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Full Length Research Paper

Effects of two drip-irrigation regimes on sap flow, water potential and leaf photosynthetic activity of mature olive trees

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We evaluated the potential of sap flow values estimated from records with the heat dissipation method for irrigation in an olive orchard (*Olea europaea* L, cv. Meski) near Enfidha, Tunisia. Trees were cultivated at 7 × 7 m spacing. Two drip irrigation treatments were imposed using the sap flow and the FAO methods. The two treatments were irrigated by 100% of crop evaptranspiration (ETc). T1: ETc measured by the sap flow method and T2: ETc estimated by the FAO method. Sap flow, leaf and stem water potentials, leaf photosynthetic activity, stomatal conductance and transpiration rate were recorded in representative trees from both treatments, during the full irrigation season from April to August. Results showed that the irrigation dose calculated from T2, based on FAO method compared to the T1, based on sap flow decreased by about 25%. Under T1 irrigation scheduling strategy, the daily transpiration decreased by 20% and consequently the water potentials were decreased significantly. Infect, olive trees under T1 were moderately stressed and subsequently leaf gas exchange parameters were affected by about 15%.

Key words: Sap flow, water potential, leaf photosynthetic activity, olive tree, *Olea europaea* irrigation scheduling.

INTRODUCTION

Olive orchards are main components of agricultural systems in many semiarid regions of Mediterranean climate. In Tunisia, more than 1.68 million hectares are occupied by olive orchards. Most of them are rain fed, with yields limited mainly by water supply. Modern orchards are usually drip-irrigated, with plant densities ranging from 200 trees ha^{-1} to more than 1000 trees ha^{-1}.

Drip irrigation has also been extended to numerous traditional orchards but through the use of poor-quality groundwater from uncertain supply. Commonly, crop evapotranspiration approach (ETc) was used to scheduling irrigation of olive orchards.

The use of irrigation scheduling based on the direct measurements of olive tree water statutes seems to be a suitable alternative to determine the irrigation doses to be applied in the orchard (Nicolás et al., 2005; Tognetti et

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al., 2009). Two interesting measurement effectively related to the water status of the tree were used in olive orchards. Sap flow is considered as the most promising plant-based indicator for the control of irrigation in fruit tree orchards (Ortuno et al., 2005). Sap flow records have been reported as useful to determine actual olive water needs (Fernandez et al., 2001). The heat dissipation method (Granier, 1987) has been used successfully to study transpiration and some physiological aspects of fruit trees (Sellami and Sifaoui, 2008). Compared to other methods, the Granier method is relatively simple, easy to use, and can be used for long-term continuous measurements. To our knowledge, an irrigation controller based on sap flow using the heat dissipation method has not been developed yet, although irrigation protocols based on heat pulse approach have been suggested by Fernandez et al. (2008b).

The main objectives of this study was: To compare the crop evapotranspiration measured by the sap flow and the FAO methods: To evaluate sap flow sensors using heat dissipation method for scheduling irrigation in an intensive olive orchard under arid climate in Tunisia; and - to test this method using some physiological traits of olive trees especially sap flow, leaf water potential, leaf photosynthetic activity and stomatal conductance.

MATERIALS AND METHODS

Site description and environmental measurements

This experiment was conducted from April to August during 2008 at the irrigated olive orchards of Enfidha, Tunisia (36°08'N, 10°22'E, 23 amsl). Our study was performed at commercial olive (*Olea europaea* L. cv. Meski) orchard of about 40 ha. The trees were planted at 1985 with trees density of 204 trees ha^{-1}. The soil was classified as sandy-loam. Soil water content at wilting point and field capacity were 11 and 26% respectively. Air temperature (T, °C), relative humidity (RH, %), global radiation (Rg, Kw m^{-2}) and wind speed (U, m s^{-1}) were registered by a weather station. Soil water content (Hv, %) was measured gravimetrically in watered areas to 0.6 m depth at various distances (0-20, 20-40, 40-60 cm).
During the study period, air temperature ranged from 11 to 33°C, whereas relative humidity varied between 30 and 85%. Wind speed varied between 1 and 4 $m.s^{-1}$. Maximum humidity and minimum temperature were observed in April, whereas minimum humidity and maximum temperature were recorded in August (Figure 1a). Minimum and maximum solar radiation were 6 and 16 Kw m^{-2} at first April and mid-May, they presented consistently high values during summer (Figure 1b). Potential evapotranspiration showed two periods; during April and June was approximately between 1.6 and 2.9 mm day^{-1}. During the second period (mid June to August), ET_0 ranged between 2.3 and 3.7 mm day^{-1} (Figure 1c).

Irrigation management and experimental design

Water for irrigation was delivered daily using a localized irrigation system with two lines of nozzles, each at 1.0 m from the trunk. Each tree was equipped with four nozzles, 8 L h^{-1} each per side. A randomized complete block design was used with 6 blocks of 6 trees each that received the irrigation treatments denominated T1 and T2.

