Predicting soil and plant water status dynamic in olive orchards under different irrigation systems with Hydrus-2D: Model performance and scenario analysis

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Abstract

The paper analyzes the performance of Hydrus-2D model to simulate the dynamic of soil water contents and transpiration fluxes in an olive orchard in which two different irrigation systems were used in 2011 and 2012. Secondly, the relationship between midday stem water potential, *MSWP*, and relative transpiration (ratio between simulated actual and maximum crop transpiration), K_s, was identified with the aim to use the model for crop water status predictions. Model validation was carried out based on the comparison between simulated and measured soil water contents at different points of soil domain, as well as between simulated root water uptake and transpiration fluxes measured with sap flow sensors. The latter were examined under the hypothesis to neglect tree capacitance and hence the contribute of water stored in leaves, branches and trunk of the tree to transpiration fluxes. Finally, a scenario analysis was carried

out for irrigation management purposes, by considering the level of crop water stress achieved in the different phases of the vegetative growth.

Data used to parametrize the model were acquired in a commercial farm located in South-West of Sicily, in an area where olive represents the main orchard crop. Preliminary experiments allowed parametrizing soil hydraulic and root density distribution functions in the soil domain of a single tree. During the first year irrigation water was applied with a drip lateral placed along the plant row, whereas in the second year by means of a network of emitters laid on the soil and covering the entire surface dominate by a plant. Soil water contents at different depths and distances from the plant row were monitored by a Frequency Domain Reflectometry (*FDR*) sensor, whereas sap flow velocity by Thermal Dissipation Probes (*TDP*). The latter then allowed estimating transpiration fluxes based on the measured conducting sapwood. Moreover, in 2011 crop water status was monitored according to *MSWP* measured roughly weekly, with a Scholander chamber.

The results evidenced that active roots ($d<2.0$ mm) were mainly detected along the tree row where is installed the drip irrigation pipe, with concentrations that tended to decrease at increasing depth and with the distance from the plant row. It was demonstrated that Hydrus-2D model is generally able to reproduce the trends of measured soil water contents at different distances and depths from the plant row with *RMSE* equal to 0.04 cm^3 cm^{-3} in 2011 and 0.09 cm^3 cm^{-3} in 2012, because of the inadequate schematization of the root system, that could have changed according to the different irrigation system. Moreover, the model was also suitable to estimate actual transpiration with *RMSE* values, in the two years, of 0.09 and 0.05 mm. It was also observed that measured *MSWPs* are linearly correlated to the ratio between actual and maximum transpiration; under the examined conditions in fact, reductions of *MSWP* from -1.5 MPa to -3.1 MPa determined a decline of actual transpiration from about 86% to 50% of

maximum. Finally, the performed scenario analysis evidenced the potential of the model to identify crop water status during the different stages of crop growth, that can be used to identify irrigation strategies aimed to cope with water scarcity.

Key-words

Hydrus-2D; Olive tree; Actual evapotranspiration; Water stress; Midday Stem Water Potential;

Introduction

In several regions of the world, the scarcity of freshwater represents one of the most important environmental concerns due to agricultural intensification associated to the increasing population and rapid economic growth. Moreover, the climate change scenario may exacerbate the problem, creating new drought-prone areas or increasing those affected by severe aridity (Provenzano and Rodriguez-Sinobas, 2014). Compared to the traditional surface or sprinkler irrigation, well-designed drip systems, characterized by high field distribution uniformity, can allow enhancing irrigation efficiency (Autovino et al., 2016; Martì et al., 2010) however, there are many other management factors that may affect the performance of these systems (Egea et al., 2016). Further findings in implementation and testing of water-saving strategies associated to irrigation scheduling are therefore desirable, even to assure the appropriate feedback between research and practice (Provenzano et al., 2014). Researches related to the optimization of irrigation for olive trees have demonstrated that slight or moderate crop water stress in specific phenological stages can contribute to increase crop productivity and water use efficiency (Tognetti et al., 2004).

When applying water-saving strategies it is necessary the precise control of irrigation by monitoring specific indicators related to soil and plant water status (soil matric potential, leaf or stem water potential, trunk diameter variations, relative transpiration) aimed to identify proper irrigation timing and depth (Rallo et al., 2014a), so to prevent severe stress conditions and unreasonable water consumes. As stated by Kramer (1969), “the status of water in the plant represents an integration of the atmospheric demand, soil water potential, rooting density and distribution, as well as other plant characteristics”. For these reasons, the monitoring of plant water status should be preferred to that related to the soil water status or to the climatic variables.

Leaf or stem water potential, measured at predawn or midday, are in fact considered among the most reliable indicators of crop water status, whereas sap flow sensors are suitable to quantify the plant transpiration fluxes. In remote modality, crop reflectance spectroscopy or thermal images are also considered valid tools to detect crop water status at various spatial scales (Gamon and Qiu, 1999; Rallo et al., 2014b). In alternative, measurements of soil water contents have been quite often preferred because of their simplicity even though, under trickle irrigation, the high water gradients around the emission points makes it difficult to identify the spot in which the soil water content representative of the root volume has to be detected. However, despite crop-base measurements represent the most effective way to schedule irrigation because integrates environmental effects and potentially very sensitive, these don't indicate how much water to apply. Moreover, calibration procedures are required to determine control thresholds (Jones, 2004).

For these reasons easy-to-use tools, such as software packages simulating water transfer in the soil-plant-atmosphere (SPA) continuum, are often used for indirect evaluations of soil and crop water status and to estimate indicators related to water stress (Minacapilli et al., 2009; Cammalleri et al., 2013; Rallo et al., 2017). Several agro-hydrological models have been implemented and used to explain the water exchange processes occurring in the SPA continuum (Rallo and al., 2012). The complexity of the system not only derives from the high number of variables to be defined, but also from internal self-regulation phenomena occurring between the system components (Rallo et al., 2010).

Hydrus-2D package (Šimůnek et al., 1999) allows simulating water, heat and multiple solute transfer in variably saturated porous media. Since its implementation, the model been extensively applied as summarized in the review of Šimůnek et al., (2016), in which the capabilities and the major applications allowed by the different versions were presented and discussed. Despite several applications on horticultural crops and under different climates have been provided the model validation with reference to soil water content (Mguidiche et al., 2015; Egea et al., 2016; Ghazouani et al., 2016) only a few have accounted for the impact of irrigation strategies on water plant uptake, actual crop transpiration or crop yield (Mailhol et al., 2011). Phogat et al. (2013) used the model to evaluate daily fluctuations of water fluxes of almond trees under different irrigation management. These authors evidenced the good performance of the model to reproduce the spatial and temporal water dynamic in the soil domain, also observing that the model simulates daily values of root water uptake well responding to the fluctuations of evapotranspiration demand; however, according to their results, the magnitude of simulated root water uptake resulted generally greater than the corresponding measured with sap-flow sensors.

The main objective of the paper was to assess the performance of Hydrus-2D model to predict soil water contents and transpiration fluxes in an olive orchard maintained under two different irrigation systems. After validating the model and assessing the relationship between midday stem water potential (*MSWP*) and the ratio between simulated actual and maximum crop transpiration, a scenario analysis was carried out in order to verify the possibility to decrease seasonal ~~irrigation~~ water requirement by controlling the levels of water stress achieved in the different phases of the vegetative crop growth.

Background of Hydrus-2D model

Hydrus-2D model (Simunek et al., 1999) allows simulating water flow, heat and solute transport in two-dimensional variably-saturated flow domain. Furthermore, the model allows estimations of root water uptake, according to which the spatial distribution of soil water content is evaluated.

A modified form of Richards equation is used to describe water movement in the soil, under the hypotheses to neglect the air phase and the thermal gradients in the soil (Celia et al., 1990):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\ \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\ \frac{\partial h}{\partial z} + K(h)\right] - S(h) \qquad (1)$$

where θ [L^3 L^{-3}] is volumetric soil water content, t [T] is time, h [L] is soil matric potential, $K(h)$ [L T^{-1}] is unsaturated soil hydraulic conductivity, x [L] and z [L] are the horizontal and vertical (positive upwards) spatial coordinates and finally, $S(h)$ [T^{-1}] is a sink term representing the volume of water extracted by plant roots from the unit soil volume and in a time unit. Equation (1) is solved by using the Galerkin-type finite element method applied to a network of triangular elements (mesh).

The model requires the knowledge of the soil water retention curve, $\theta(h)$ and the hydraulic conductivity function, $K(h)$, that can be mathematically described by means of the van Genuchten-Mualem model (Mualem, 1976; van Genuchten, 1980):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (ah)^n]^m}\ h < 0 \qquad (2)$$

$$\theta(h) = \theta_s \quad h \geq 0 \qquad (3)$$

$$K(h) = \ K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad (4)$$

where θ_s [L^3 L^{-3}] and θ_r [L^3 L^{-3}] are saturated and residual soil water content, m, n and a are function shape parameters, with $m = 1 - 1/n$, K_s [L T^{-1}] is saturated hydraulic conductivity, l is the pore connectivity parameter and S_e is relative saturation, defined as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (5)$$

In the absence of osmotic stress, the actual rate of root water uptake, $S(h)$, in any point of simulation domain is computed according to the Feddes model (Feddes et al. 1978), that assumes that $S(h)$ is proportional to the maximum root uptake rate occurring when water is not limiting plant transpiration, S_m [T^{-1}]:

$$S(h) = \alpha(h)\, S_m \tag{6}$$

where the water stress response function, $\alpha(h)$ [-], locally depends on soil matric potential. To describe the water stress response function, van Genuchten (1987) suggested the following sigmoid function (S-shape), valid in the absence of osmotic stress:

$$\alpha(h) = \frac{1}{1 + \left(\frac{h}{h_{50}}\right)^{P}} \tag{7}$$

The model assumes that the reductions of water uptake depends on i) the soil matric potential for which the ratio between actual and maximum crop transpiration is equal to 0.5, h_{50} [L], and on ii) a dimensionless parameter, p [-], whose value is influenced by soil, crop and climate conditions (Homaee, 1999).

