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Transpiration by sap flow Thermal Dissipation Method: applicability to a hedgerow olive orchard

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Abstract. The climate change requires thrifty use of water resources in agriculture since irrigation is became common also for those crops like olive orchard that were traditionally grown in rainfed conditions. The water requirement is imperative in semi-arid conditions of the Mediterranean basin especially if the olive orchards are cultivated in super high density. For a correct irrigation scheduling, methods to measure transpiration (Tr) at plant level are used. Among the most spread methods to determine Tr, the thermal dissipation method (TDM) has been applied on a hedgerow olive orchard considering: (i) species-specific local calibration, (ii) wound effects, (iii) azimuth correction, and (iv) radial gradient corrections. The performances of the corrected TDM method have been evaluated with respect an independent method, the water balance at weekly scale. If any correction nor specific calibration is carried out, the underestimation of the actual transpiration calculated by TDM was of about -18% with respect to the water balance method.

Keywords: *Olea europaea* cv. *Arbosana*, semi-arid climate, wound effect, radial gradient effect, azimuthal effects, water balance.

HIGHLIGHTS

- Transpiration (Tr) on olive orchard was measured by thermal dissipation method (TDM)
- calibration, wound effects, azimuth and radial gradient corrections were applied
- Tr by uncorrected TDM was of about -18% with respect to Tr by water balance method

1. INTRODUCTION

The increasing instabilities of precipitation regimes, together with the stable increase of air temperature due to the global warming, requires the adaptation of agronomic techniques to climate change. Irrigation is common also for those crops that were commonly grown in rainfed conditions. In the Mediterranean basin, the case of olive is emblematic: this fruit tree crop is notably efficient to face drought, and although it is very well adapted to the arid and semiarid climates (Tognetti et al. 2009), it is often irrigated to save the production and the oil quality (Iniesta et al. 2009). Since last decades of the past century olive growing moved towards great intensification, with the large diffusion in Mediterranean region of the super high density (SHD) cropping systems. These full mechanized olive groves, known as hedgerow orchards, as well, are characterised by a density over 1,200 trees per hectare and by continuous fruit harvesting and show positive both economic and environmental impacts compared to rainfed traditional olive orchards (Russo et al. 2015).

The Mediterranean region is known to be strongly negatively affected by air temperature increase and changes of seasonal rainfall distribution (Katerji et al. 2017). In these weather conditions, SHD olive cropping systems significantly decrease water use under irrigated conditions, with an estimated reduction in water footprint of one half with respect to the traditional ones (Pellegrini et al. 2016).

To correctly evaluate the water requirement of a crop, it is necessary to determine with high accuracy the actual evapotranspiration (Katerji et al. 2008), particularly complex for orchards, since the water follows complex paths for tree transpiration (Tr) and soil evaporation, separately (Scanlon and Kustas 2012). The micrometeorological methods generally resulted the best way to measure evapotranspiration (ET) with a suitable accuracy, but measurements must be carried out above large surfaces (Lee et al. 2004). When large surfaces are not available or are not homogeneous, methods to measure transpiration at plant level are preferred, and the most spread methods to determine Tr are the techniques based on the measurement of the sap flow density (Rana and Katerji 2000). The thermal dissipation method (TDM) (Granier 1985) has been frequently used to determine actual transpiration of olive orchards in different situations (Masmoudi et al. 2011; Cammalleri et al. 2013; Agüero Alcaras et al. 2016; Conceição et al. 2017). However, while TDM-type sap flow sensors are surely suitable to monitor the dynamics of the sap flow or for comparing different treatments in relative terms, they cannot be used to quantify water losses by trees in absolute terms, unless species-specific calibration has carried out (Fuchs et al. 2017; among others). Furthermore, systematic underestimations of the transpiration determined by TDM approach (see Flo et al. 2019 for a review) occur, due to: (i) wound effects (Wullschleger et al. 2011; Wiedemann et al. 2016); (ii) errors due to azimuthal variations (Molina et al. 2016; Shinohara et al. 2013); and (iii) errors caused by differences in radial gradient sap flux density profiles (Clearwater et al, 1999; Cohen et al. 2008; Bush et al. 2010).

