Assessment of discretely measured indicators and maximum daily trunk shrinkage for detecting water stress in pomegranate trees

A. Galindo[a], P. Rodríguez[b], C.D. Mellisho[a], E. Torrecillas[c], A. Moriana[d], Z.N. Cruz[b], W. Conejero[a], F. Moreno[e], A. Torrecillas*[,a,f]

[a] Dpto. Riego. Centro de Edafología y Biología Aplicada del Segura (CSIC).
P.O. Box 164, E-30100 Espinardo, Murcia, Spain.

[b] Dpto. Fisiología y Bioquímica, Instituto Nacional de Ciencias Agrícolas (INCA).
Ctra. de Tapaste, km 3.5. San José de Las Lajas, Mayabeque, Cuba

[c] Dpto. Conservación de Suelos y Agua. Centro de Edafología y Biología Aplicada del Segura (CSIC). P.O. Box 164, E-30100 Espinardo, Murcia, Spain.

[d] Escuela Técnica Superior de Ingeniería Agronómica. Universidad de Sevilla,
Carretera de Utrera, km 1, E-41013 Sevilla, Spain

[e] Instituto de Recursos Naturales y Agrobiología (CSIC), P.O. Box 1052, E-41080 Sevilla, Spain

[f] Unidad Asociada al CSIC de Horticultura Sostenible en Zonas Áridas (UPCT-CEBAS). Paseo Alfonso XIII s/n, E-30203 Cartagena, Murcia, Spain.

*Corresponding author. Tel.: +34 968 396330; fax: +34 968 396213.

E-mail address: atorreci@cebas.csic.es (A. Torrecillas).

Abstract

Measurements obtained by the continuous monitoring of trunk diameter fluctuations were compared with discrete measurements of midday stem water potential (Ψ_{stem}) and midday leaf conductance (g_l) in adult pomegranate trees (*Punica granatum* (L.) cv. Mollar de Elche). Control plants (T0) were irrigated daily above their crop water requirements in order to attain non-limiting soil water conditions, while T1 plants were subjected to water stress by depriving them of irrigation water for 34 days, after which time irrigation was restored and plant recovery was studied for 6 days. The water relations in T0 pomegranate plants confirmed that they had not suffered waterlogging. In contrast, T1 plants showed a substantial degree of water stress, which developed slowly. Maximum daily trunk shrinkage (MDS) was seen to be the most suitable plant-based indicator for precise irrigation scheduling in adult pomegranate trees, because its signal:noise ratio was higher than that for Ψ_{stem} and g_l. MDS increased in response to water stress, but when the Ψ_{stem} fell below −1.67 MPa, the MDS values decreased. Reference or baseline relationships for MDS measurements can be obtained by pooling data across several seasons using crop reference evapotranspiration (ETo), mean daily air vapour pressure deficit, mean daily air temperature and solar radiation. In this way, ETo was seen to be the best predictor of MDS. These findings open up the possibility of normalizing MDS measurement at a given time respect to the expected value under non-limiting water conditions, which can be calculated from the reference relationships.

Key words: Plant water relations; Punica granatum; trunk diameter fluctuations; water stress

1. Introduction

Pomegranate (*Punica granatum* L.) is one of the oldest known edible fruits, being among the seven kinds of fruit mentioned in the Bible (Blumenfeld et al., 2000). However, despite being grown commercially in many regions of the world, including countries of the Mediterranean Basin (Stover and Mercure, 2007; Holland et al., 2009), it has frequently been considered a minor crop. The way at which it is regarded is beginning to change and there is a growing interest in the consumption of its fruits for their organoleptic characteristics and their perceived health benefits (Michel et al., 2005; Lansky and Newman, 2007). Moreover, pomegranate is a very interesting fruit tree species because it has drought tolerance characteristics common in xeromorphic plants, such as high leaf relative apoplastic water content, and it is able to confront water stress by developing complementary stress avoidance and stress tolerance mechanisms (Rodríguez et al., 2012). For these reasons, this drought-hardy crop thrives well in arid and semiarid areas, even under desert conditions (Sarkhosh et al., 2006; Zamani et al., 2008).

Frequent situations of imbalance between water supply and demand occur in Mediterranean agrosystems, which are facing increasing pressure to reduce water use. Indeed, there is a constant need to improve water use efficiency, and among the tools that growers can use to achieve this goal are more precise irrigation scheduling procedures that will protect water resources and their integrity for their future use (Naor and Cohen, 2003; Katerji et al., 2008)

Bhantana and Lazarovitch (2010) measured the evapotranspiration (ET), crop coefficients (K_c) and growth in two young pomegranate tree cultivars grown in lysimeters to varying electrical conductivity of the irrigation water. Also, Intrigliolo et al. (2011a) suggested tentative preliminary irrigation recommendations for pomegranate trees. However, to our knowledge, no specific studies have been conducted on irrigation water requirements in adult pomegranate plants under field conditions. Moreover, to reach optimal growth, yield and fruit quality in arid and semiarid conditions, pomegranate trees require regular irrigation, particularly during the dry season (Holland et al., 2009; Prasad et al. 2003; Shaliendra and Narendra, 2005; Sulochanamma et al., 2005). Hence, studies on pomegranate water requirements and related criteria for precise irrigation management practices are needed.

