Assessing AQUACROP water atress function to evaluate the transpiration reductions of olive mature tree

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Abstract: *Quantitative evaluation of the drought adaptation processes of crops is an important prerequisite for efficient irrigation management. Modeling the plant response under water stress conditions is crucial to identify the exact irrigation timing. Assessment of any water stress function requires the knowledge of its shape and then the estimation of critical thresholds of the soil water status, below which a strong reduction of plant transpiration occurs. In this work, the macroscopic approach is used to assess the water stress function implemented in AQUACROP for mature olive tree. In particular, after discussing about the function shape, the critical thresholds of soil water status are proposed according to experimental data. Eco-physiological measures (leaf and stem water potentials) were used as water stress indicators, whereas the relative depletion was considered as independent variable. The investigation evidenced, for the investigated crop, that a convex shape better reproduces the water stress function.*
Keywords: *Olive crop, Water stress functions, Leaf water potentials.*

Riassunto: *Valutare quantitativamente i processi di adattamento ai fenomeni di deficit idrico del suolo è un importante prerequisito per una gestione efficiente dell'irrigazione. La modellizzazione della risposta della pianta alle condizioni di deficit idrico del suolo è cruciale soprattutto per definire l'esatto momento di intervento irriguo. Per la definizione della funzione di stress idrico è richiesta la conoscenza della forma del tratto che descrive lo stress come anche la definizione della soglia critica di stato idrico del suolo che segna il passaggio alla condizione di stress. In questo lavoro, con riferimento all'olivo, l'ausilio dell'approccio macroscopico è stato usato per validare la funzione di stress idrico implementata in AQUACROP. In particolare, le soglie critiche di stato idrico del suolo sono state determinate partendo da un data set sperimentale collezionato con misure di campo. Misure di potenziale xilematico sono state utilizzate come base per la quantificazione dello stress idrico, mentre lo stato idrico del suolo è stato monitorato considerando la depletion relativa. La sperimentazione ha evidenziato, per la coltura investigate, che la forma convessa meglio descrive la risposta dell'olivo alla variazione dello stato idrico del suolo.*
Parole chiave: *Olivo, Stress idrico, Potenziale xilematico.*

INTRODUCTION

Table Olive (*Olea europeae* L.) is an important crop for the Mediterranean countries. In the past, olive grove were mostly rain fed, due to their resilience to water scarcity; the practice of irrigation is relatively recent and it has been introduced in order to increase crop productions and to improve yield quality (Patumi *et al.*, 2002; D'Andria *et al.*, 2004). Several researches have been focusing on the optimization of irrigation for olive trees (Fernandez and Moreno, 1999) and it has been recognized how, maintaining olive trees under slight or moderate water stress at specific phenological stages, can contribute to optimize yield and water use efficiency (Patumi *et al.*, 1999; Berenguer *et al.*, 2006; Caruso *et al.*, 2011).
The impact of water stress, as well as its feasible duration and intensity, depends on crop phenological phase in which the stress occurs. Defining irrigation doses and timing under slight or moderate water stress levels, requires to monitor the water status in the soil-crop system and to identify affordable indicators, able to provide suggestions for irrigation scheduling in order to optimize crop yield and water use efficiency.
Modeling the crop response to soil water deficit plays therefore a key role for irrigation scheduling, especially under limited water supply.
Even if various linear and nonlinear functions, aimed to relate the water stress coefficient to the soil/plant water status, have been proposed for different crops (Ahuja *et al.*, 2008), there is a lack of knowledge relatively to olive orchards, so that specific investigations are required.
AQUACROP (Steduto *et al.*, 2009) is a crop-model recently proposed by FAO, simulating yield response to water of several herbaceous crops. It is designed in particular to address conditions where water is a key limiting factor in crop production.
The natural crop response to water deficit can be monitored through the environmental and soil

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variables associated to water requirements, controlling the transpiration reduction processes. The definition of the water stress function characterizing the crop response under protracted water deficit, however, needs the knowledge of critical thresholds of soil-plant water status allowing to recognize when incipient or critical conditions of crop water stress occurs. Fernandez *et al.* (1997) found an almost value of pre-dawn xilematic water potential around 0.46 MPa, identifying a condition of absence of water stress, when the fraction of the total soil extractable water was higher than 0.4.