T1:18 olive trees that received a daily irrigation amount of 100% of crop evapotranspiration measured by sap flow (Figure 2).

$$T1 = Tsf + Es$$

Where Tsf is the tree transpiration measured by sap flow meter and Es is the soil evaporation measured by microlysimeter.
T2: 18 olive trees that received a daily irrigation amount of 100% of crop evapotranspiration (ETc).

$$T2 = Kc * Kr * ET_0$$

ETc was determined according to Allen et al. (1998) with values of 0.6 for the crop coefficient (Kc) and 0.7 canopy size (Kr) to account for tree age and biomass soil coverage. The reference evapotranspiration (ET_0) was estimated by Penman-Monteith equation (Allen et al., 1998) using daily data from a nearby weather station.

Sap flow and soil evaporation measurements

The measurement of sap flow according to Granier (1985, 1987) was based on two cylindrical probes, 2 mm in diameter and 20 mm in length inserted radially in the xylem and spaced vertically by 8 cm. The upper probe was continuously heated, whereas the lower probe was unheated and the resulting temperature difference was measured with copper constantan thermocouples placed in each probe. Under zero flow conditions, the temperature around the heated probe increases to the point where heat dissipation by xylem conduction was in equilibrium with the heat energy supplied, which gives a maximum temperature difference. When sap is flowing, heat dissipation increases by convection and the temperature difference decreases. The major advantages of the method were its easy installation, a simple sap flow calculation and a low cost (Smith and Allen, 1996). Nevertheless, in open stands, natural temperature gradients in the stems of trees give rise to errors. This drawback can be eliminated by the non continuous thermal dissipation method devised by Do and Rocheteau (2002a, b), which is the technique used for our measurements.

Sap flow was recorded at 30 min intervals using heat dissipation instrumentation controlled by a data-logger type (model DL2, Delta-T Devices Cambridge, England). To convert sap flow density to tree transpiration a relationship between sapwood area (S) and trunk diameter was experimentally determined by colouring the sapwood area with safranin. Measurements were taken using three probes at different sides of the trunks of three olive trees with similar cross-sections on each treatment during the fully irrigation season from April to August.

To compare sap flow measured to tree transpiration, we used the same mature olive tree cultivar and assessed transpiration simultaneously with sap flow measurement using a balance during one month. To suppress evaporation from the surface of the pot, the pot was covered with plastic film. The transpiration rate was calculated daily from the amount of weight lost, excluding the weight of the irrigation water. Soil evaporation (Es) was measured using twelve cylindrical microlysimeters, 8 cm deep, with 20 cm of internal diameter according to Paco et al. (2006).

Leaf water potential

During the fully irrigation season from April to August 2008, leaf water potential was measured using a portable pressure chamber (Scholander et al., 1965, Turner ,1981). For all measurements, data were collected during sunny days at predawn and midday on the same trees (3 trees from each treatment). Leaf water potentials were established by sampling a total of 3 fully sunlit and 3 covered leaves from each tree. For xylem water potentials 3 leaves from