The use of plant-based water status indicators has become very popular for planning precise irrigation, because plant water status is the best way for predicting crop performance to a given irrigation scheduling regime. Since the plant water status controls many physiological processes and crop productivity, this information can be highly useful in irrigation scheduling (Fernández and Cuevas, 2010; Ortuño et al., 2010). Measurements of trunk diameter fluctuations (TDF) using LVDT (linear variable differential transducer) sensors provide continuous and automated recording of maximum daily trunk shrinkage (MDS), which seem suitable for the development of automated irrigation scheduling in fruit trees (Conejero et al., 2007; Ortuño et al, 2009a; Moriana et al., 2010).

Because plants are in the middle of the soil-plant-atmosphere continuum, plant water status is the result of the soil water availability and the evaporative demand. Therefore, absolute water stress indicator values recorded without considering the evaporative demand might be meaningless. For this reason, it is better to use the concept of signal intensity (SI) for irrigation scheduling, normalizing the indicator absolute values with respect to values in non-limiting soil water conditions (Naor and Cohen, 2003; Goldhamer and Fereres, 2001; Ortuño et al., 2005, 2006). Water stress indicator SI is a dimensionless variable, where values above unity indicate water stress levels, while SI values of unity indicate the absence of irrigation-related stress (Goldhamer and Fereres, 2004). One option for obtaining water stress indicator reference values could be to previously define the effects of the evaporative demand on the plant water status indicator and later to use this relationship or baseline as a reference to correct the actual water stress indicator values obtained.

Intrigliolo et al. (2011b) suggested i) that differences in pomegranate water status could be detected earlier for midday stem water potential (Ψ_{stem}) than for MDS, ii) also, these authors found a significant, but relatively low, correlation between MDS and crop reference evapotranspiration (ETo) (MDS (µm) = 23.0 ETo (mm) + 8.8. r^2 = 0.44***), whereas the relationships between MDS and air temperature and air vapour pressure deficit were even weaker, and iii) as a final point, these authors indicated that the best fit between MDS and Ψ_{stem} was obtained with a linear regression, which changed in concordance with some changes in the fruit growth pattern or fruit removal. These behaviors present some differences respect to those observed in other fruit trees. For example, i) MDS has been frequently found as more sensitive than the other indicators in detecting plant water stress (Ortuño et al., 2010), ii) some authors have showed that it is possible to predict adequately MDS reference values in crop trees when meteorological variables measured on a whole-day basis are used (Moreno et al., 2006; Ortuño et al., 2009b; Conejero et al., 2011), and iii)

Ortuño et al. (2010) indicated that in several fruit tree species under drought stress the decrease in Ψ_{stem} is associated with an increase in MDS, but this pattern changes at values below a Ψ_{stem} threshold and any further reduction in Ψ_{stem} is associated with a decrease in MDS values.

For these reasons, the objective of the present study was to compare the sensitivity of MDS and discretely measured indicators of the plant water status in adult pomegranate trees in response to a cycle of water deprivation and recovery, establishing the relationship between MDS and the plant water status. The feasibility of obtaining baselines for tree water status indicators in trees under non-limiting water conditions and their inter-season constancy was also investigated.

2. Materials and Methods

2.1. Plant material, experimental conditions and treatments

Experiment 1 (2009)

The experiment was carried out in 2009 on a farm located near the city of Murcia (Spain) (37°57' N, 0°56'W). The plant material consisted of own rooted 10-year old pomegranate trees (*Punica granatum* L.) cv. Mollar de Elche, with an average trunk diameter of about 15 cm. Tree spacing followed a 3 m × 6 m pattern, with an average ground cover of about 59 %.

The soil of the orchard was a weakly saline (2.1 dS m^{-1}) Xeric Torriorthent, with silt loam texture, high lime content (46 % calcium carbonate), very low organic matter content (0.92 %), low cationic exchange capacity (7.93 meq 100 g^{-1}), and low available potassium and phosphorus levels. The irrigation water had an electrical conductivity of between 1.7 and 2.2 dS m^{-1} and the Cl^-

concentration in the irrigation water ranged from 36 to 48 mg l^{-1}.

Control plants (treatment T0) were irrigated above crop water requirements (115 % ETo), using six emitters (each delivering 4 l h^{-1}) per plant. Irrigation in T1 plants was withheld for 34 days (from day of the year (DOY) 209 to 243, second half of rapid fruit growth period). The recovery of plants was ensured by re-irrigation at the levels used in T0 for 6 days (from DOY 244 to 250). Total water amounts applied in experimental period were 261 and 38 mm for T0 and T1 treatments, respectively.

Experiment 2 (2010)

The experiment was performed in 2010 on other farm also located near the city of Murcia (Spain) (37º47'N, 1º25'W). The plant material was own rooted 10-year old pomegranate trees (*Punica granatum* L.) cv. Mollar de Elche, with an average trunk diameter of about 17 cm. Tree spacing followed a 3 m × 6 m pattern, with an average ground cover of about 68 %.

The soil of the orchard was a Hyposalic Calciorthid moderately saline (5.9 dS m^{-1}), with a silt loam texture, moderate lime content (20 % calcium carbonate), very low organic matter content (1.1 %), low cationic exchange capacity (9.32 meq 100 g^{-1}), low available potassium and high available phosphorus levels. The irrigation water used had an electrical conductivity of between 0.8 and 1.0 dS m^{-1}. The Cl^- concentration in the irrigation water ranged from 62 to 70 mg l^{-1} during the experimental period.