Objective of the work is to investigate on the relationship between plant and soil water status for mature olive orchards, in order to define critical thresholds of soil water content determined according to predawn leaf or midday stem water potentials. Finally, for the investigated crop, the value of the calibration parameter, appearing in the water stress functions implemented in AQUACROP, is evaluated according to the experimental measurements.

Modeling Plant Water Stress Response

Under water stress conditions transpiration fluxes are limited by the reduction of the stomatal opening (Farquhar and Sharkey, 1982). Accurate estimation of the plant water status is possible when the level of free energy in each point of the soil-plant is known (Reigosa Roger, 2001). This approach, defined as "microscopic approach", needs the definition of the water potentials gradient at the interface between soil and roots and the flux resistances along the path. Furthermore, it requires the determination of many parameters like the roots surface, often difficult to determine (Gardner *et al.*, 1991).

Due to these difficulties, a simpler approach, accounting for global stress indicators (relative transpiration, xylematic water potential, etc.), can allow to identify empirical functions, describing the observed plant response to water stress. Actual transpiration values can be evaluated multiplying the potential transpiration for a water stress coefficient, under the hypothesis that the root density is constant in depth and time. In such approach, the water uptake by roots is described from a macroscopic viewpoint. It considers in fact a bulk volume of soil and roots, rather than the transport mechanism through each single root, as considered in the microscopic approach.

Application of macroscopic approach does not require the detailed knowledge of the physical processes related to the root water uptake and removes the difficulties to measure soil and plant related parameters. On the other hand, it is necessary to define the water stress function for each different soil-plant system.

The shape of transpiration reduction function depends on several factors and in particular on the eco-physiological processes, like plant resistance/tolerance/avoidance to water stress (Larcher, 1995), as well as on soil water availability in the root zone (Guswa *et al.*, 2004).

The water stress function for xerophytes species is generally represented with a convex curve, because the reduction of actual transpiration becomes severe only for extreme water stress. On the other hand, concave shapes of the function, denote strong reductions of actual transpiration, even for slight stress levels.

In AQUACROP a non-linear water stress function was proposed by Steduto *et al.* (2009). Authors suggested to describe the plant stress response with a crop transpiration reduction coefficient, K_s, function of the relative depletion, D_{rel}:

$$K_s\left(D_{rel}\right) = 1 - \frac{e^{D_{rel} f_s} - 1}{e^{f_s} - 1} \qquad (1)$$

in which f_s is a parameter defining the shape of the stress function $K_s(D_{rel})$. In particular, this function is linear when f_s tends to 0, concave for f_s<0, and convex for f_s>0. The relative depletion can be evaluated as:

$$D_{rel} = \frac{\theta^* - \theta}{\theta^* - \theta_{\min}} \qquad (2)$$

where θ is the threshold value of the soil water content below which water stress occurs and $\theta_{\min}$ corresponds to the soil water content for which the stress is at its full strength.

According to eq. 1, water stress starts when D_{rel}>0 (K_s<*1*); at the lowest water content (θ_{min}), the effect of water stress is extreme (D_{rel}=1; K_s =0).

For each value of the relative depletion, the stress coefficient K_s can be evaluated in terms of leaf/steam water potentials or stomatal conductance (Raes, 2008). Whatever eco-physiological variable is used, it is necessary to normalize its measured value to a fractional scale variable in the range 0-1.

Predawn leaf water potential, *PLWP*, measures the plant water status at theoretical (or nominal) zero plant water flux and provides information on soil water potential in the root zone as a consequence of the equilibrium between soil and atmosphere. Midday stem water potential, *MSWP*, measured on a non-transpiring leaf (Begg and Turner, 1970), for a certain soil-plant-atmosphere system, depends on soil water status. It is in fact the result of the whole plant transpiration depending on the soil and root/soil hydraulic conductivity.