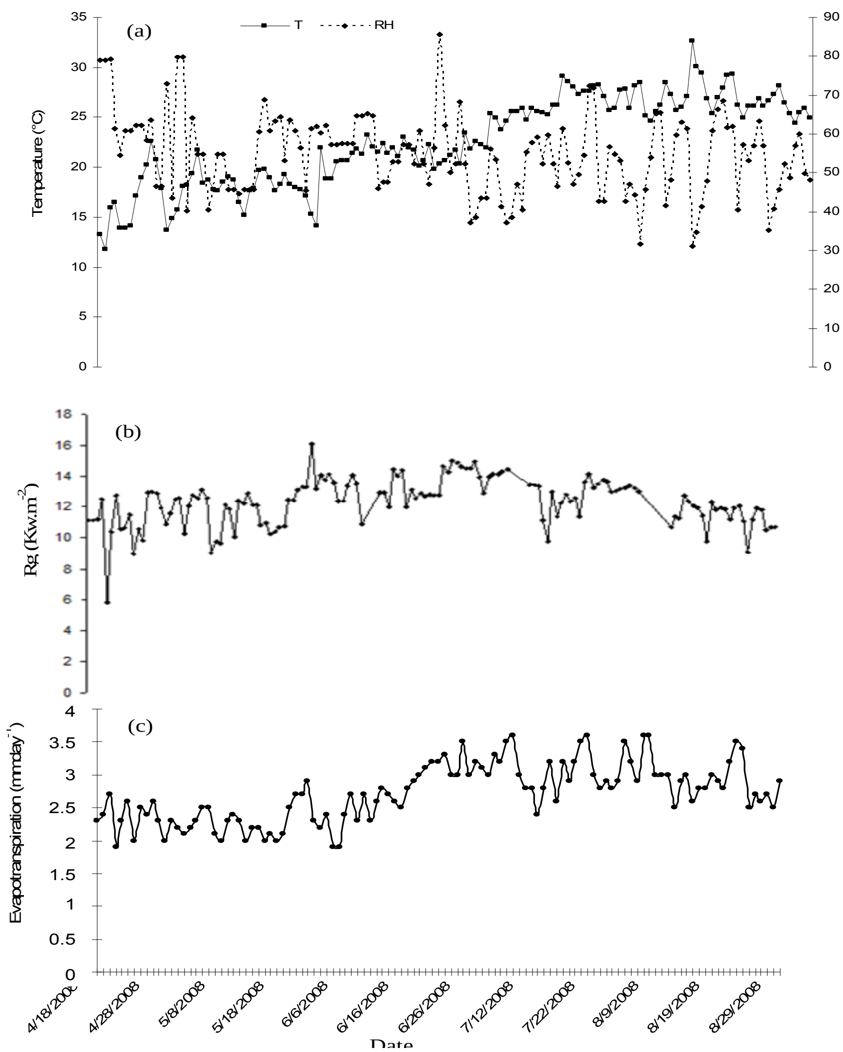

Figure 1. Climatic parameters, temperature and air humidity (a), global radiation (b) and evapotranspiration (c) during the study period.

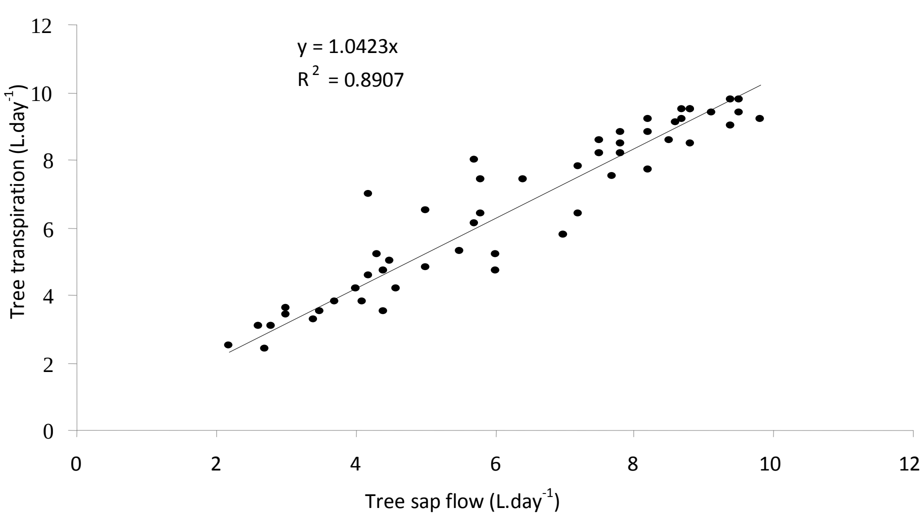

Figure 2. Regression between sap flow and transpiration measured by the weighting method.