In 2010, from DOY 210 to 294 (from the beginning of the second half of rapid fruit growth period to the beginning of leaf fall), only over irrigated plants (T0) were considered. In order to guarantee non-limiting soil water conditions, control plants (treatment T0) were irrigated above crop water requirements (107 % ETo), using three emitters (each delivering 4 l h^{-1}) per plant. Total water amount applied during the experimental period to T0 plants was 414 mm.

During both experiments pest control and fertilization practices were those usually used by local growers, and no weeds were allowed to develop within the orchard. Irrigation was carried out daily and during the night using a drip irrigation system with one lateral pipe per tree row.

2.2. Measurements

Micrometeorological data, namely air temperature, solar radiation, air relative humidity, rainfall and wind speed 2 m above the soil surface, were collected every 15 min by automatic weather stations located near the experimental sites. Mean daily air vapour pressure deficit (VPD_m) and daily crop reference evapotranspiration (ETo) were calculated according to Allen et al. (1998).

Midday (12 h solar time) stem water potential (Ψ_{stem}) was measured on the south facing side and the middle third of the trees, in two fully developed leaves per tree of each replicate, enclosing leaves in small black plastic bags covered with aluminium foil for at least 2 h before measurements in the pressure chamber (model 3005, Soil Moisture Equipment Co., Santa Barbara, CA, USA).

Midday leaf conductance (g_l) in attached leaves was measured with a steady-state porometer (LI-1600, LICOR Inc., Lincon, USA) on the abaxial surface of the leaves and in a similar number and type of leaves as used for the Ψ_{stem} measurements.

The micrometric trunk diameter fluctuations (TDF) were measured throughout the experimental periods in four trees per treatment, using a set of linear variable displacement transducers (LVDT) (model DF ± 2.5 mm, accuracy ± 10 μm, Solartron Metrology, Bognor Regis, UK) attached to the trunk, with a special bracket made of invar, an alloy of Ni and Fe with a thermal expansion coefficient close to zero (Katerji et al., 1994), and aluminium. Sensors were placed on the north side and were covered with silver thermoprotected foil to prevent heating and wetting of the device. Measurements were taken every 2 s and the datalogger (model CR10X with AM25T multiplexer, Campbell Scientific, Logan, UT) was programmed to report 15 min means. Maximum daily trunk shrinkage (MDS) was calculated as the difference between the daily maximum diameter (reached early in the morning) and the minimum diameter (usually reached in the afternoon).

For comparing the sensitivity of the above mentioned plant-based indicators for use as water stress indicators, it is important to take into account that the absolute values of these indicators are influenced not only by the soil water availability but also by the evaporative demand, and consequently it is more suitable to compare their values relative to those of the control trees (Naor and Cohen, 2003). For this, the signal intensity of both continuous and discrete plant water status measurements were defined as the relative values (T1/T0 or T0/T1), while variability or noise was defined as the coefficient of variation of the mean. Thus, the signal:noise ratio integrates both the indicator strength and its variability, and is important for assessing the usefulness of plant-based water stress indicators for irrigation scheduling (Moreno et al., 2006; Goldhamer et al., 2000; Ortuño et al., 2004).

2.3. Statistical design and analysis

The design of the experiments was completely randomized with four replications, each replication consisting of three adjacent tree rows, each with eleven (2009) or thirteen (2010) trees. Measurements were taken on the inner tree of the central row of each replicate, which were very similar in appearance (leaf area, trunk cross sectional area, height, ground shaded area, etc.), while the other trees served as border trees. Data were analyzed using SPSS software (SPPS Inc., 2002). Analysis of variance was performed and mean values were compared by an $LSD_{0.05}$ test. Values for each replicate were averaged before the mean and the standard error of each treatment were calculated. Linear regression analysis was carried out to explore relationships between variables, and linear regression differences were determined using covariance analysis.

3. Results

During the 2009 and 2010 experimental periods, average daily maximum and minimum air temperatures were 32.5 and 20.2 ºC and 28.9 and 16.3 ºC, respectively (Fig. 1). VPD_m ranged from 0.98 to 2.84 kPa in the 2009 experimental period and from 0.67 to 2.96 kPa in the 2010 experimental period (Fig. 1), and accumulated ETo was 226 and 387 mm in the 2009 and 2010 experimental periods, respectively (Fig. 1). There was no rainfall during the 2009 experimental period, but in the 2010 experimental period total rainfall was 51 mm, which took place mainly on DOY 214 (7 mm), 232 (20 mm) and 291 (6 mm) (Fig. 1).

Ψ_{stem} values in control (T0) plants were high and quite constant, ranging between -0.73 and -0.98 MPa and between -0.76 and -0.92 MPa during the

2009 and 2010 experimental periods, respectively (Figs. 2A and 3A). During the 2009 water withholding period, Ψ_{stem} values in T1 plants gradually declined, the decrease started to be significant from DOY 212 onwards and reaching minimum values at the end of the stress period. When plants were rewatered, Ψ_{stem} values gradually increased, reaching similar values to those of the T0 plants at the end of the measurement period (Fig. 2A).

