminary investigation on the root spatial distribution was carried out in order to identify

164 the soil volume within which the highest root density is localized and where most of water

165 uptake processes occur. A more detailed description of the soil physical properties and the

166 root distribution is presented and discussed in Rallo and Provenzano (2013).

167

168   Irrigation scheduling followed the ordinary management practised in the surrounding area.

169   The total irrigation depth provided by the farmer was equal to 80 mm in 2009, 33 mm in 2010

170   and 150 mm in the 2011.

171   **Soil and crop water status measurements**

172   During the investigation periods, soil water contents were measured with Time Domain

173   Reflectometry (TDR 100, Campbell Inc.) and Frequency Domain Reflectometry (FDR,

174   Diviner 2000, Sentek) probes. On the basis of the results of Rallo and Provenzano (2013), the

175   soil volume in which most of the root absorption occurs have been considered, in order to

176   install the soil moisture probes and to dispose of a representative measure of the average SWC

177   in the entire system (Xiloyannis et al., 2012). In particular, the soil volume where 80% of

178   roots are localized, can be assumed as a parallelepiped with a length equal to the tree spacing

179   (5.0 m), a width of 1.5 m and a depth of 0.75 m. Referring to this soil volume, spatial and

180   temporal variability of soil water contents was monitored, from the soil surface to a depth of

181   100 cm, using a FDR probe. Five access tubes were installed along two parallel directions, the

182   first below the irrigation pipeline, at distances of 1.0 m, 2.0 m and 2.5 m from the plant and

183   the second along a parallel direction, at a distance of 0.50 m from the first and about 1.0 m

184   and 2.50 m from the plant. In this way it was possible to take into account the spatial

185   variability of soil water content after irrigation. Additional measurements of soil water

186   contents were carried out using nine TDR probes connected to a multiplexer. The probes,

187   having a length of 20 cm, were installed below the irrigation pipeline, at the same distances of

188   the FDR access tubes, but opposite side of the plant, in the layer 10-30 cm, 35-55 cm and 60-

189   80 cm. Values of soil water contents measured with FDR and TDR systems were then

190   averaged in order to determine, for each measurement day, a single value of SWC

191   representative of the soil layer where most of the root absorption takes place.

192   Transpiration fluxes were monitored on three consecutive trees, selected within the field

193   according to their trunk diameter, so that they can be considered representative of the grove,

194   using standard sap flow sensors (Thermal Dissipation Probes, Granier, 1987). For each plant,

195   two probes were installed on the north side of the trunk and then insulated, to avoid the direct

196   sun exposure. The measurements acquired by the two sensors were then averaged. The central

197   plant was the same in which $SWCs$ were measured.

198   Daily values of actual transpiration were obtained by integrating the sap flux, under the

199   hypothesis to neglect the tree capacitance. Daily transpiration depth [mm d^{-1}] was obtained

200   dividing the daily flux [l d^{-1}] for the pertinence area of the plant, equal to 40 m^2. Then, in

201 order to evaluate a representative value of the stand transpiration referred to the entire field, it

202 was necessary to up-scale the plant fluxes by considering, as a proximal variable, the ratio

203 between the average Leaf Area Index, LAI (m^2 m^{-2}), measured in field, and the average value,

204 LAI_p (m^2 m^{-2}), measured on the plants in which sap fluxes were monitored.

205 In the same trees selected for transpiration measurements, midday stem water potentials

206 ($MSWP$) were measured in 2009 and 2011 by using a pressure chamber (Scholander et al.,

207 1965), according to the protocol proposed by Turner e Jarvis (1982).

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

209 FAO 56 model has been applied i) in the original form and ii) in its amended version, in

210 which the stress function, the threshold value of the soil water content below which water

211 stress occurs, SWC^*, and the minimum seasonal value of soil water content recognized in the

212 field, SWC_{min}, were experimentally determined.

213 In the first case, the model parameter p was assumed equal to 0.65, as indicated in table 22 of

214 the original paper, corresponding for the investigated soil to SWC^*=0.20, whereas SWC_{fc} and

215 SWC_{wp} were considered equal to 0.33 and 0.13, determined according to the soil water

216 retention curve, for matric potentials of -0.33 MPa and -1.50 MPa respectively.