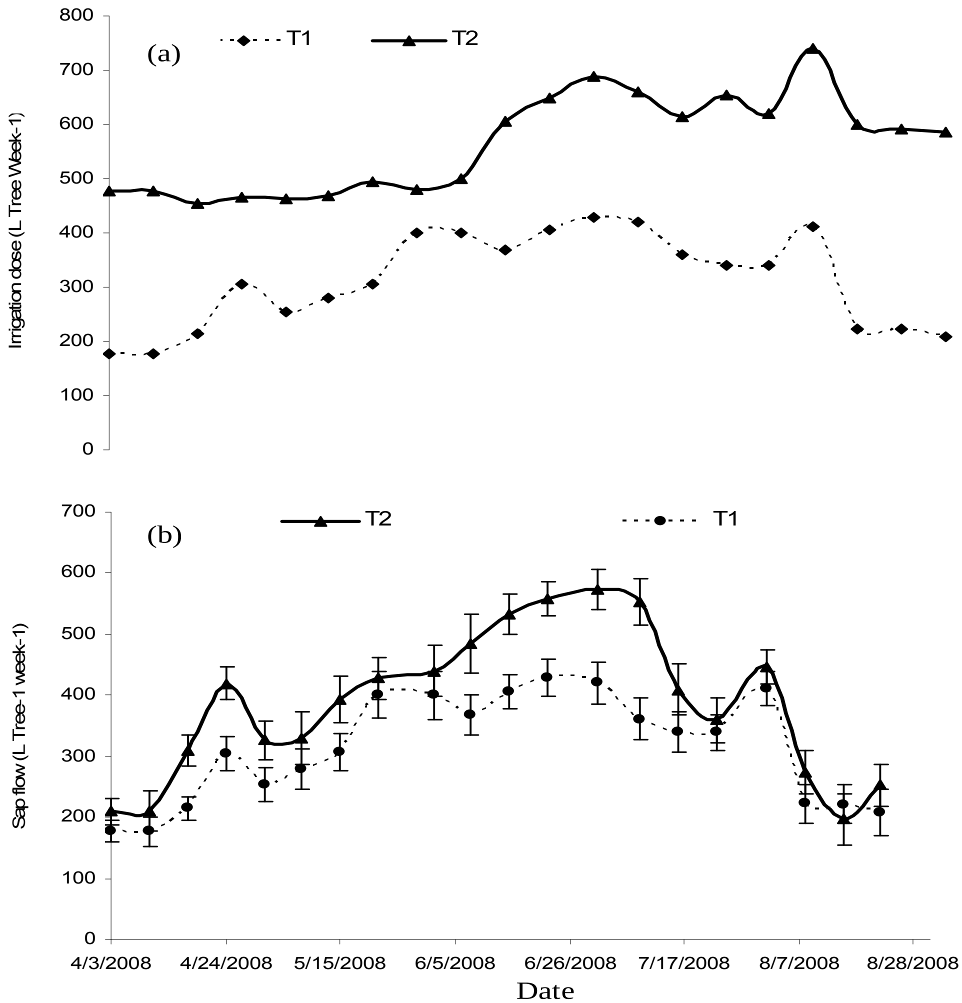

Figure 3. Weekly evolution of irrigation dose (a) and sap flow (b) following the irrigation treatments T1 and T2 during the study period (average ± SE, n = 3). Different letters indicate significantly different values at P≤0.05 according to Duncan test.

each tree were covered with aluminium paper for two hours before measurement to avoid transpiration and establish the equilibrium water potential between leaf and xylem.

Leaf photosynthetic function and water-use efficiency'

Leaf photosynthesis rate, stomatal conductance and transpiration were measured using a portable system IRGA (LI-COR, LI-6400) on 9 sunny leaves per treatment (three leaves per tree). Data were collected monthly from April to August 2008. All measurements were carried out between 9:00 and 11:00 h on cloudless days. Photosynthetic photon flux density was fixed at 1500 µmol m^{-2} s^{-1}. Temperature and humidity rate through the chamber were 25 °C and 60% respectively.

Statistical analysis

All parameters were determined in triplicate for each sample. Analysis of variance (ANOVA) and linear regression analyses were processed by SPSS statistical package (Version 16.00 for Window, SPSS Inc.). Duncan test ($P < 0.05$) was used to determine significant differences between means.

RESULTS

Irrigation doses and soil water content

Irrigation dose in T2 presented similar values during April until the beginning of June approx 490 L $Tree^{-1}$ $Week^{-1}$. This dose increased to reach a maximum value of 700 L $Tree^{-1}$ $Week^{-1}$ at the beginning of August (Figure 3a). Similarly, the irrigation dose obtained from sap flow measurements increased from 180 L $Tree^{-1}$ $Week^{-1}$ in April to reach a maximum level of 400 L $Tree^{-1}$ $Week^{-1}$ in August (Figure 3a). During the full irrigation season from April to August 2008, the total irrigation doses were 7800 (160 mm) and 11300 L $Tree^{-1}$ (230 mm) in T1 and T2 respectively. Soil water content was influenced by the