The g_l in T0 plants were high and showed fluctuations, especially during the 2009 experimental period (Figs. 2B and 3A). In T1 plants, water deficit caused a gradual decrease in g_l, the reduction started to be significant after ten days and reaching minimum values at the end of the stress period, before recovering when irrigation was renovated (Fig. 2B).

MDS values showed substantial fluctuations during the 2009 experimental period both in T0 and T1 plants (Fig. 2C). Differences between T0 and T1 treatments were evident as early as four days after the imposition of water stress, due to the MDS increase in T1 plants (Fig. 2C). When T1 plants were rewatered, MDS values fell and were similar in both treatments during the recovery period. MDS values in T0 plants during the 2010 experimental period fluctuated sharply before DOY 280, although from this day onwards, when evaporative demand decreased (Fig. 1B), MDS values were low and quite constant (Fig. 3B).

Taking into consideration the Ψ_{stem} values obtained during the 2009 experimental period and the MDS values taken at the same times, a polynomial relationship between both parameters (MDS (mm) = 0.419 + 0.979Ψ_{stem} (MPa) + 1.118Ψ_{stem}^2 (MPa) + 0.331Ψ_{stem}^3 (MPa), $r^2 = 0.685$, MSE = 0.003) was evident in the range of water stress studied (Ψ_{stem} values from –0.72 to –1.98 MPa)

(Fig. 4). This relationship was characterized by two different phases. Above Ψ_{stem} values of -1.67 MPa, MDS values increased sharply as Ψ_{stem} decreased, and when Ψ_{stem} values were below this threshold value the relationship changed and any further reduction in Ψ_{stem} was associated with a decrease in MDS. Also, despite the wider scatter, linear regression (MDS (mm) = 0.056 - 0.168Ψ_{stem} (MPa), r^2 = 0.587, MSE = 0.004) may be a good approach for modeling the relationship between Ψ_{stem} and MDS in the water stress range studied (Fig. 4).

For precise irrigation scheduling based on changes in the plant water status, it is necessary to use plant-based water stress indicators able to develop an immediate, consistent and reliable response to water deficit. As a consequence, to compare the sensitivity of the measured indicators we looked at MDS as a continuously recorded plant-based indicator and at Ψ_{stem} and g_l as discretely measured plant-based indicators. In response to water stress the SI values in the three considered plant-based water stress indicators increased, with the particular characteristic that, at the beginning of the stress period, the MDS and Ψ_{stem} SI (T1/T0) increased earlier than g_l SI (T0/T1), while MDS SI values during the water stress period showed more pronounced oscillations than the other indicators (Fig. 5). Moreover, when irrigation was restored, the SI values sharply decreased, minimum values of around unity occurring during the last days of the experiment (Fig. 5).

In a complementary manner, we studied the signal intensity, noise, and signal:noise ratio for MDS, Ψ_{stem} and g_l during increasing intervals of time from the beginning to the end of the stress period (Table 1). The data indicated that at the beginning of the water stress period MDS, Ψ_{stem} and g_l (DOY 209-217) presented similar mean SI and mean noise values. However, as the interval of time considered grew (DOY 209-238 and DOY 209-243), the Ψ_{stem} SI was significantly higher than those for MDS and g_l, while Ψ_{stem} and g_l average noise values showed a tendency to be similar and higher than those observed in MDS (Table 1). For these reasons, the MDS signal:noise ratio was the highest ratio for all the intervals of time considered, indicating that the MDS is more sensitive than the other indicators for detecting the plant water stress in our experimental conditions.

During the 2009 and 2010 experimental periods, the observations of MDS in trees under non-limiting soil water conditions correlated significantly with meteorological variables measured on a whole-day basis (ETo, VPD_m, T_m and R_s) (Table 2). These baselines in pomegranate trees suggested that the best predictor for MDS reference values is the ETo because the relation between both variables was the tightest, whereas the relation between MDS and T_m presented the widest scatter (Table 2). Moreover, the covariance analysis of the MDS seasonal baselines using ETo, VPD_m, T_m and R_s as independent variables showed that differences in slopes and intercepts between both experimental seasons were not statistically significant. This suggests that it is possible to evaluate MDS by means of a first-order fit and by pooling data across both experimental seasons (Fig. 6). The pooled data over both experimental seasons confirmed a tighter correlation for the regression of MDS versus ETo than those of MDS versus VPD_m, R_s and T_m (Fig. 6).

4. Discussion

The fact that Ψ_{stem} and g_l values in T0 plants were high throughout both experimental periods (Figs. 2A and 3A) suggesting that control pomegranate plants, despite being under non-limiting soil water conditions, never became waterlogged. In this sense, water relations under flooding conditions are characterized by a similar behaviour to those observed under water stress due to chemical signals from roots and an increase in the resistance to water flowing through the plant (Ruiz-Sánchez et al., 1996; Ortuño et al., 2007).

Ψ_{stem} values in T1 plants at the end of the water withholding period (Fig. 2A) and the stomatal regulation observed (Fig. 2B) pointed to a relatively strong water stress situation. However, the fact that Ψ_{stem} values decreased at a rate of around 0.025 MPa d^{-1} indicates that the water stress developed quite slowly (Hale and Orcutt, 1987).