The general objective of this study was to analyse the applicability of TDM to olive trees (cv. *Arbosana*) grown in a hedgerow orchard submitted to full irrigation regime. Sap flow density was monitored by TDM for 15 weeks in 2022 in a Mediterranean region (southern Italy), considering the species-specific local calibration, the wound effects, the azimuth correction, and the radial gradient corrections. This TDM transpiration was compared with an independent method (soil water balance) and the percentage correction was quantified with respect to the TDM application without considering all these corrections.

2. MATERIALS AND METHODS

2.1 The experimental site

The study was carried out in the period 26 June – 30 September 2022, including the most evaporative demanding periods in the site (Katerji et al. 2017). The olive orchard (cv. *Arbosana*) is located at the University of Bari experimental farm, southern Italy (41°01'N; 16°45'E; 110 m a.s.l.), on a shallow sandy clay soil (sand 630 g kg^{-1}; silt 160 g kg^{-1}; clay 210 g kg^{-1}) classified as a Typic Haploxeralf (USDA) or Chromi-Cutanic Luvisol (FAO). At 0.5 m of depth is present a parent rock that reduces the capacity of the root systems to expand beyond this layer. The site is characterised by typical Mediterranean climate with a long-term average (1988-2018) annual rainfall of 560 mm, two third concentrated from autumn to winter, and a long-term average annual temperature of 15.6 °C. The olive grove has been planted in early summer 2006; the self-rooted trees were trained according to the central leader system and spaced 4.0 m × 1.5 m (1,667 trees ha^{-1}) with a North–South rows orientation. Trees were 1.75±0.46 m high. Routine nutrition and soil management, pests and diseases control practices were set up as described by Camposeo and Godini (2010). Irrigation was scheduled following the FAO56 guideline (Allen et al. 1998), restoring 86% of crop evapotranspiration. The plots were irrigated by a dripline equipped with 2.5 L h^{-1} emitters, 0.6 m apart.

Air temperature (T_{air}, °C) and vapour pressure deficit (D, kPa) through air relative humidity, global radiation (R_g, W m^{-2}) and precipitation (P, mm), wind speed (u, ms^{-1}) were collected at a standard agrometeorological station 120 m far from the experimental field. Net Radiation R_n in Wm^{-2}, was calculated following Allen et al., (1998) as Rana and Katerji (2009):

$$Rn = (1-\alpha)R_g - \sigma\left(\frac{T_{max}^4+T_{min}^4}{2}\right)\left(0.34-0.15\sqrt{e_a}\right)\left(1.35\frac{R_g}{R_{g0}}-0.35\right) \quad (1)$$

where α is the albedo of the crop, directly determined on the orchard as mean of hourly daytime values (0.27) from January to December 2021; T_{max} and T_{min} (K) are maximal and minimal air temperatures; σ (4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}) is the Stefan-Boltzman constant; e_a (kPa) is the actual vapour pressure; R_g (MJ m^{-2}) was integrated in the time interval and R_{g0} (MJ m^{-2}) is the calculated clear-sky radiation (Allen et al. 1998). After a local calibration of twelve months (January-December 2021), soil heat flux, G, was considered as a constant at daily scale and equal to 0.09 R_n.

Soil water content in volume (θ, m^3 m^{-3}) was measured by capacitive probes (5TM, Decagon Devices Inc., USA). Three points were monitored following the protocol described in Campi et al. (2020): two points in the rows to intercept the dynamics of θ below the dripping lines, and one point among the rows. At each point, two capacitive probes were installed horizontally into the soil profile and transversely to the row, at -0.12 and -0.37 m from the soil surface. All sensors were connected to data-loggers (Tecno.el srl, Italy) and acquired at hourly scale; daily soil water content was determined for the soil profile (0.5 m) by integrating the values measured at each depth, since each probe was supposed to detect the water content in a 0.25 m soil layer. θ measurements from the three points were pooled to obtain a single average value for each treatment.