217 In the second case, in order to consider a more realistic water stress response of olive crops,

218 the original function, as implemented in the model, was modified according to the

219 relationship proposed by Steduto et al., 2009, in which K_s is a function of the relative

220 depletion, D_{rel}:

221 $$Ks = 1 - \frac{e^{D_{rel} f_s} - 1}{e^{f_s} - 1} \qquad (6)$$

222 where f_s is a fitting parameter characterizing the shape of the stress function. The value of f_s

223 was assumed equal to 2.89 as experimentally determined by Rallo and Provenzano (2013).

224 Relative depletion can be determined as:

225 $$D_{rel} = \frac{SWC^* - SWC}{SWC^* - SWC_{min}} \qquad (7)$$

226 in the domain of soil water contents determining stress conditions for the crop

227 ($SWC_{min}<SWC<SWC^*$).

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

229
230 **Figure 1 – Water stress functions for table olive orchards, as implemented in the**
231 **spreadsheet**
232
233

234 The shape of the considered function evidences that the water stress models is convex and
235 demonstrates that water stress becomes more and more severe at decreasing soil water status
236 (D_{rel} tending to 1); therefore, the reduction of actual transpiration is critical only for the most
237 extreme water stress conditions. Moreover, the modified crop water stress function allows
238 smoothing the unrealistic angular point indicating, in the K_s linear relationship, the passage
239 from no-water stress to water stress conditions.

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

244 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},
245 represents the minimum soil water content measured during the investigated seasons. The
246 choice to consider SWC_{min} as the minimum seasonal value of soil water content recognized in
247 the field and not the soil wilting point, as traditionally used for most crops, followed the
248 suggestion of Ratliff et al., 1983 and, more recently, of Pellegrino et al. (2006). This
249 assumption allowed to consider the strong ability of olive trees to extract water from the soil
250 even below the soil wilting point and consequently a more coherent evaluation of the crop
251 water availability (Lacape et al., 1998).

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

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

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

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

264

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

267

268 **Performance of the models**

269 The performance of the models was evaluated by the root mean square error (RMSE), and the

270 mean bias error (MBE), defined as:

271 $$RMSE = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N} d_i^2\right)} \qquad (8)$$

272 $$MBE = \frac{1}{N}\sum_{i=1}^{N} d_i \qquad (9)$$

273 where N is the number of measured data, d_i is the difference between predicted and measured

274 values (Kennedy and Neville, 1986).

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

276 $$t = \sqrt{\frac{(N-1)MBE^2}{RMSE^2 - MBE^2}} \qquad (10)$$

277 To determine if the differences between measured and simulated soil water contents are

278 statistically significant, the absolute value of the calculated t must be less than the critical t

279 value (t_{crit}), for a fixed significance level. In this analysis, a significance level α=0.05 was

280 assumed.

281

282 # Results and discussion

283 Fig. 2 shows the temporal dynamic of measured $SWCs$ during the investigation periods 2009,

284 2010 and 2011 (2a-c), as well as the estimated potential crop transpiration (dashed line), T_c,

285 and the measured actual transpiration, T_a, in the same time intervals (2d-f). In addition the

286 figure displays the corresponding simulation results obtained by considering the original

287 (light line) and the modified (bold line) versions of the model. At the top of the figure the

288 water supplies (precipitation and irrigation) are also shown.

289 As can be observed, compared to the original version, the amended model, provides better

290 estimation in terms of either actual transpiration fluxes and soil water contents.

291 The statistical comparison, express in term of $RMSE$ and MBE associated to SWC and T_a

292 simulated by modified and original models are presented in table 2.

293

294 **Fig. 2a-i - Temporal dynamic of observed and simulated $SWCs$ and T_a fluxes during**
295 **2009, 2010 and 2011. Potential transpiration fluxes and total water supplies are also**
296 **shown**

297

298

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 ($\alpha=0.05$). 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.