Under non-uniform root distribution, the spatial variation of maximum root extraction, S_m, is expressed as:

$$S_m = \beta(x,z)\, L_t\, T_m \tag{8}$$

where $\beta(x,z)$ [L^{-2}] is a normalized distribution of maximum root water uptake over a soil volume of arbitrary shape (Vogel, 1987), L_t [cm] is the width of soil surface associated with the transpiration process and T_m [L T^{-1}] is the maximum transpiration.

The actual water uptake distribution in any point of the simulation domain is obtained by introducing eq. (8) into eq. (6):

$$S(h,x,z) = \alpha(h,x,z)\, \beta(x,z)\, L_t\, T_m \tag{9}$$

By integrating eq. (9) in the region occupied by roots it is possible to obtain the total actual root water uptake that, by neglecting the tree capacitance, can be assumed corresponding to actual plant transpiration.

In Hydrus-2D, the normalized $\beta(x,z)$ function is implemented according to the model proposed by Vrugt et al. (2001):

$$\beta(x,z) = \left[\left(1-\frac{z}{Z_m}\right)\right]\left[\left(1-\frac{x}{X_m}\right)\right] e^{-\left(\frac{p_z}{Z_m}|z^*-z|+\frac{p_x}{X_m}|x^*-x|\right)} \quad (10)$$

where Z_m [L] and X_m [L] are the maximum rooting lengths in the z and x directions, z^* [L] and x^* [L] define the location of the maximum root water uptake in vertical (z) and horizontal (x) directions and finally, p_z [-] and p_x [-] are empirical coefficients.

Materials and Methods

Study area and data collection

Experiment was conducted at "Tenute Rocchetta", a commercial farm (*Olea europaea L.*, *cv. Nocellara del Belice*) located in South-West of Sicily, Italy (37.6494 N, 12.8492, E, 123 m a.s.l.) during two irrigation seasons (2011 and 2012). The farm, specialized in the production of oil and table olives, is located in a quite flat area with a rather homogeneous silty-clay-loam soil texture. Climate is typically Mediterranean with precipitation concentrated in fall and winter and a dry season lasting 4-5 months, from late spring to late summer. A standard weather station by the Sicilian Agrometeorological Information Service (SIAS) located 500 m apart the experimental site, allowed acquiring daily precipitations, as well as the climate variables to estimate reference evapotranspiration, ET_0, with the Penman Monteith equation (Allen et al., 1998), whose validity for the experimental site has been previously assessed (Minacapilli et al., 2016).

The orchard was planted about 25 year ago, with rows roughly oriented along the East-West direction and plant spaced 5.0 m within rows and 8.0 m between rows. Two undisturbed cylindrical soil samples, 8.5 cm diameter and 5.0 cm height, were collected at different depths

(0-15, 15-45, 50-70 and 80-100 cm) to determine soil water retention curve and hydraulic conductivity function. Hanging water column apparatus (Burke et al., 1986) was used for soil matric potential ranging between -0.05 m and -1.50 m, whereas the pressure plate apparatus (Dane and Hopman, 2002) for soil matric potential values from -3.37 to -153.0 m. Soil water conductivity corresponding to matric potentials close to saturation were determined by tension disc infiltrometer (Logsdon et al., 1993) and the Beerkan Estimation of Soil Transfer (BEST) method (Bagarello et al., 2011).

During the first year (2011) investigated trees were irrigated by a single drip lateral per plant row, with four 8.0 l/h emitters per plant, installed at both sides of each trunk at distances of 0.50 m and 1.50 m (fig. 1a). In 2012, in order to reproduce a different irrigation system, water was distributed over the entire soil surface dominated by a plant, with 8.0 l/h emitters installed according to a square grid spaced 50 cm, and positioned on the ground (fig. 1b). In both years, phase I of vegetative growth lasted around 10 of July, the end of the pit hardening stage around 20 of August, whereas phase II of vegetative growth continued till the end of October. Irrigation events were scheduled from mid of July to the end of August, whereas all the other management and fertilization options followed the ordinary practices used by the farmer.

Soil water contents were monitored by Frequency Domain Reflectometry (FDR) downhole sensor (Diviner 2000, Sentek), after evaluating the site-specific calibration equation (Rallo and Provenzano, 2014; Provenzano et al., 2015). Sixteen 120 cm long access tubes (P1-P16) were installed in a quarter of a tree, as indicated in fig. 1a,b.

In order to detect the spatial distribution of active roots from soil surface to 105 cm depth, seven undisturbed cylindrical soil cores, 5 cm diameter and 15 cm height, were collected during the installation of each *FDR* access tube, for a total of 112 samples. Root extraction was carried out by following a standard procedure of wash and filtration (Newman, 1966). In each sample, the total length of roots with diameter lower than 2 mm was scanned and measured with Image-Pro Plus 6.0 software (Media Cybernetics, Silver Spring, US). Values of normalized Root Length Density (*RLD*) were finally determined and assumed as the length of active roots in each soil unit.

In order to monitor sap flow velocity, v [cm min^{-1}], two pairs of thermal dissipation probes, *TDP*, (Granier, 1987) were installed in an olive tree at height of about 40 cm from the ground in the convex and concave side of the trunk, which was then wrapped in reflective insulation. The probes were connected to a Campbell CR1000 (Campbell Scientific Inc., Logan, Utah) datalogger, programmed to acquire at hourly time-step. Sap flow velocity [cm min^{-1}] was obtained by combining the difference of temperature between heated and un-heated needle with the corresponding difference registered at night (absence of flux). Sap fluxes, q [cm^3 min^{-1}], were then evaluated by multiplying sap flow velocity to the cross-area, S [cm^2], of the conducting sapwood, measured by colorimetric method on trunk samples extracted with the Pressler gimlet (Cammalleri et al., 2013). Hourly fluxes were then aggregated at daily time-step and assumed equivalent to plant transpiration, under the hypothesis to neglect tree capacitance. Crop water status was monitored based on Midday Stem Water Potential (*MSWP*), measured with Scholander pressure chamber (Scholander et al., 1965) by following Turner and Jarvis (1982) protocol. Two measurements of *MSWP* [MPa] were carried out roughly every week from June 27 to September 18, 2011, on non-transpiring stems collected in the same trees where sap flow sensors were installed. Measurements were carried out at least 30 minutes after insulating the stems with aluminum foil faced bags.

Parametrization of Hydrus-2D model and scenario analysis

Hydrus-2D model validation was carried out by considering both the described drip distribution systems. A two-dimensional simulation domain perpendicular to the drip pipe, 150 cm deep and 400 cm wide, was used to schematize the soil volume around a single tree as shown in fig. 1a,b. Simulations were run from January, 1, 2011 to December 31, 2012, with daily time step (731 days). For both years, the flow domain was discretized by unstructured mesh with a total of 1134 nodes and 2147 finite triangular elements, whose dimensions were assumed smaller at the top layer, where the highest hydraulic gradients occurred. In 2011, drip irrigation was simulated by an infinite line source perpendicular to the flow domain, as previously adopted by other authors (Skaggs et al., 2010; Phogat et al., 2013). This assumption is consistent with the long lasting irrigation, during which the overlapping of wetted bulbs was observed in the field. The atmospheric boundary condition was set at the top edge of the simulation domain, with the exception of the three nodes (12.5 cm) placed below the emitter, in which a time-variable boundary condition was considered. By assuming that in 2011 the area wetted by emitters is 25 cm wide and 500 cm long (12,500 cm^2) and considering the volume distributed during each irrigation event equal to 400 dm^3 d^{-1}, a flux q=32 cm d^{-1}, was obtained. In 2012, based on the adopted distributed drip system, watering was simulated as a daily event, whose height was obtained by dividing the irrigation volume to the surface dominated by a single plant. In both the considered years, the absence of flux was assumed along the lateral boundary surfaces and free drainage at the bottom of soil profile.

The maximum daily crop transpiration, T_m, and soil evaporation, E_m, used to define the time-variable atmospheric boundary condition, were estimated from ET_0 values by following the dual crop coefficient approach (Allen et al., 1998), as:

$$T_m = K_{cb}\, ET_0 \tag{11}$$

$$E_m = K_e\, ET_0 \tag{12}$$

in which K_{cb} is the basal crop coefficient evaluated on the basis of the canopy fraction cover and the tree height (Allen and Pereira, 2009) and K_e is the coefficient of soil evaporation, that was set equal to 0.1.

Soil hydraulic functions for the different soil layers, expressed through the van Genuchten-Mualem model, were determined according to the experimental data by using the retention curve (*RETC*) computer program (van Genuchten et al., 1991). The root distribution parameters were obtained after calibrating eq. (10) based on the values of normalized *RLD* measured in the field. The van Genuchten (1987) S-shape model (eq. 7) was adopted to represent the root water uptake stress function by assuming h_{50}=-15,200 cm and p=4.284, as estimated by Rallo and Provenzano (2013) in the same experimental field.

Soil water content at the beginning of simulation was supposed constant and equal to 0.25 cm^3 cm^{-3} in the whole simulation domain. However, this assumption had a limited effect on soil water contents and transpiration fluxes measured during irrigation seasons and later used to validate the model. In fact, after large rainfall events occurring between January and February 2011 the soil reached the field capacity and, as observed in the field, maintained similar conditions approximately until the end of May.