2.2 The TDM method

The transpiration at tree level, as determined by TDM, foresees the measurement of difference in temperature (ΔT, °C) between two probes placed in the conducting xylem of the stem; when the sap flow is low, or close to zero, a maximum difference in temperature (ΔT_{max}) is recorded and the variable K [unitless] was calculated as:

$$K = \frac{\Delta T_{max} - \Delta T}{\Delta T} \quad (2)$$

ΔT_{max} was determined using night-time measurements, separately for each sensor, according to Lu et al. (2003) and Peters et al. (2010).

Commercial 20 mm sap flow probes (SFS2 Type M, UP, Steinfurt, Germany) were installed at 0.30-0.40 m height above the ground. Probes were installed in each sampled tree in the north side to avoid direct solar heating; to prevent thermal interference, the heated probe was inserted 0.10 m above the unheated one; the probes in each sampled tree were covered by a reflecting radiation screen which also protected them from rain. ΔT was continuously monitored by a data loggers (CR10X, Campbell Scientific, Utah, USA) every 10 s, and the average values recorded every 10 min, to be further averaged at hourly scale.

The sap flow density (J_{s0}, gm^{-2}s^{-1}) was determined by the relation (Granier 1985; Lu et al. 2003):

$$J_{s0} = aK^b \quad (3)$$

with a and b determined by specific calibration as detailed in the following. Measurements were carried out in three replicate trees chosen to be representative of the olive orchard, considering the similar vigour, according to frequency distribution of trunk diameters and tree size of whole plot.

2.3 The TDM species-specific local calibration

According to Alarcón et al. (2005), McCulloh et al. (2007) and Zhou et al. (2017), the calibration to find the specific coefficients a and b in the Eq. (3) was carried out on three 5-year-old trees of the investigated variety (*Arbosana*) cultivated in pots placed in plastic cylindric pots (diameter 0.45 m, height 0.66 m) filled by the same soil of the experimental field and mulched by a plastic film to avoid soil evaporation. Sap flow density J_{s0} was computed as

$$J_{s0} = \frac{Tr_m}{SWA} \quad (4)$$

where Tr_m is the measured transpiration (g s^{-1}) determined by recording the weight loss in the pots at 150 minutes intervals, for one week (15 – 21 July 2022) during daytime, with an electronic balance (Radwag, Poland, model C315.150.C5.K). Every 150 minutes, the pot weights were obtained by averaging measurements carried out every one minute for 10 minutes; the pots were placed in open air, close to the experimental field to avoid differences in the mean meteorological conditions. SWA is the sapwood area determined by measuring sapwood depth on a core collected, at the end of the experiment, with a 5-mm-diameter increment borer at the middle between the two probes in the north side of monitored trees (Rana et al., 2019). At the same time, ΔT was continuously monitored by the same type of TDM sap flow probes used in the field, following the same protocol, recording data every 10 s (data logger CR10X, Campbell Scientific, Utah, USA), with the average values recorded every 10 min. In post processing, the 10-minute values were averaged to meet the interval times of the pot weight determination. By using these measurements of temperature, K values were determined. The calibration curve is obtained plotting the J_{s0} of eq. (4) vs the K values.

2.4 The TDM corrections

To assure the correctness of the TDM in the sap flow density measurement at tree level, J_{s0} was corrected for: (i) the damages caused by the trunk wounds by the probes set up, (ii) the azimuth variations (iii), the radial gradient of sap velocity in trunks.