Considering that the described stress function, $K_s(D_{rel})$, is empirical, upper and lower thresholds of soil/crop water status must be locally evaluated, in order to take into account, the crop, the climate and the soil properties. Moreover, for each soil-crop system the definition of the water stress function requires also the estimation of its shape parameter.

MATERIALS AND METHODS

Site descriptions and soil characteristics

Experiments were carried out during irrigation seasons 2008 and 2009 (from June to September), in the farm "Tenuta Rocchetta" located near Castelvetrano, in SW of Sicily (Lat. 37° 38' 36,8", Long. 12° 50' 49,8").

The farm, having an extension of about 13 ha, is mostly cultivated with table olive grove (*Olea europaea* L., var. Nocellara del Belice), representing the main crop in the surrounding area. In the experimental plot, whose extension is about 3 ha, 15 years old olive trees are planted on a regular grid of 8 x 5 m (250 plants/ha); the mean canopy height is kept to about 3.7 m and the average crop fraction coverage is about 0.35. Irrigation is practiced by means of a drip irrigation system, with four 8 l h^{-1} emitters per plant.

Meteorological data (incoming short-wave solar radiation, air temperature, air humidity, wind speed and rainfall) were hourly collected by SIAS (Servizio Informativo Agrometeorologico Siciliano), with standard equipments installed approximately 500 m apart from the experimental field. The weather data were used to calculate the reference evapotranspiration (ET_{ref}) with the FAO-Penmann equation (Allen *et al.*, 1998), as well as the vapor pressure deficit (*VPD*).

For the investigated soil profile, water retention curves were determined on eight undisturbed soil samples, 0.08 m diameter and 0.05 m height, collected at depth of 0, 30, 60 and 100 cm. Hanging water column apparatus (Burke *et al.*, 1986) was used to evaluate soil water contents corresponding to h values ranging from -0.05 to -1.0 m; pressure plate apparatus (Dane and Hopmans, 2002), with sieved soil samples 0.05 m diameter and 0.01 m height, was used to determine soil water contents corresponding to h values of -3.37 m, -10.2 m, -30.6 m, and -153.0 m. For each undisturbed sample dry bulk density, ρ_b, [Mg m^{-3}] was also determined.

The van Genuchten model (van Genuchten, 1980) was the used to fit experimental data; the water retention curve parameters were obtained by means of the RETC code (van Genuchten *et al.*, 1992).

The total irrigation depth provided by the farmer in 2008 and 2009 was equal to 122 mm, divided in four watering and 127 mm divided in five watering, respectively.

In order to evaluate the water stress thresholds and to estimate the model's parameter, experiments were carried out by monitoring, during a dry period and at the scale of the plant, the evolution of the water stress coefficient, K_s, determined according to plant water status and the corresponding relative depletion, D_{rel}, depending exclusively on soil water status.

Measurements of soil and plant water status

The dynamic of soil and tree water status was investigated in the area surrounding three olive plants, located inside the 3 ha plot.

Spatial and temporal variability of soil water contents was monitored, from the soil surface to a depth of 100 cm, using the Diviner 2000 Sentek FDR probe (Frequency Domain Reflectometry). The probe containing the sensor, when inserted in the access tube, allows to measure soil water content at different depths. Before using the probe a site specific calibration was carried out (Rallo, 2010), with the aim to determine the relationship between the Scaled Frequency, measured by the probe and the volumetric soil water content, θ. Five access tubes were installed between two consecutive trees, along the direction of the irrigation pipeline, where the highest gradient of soil water content occurs. Soil water content measurements were carried out every five days, as well as before and after irrigation.

Values of soil water contents measured with the FDR systems were then averaged proportionally to the measured spatial root density (Rallo *et al.*, 2009), in order to evaluate, for each measurement, a single value of θ, representative of the soil layer where the water uptake mainly occurs.