It is well known that water stress triggers hormonal changes in leaves, such as an increase in abscisic acid and/or decrease in cytokinins, both mechanisms that delay stomatal aperture after rehydration (Mansfield, 1987; Davies and Zhang, 1991; Ruiz-Sánchez et al., 1997). In contrast, the speedy recovery of g_l values in T1 plants when irrigation was restarted could indicate that, at the level of water stress reached at the end of the irrigation withholding period, the stomatal regulation achieved was not mediated by hormonal changes in the leaf (Torrecillas et al., 1995; Mellisho et al., 2012).

Considering that the three measured plant-based water stress indicators have different dimensions, it is not possible to evaluate their sensitivity using their absolute values, and it is more meaningful to compare their values relative to those of the control trees (Fig. 5) (Naor and Cohen, 2003). For this, and bearing in mind that the strength of an indicator signal intensity must be seen in the context of its variability, their signal:noise ratio was compared at different time intervals (Table 1). The finding suggested that MDS is the most suitable indicator for pomegranate irrigation scheduling, because its signal:noise ratio was higher than that for Ψ_{stem} and g_l for all the intervals of time considered. In this sense, Ortuño et al. (2004, 2006) showed that continuously measured plant water status indicators were more immediate and sensitive than discretely measured indicators. Moreover, Remorini and Massai (2003) indicated that trunk diameter fluctuations differed between irrigation treatments even in the absence of differences in Ψ_{stem}, and Goldhamer et al. (1999) indicated that MDS responded sooner than Ψ_{stem} to water stress.

The changes in stem diameter are closely related to changes in water content in the whole plant (Simonneau et al., 1993). For this, several authors have observed that MDS values are a good indicator of transpiration intensity when the soil water content is not strongly depleted, and increases in MDS have been associated with decreases in water potential (Huguet et al., 1992; Herzog et al., 1995). In accordance with these ideas, our results indicated that the best fit between MDS and Ψ_{stem} was obtained with a polynomial regression model (Fig. 4), which is the behaviour more frequent in most species and it is characterized by the existence of a Ψ_{stem} threshold value (-1.67 MPa) below which any further reduction in Ψ_{stem} is associated with a decrease in MDS values (Ortuño et al., 2010; Moriana et al., 2000). However, Intrigliolo et al. (2011b), suggested that the best fit between MDS and Ψ_{stem} in pomegranate trees was obtained with a linear regression, and that there was not a single unique relationship between both variables valid for the whole season due to changes in fruit growth pattern and fruit removal. In this sense, our data also revealed the possibility of presenting the relationship between MDS and Ψ_{stem} by means of a first-order fit but the correlation obtained worsened respect to that obtained with the polynomial regression model (Fig. 4). In our opinion, to clarify the model that defines the relationship between both variables, a higher number of MDS data point corresponding to Ψ_{stem} values below -1.67 MPa would have been necessary.

The significant relations between MDS and ETo, VPD_m, T_m and Rs in pomegranate trees growing under non-limiting soil water conditions (Table 2, Fig. 6) indicated that MDS, as well as reflecting tree water status, was clearly influenced by weather conditions (Fernández and Cuevas, 2010; Ortuño et al., 2010, 2009b; Conejero at al., 2011; Moriana et al., 2011). Moreover, the possibility of obtaining these individual baselines or reference equations between MDS and environmental variables confirmed the possibility of obtaining MDS reference values to normalize the actual absolute values of MDS with respect to those in non-limiting soil water conditions.

Taking into consideration that MDS reflects the continuous trunk diameter records on a diurnal basis, being an integrative indicator could explain its direct relation with climatic variables measured on a whole-day basis (ETo, VPD_m, T_m and Rs) (Table 2, Fig. 6). However, it is difficult to explain why the behaviour of MDS under non-limiting soil water conditions can be adequately predicted by changes in T_m because it is known that temperature is not an accurate indicator of the evaporative demand of the atmosphere (Hatfield and Fuchs, 1990). Nevertheless, earlier reports in almond (Fereres and Goldhamer, 2003), plum (Intrigliolo and Castel, 2006) olive (Moreno et al., 2006) and lemon (Ortuño et al., 2009b) showed that air temperature is a good predictor of MDS. In any case, it must be considered that T_m is a climatic variable that is easier and less costly to measure than ETo, VPD_m and Rs. The fact that Intrigliolo et al. (2011b) indicated that relationships between MDS and air temperature and air vapour pressure deficit were weaker than that between MDS and ETo confirmed that in pomegranate trees the best predictor for MDS reference values is the ETo.

In spite of the existence of some differences in the location of experimental plots and tree size, the inter-seasonal constancy in the reference equations to estimate MDS as a function of ETo, VPD_m, T_m and Rs (Fig. 6) was in agreement with the results showed by other authors in lemon and peach trees (Ortuño et al., 2009b; Conejero at al., 2011). These authors showed the constancy of MDS reference equations in trees with very different crop load levels.

Overall, the results indicated that MDS is a reliable plant-based water stress indicator in adult pomegranate trees. In addition, the fact that LVDT sensors used in the experiment did not have to be repositioned, together with other operational advantages over discretely measured indicators, such as the low labour costs involved and the possibility of connection to remotely operated automata, confirm that MDS is a suitable plant-based indicator for precise irrigation scheduling practices. Moreover, MDS reference equations can be obtained by pooling data across several seasons for ETo, VPD_m, T_m and Rs, meaning that it is possible to compare MDS measurements at a given time with the expected value under non-limiting water conditions, which can be calculated from the reference relationships.