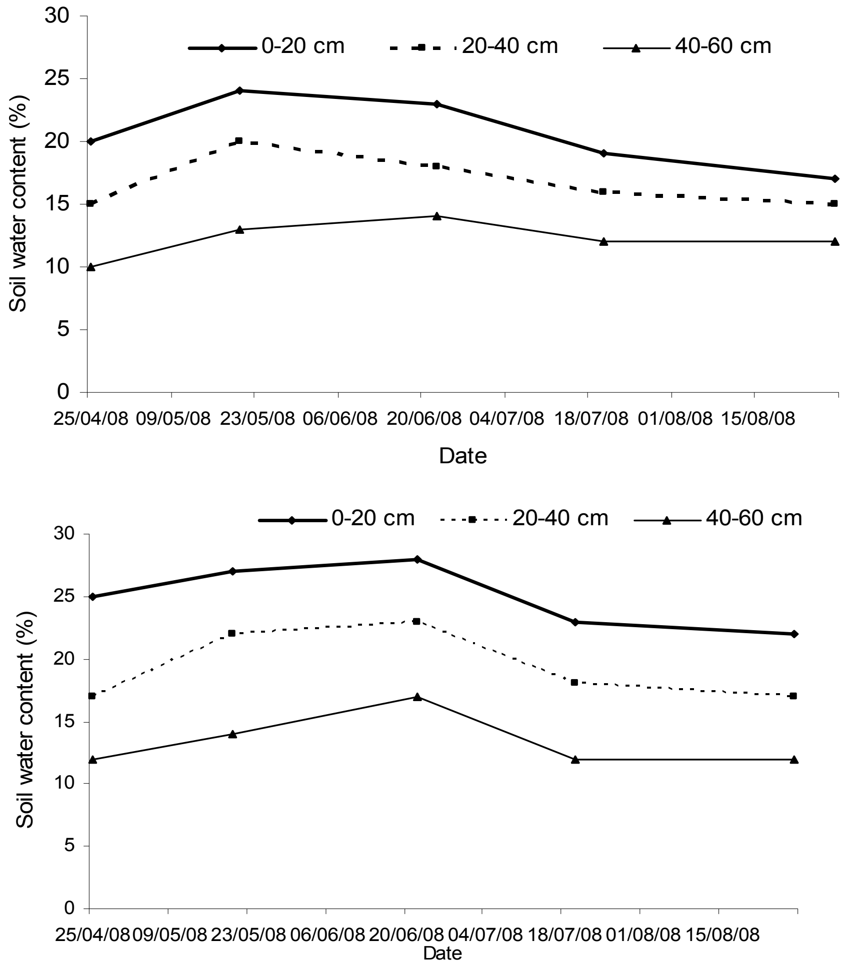

Figure 4. Seasonal patterns of soil water content at different depths following the irrigation treatments T1 and T2 during the study period.

irrigation doses and increased with increasing depth (Figure 4). Under T1, irrigated with the sap flow method, soil water content measured at 20 cm depth increase from 20% (April) to 25% (May), than decreased gradually to reach 18% at the end of the irrigation season (August). Under T2, irrigated with the FAO method, soil water content was very high and ranged between 23 and 28% at 20 cm depth. Large differences of soil water content were observed between treatments at different depths.

Sap flow measurements

Average of the canopy transpiration estimated by sap flow meter was at their minimum during spring (April) and at their maximum during the warmest summer period (July) (Figure 4b). During June and July, transpiration of T2 treatment was 23% higher that of the T1 treatment. During the full irrigation season from April to August, total whole trees sap flow were 6300 and 8400 L $Tree^{-1}$ in T1 and T2 respectively.

Leaf water potential

Predawn leaf water potential (Ψ_{pd}) increased during the full irrigation season from April to August. Infect, under T1 and T2 treatments Ψpd ranged between - 0.3 MPa and - 0.4 MPa and between -0.4 MPa and - 0.6 MPa respectively (Figure 5a). In the two treatments, xylem and leaf water potentials presented a similar seasonal pattern. Higher water potentials values were observed under T2, significant different from those of T1 (Figure 5b and c). Minimums values of Ψ_x and Ψ_{md} were -3.2 MPa and -2.2 MPa in T1 and -2.7 MPa and -2.4 MPa in T2.

Leaf photosynthetic activity

Seasonal patterns of photosynthesis measured during the full irrigation period were similar in both treatments with higher values in T2 (10-16.8 µmol m^{-2} s^{-1}) than in T1(10-14µmol m^{-2} s^{-1}). CO_2 assimilation rates were low in April, increased by 60% during May, reached a maximum