2.4.1 The wound effect

A coefficient C_w was determined to correct the sap flow density for the wound effects (Wiedemann et al. 2016). For this aim, a couple of TDM probes (20 mm) were installed in parallel to the already measuring probes (installed in the first part of January 2021) in two trees, at the same height and 20 mm from the already installed ones, in the period 23 June – 23 August 2022. Hence, since the wound effect is due to the probe insertion in the trunk and then, affects the measured ΔT, correction is limited to the K parameter (see eq. 2) and the sap flux density becomes:

$$J_{s0} = a(C_w K)^b \quad (5)$$

2.4.2 The azimuth effect

The azimuthal variations of sap flux density were analysed in two sampled trees, by adding two couples of TDM probes (20 mm) at 120° and 240°, in the period 23 June – 23 August 2022. For taking into account this azimuth effect, a correction coefficient due to azimuthal variations, C_a, was introduced following Shinohara et al. (2013), to extrapolate sap flux density in the north direction, using the north sensor as a reference to the three integrated directions (averaged over the three directions). Hence, C_a is calculated as the ratio of the mean sap flux density in the three directions to sap flux density in the north direction; therefore, the sap flow density is now:

$$Js_0 = C_a a(C_w K)^b \quad (6)$$

2.4.3 The radial gradient effect

Finally, to account for radial gradient in sap flux density, following Ford et al. (2009) the whole sapwood depth of each sampled tree was divided in a set of 20 mm increments and a 3-parameter Gaussian function (Ford et al. 2004) was applied to estimate the sap flux density in each increment. In this application, the denominator of the exponent in Eq. (5) is inversely related to the rate of decrease in sap flux density with radial depth; the fitting of this parameter allows that the rate of radial decrease varied from tree to tree and with time (Ford et al. 2004). In this case, as suggested by Pataki et al. (2011), for angiosperms the used function is:

$$J_{si} = 1.033 J_{s0} \exp\left[-0.5\left(\frac{x-0.09963}{0.4263}\right)^2\right] \quad (7)$$

where J_{si} (g m^{-2} s^{-1}) is the sap flux density in each increment i, x is the normalized depth of each sapwood increment ($0 \leq x < 1$) and J_{s0} is calculated using Eq. (6).

Here, to test the used function (Eq. 7) over the active sapwood (Rana et al., 2019), two new set of TDM probe were installed in parallel to the already measuring probes in two sampled trees, at the same height and 20 mm from the other ones, in the period 23 June – 23 August 2022. In this case, beyond the 20 mm probes, commercial sap flow probes of 10 mm length (SFS2 Type M, UP, Steinfurt, Germany) were installed. From the sap flow density measured from the couple of probes, the J_{s0} values in the layer 10–20 mm of the sapwood depth was derived according to Iida and Tanaka (2010) as follows:

$$J_{s10\text{-}20} = \frac{J_{s\,0-20} - \alpha J_{s\,0-10}}{\beta} \quad (8)$$

where α and β are the proportions of the sapwood area from depths of 0–10 mm to that of 0–20 mm, and from depths of 10–20 mm to that of 0–20 mm, respectively.

2.5 The transpiration at field scale

Finally, the whole tree transpiration of each sampled tree (Tr_{tree}, g s^{-1}) was determined as:

$$Tr_{tree} = \sum_{i=0}^{m} J_{si} SWA_i \quad (9)$$

where m is the number of 20-mm increments in sapwood depth (m=2 for the sapwood depth measured in this case), J_{si} is the sap flux density determined by Eq. (7) and SWA_i is the sapwood area at each depth increase i. SWA was determined as above described in pot experiment.

Since Tr_{tree} measurements were referred to the projected canopy area, transpiration by TDM at field scale was calculated as

$$Tr_{TDM} = A_p \overline{Tr_{tree}} \tag{10}$$

where Tr_{TDM} is expressed per unit of projected canopy area, i.e., kg m^{-2} or mm, with $\overline{Tr_{tree}}$ the mean of the monitored trees and A_p (m^2) the area occupied by the mean vertical projection of each tree, (Lu et al. 2003).

A_p was calculated using a digital surface model (DSM) obtained from an automatic flight of an Unmanned Aerial Vehicle (UAV); a Phantom 4 multispectral with RTK system was used. The flight was planned at 40 m altitude with 85% overlap in vertical and horizontal. The acquired images were processed with Pix4d software to obtain the orthomosaic and DSM. The DSM was then used in QGIS environment to extract the canopy surface in accordance with Albuquerque et al. (2022) and Torres-Sanchez et al. (2017) (Figure 1). A value of A_p equal to 0.25 was used in eq. (1).