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Table 1

Maximum daily trunk shrinkage (MDS), midday stem water potential (Ψ_{stem}) and midday leaf conductance (g_l) mean signal intensity, mean noise, and signal/noise ratio at different intervals of the 2009 water stress period. For each interval, mean signal or mean noise values that do not have a common letter are significantly different according to the $LSD_{0.05}$ range test.

DOY		Mean signal	Mean noise	Signal/noise
209-217	MDS	1.24a	0.17a	7.31
	Ψ_{stem}	1.27a	0.21a	6.16
	g_l	1.04a	0.15a	6.93
209-224	MDS	1.31ab	0.17b	7.84
	Ψ_{stem}	1.46a	0.23a	6.27
	g_l	1.15b	0.15b	7.73
209-231	MDS	1.37ab	0.17b	7.95
	Ψ_{stem}	1.59a	0.22ab	7.13
	g_l	1.29b	0.24a	5.34
209-238	MDS	1.41b	0.17b	8.24
	Ψ_{stem}	1.72a	0.23a	7.39
	g_l	1.40b	0.23a	6.07
209-243	MDS	1.46b	0.18b	8.31
	Ψ_{stem}	1.81a	0.24a	7.63
	g_l	1.49b	0.26a	5.82

Table 2

Intercept (*a*), slope (*b*), coefficient of determination (r^2), number of data points (*n*) and mean square error (MSE) of best fit first-order linear equations ($y = ax + b$) between maximum daily trunk shrinkage (MDS, mm) and selected environmental variables for 2009 and 2010 seasons

Season	*a*	*b*	r^2	*n*	MSE
MDS vs. ET_o (mm)					
2009	-0,0841	0,0557	0,7519***	49	0,0009
2010	-0,068	0,0519	0,7482***	85	0,0017
MDS vs VPD_m (kPa)					
2009	0,0329	0,1001	0,598***	49	0,0015
2010	-0,0249	0,137	0,6152***	85	0,0025
MDS vs T_m (ºC)					
2009	-0,2922	0,0192	0,4197***	49	0,0021
2010	-0,2363	0,0181	0,5933***	85	0,0027
MDS vs R_s (W m^{-2})					
2009	-0,0615	0,001	0,665***	49	0,0012
2010	-0,0739	0,001	0,6024***	85	0,0025

ETo daily crop reference evapotranspiration, T_m daily mean air temperature, VPD_m daily mean air vapour pressure deficit, R_s solar radiation

*** Significant at $P < 0.001$

Figure

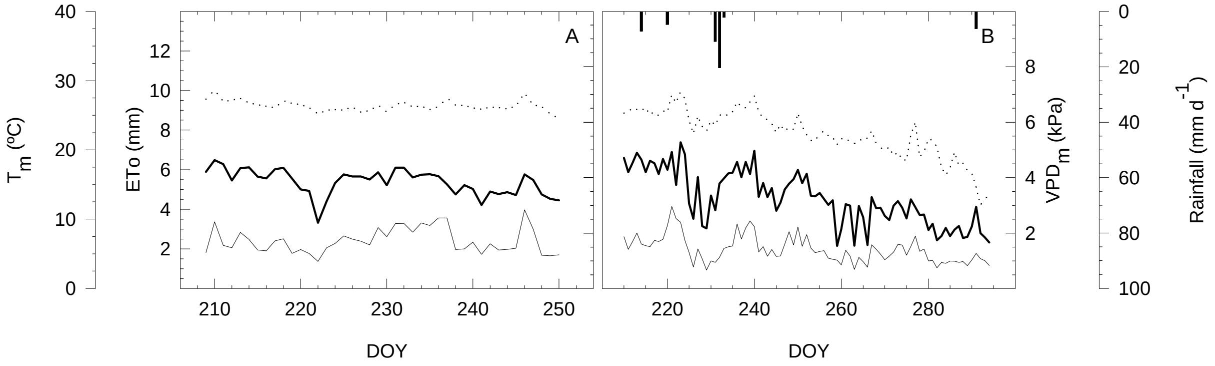

Fig. 1. Daily crop reference evapotranspiration (ETo, solid thick line), daily mean air temperature (T_m, dotted line), mean daily air vapour pressure deficit (VPD_m) (solid thin line) and daily rainfall (vertical bars) during the 2009 (A) and 2010 (B) experimental periods.