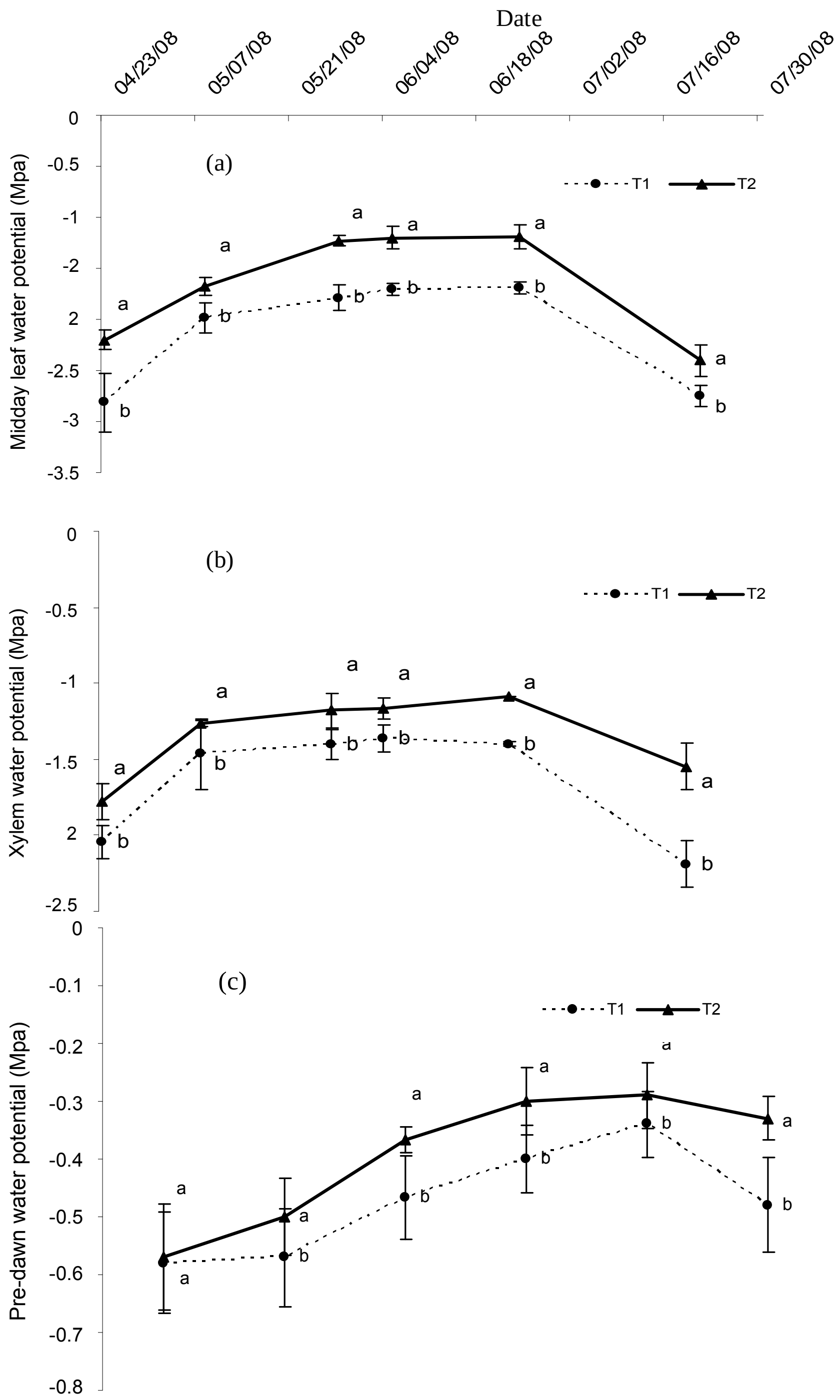

Figure 5. Seasonal patterns of predawn leaf water potential (a), xylem water potential (b), midday leaf water potential (c) following the irrigation treatments T1 and T2 during the study period.(average ± SE, n = 9). Different letters indicate significantly different values at P≤0.05 according to Duncan test.

in June and increased again during August (Figure 6a). During the full growing season, CO_2 assimilation rates were significantly higher under T2 by about 15% to that T1 treatment. Stomatal conductance (gs) followed similar trends to that of CO_2 assimilation rates (Figure 6b). The gs increased from April to June and decreased during August. The maximum gs values were 0.24 and 0.17 μmol m^{-2} s^{-1} in T2 and T1 respectively. Similarly to photosynthesis and stomatal conductance patterns, transpiration rate (E) increased from April to June and