The model was validated according to temporal dynamic of both soil water content and root water uptake. The latter, under the hypothesis to neglect the tree capacitance, was assumed corresponding to the dynamic of transpiration fluxes measured with sap flow sensors. The comparison between measured and simulated soil water contents was carried out in 25 control points (five different depths of five soil profiles). At each distance and depth from the plant row, the average *SWC* and the corresponding standard deviation were obtained by considering the values measured with the *FDR* probe within the installed access tubes. On the other hand, measurements of actual transpiration fluxes were obtained by averaging the daily cumulative values acquired by sap flow sensors.

Once the model was validated, the relationship between *MSWP* and the ratio between actual and maximum tree transpiration, identifying the crop water stress coefficient ($K_s=T_a/T_m$), was assessed. Hydrus-2D model allowed then to simulate, under different scenario, the levels of crop water stress achieved during the different phases of phenological growth. In particular, scenario analysis was carried out to estimate *Ks* and *MSWP* in the absence of irrigation (NI), as well as by applying 15%, 30% and 50% of maximum transpiration registered between June 13 and August 30 of both years, divided in thirteen irrigation events of equal volume applied weekly.

Evaluation of model performance

Hydrus-2D model performance to estimate the spatial and temporal dynamics of soil water contents and transpiration fluxes was evaluated based on Mean Bias Error (*MBE*), Root Mean Square Error (*RMSE*) and the Efficiency index (*NSE*) proposed by Nash and Sutcliffe, (1970).

$$MBE = \frac{\sum_{i=1}^{N}(X_{obs,i}-X_{sim,i})}{N} \tag{13}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(X_{obs,i}-X_{sim,i})^2}{N}} \tag{14}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(X_{obs,i}-X_{sim,i})^2}{\sum_{i=1}^{N}(X_{obs,i}-\overline{X_{obs}})^2} \tag{15}$$

where X_{obs} is the generic value of the considered variable acquired at day i, X_{sim} is the corresponding simulated and *N* is the number of measured data.

The value of *NSE* can range between $-\infty \leq NSE \leq 1$. *NSE* value ranges between 0 and 1 indicates that the model is suitable to well reproduce the measured variable, with *NSE*=1 expressive of the perfect agreement, whereas *NSE* values lower than zero identify unacceptable performance of the model.

Results and Discussion

Physical characterization of soil and root systems

Table 1 shows the van Genuchten-Mualem parameters of soil water retention and conductivity functions (eqs. 2-4) obtained for the different investigated soil layers and used for model simulations. As can be observed, even though quite similar parameters characterized the soil water retention curves at the different depths, the saturated hydraulic conductivity decreased at increasing depth from 70 to 20 cm d^{-1}, due to soil compaction occurring at the higher depths. Figure 2 shows the normalized root length density (*RLD*) corresponding to the different soil depths (profiles P1-P13), measured at distances of 0, 50, 100 and 200 cm from the plant row; the root distribution function obtained after fitting the Vrugt model (eq. 10) to experimental data is also shown. At each distance from plant row, the mean *RLD* values were initially determined at the different depths and then used to calibrate the model (eq. 10) according to a nonlinear Generalized Reduced Gradient (*GRG*) algorithm, by minimizing the variance of residuals between measured average and estimated *RLD*. The values of parameters, later used for simulations, resulted respectively equal to Z_m =120 cm, X_m = 580 cm, z^*=30 cm, x^*=0 cm, p_z =1, p_x =2.

As can be noticed when observing measured data in figure 2, active roots (d<2.0 mm) exist in the whole soil domain, even at a certain distance from the tree row along which is installed the irrigation pipe. For a fixed soil profile, root density tends to decrease at increasing depth, whereas for a fixed depth with the distance from the plant row; roots are mostly concentrated in the upper soil layers, till about 40 cm depth. Moreover, closer the soil profile to plant row, more variable *RLD* values, as a consequence of micro irrigation system used for irrigation (drip lateral along the plant row with four emitters per plant). In fact, the quite high gradients of soil water content occurring after irrigation events have determined the development of an extended root system within the wetted soil volume, that justifies the highest (on average) root density generally detected along the tree row. The achieved results are in agreement with those observed by Fernandez et al. (1991), who evidenced that under dry conditions, adult olive trees adapt their roots to the installed drip system, with the highest concentration detected within the soil volume wetted by emitters. Similarly to what observed by Searles et al. (2009), about 70% of active roots were found in the soil volume 0.5 m depth and 0.5 m wide, along the drip line. However, despite a number of papers investigated on root distribution in olive orchards (Rieger, 1995; Moreno et al., 1996; Palese et al., 2000), little information have been provided on the temporal dynamic of root system distribution (Connor and Fereres, 2005).

Model simulations

Figure 3a shows the temporal dynamic of daily precipitation and reference evapotranspiration, whereas fig. 3b illustrates the temporal patterns of maximum soil evaporation and plant transpiration occurred during 2011 and 2012, as used to run Hydrus-2D simulations. During both years, similar climate conditions can be observed, with reference evapotranspiration ranging between about 1.0 and 6.5 mm d^{-1}, and the absence or rainfall during July and August, during which the highest atmospheric evaporative occurred. Annual reference evapotranspiration was equal to 1149.3 mm in 2011 and 1153.6 mm in 2012, whereas total rainfall resulted in the two years of 566.0 and 580.2 mm. The temporal patterns of maximum evaporation, E_m, and transpiration, T_m, (fig. 3b) follow, of course, the dynamic of ET_0. Annual

T_m resulted of 459.7 and 403.6 mm, whereas E_m was equal to 114.9 and 115.3 mm respectively in 2011 and 2012.

Figure 4 shows the temporal dynamic of measured and simulated soil water contents at different depths and distances from plant row, as obtained from May to November 2011. At each soil depth, mean and standard deviation of measured soil water content were obtained by averaging the values detected in the soil profiles along planes parallels to the plant row. The quite high standard deviations characterizing all the depths along the plant row (left column of fig. 4) are due to the high gradient of soil water content consequent to the adopted localized irrigation system. As it can be observed, Hydrus-2D is in general able to reproduce the trends of measured soil water contents at the different distances and depths from the plant row, despite simulated values are referred to the mesh nodes, whereas the corresponding measured are representative of finite soil volumes. Analogous results were obtained in 2012 in which, however, variability of measured soil water contents resulted systematically lower than that observed in 2011 (fig. 5). This situation can be related to irrigation system, according to which water was distributed on the soil surface almost uniformly and thus infiltration process was practically mono-dimensional. Moreover, overestimations of soil water contents mainly simulated at high depths and distances from the plant row could be a consequence of the inadequate schematization of root system, whose distribution was assumed similar to that of 2011. In fact, due to irrigation system adopted in 2012, the plant could have developed a different root distribution and thus locally modified root water uptake. The lack of knowledge about the temporal patterns of active root system, however, does not allow further speculations but the auspice of future investigations.

The temporal dynamic of measured and simulated actual transpiration fluxes, from May 1 to November 27 of both the examined years, is shown in fig. 6, in which the patterns of maximum transpiration, precipitation and irrigation are also displayed. It can be noticed that simulated transpiration fluxes in the investigated periods resulted similar to those obtained by integrating, at daily time-step, sap flow measurements. The local discrepancies, mainly observed around the end of June and in September 2011, could be due to the neglected tree capacitance and therefore to the contribute to transpiration fluxes of the water stored in leaves, branches and trunk of the tree. Table 2 summarizes the results of statistical comparisons between simulated and measured soil water contents and transpiration fluxes in 2011 and 2012. The best performance of the model, in terms of both soil water contents and plant transpiration fluxes was obtained in 2011, as confirmed by the highest values assumed by the Nash-Sutcliffe efficiency index. However, even in 2012, despite the discussed limitations caused by the imprecise schematization of root system distribution, *RMSE* values associated to soil water contents and transpiration fluxes resulted of 0.09 $cm^3\ cm^{-3}$ and 0.05 mm, respectively, with *NSE* index always positive. The achieved results evidences that more appropriate the schematization of root system, better the model outputs in terms of soil water contents and transpiration fluxes. Even Phogat et al. (2013), in a study on almond crop, concluded that Hydrus-2D model is able to reproduce the spatial and temporal dynamic of water content within the soil domain. On the other hand, for corn crop, Mailhol et al. (2011) stated that the model ability to simulate actual transpiration fluxes under severe water stress conditions is questionable. It is necessary to stress in fact, that in the investigated silty-clay-loam soil, the root system occupies approximately the whole soil domain. Under these conditions, plant can modify its capability to uptake water from soil, by activating roots located in soil regions where water is more easily available. This situation has been observed when examining the variations of soil water contents in the different regions of root domain after an irrigation or a rainfall event. In the former, according to root distribution and to drip irrigation system, water uptake occurred mainly from a parallelepiped soil volume having width, length and depth respectively of about 1.50, 5.00 and 0.75 m, whereas in the latter root water uptake took place from all the root domain (data not shown). The relatively limited soil water contents measured in 2012 at higher distances from plant row and deeper soil layers, associated to the relatively high values of actual evapotraspiration (practically equal to maximum), confirms the root system adaptation capabilities to restrictive soil water status.

Figure 7 shows the absolute values of *MSWP* measured in 2011 as a function of relative transpiration, calculated as the ratio between simulated actual and maximum crop transpiration ($K_s=T_a/T_m$). As can be observed the two variables are strongly correlated, being the trend of *MSWP* (absolute value) decreasing at increasing K_s. In particular, according to experimental data and simulation results, a value of *MSWP*=-1.5 MPa brings to actual transpiration of about 86% of maximum, whereas *MSWP*=-3.1 MPa determines actual transpiration of 50% of the corresponding maximum. Rallo et al. (2017), even for citrus crop, identified the relationship between *MSWPs* and crop water stress coefficients simulated by FAO-56 model, later used to assess the linear correlations existing between measured and simulated water stress integrated over the season, which was dependent on the adopted irrigation strategy. According to the performed analysis then, it is possible to conclude that Hydrus-2D model, under the examined conditions, is also suitable to identify the variability of crop water status.