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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

**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

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
Click here to download Figure: FIG-1.pdf
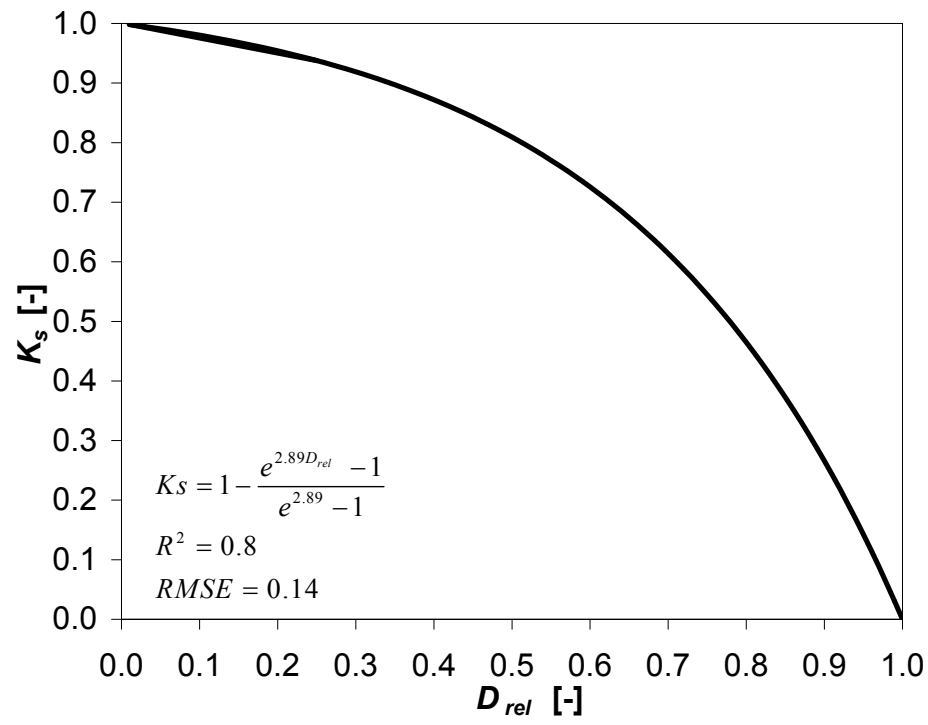
$$Ks = 1 - \frac{e^{2.89 D_{rel}} - 1}{e^{2.89} - 1}$$