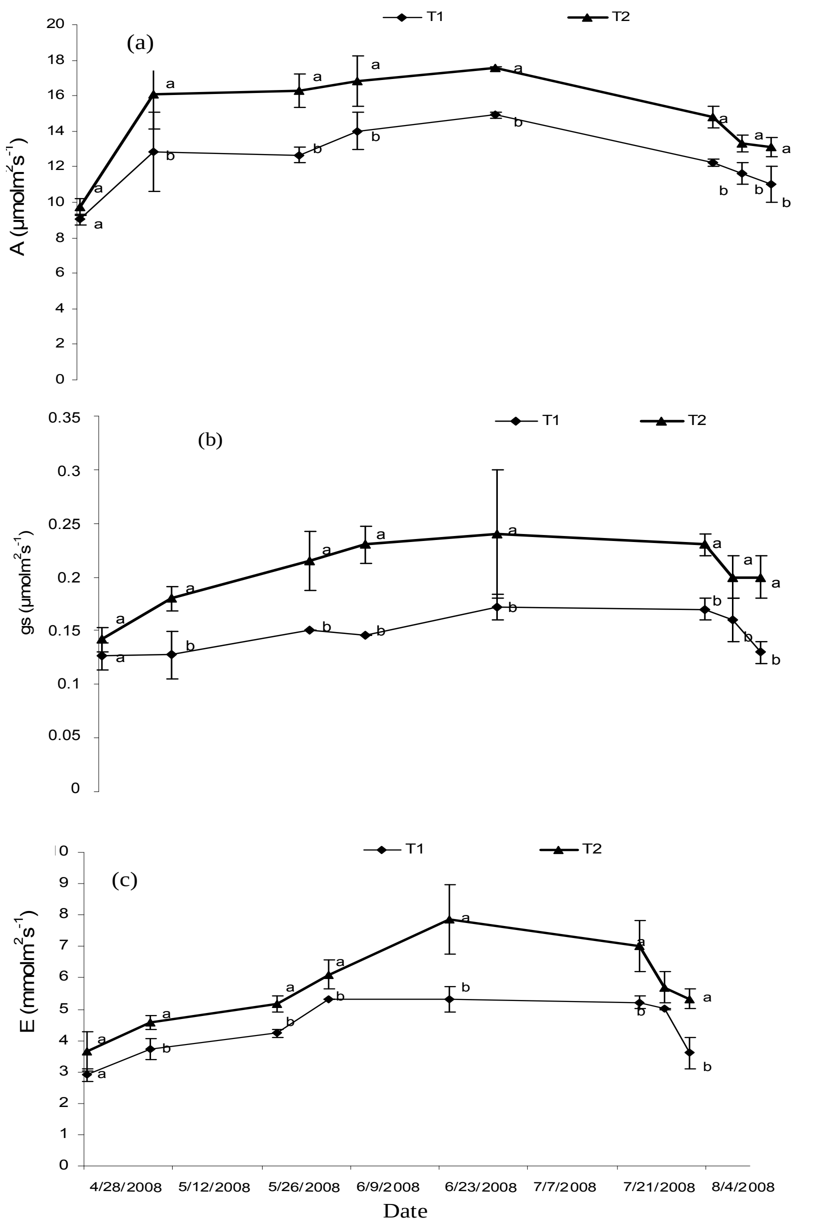

Figure 6. Seasonal patterns of photosynthesis (a), stomatal conductance (b) and transpiration (c) following the irrigation treatments T1 and T2 during the study period. (average ± SE, n = 9). Different letters indicate significantly different values at P≤0.05 according to Duncan test.

decreased during August. The maximum E, values were 5.3 mmol H_2O^{-1} m^{-2} s^{-1} and 7.3 mmol H_2O^{-1} m^{-2} s^{-1} in T1 and T2 respectively (Figure 5c).

Photosynthetic water use efficiency

Photosynthetic water use efficiency (PWUE) expressed as function between photosynthesis rate and transpiration in T1 and T2 have a similar pattern, but there are significant differences between them in some times especially during July. PWUE increased from April, reached a maximum value in May (3.5 µmolCO_2 mmol H_2O^{-1}), and decreased slightly to a minimum values in August (Figure 7).

DISCUSSION

A precise scheduling irrigation can improve the water use

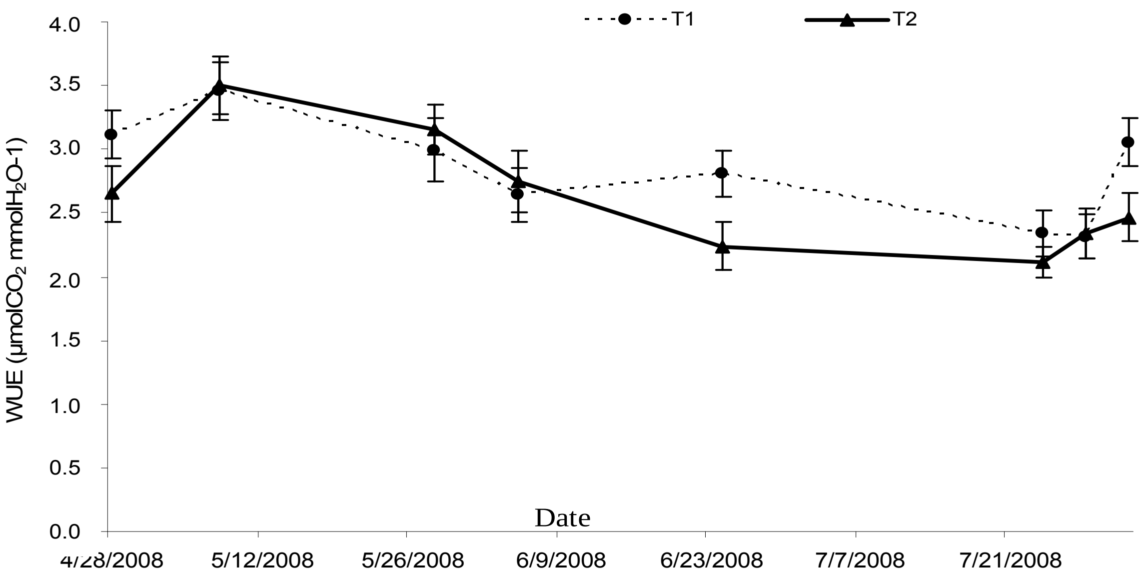

Figure 7. Seasonal patterns of water use efficiency following the irrigation treatments T1 and T2 during the study period (average ± SE, n = 9). Different letters indicate significantly different values at P≤0.05 according to Duncan test.

efficiency and protect the orchards against drought. Plant based indicators for scheduling irrigation, especially sap flow were successfully introduced in fruit trees (Ortuno et al., 2005). Until now several studies have demonstrated that the heat dissipation method developed by Granier (1987) and ameliorated by Do and Raucheteau (2002a, b) can be introduced easily to study water needs in fruit trees (Sellami and Sifaoui, 2003), but it has not been tested for scheduling irrigation. Smith and Allen (1996) advised that the Granier method should be calibrated for individual species.

To evaluate this technique, results from the Granier sap flow method were compared with the transpiration measured by the weighting method. Results show a good relationship between the daily sap flow rate and the daily transpiration rate (Figure 6) with a coefficient of determination (R^2) equal to 0.89.