Figure

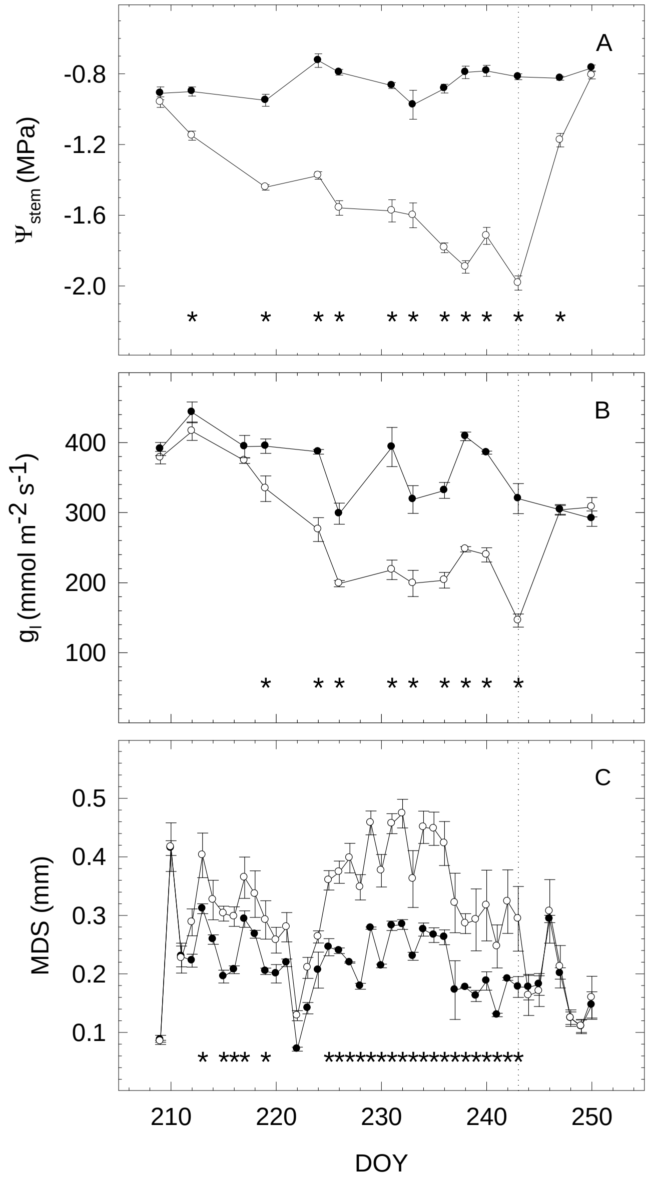

Fig. 2 Midday stem water potential (Ψ_{stem}) (A), midday leaf conductance (g_l) (B) and maximum daily trunk shrinkage (MDS) (C) in T0 (closed symbols) and T1 (open symbols) plants during the 2009 experimental period. Bars on data points are ± S.E. of the mean (not shown when smaller than symbols). Vertical dotted line indicated the time at which irrigation was restored. Asterisks indicate statistically significant differences by least significant difference at 5% level ($LSD_{0.05}$) range test. Each point is the mean of four values

Figure

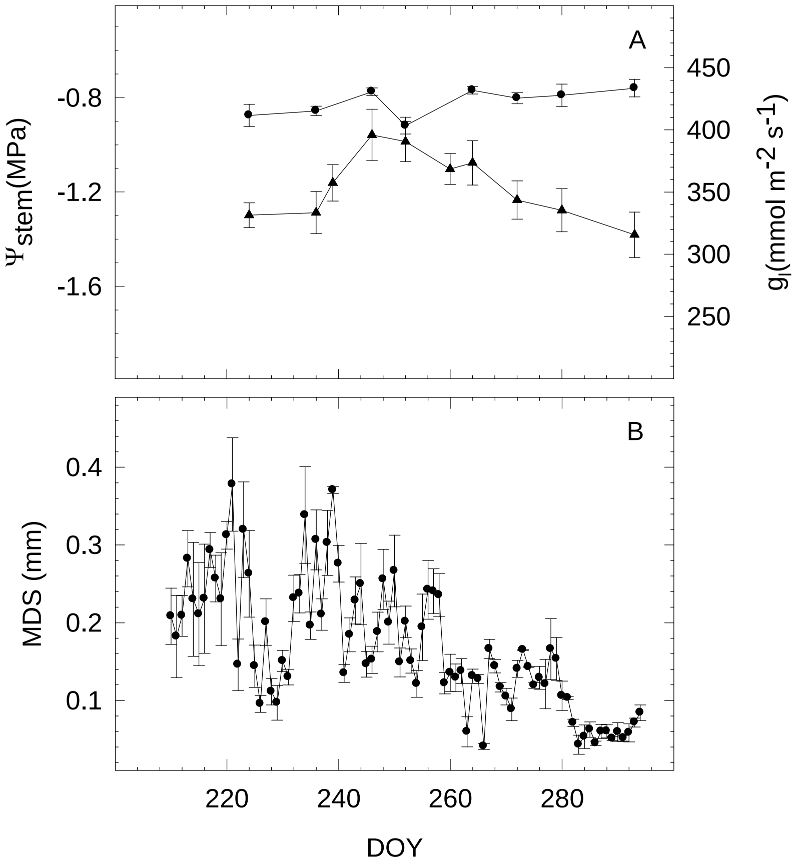

Fig. 3. Midday stem water potential (Ψ_{stem}, circles) (A), midday leaf conductance (g_l, triangles) (A) and maximum daily trunk shrinkage (MDS) (B) in T0 plants during the 2010 experimental period. Bars on data points are ± S.E. of the mean (not shown when smaller than symbols). Each point is the mean of four values.