$$R^2 = 0.8$$

$$RMSE = 0.14$$
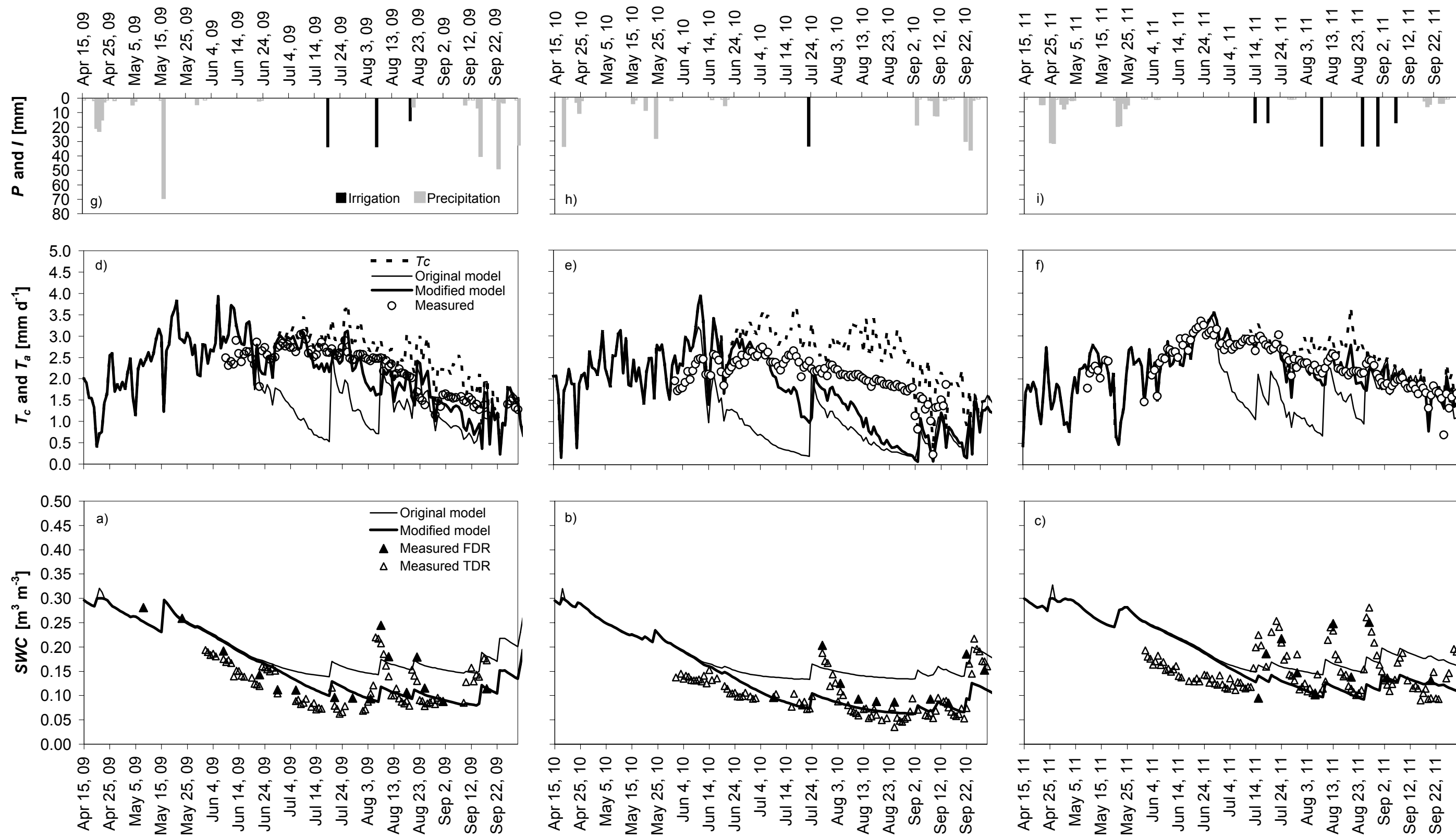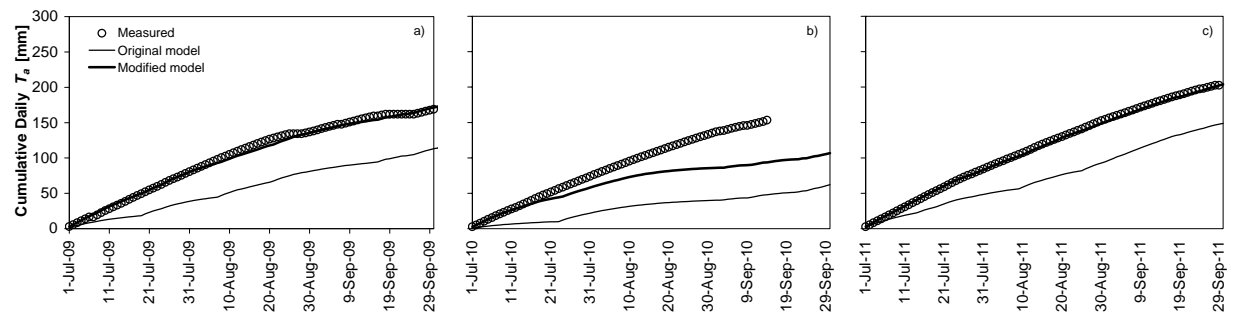
Figure 2

Figure 3

Figure 4
[Click here to download Figure: FIG-4.pdf](#)

a)
$y = 0.0168x + 0.0907$
$R^2 = 0.06$
$p\text{-}value =$ n. s.