The model was finally used to simulate the levels of crop water stress achieved in the different phenological phases. Table 3 summarizes the values of cumulative precipitation, irrigation, maximum and actual transpiration registered in 2011 and 2012, between June 13 and August 30, as well as average (μ) and standard deviation (σ) of *MSWP* in the different stages of vegetative growth occurring in the period. On the other hand, fig. 8a,b illustrates the temporal dynamic of maximum and actual transpiration, whereas fig. 8c,d shows the corresponding crop water stress coefficient, obtained respectively in 2011 and 2012 under the examined scenarios. At the beginning of both years actual transpiration simulated in all the examined scenarios resulted equal to the maximum, as a consequence of soil water status that did not result limiting crop transpiration. Then, as expected, actual transpiration decreased more and more rapidly at decreasing irrigation depths, being the minimum values achieved in the absence of irrigation (*NI*). The values of relative transpiration, ranging approximately between 0.3 and 1.0, reached the minimum around the begin of October in 2011 and at the end of August in 2012.

Based on the empirical relationship between midday stem water potential and K_s obtained for the examined site (fig. 7), the temporal dynamic of *MSWP* was also determined for the two years and under the different irrigation scheduling scenarios, as shown respectively in fig. 8e,f. Horizontal lines specifies the thresholds for mild (-2.0 MPa) and moderate (-3.5 MPa) water stress levels as obtained over four growing season by Ahumada-Orellana et al. (2017) in a super-high density olive orchards. The results of these Authors evidenced in particular, that reducing *MSWP* till reaching the threshold of -3.5 MPa during pit hardening has not significant effects on crop yield and determines a reduction of about 20% of seasonal irrigation. The reduction of irrigation during pit hardening, generally characterized by high atmospheric evaporative demands, has been suggested by many authors as suitable *RDI* strategy for the examined crop, because this phase of vegetative growth is the least sensitive to water deficit (Goldhamer, 1999). However, it has to be considered that the optimal *MSWP* may be different according to soil physical characteristics or with climate variables, such as vapour pressure deficit and air temperature (Corell et al., 2016). Under the examined scenarios, whilst maintaining the olive trees under rainfed conditions may bring to severe crop water stress during stage II of fruit growth with consequent reductions of crop yield, the scenario S_{50}, obtained by scheduling irrigation of the period between June 13 and August 30 as 50% of maximum transpiration, allows maintaining *MSWP* always below the threshold of mild water stress. However, independently from the chosen thresholds, a physically based model such as Hydrus-2D can represent a powerful tool to improve irrigation strategies under water constraints, also accounting for economic considerations.

Conclusion

The knowledge of actual *ET* fluxes and crop water status has a significant role in regions where water resources for agriculture are limited and deficit irrigation is practiced as water management strategy. This study examined the performance of Hydrus-2D numerical model to predict soil water contents and transpiration fluxes in an olive orchard irrigated with two different irrigation systems. Additional measurements of midday stem water potential (*MSWP*) allowed calibrating the relationship occurring with the relative transpiration simulated by the model. A scenario analysis was finally carried out in order to verify the possibility to decrease the seasonal ~~irrigation~~ water requirement by controlling the levels of crop water stress achieved ~~by crop~~ in the different phases of vegetative growth.

The analysis demonstrates that the patterns of soil water contents reproduced by the model were comparable to the corresponding measured at the experimental site, with *RMSE* values of 0.04 and 0.09 $cm^3\ cm^{-3}$ in 2011 and 2012, respectively. Moreover, ~~when the model is adequately calibrated and the root system correctly schematized,~~ Hydrus-2D it is able to reproduce the temporal dynamic of actual daily transpiration, with *RMSE* values of 0.09 and 0.05 mm in the examined years and with *NSE* index always positive. The obtained results evidenced that more appropriate the schematization of root system, better the model outputs in terms of soil water contents and transpiration fluxes.

With respect to scenario analysis, it was verified that under the examined conditions the absence of irrigation may bring to severe stress in periods when the crop is sensitive to water deficit (stage II of vegetative growth). On the other hand, the application of volumes equal to 50% of maximum transpiration in the period from June 13 to August 30, allows maintaining *MSWP* always below the threshold of mild water stress. Hence, independently from the thresholds chosen to describe the levels of crop water stress, a physically based model such as Hydrus-2D can represent a powerful tool in evaluating the impact of deficit irrigation and improving water saving strategies under water constraints. We believe that information obtained in this study can be utilized for developing better management practices for olive orchards.

Further investigations, however, have to consider the effects of tree capacitance on transpiration fluxes, as well as how irrigation systems can affect the patterns of active roots and the dynamic of water uptake.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. Crop evapotranspiration. Guideline for computing crop water requirements. FAO irrigation and drainage paper n. 56, Rome, Italy, 326 pp.

Allen, R.G., Pereira, L.S. 2009. Estimating crop coefficients from fraction of ground cover and height. Irrigation Science 28, 17-34. DOI:10.1007/s00271-009-0182-z.

Ahumada-Orellana, L.E., Ortega-Farías, S., Searles, P.S., Retamales, J.B. 2017. Yield and water productivity responses to irrigation cut-off strategies after fruit set using stem water potential thresholds in a super-high density olive orchard. Frontiers in Plant Science, 8, article 1280. DOI: 10.3389/fpls.2017.01280.

Autovino, D., Provenzano, G., Monserrat, J., Cots, L., Barragán, J. 2016. Determining optimal seasonal irrigation depth based on field irrigation uniformity and economic evaluations: Application for onion crop. Journal of Irrigation and Drainage Engineering 142(10). DOI: 10.1061/(ASCE)IR.1943-4774.0001048.

Bagarello, V., Di Prima, S., Iovino, M., Provenzano, G., Sgroi, A. 2011. Testing different approaches to characterize Burundian soils by the BEST procedure. Geoderma 162(1-2), 141-150. DOI: 10.1016/j.geoderma.2011.01.014.

Burke, W., Gabriels, D., Bouma, J. 1986. Soil Structure Assessment. Balkema, Rotterdam, The Netherlands.

Cammalleri, C., Rallo, G., Agnese, C., Ciraolo, G., Minacapilli, M., Provenzano, G. 2013. Combined use of eddy covariance and sap flow techniques for partition of ET fluxes and water stress assessment in an irrigated olive orchard. Agricultural Water Management, 120, 89-97. DOI: org/10.1016/j.agwat.2012.10.003.

Celia, M.A., Bouloutas, E.T., Zarba, R.L. 1990. A general mass conservative numerical solution for the unsaturated flow equation. Water Resources Research 26, 1483-1496.

Connor, D.J., Fereres, E., 2005. The physiology of adaptation and yield expression in olive. Hortic. Rev. 31, 155–229.

Corell, M., Pérez-López, D., Martín-Palomo, M. J., Centeno, A., Girón, I., Galindo, A., et al. (2016). Comparison of the water potential baseline in different locations. Usefulness for irrigation scheduling of olive orchards. Agricultural Water Management, 177, 308-316. doi: 10.1016/j.agwat.2016.08.017.

Dane, J.H., Hopman, J.W. 2002. Water retention and storage. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis: Part 4-Physical methods. SSSA Book Ser. 5. SSSA, Madison.

Egea, G., Diaz-Espejo, A., Fernández, J.E. 2016. Soil moisture dynamics in a hedgerow olive orchard under well-watered and deficit irrigation regimes: Assessment, prediction and scenario analysis. Agricultural Water Management 164, 197-211. DOI: 10.1016/j.agwat.2015.10.034.

Feddes, R.A., Kowalik, P.J., Zaradny, H. 1978. Simulation of field water use and crop yield. Pudoc, Centre Agric. Publ. Doc., Wageningen, The Netherland.

Fernandez, J.E., Moreno, F., Cabrera, J.L., Arrue, J.L., Martin-Aranda, J., 1991 - Drip irrigation, soil characteristics and the root distribution and root activity of olive trees. Plant and Soil, 133, 239-251.

Gamon, J. A., Qiu, H. 1999. Ecological applications of remote sensing at multiple scales. In F. I. Pugnaire, & F. Valladares (Eds.), Handbook of functional plant ecology. New York: Marcel Dekker, Inc.

Ghazouani, H., Autovino, D., Rallo, G., Douh, B., Provenzano, G. 2016. Using Hydrus-2D model to assess the optimal drip lateral depth for Eggplant crop in a sandy loam soil of central Tunisia. Italian Journal of Agrometeorology 1, 47-58. DOI: 10.19199/2016.1.2038-5625.047.

Goldhamer, D.A. 1999. Regulated deficit irrigation for California canning olives. Acta Hortic. 474, 369–372. doi: 10.17660/ActaHortic.1999.474.76.

Granier, A. 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiology 3, 309-320.

Homaee, M. 1999. Root water uptake under non-uniform transient salinity and water stress. Ph.D. dissertation. Wageningen Agric. Univ., Wageningen, The Netherlands, 173 pp.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods Journal of Experimental Botany, Volume 55, Issue 407, 1 November 2004, Pages 2427–2436,

Kramer, P.J. 1969. Plant and soil water relationships. Mc-Graw-Hill Book Co., New York.

Logsdon, S.D., Radke, J.K., Karlen, D.L. 1993. Comparison of alternative farming systems. I. Infiltration techniques. American Journal of Alternate Agriculture 8(1), 15-20. DOI: 10.1017/S0889189300004860.