During the full irrigation season from April to August, the total irrigation doses were 7800 L Tree^{-1} (160 mm) and 11300 L Tree^{-1} (230 mm) in T1 and T2 respectively. Compared to the irrigation dose estimated by the FAO method (T2 = 230 mm) we can by the sap flow technique (T1 = 160 mm) increase the irrigation dose by 70 mm (30%) an agreement with the results published by Fernandez et al. (2008b).

Under T1, irrigation dose decreased and affected significantly the soil water content during the irrigation season, it seems act as a moderate water stress on the physiological characteristics of the tested olive tree cultivar cv Meski. Fernandez et al. (2008b) show that olive trees irrigated using sap flow, xylem water potential decreased significantly in olive trees, indicating that the soil water content was too low to prevent water stress in the olive trees. Our results show that leaf water potentials decreased significantly under T1. Minimum values of ψ_{pd} never exceeded -1.5 and hardly reached -2 MPa, regardless the water treatments (Tognetti et al., 2009) an agreement with our results. During 90 days of experiment, xylem water potential of olive trees irrigated daily near to the field capacity, reached between - 0.9 and - 1.5 MPa (Lopez et al., 2007, 2008). According to our results, under T1, xylem water potential of olive trees cv Meski ranged between –1.5 and –2 MPa. This moderately water stress affects directly and significantly photosynthesis, stomatal conductance and transpiration rate during the full irrigation season. The reduction of the water status has been followed by a stomatal conductance reduction that is due to the closing of the stomata. This state will normally have for consequence a decrease of the photosynthetic assimilation (Ben Ahmed et al., 2007). For the Meski olive tree under T1 treatment, photosynthetic assimilation decreased by 15% compared to irrigated olive trees by T2. Whereas, the irrigation doses decreased by 30% from T2 to T1.

Proietti (2000) and Hagidimitriou and Pontikis (2005) reported that the high leaf CO_2 assimilation rate value of olive trees observed under full irrigation conditions during spring was probably due to favourable air temperature and humidity rate. According to Proietti et al. (2013), the decrease in photosynthesis rate in August is probably due to high temperature and low air humidity registered during this period in our experiment olive orchard. However, Proietti et al. (2012) reported that the lower photosynthetic values in the warmer period of the summer were not caused only by the lower stomatal conductance reduction but rather by non stomatal effects damage to the photosystem induced by high temperature and drought, increase of dark respiration rate.

Photosynthetic water use efficiency of T1 and T2 irrigation treatments estimated in our experiment seems to verify the possibility to introduce the sap flow method to estimate olive water consumption and schedule irrigation on olive tree orchards with accuracy especially during warmer seasons.

The significant differences observed in seasonal variation of water relations and leaf gas exchange proved a moderately stressed trees under T1 (irrigation based on sap flow), due to the lower irrigation dose estimated by the sap flow meter using the heat dissipation method. Infect, Steppe et al. (2010) reported that under laboratory conditions, the heat dissipation method substantially underestimated sap flux density, which indicated that this technique has unique sensitivities to errors in parameter estimates which need to be taken into consideration. The heat dissipation method used in our experiment determined the onset of water stress quite accurately, but it was not as reliable to estimate transpiration because sap flow is determined only in a single point in the radial profile, even though profile correction were done (Altozano et al., 2008). Additionally, for the olive tree, Fernandez et al. (2001) reported that olive sap wood is characterized by heterogeneity on the radial sap flux, than can be considered as a limitation for the heat dissipation method and necessities a large number of sensors to monitor irrigation. Under Tunisian climatic conditions, Masmoudi et al. (2011) reported the possibility to estimates young olive tree transpiration by the heat dissipation method, the maximum transpiration represented only 53% of the ETc as determined by the FAO method. Whereas, the FAO approach based on climatic data overestimated evapotranspiration by more than 15% for some situations (Allen, 2000). For olive and citrus orchards (Testi et al., 2004; Rana et al., 2005) found that crop coefficient vary significantly during the growth season being impossible to assume a constant value. Therefore, some limitations should be expected in the application of the FAO approach to estimate crop evapotranspiration (Paco et al., 2006). Compared to irrigation scheduling methods based on the atmospheric demand, such as the FAO method (Allen et al., 1998), plant-based measurements using the sap flow meter could increase the resolution of the calculated irrigation dose; reduce water use on irrigated olive orchard which is certainly an advantage for precise high-frequency irrigation. In addition, sap flow method can be easily automatized, which is particularly valuable for scheduling irrigation (Jones, 2007).

Conclusions

The sap flow method seems to be a good device able to calculate the real water needs of olive trees and save water by 30%. Under Mediterranean climate in Tunisia, irrigation scheduling of olive orchards based on sap flow technique caused a moderate drought stress affecting soil water content, and consequently leaf water potentials and leaf photosynthetic activity. This problem (underestimation of the irrigation dose by the sap flow meter) seems to be due to the heat dissipation method and the olive wood characteristics.

Conflict of Interest

The authors have not declared any conflict of interest.

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