b)
$y = -0.0159x + 1.195$
$R^2 = 0.46$
$p\text{-}value =$ 0.01
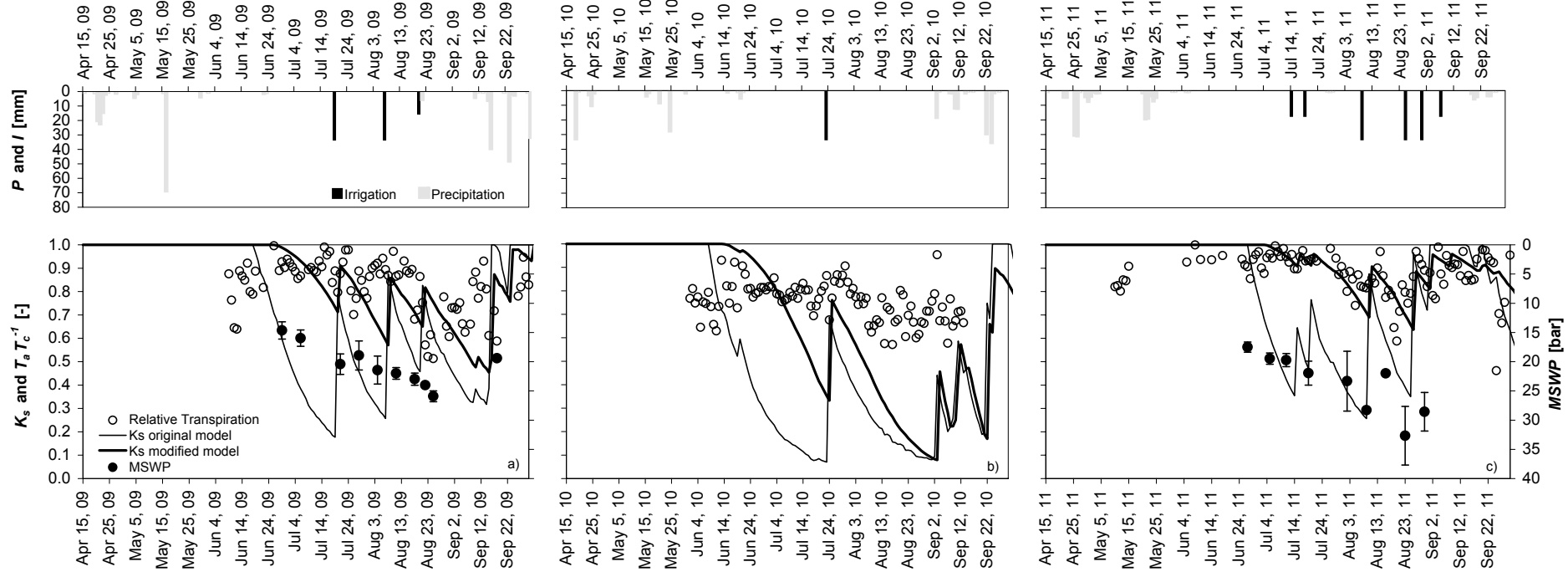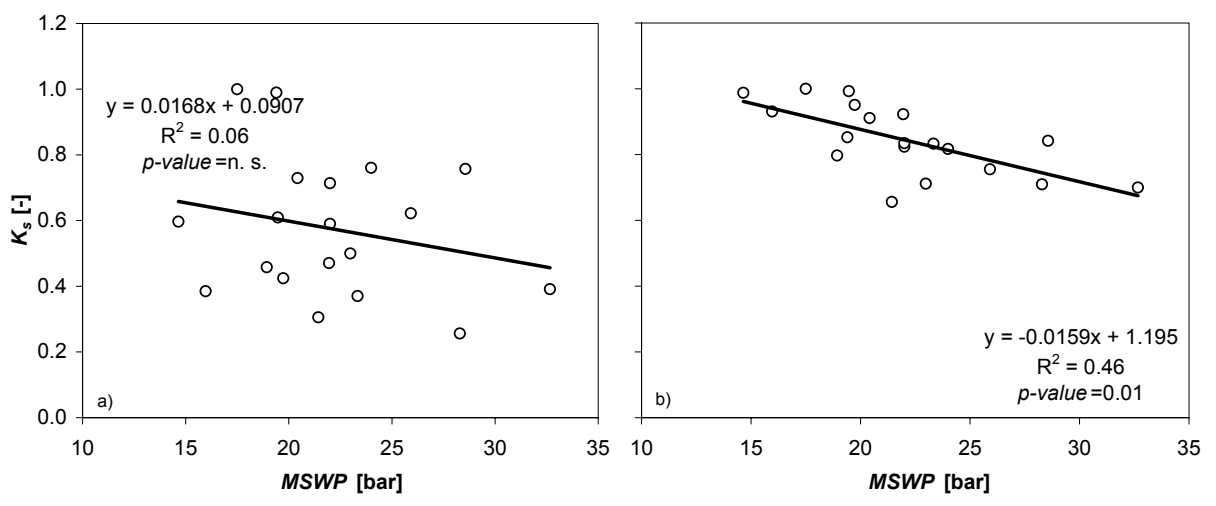
Figure Caption List

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