After determining the limits of the soil water content domain in which the crops is under stress condition, for each soil water content, θ, the relative depletion was determined with eq. 2. The knowledge of the soil water retention curve allowed also to evaluate the average soil matric potential in the root zone, h, corresponding to θ. On the other side, plant water status was evaluated by means of *PLWP* and *MSWP*, measured by using a pressure chamber (Scholander *et al.*, 1965) with the protocol proposed by Turner e Jarvis (1982), in the same three trees, where the soil water status was monitored. Measurements were carried out every five days, as well as the days immediately before and after each irrigation.

RESULTS AND DISCUSSION

Analysis of soil-plant water status and atmosphere evaporative demand

Fig. 1 shows the temporal dynamic, between July and September 2008 and 2009, of reference evapotranspiration (ET_{ref}) and vapor pressure deficit (*VPD*), calculated by means of the FAO procedure (Allen *et al.*, 1198). Predawn leaf and midday stem water potentials (*PLWP* and *MSWP*), the average of soil water content in the layer 0-100 cm, as well as irrigation and precipitation heights are also showed.

In the first decade of July 2008, the predawn leaf water potentials are around the critical values of 0.5 MPa, representing the stress condition

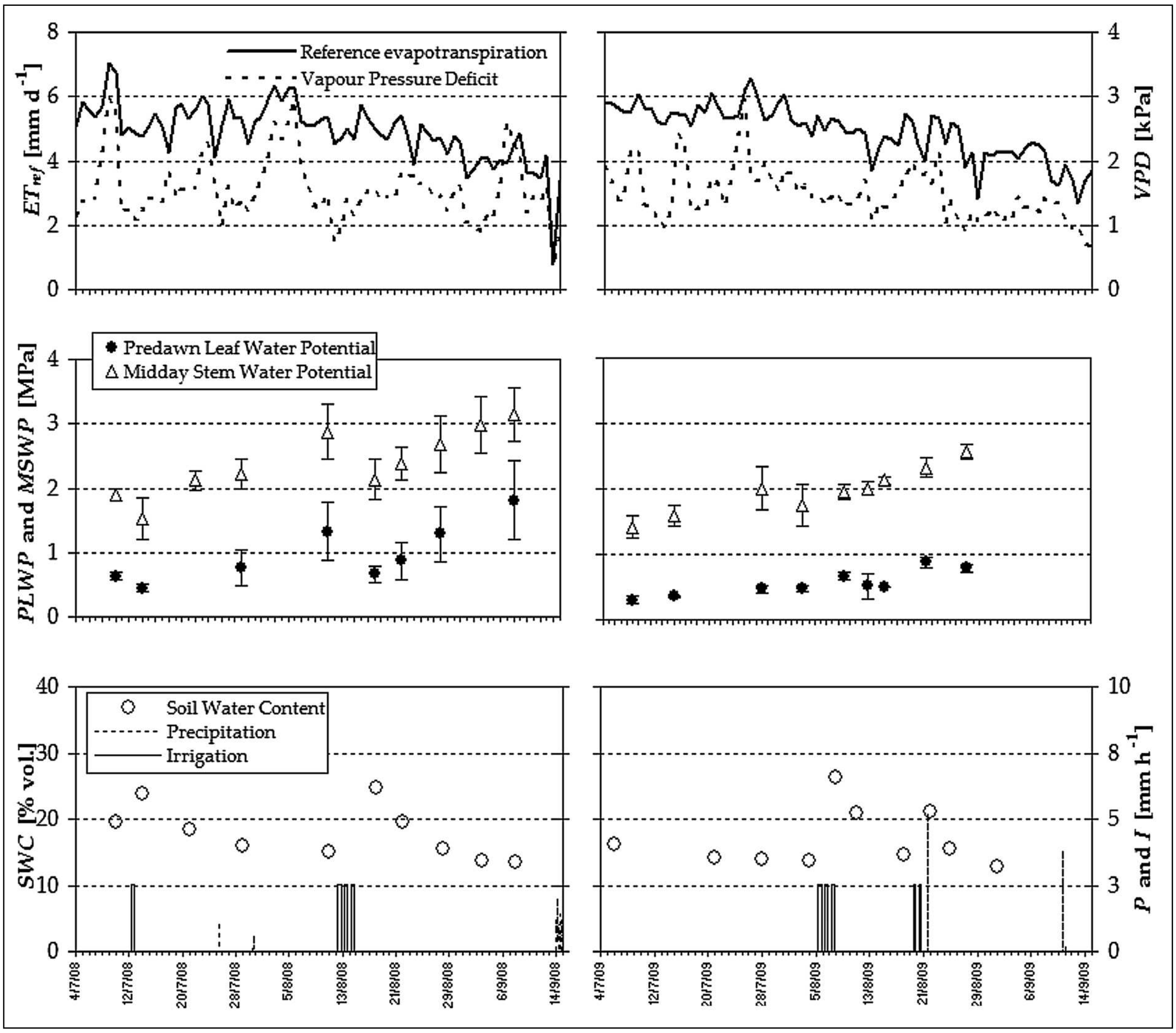

Fig. 1 - Temporal dynamic of reference evapotranspiration (ET_{ref}), vapour pressure deficit (*VPD*), predawn leaf and midday stem water potential (*PLWP* and *MSWP*) and soil water content for the 2008 (left) and 2009 (right) investigated period.