Mailhol J.C., Ruelle, P., Walser, S., Schütze, N., Dejean, C. 2011. Analysis of AET and yield predictions under surface and buried drip irrigation systems using the Crop Model PILOTE and Hydrus-2D. Agricultural Water Management, 98, 1033-1044. doi:10.1016/j.agwat.2011.01.014.

Martí, P., Provenzano, G., Royuela, T., Palau-Salvador, G. 2010. Integrated emitter local loss prediction using artificial neural networks. Journal of Irrigation and Drainage Engineering 136(1), 11-22. DOI: 10.1061/(ASCE)IR.1943-4774.0000125.

Mguidiche, A., Provenzano, G., Douh, B., Khila, S., Rallo, G., Boujelben, A. 2015. Assessing Hydrus-2D model to simulate water content and salt accumulation in a soil irrigated with a subsurface drip system: Application in a semiarid area of central Tunisia. Irrigation and Drainage 64(2), 263-274. DOI: 10.1002/ird.1884.

Minacapilli, M., Agnese, C., Blanda, F., Cammalleri, C., Ciraolo, G., D'Urso, G., Iovino, M., Pumo, D., Provenzano, G., Rallo, G. 2009. Estimation of actual evapotranspiration of Mediterranean perennial crops by means of remote-sensing based surface energy balance models. Hydrology and Earth Science System 13(7), 1061-1074.

Minacapilli, M., Cammalleri, C., Ciraolo, G., Rallo, G., Provenzano, G. 2016. Using scintillometry to assess reference evapotranspiration methods and their impact on the water balance of olive groves. Agricultural Water Management 170, 49-60. DOI: 10.1016/j.agwat.2015.12.004.

Moreno, F., Fernández, J.E., Clothier, B.E., Green, S.R. 1996. Transpiration and root water uptake by olive trees. Plant Soil 184, 85-96.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research 12, 513-522.

Nash J.E., Sutcliffe J.V. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. Journal of Hydrology 10(3), 282-290.

Newman, E.I., 1966. A method of estimating the total length of root in a sample. Journal of Applied Ecology 3, 139-145.

Palese, A.M., Nuzzo V., Dichio B., Celano G., Romano M., Xiloyannis C., Ferreira, M.I., Jones, H.G. 2000. The influence of soil water content on root density in young olive trees. Acta Hort. 537, 329-336.

Phogat, V., Skewes, M.A., Mahadevan, M., Cox, J.W. 2013. Evaluation of soil plant system response to pulsed drip irrigation of an almond tree under sustained stress conditions. Agricultural Water Management 118, 1-11. DOI: 10.1016/j.agwat.2012.11.015

Provenzano, G., Rodriguez-Sinobas, L. 2014. Special issue on trends and challenges of sustainable irrigated agriculture. Journal of Irrigation and Drainage Engineering 140(9), DOI: 10.1061/(ASCE)IR.1943-4774.0000773.

Provenzano, G., Rodriguez-Sinobas, L., Roldán-Cañas, J. 2014. Irrigated agriculture: Water resources management for a sustainable environment. Biosystems Engineering 128, 1-3. DOI: 10.1016/j.biosystemseng.2014.10.008.

Provenzano, G., Rallo, G., Ghazouani, H. 2015. Assessing field and laboratory calibration protocols for the Diviner 2000 probe in a range of soils with different textures. Journal of Irrigation and Drainage Engineering 142(2). DOI: 10.1061/(ASCE)IR.1943-4774.0000950.

Rallo, G., Provenzano, G. 2013. Modelling eco-physiological response of table olive trees (*Olea Europea L.*) to water stress. Agricultural Water Management 120, 79-88. DOI: org/10.1016/j.agwat.2012.10.005.

Rallo, G., Provenzano, G. 2014. Discussion of "Laboratory and Field Calibration of the Diviner 2000 Probe in Two Types of Soil, by J. Haberland, R. Gálvez, C. Kremer, and C. Carter." Journal of Irrigation and Drainage Engineering 141(8). DOI: 310.1061/(ASCE)IR.1943-4774.0000856.

Rallo, G., Agnese, C., Blanda, F., Minacapilli, M., Provenzano, G. 2010. Agro-Hydrological models to schedule irrigation of Mediterranean tree crops. Italian Journal of Agrometeorology (1), 11-21.

Rallo, G., Agnese, C., Minacapilli, M., Provenzano, G. 2012. Comparison of SWAP and FAO Agro-Hydrological Models to Schedule Irrigation of Wine Grape. Journal of Irrigation and Drainage Engineering 138(1). DOI: 10.1061/(ASCE)IR.1943-4774.0000435.

Rallo, G., Baiamonte, G., Manzano, J., Provenzano, G., 2014a. Improvement of FAO-56 model to estimate transpiration fluxes of drought tolerant crops undersoil water deficit: application for olive groves. Journal of Irrigation and Drainage Engineering 140(9). DOI: 10.1061/(ASCE)IR.1943-4774.0000693.

Rallo, G., Minacapilli, M., Ciraolo, G., Provenzano, G. 2014b. Detecting crop water status in mature olive groves using vegetation spectral measurements. Biosystems Engineering 128, 52-68. DOI: 10.1016/j.biosystemseng.2014.08.012.

Rallo, G., González-Altozano, P., Manzano-Juárez, J., Provenzano, G. 2017. Using field measurements and FAO-56 model to assess the eco-physiological response of citrus orchards under regulated deficit irrigation. Agricultural Water Management 180, 136-147. DOI: 10.1016/j.agwat.2016.11.011.

Rieger, M. 1995. Offsetting effects of reduced root hydraulic conductivity and osmotic adjustment following drought. Tree Physiol. 15, 379-385.

Scholander, R.R., Hammel, H.T., Bradstreet, E.D., Hemmiegsen, E.A. 1965. Sap pressure in vascular plants. Science 148, 339-346.

Searles, P.S., Saravia, D.A., Rousseaux, M.C. 2009. Root length density and soil water distribution in drip-irrigated olive orchards in Argentina under arid conditions. Crop Pasture Sci., 60, 280-288. https://doi.org/10.1071/CP08135

Šimůnek J., Šejna M., van Genuchten M.Th. 1999. The Hydrus-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably saturated media. Version 2.0, IGWMC - TPS - 53, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, 251pp.+

Šimůnek, J., van Genuchten, M.Th., Šejna, M. 2012. Hydrus: Model use, calibration and validation. Transaction of the ASABE 55(4), 1261-1274. DOI: 10.13031/2013.42239.

Šimůnek, J., Šejna,M., van Genuchten, M.Th. 2016. Recent Developments and Applications of the Hydrus Computer Software Packages. Vadose Zone Journal, 1-25. DOI: 10.2136/vzj2016.04.0033.

Skaggs, T.H., Trout, T.J., Rothfuss, Y. 2010. Drip irrigation water distribution pattern: Effects of emitter rate, pulsing and antecedent water. Soil Science Society of America Journal 74, 1886-1896. DOI: 10.2136/sssaj2009.0341.

Tognetti, R., D'Andria, R., Morelli, G., Calandrelli, D., Fragnito, F. 2004. Irrigation effects on daily and seasonal variations of trunk sap flow and leaf water relations in olive trees. Plant and Soil 263(1-2), 249-264. DOI: 10.1023/B:PLSO.0000047738.96931.91.

Turner, M.T., Jarvis, G.P. 1982. Measurement of plant water status by the pressure chamber technique. Irrigation Science 9, 289-308.

van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892-898.

van Genuchten, M. Th. 1987. A numerical model for water and solute movement in and below the root zone. Research Report No 121, U.S. Salinity laboratory, USDA, ARS, Riverside, California, 221 pp.

van Genuchten, M.T., Leij, F.J., Yates, S.R. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. Version 6.02. EPA Report 600/2-91/065, Riverside, California, 93 pp.

Vogel, T. 1987. SWMII - Numerical model of two-dimensional flow in a variably saturated porous medium, Research Report no. 87, Dept. of Hydraulics and Catchment Hydrology, Agricultural University, Wageningen, The Netherlands.

Vrugt J.A., Hopmans J.W., Šimůnek J. 2001. Calibration of a two-dimensional root water uptake model. Soil Science Society of America Journal 65(4), 1027-1037.

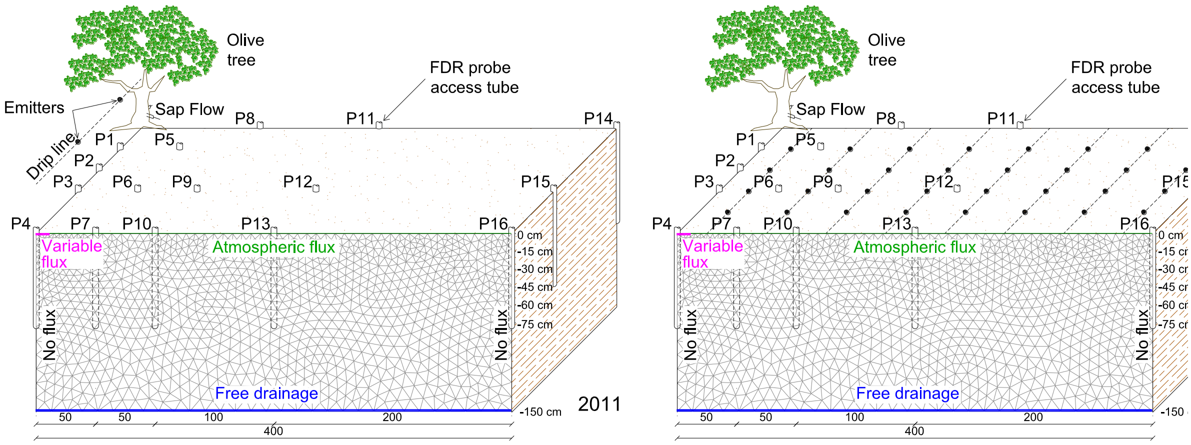

Figure 1a, b - Schematization of simulation domains, positions of FDR probe access tubes and layout of irrigation systems used in 2011 (a) and 2012 (b)