Figure

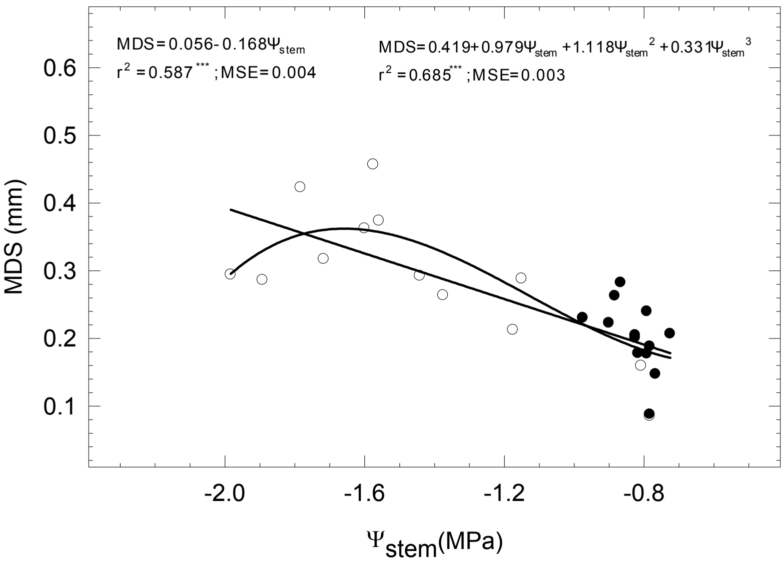

Fig. 4 Relationship between and maximum daily trunk shrinkage (MDS) and stem water potential (Ψ_{stem}) in T0 (closed symbols) and T1 (open symbols) plants during the 2009 water stress period. Each value is the mean of four measurements

Figure

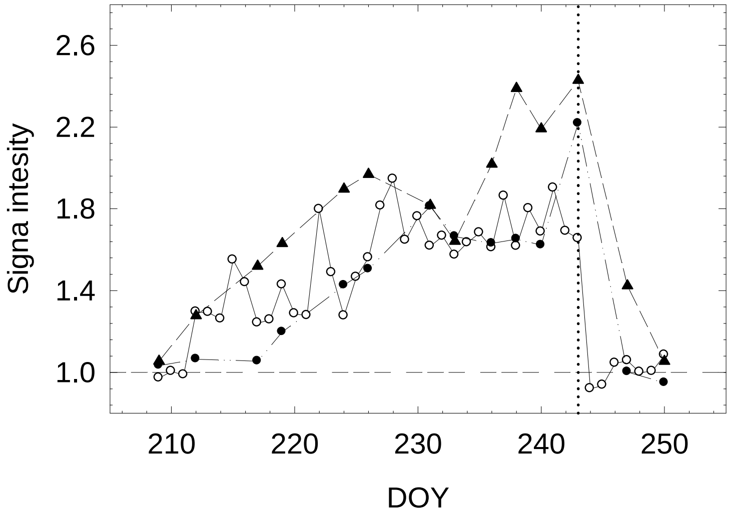

Fig. 5 Maximum daily trunk diameter shrinkage (MDS, open circles), midday stem water potential (Ψ_{stem}, triangles) and midday leaf conductance (g_l, closed circles) signal intensities during the 2009 experimental period. Each value is the mean of four measurements. Vertical dotted line indicated the time at which irrigation was restored

Figure

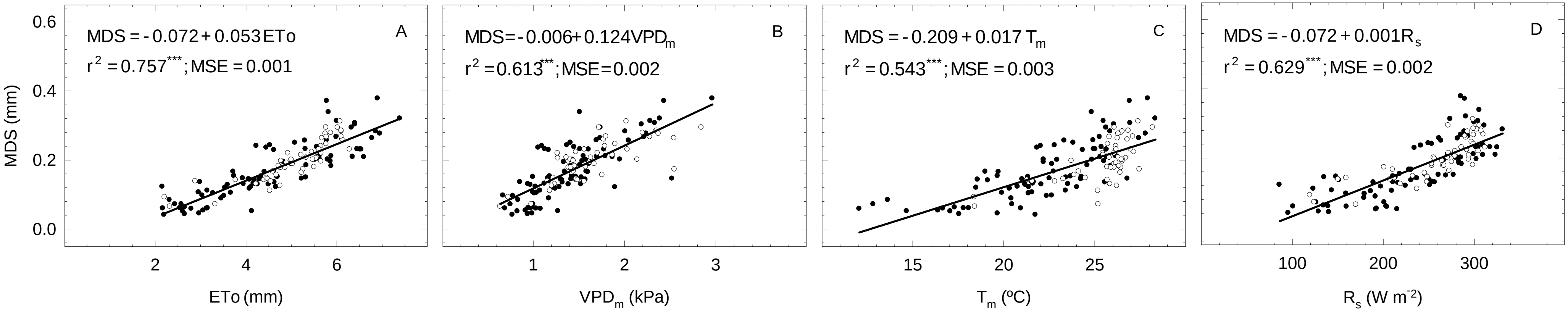

Fig. 6 Relationships for trees under non-limiting soil moisture conditions (T0) between maximum daily trunk shrinkage (MDS) and daily values of reference crop evapotranspiration (ETo) (A), mean daily air vapour pressure deficit (VPD_m) (B), mean daily air temperature (T_m) (C) and solar radiation (R_s) (D), using all data pooled (2009, open circles; 2010, closed circles). Each data point is the mean of four values