Fig. 1 - Dinamica temporale dell'evapotraspirazione della coltura di riferimento (ET_{ref}), del deficit di pressione di vapore (VPD), dei potenziali idrici xilematici (PLWP e MSWP) e dei contenuti idrici del suolo per le stagioni 2008 (a sinistra) e 2009 (a destra).

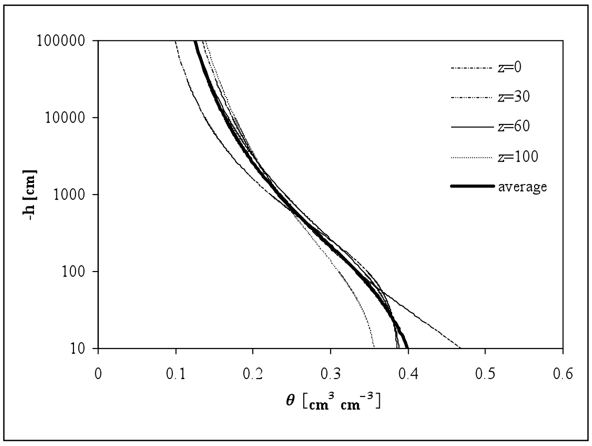

Fig. 2 - Soil water retention curves for the four investigated layers and average curve obtained for the entire soil profile (0-100 cm).
Fig. 2 - Curve di ritenzione idrica per i quattro strati di suolo investigati.

proposed by Dettori (1989). During the following period, *PLWPs* increased until the second week of August, before irrigation, due to the reduction of soil water content from 25% to less then 16%. The maximum *SWC* (26%) observed after irrigation, corresponding to a value of *PLWP* of 0.6 MPa, was followed by a second soil drying process, during which leaf potentials increased toward to value of 1.9 MPa. A similar trend was found when *MSWPs* were analyzed.
Relatively to year 2009, despite the soil water contents decreased from 16% to 12% before the first watering, *PLWP* varied around to 0.5 MPa, evidencing a condition of absence of water stress. This circumstance could be explained considering the plant ability to increase the available soil volume for water uptake. The complex root system, in fact, allows the plant to compensate the effects of the soil moisture variability, activating the roots placed in the soil volume characterized by higher water contents.
After watering, the dynamic of *PLWPs*, despite the limited variation probably due to the antecedent soil moisture distribution, followed the soil drying process. However a better comprehension of the soil-plant-water relationship could be possible with a more detailed knowledge of the soil moisture spatial variability in the root zone.