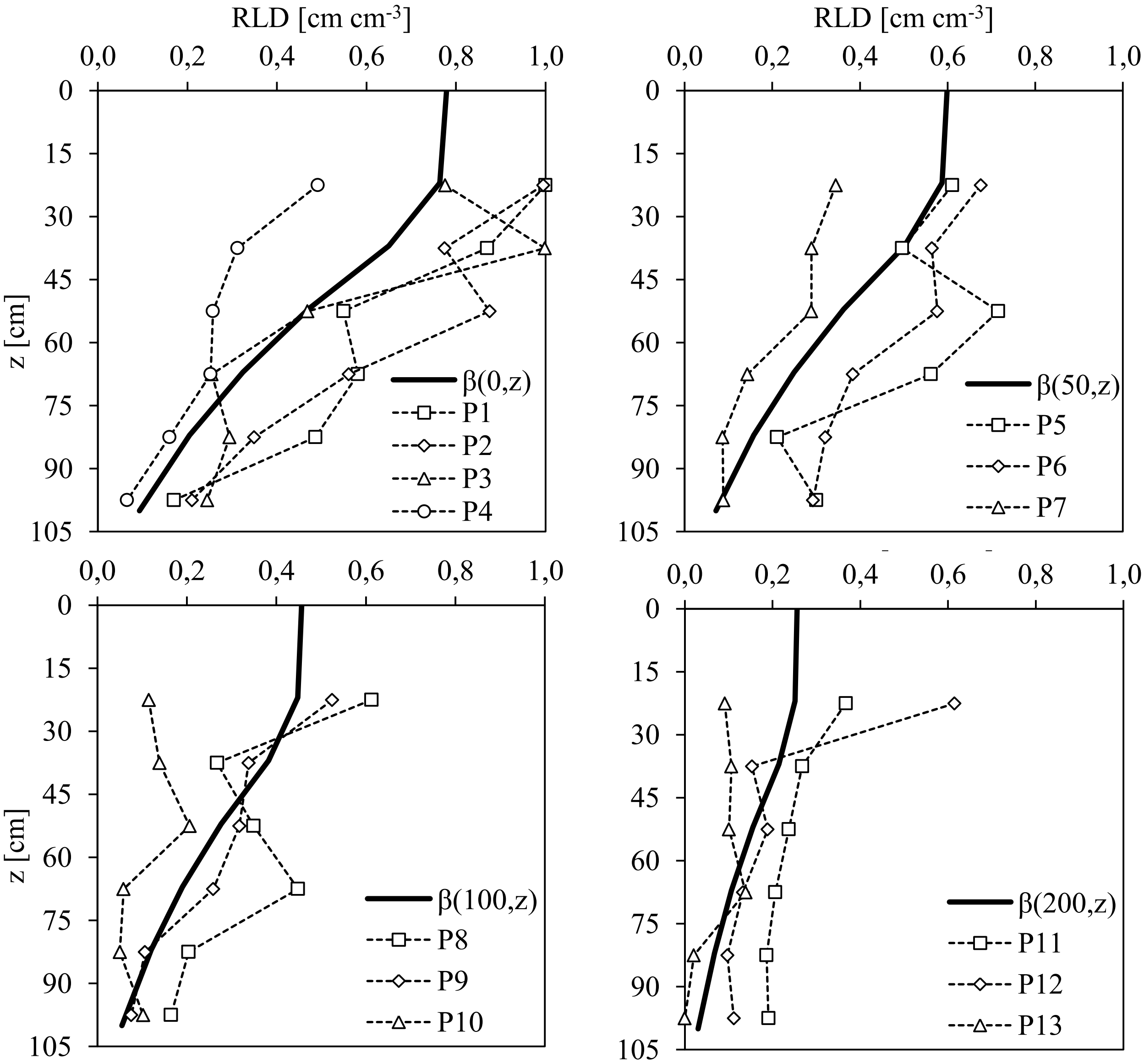

Figure 2 – Profiles of normalized root length density, *RLD*, measured in P1-P13, at distances of 0, 50, 100 and 200 cm from the plant row. *RLD* profiles, according to the Vrugt model at each distance are also shown.

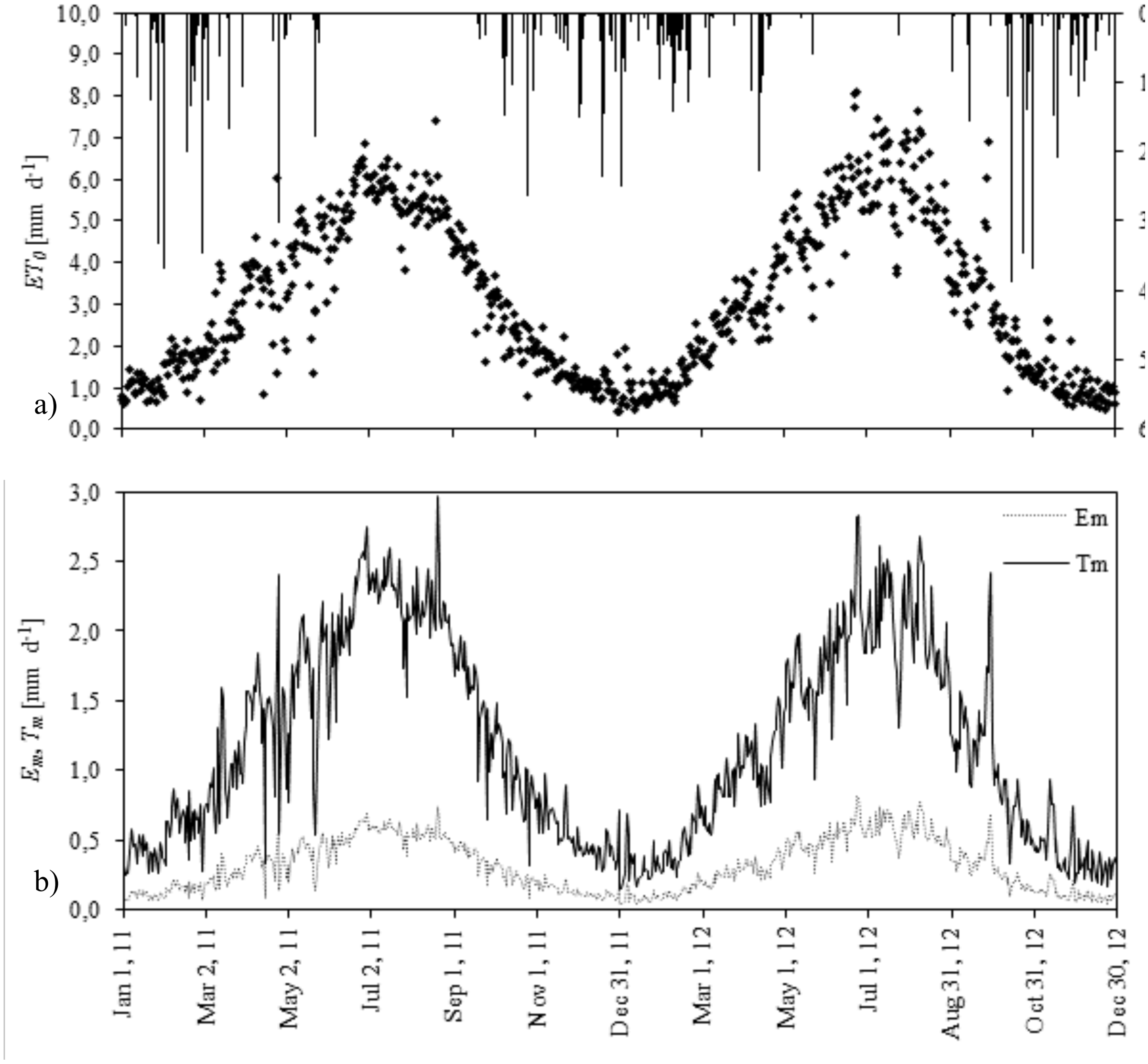

Figure 3a, b - a) Temporal dynamic of reference evapotranspiration, ET_0 and precipitation, P, and b) maximum soil evaporation, E_m, and plant transpiration, T_m, estimated in 2011 and 2012