Plant-Soil water relationships and definition of critical thresholds
Fig. 2 shows the soil water retention curves obtained for the investigated soil layers. Considering that, except near saturation, the differences between the soil water contents measured at the different layers are negligible, for each fixed matric potential, the average soil water retention curve, was considered for the entire soil profile.
Fig. 3a-b shows the experimental values of *PLWP* or *MSWP* and the corresponding soil water contents, averaged for the root density, in the layer 10-100 cm. Despite it was quite difficult to identify an unambiguous value of the critical soil water content, below which the plant is under water stress conditions, the critical value of $\theta^* \approx 16\%$, corresponding to a soil matric potential of about -40 m, was considered as the searched threshold. The observed uncertainty could be due to xilematic potentials adjustment, occurring

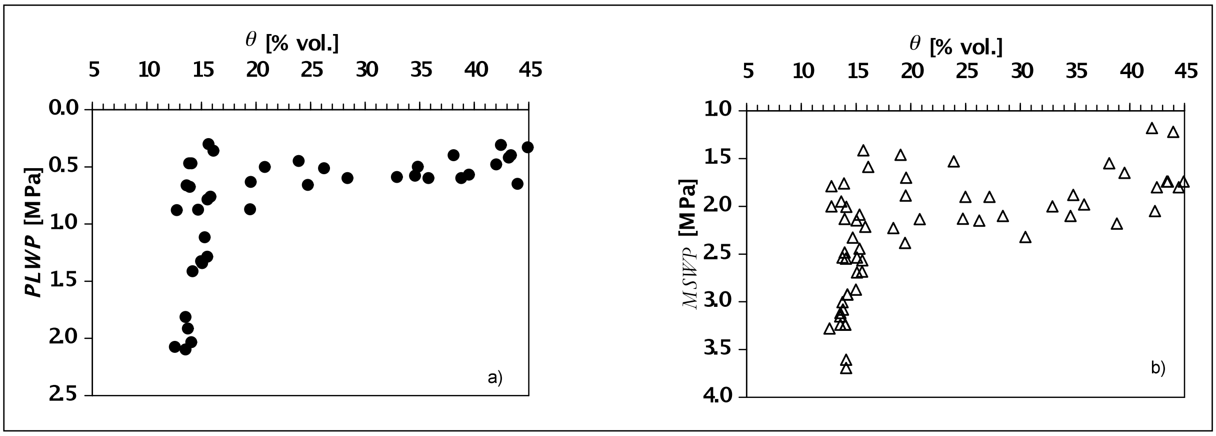

Fig. 3a-b - Experimental values of *PLWP* (a) and *MSWP* (b) and corresponding average soil water contents in the layer 10-120 cm.
Fig. 3a-b - Dati sperimentali dei potenziali idrici xilematici, PLWP (a) e MSWP (b) e corrispondenti valori di contenuto idrico del suolo per lo strato di 10-120 cm.

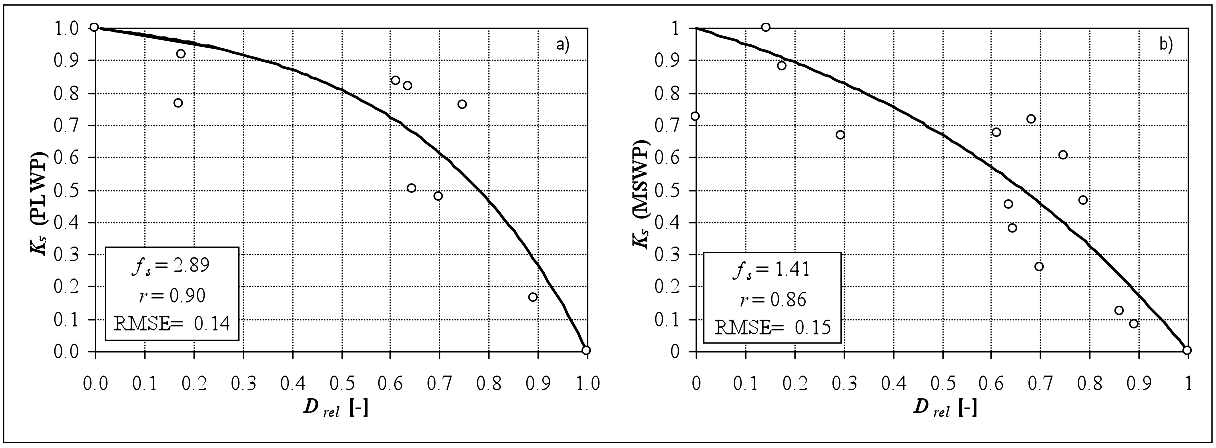

Fig. 4 a-b - D_{rel}-K_s experimental data pairs and fitted models.
Fig. 4 a-b - Coppie di valori D_{rel}-K_s con relativi modelli fittati.

when the plant is kept under soil water deficit for long time periods.
The critical value θ separates two different plant behaviors (fig. 3a): for $\theta>\theta^*$, *PLWPs* are almost constant and approximately equal to 0.5 MPa, identifying the condition of absence of water stress (Dettori, 1989). On the other side, for $\theta<\theta^*$, lower is the soil water content, smaller is the *PLWP*, as consequence of the progressively increasing crop water stress. Similar results can be observed when *MSWPs* are considered in place of *PLWPs* (fig. 3b).
The higher dispersion observable for $\theta>\theta^*$, when *MSWPs* are considered, can be explained by the sensibility of the midday stem potentials from the environmental variables. On the contrary, under water stress conditions ($\theta<\theta^*$) the dispersion is comparable, as consequence of the minor effect of the environmental variables.
Experimental data showed in fig. 3 a-b, also allowed to identify the minimum soil water content corresponding to the maximum level of water stress recognized in the field, that resulted slighted higher that 11%.

Evaluation of the water stress function parameter

According to the experimental data, water stress conditions were recognized in the range of soil water contents variable between 16% and 11%, in which the water stress model was therefore fitted. In particular, the values of D_{rel} were evaluated with eq. 2, assuming θ^*=16% (D_{rel} =0) and θ_{min}=11% (D_{rel} =1). For each D_{rel}, the values of K_s was then evaluated by normalizing the predawn leaf/midday stem water potentials respect to their domain limits, in order to obtain a fractional scale, variable in the range between 0 and 1.
The water stress model parameter, f_s, was then obtained by fitting eq. 1 to the D_{rel}-K_s experimental values with least square method, by using the package Excelstat (Addinsoft USA, 2007) and the Pearson correlation coefficient.
Fig. 4 a-b shows the experimental D_{rel}-K_s data pairs and the fitted equations, obtained considering *PLWP* (fig. 4a) and *MSWP* (fig. 4b), respectively.
As can be observed in fig. 4, for both the cases f_s>0, and therefore the shape of the model resulted convex. Despite the similar *RMSE* values, the slightly higher dispersion visible when the *MSWPs* are considered is a consequence of the sensitivity of the measurements from the variation of the environmental variables.

CONCLUSIONS

The water stress function implemented in AQUACROP model was assessed for mature olive trees, after defining critical thresholds of soil water status identifying the crop water stress conditions. Experiments carried out in SW of Sicily, allowed to determine two critical thresholds of soil water content, equal respectively to 16% (soil matric potential of about -40m) and to 11% (soil matric potential of about -200 m). In particular for θ>16%, the absence of water stress was observed, according to the predawn leaf water potentials, that resulted approximately constant and equal to about 0.5 MPa; for θ<16% instead, the crop water stress increased at decreasing soil water contents. At the minimum soil water content recognized in the field, predawn leaf water potentials, as well as midday stem water potentials, reached quite high values, both indentifying a severe water stress condition.

For the investigated crop, the shape of the examined water stress model is convex, and therefore the reduction coefficients (K_s) of actual transpiration become severe only under extreme water stress conditions. Further experiments are in progress in order to investigate about the effects on soil-plant water relationships of the soil water content spatial variability as well as to validate the estimated parameter of the proposed water stress function.

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AUTHOR'S CONTRIBUTION

Contribution to the paper has to be shared as following: Field data collection and data processing were cared by G. Rallo. Text was written by G. Rallo. Set-up of the research and the final revision of the text have to be equally divided between all the Authors.

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