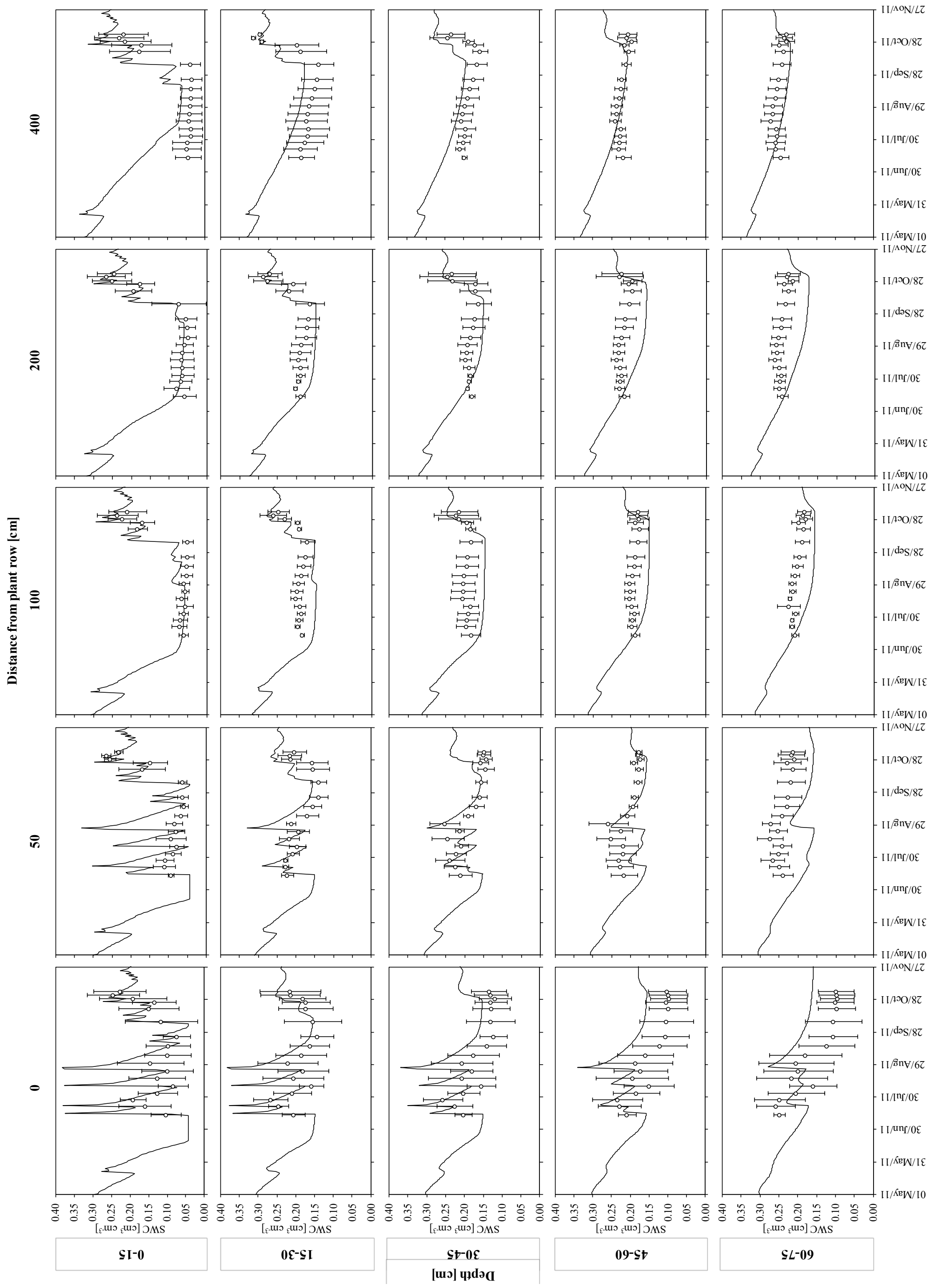

Figure 4 - Temporal dynamic of measured and simulated soil water contents at different depths and distances from the plant row, as obtained in the period May 1 - November 27, 2011

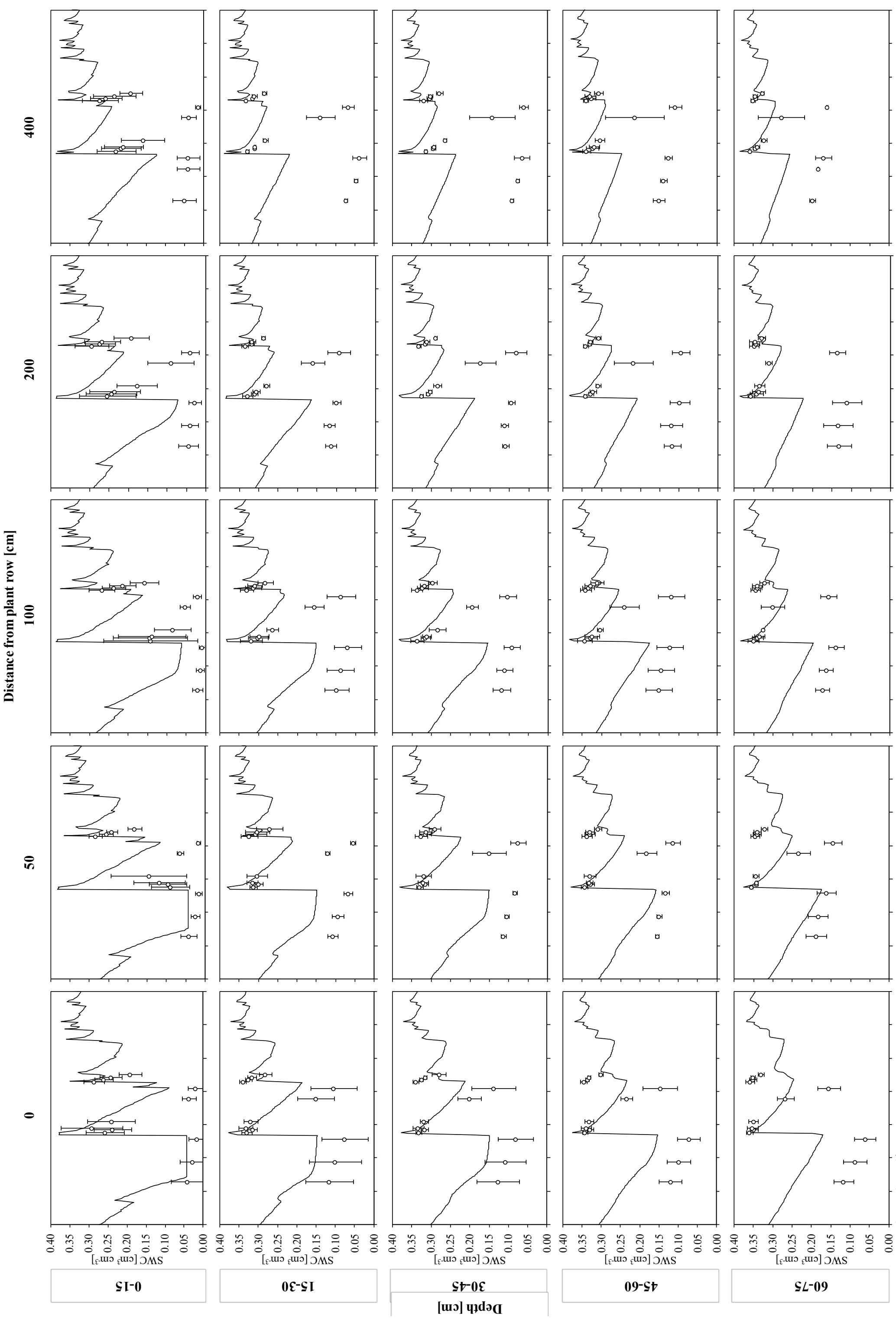

Figure 5 - Temporal dynamic of measured and simulated soil water contents at different depths and distances from the plant row, as obtained in the period May 1 - November 27, 2012

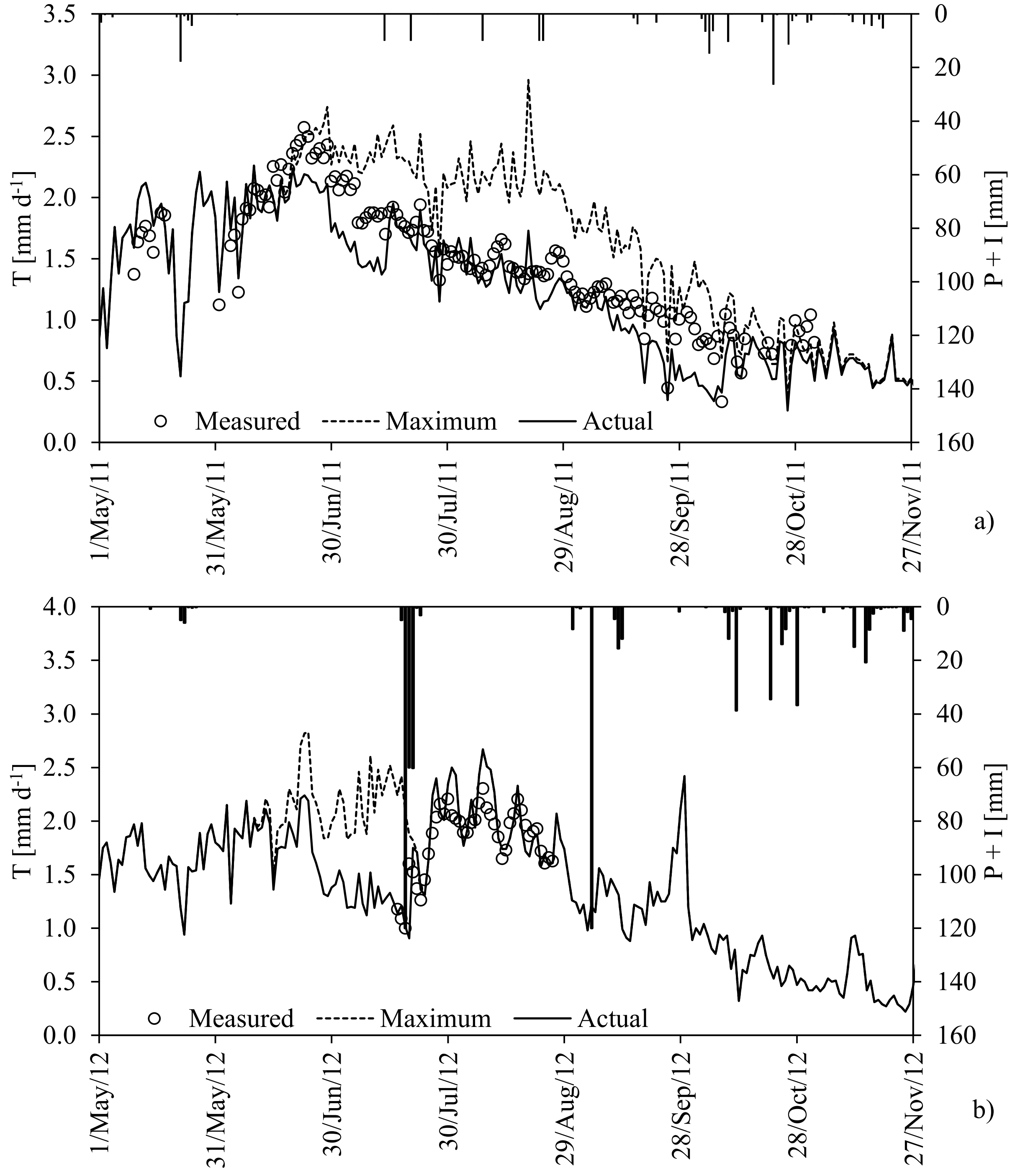

Figure 6a, b - Temporal dynamic of measured and simulated actual transpiration. T_a, from May 1 to November 27, 2011 (a) and 2012 (b). The patterns of maximum transpiration, T_m, precipitation, *P,* and irrigation, *I*, are also shown.

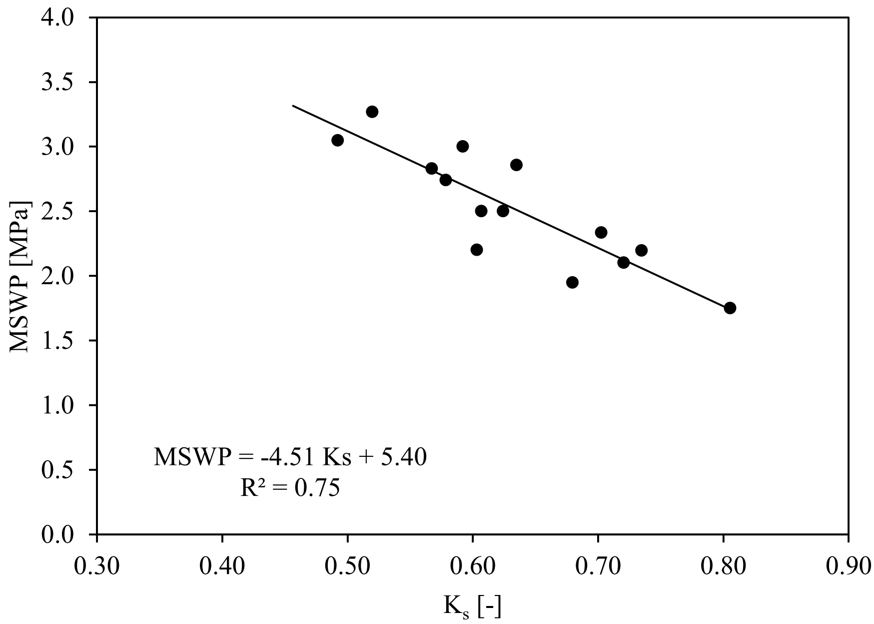

Figure 7 - Midday Stem Water Potential (MSWP) versus estimated stress coefficient (K_s=T_a/T_m)

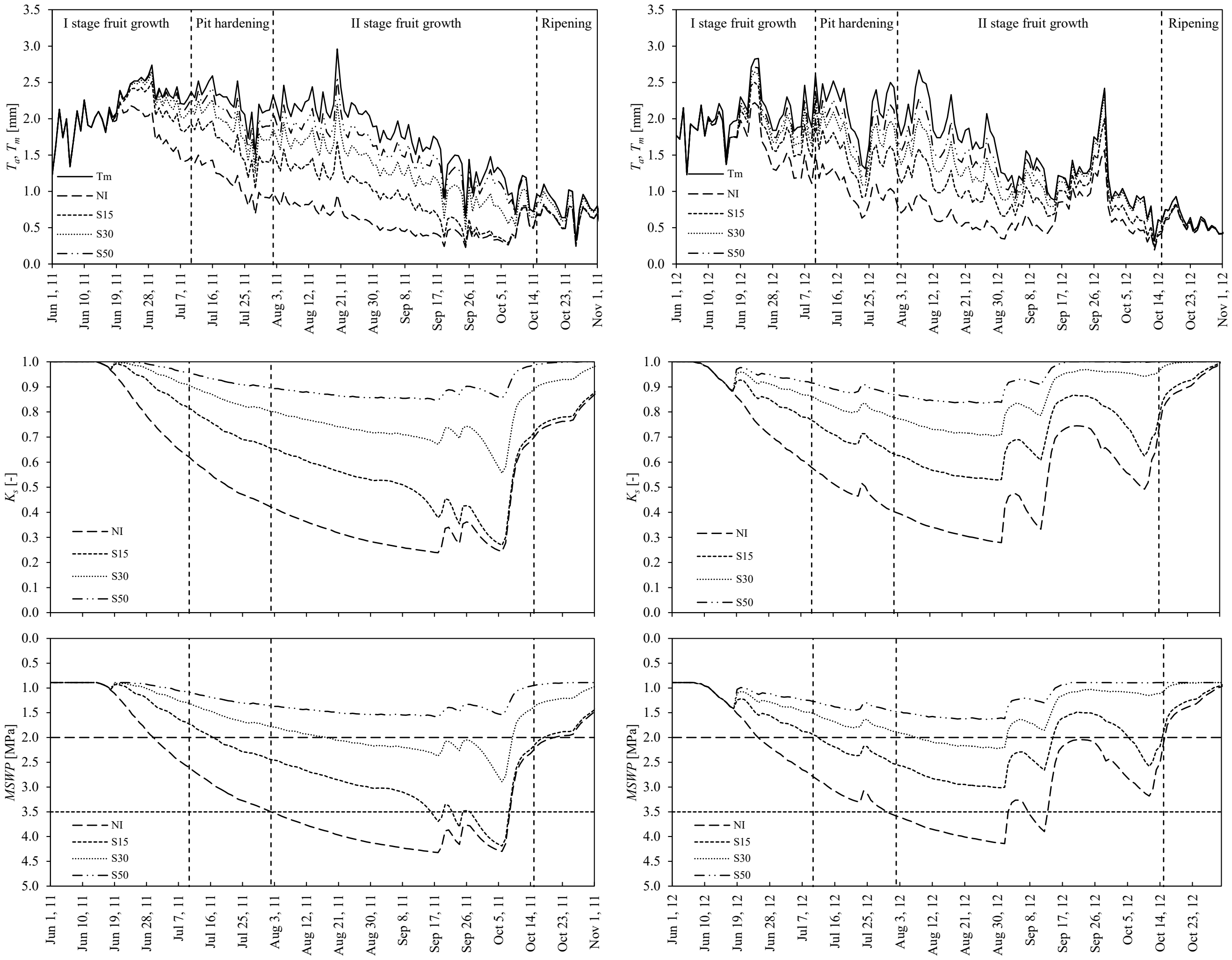

Figure 8 – Temporal dynamic of maximum and simulated actual transpiration (a, b), crop water stress coefficient (c, d) and Midday Stem Water Potential (e, f) under different irrigation scheduling scenarios, as obtained in 2011 and 2012. Horizontal lines in the lower graphs represents the thresholds of mild (2.0 MPa) and moderate (3.5 MPa) stress.

Depth [cm]	***θ_s*** [cm^3 cm^{-3}]	***θ_r*** [cm^3 cm^{-3}]	***α*** [-]	***n*** [-]	***K_s*** [cm d^{-1}]	***λ*** [-]
0-15	0.39	0.00	0.008	1.32	70	0.5
15-45	0.39	0.06	0.014	1.21	60	0.5
50-70	0.39	0.06	0.014	1.21	40	0.5
80-100	0.39	0.06	0.022	1.18	20	0.5

Table 1 - Parameters of soil hydraulic functions.

	Soil Water Contents				**Transpiration Fluxes**			
Year	***N***	***MBE*** [cm^3 cm^{-3}]	***RMSE*** [cm^3 cm^{-3}]	***NSE*** [-]	***N***	***MBE*** [mm]	***RMSE*** [mm]	***NSE*** [-]
2011	400	-0.004	0.04	0.51	152	-0.16	0.09	0.61
2012	400	-0.056	0.09	0.18	41	0.06	0.05	0.44

Table 2 – Results of statistical analysis carried out to compare simulated and measured soil water contents and transpiration fluxes in 2011 and 2012 (*N*= number of observations).

	Climate variables					MSWP					
						I Stage		Pit hardening		II Stage	
	P	I	T_m	T_a	D	μ	σ	μ	σ	μ	σ
	[mm]					[MPa]					
2011											
NI	0.4	0.0	166.6	87.9	2.1	1.4	0.6	3.1	0.3	3.9	0.5
S_{15}		25.0		121.6	2.0	1.1	0.3	2.1	0.2	3.1	0.5
S_{30}		50.0		141.3	2.1	1.0	0.1	1.6	0.1	2.1	0.3
S_{50}		83.3		153.7	5.1	0.9	0.1	1.2	0.1	1.4	0.1
2012											
NI	3.8	0.0	152.4	76.1	1.6	1.7	0.7	3.2	0.2	3.3	0.7
S_{15}		22.9		105.7	1.6	1.3	0.3	2.3	0.2	2.4	0.5
S_{30}		45.7		123.9	1.6	1.2	0.2	1.7	0.1	1.6	0.5
S_{50}		76.2		135.8	2.9	1.1	0.1	1.4	0.1	1.2	0.3

Table 3 – Values of precipitation, irrigation, maximum and actual transpiration registered in 2011 and 2012, between June 13 and August 30. Average (μ) and standard deviation (σ) of MSWP in the different stages of vegetative growth are also indicated.