Transpiration on daily time scale was calculated by integrating transpiration at daytime (i.e., when R_g > 10 W m^{-2}).

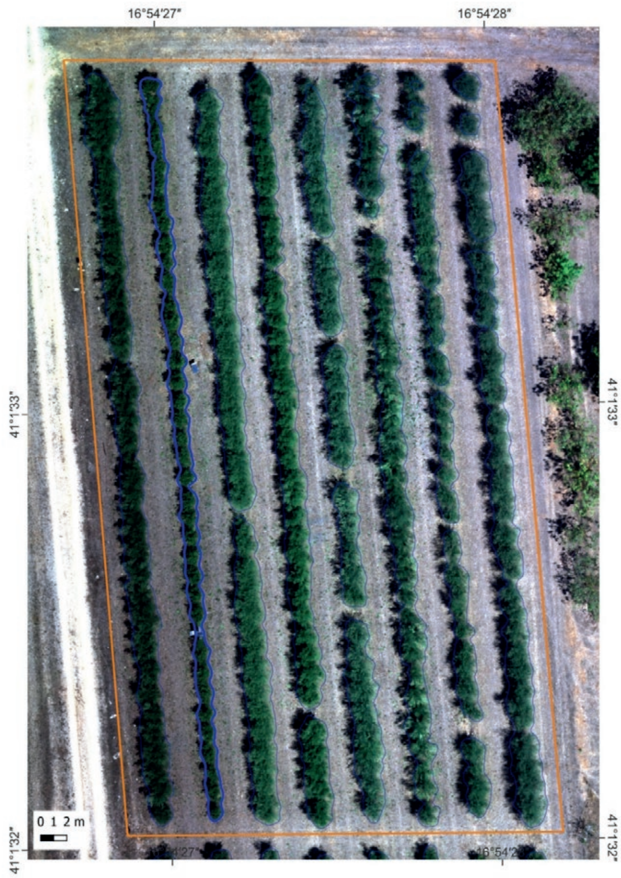

Figure 1. Canopy surface of the Valenzano experimental olive grove obtained with DSM processed from Phantom 4 drone images. The row outlined in blue is the one relating to the species analysed in this study.

2.6 Soil water balance

According to Fujime et al. (2021) the test and performance evaluation of the transpiration determined by the applied TDM has been carried out by comparing the transpiration Tr_{TDM} (mm) calculated by the Eq. (10) and the transpiration calculated from soil water balance Tr_{WB} (mm). In this Mediterranean site, characterised by shallow soil irrigated by localized drip irrigators, the soil water balance can be written:

$$ET_{WB} = P_{eff} + Ir \pm \Delta SWC \tag{11}$$

with ET_{WB} evapotranspiration (mm), P_{eff} effective rain (mm), Ir irrigation (mm); ΔSWC (mm) the difference of soil water content in the time interval; the deep percolation, runoff and capillary rising terms were considered neglectable (Rana and Katerji 2000). Due to the relatively high soil infiltration rate and the flat field, all rainfall over 0.2 mm was considered as effective precipitation (Villalobos and Fereres 2017).

Tr_{WB} comes from subtracting soil evaporation (E_S) from ET_{WB} as

$$Tr_{WB} = ET_{WB} - E_s \tag{12}$$

According to López-López et al. (2018), E_S was calculated following Bonachela et al. (2001), who modelled this term specifically for drip irrigated olive orchards. E_s is the sum of three terms: the water evaporated from the not wetted area (Bonachela et al., 1999), the water evaporated from the wetted area by emitters and a term which accounts for the advection effects increasing the evaporation from wetted zones.

3. RESULTS AND DISCUSSION

3.1 The TDM species-specific local calibration

The calibration curve obtained by the pots' experiment is shown in Figure 2, where the sap flow density values are fitted by a power function of K with specific coefficients a and b (see Eq. 3) equal to 140.0 and 1.118, respectively; this curve is robust (R^2 = 0.856) and slightly different from the original Granier (1985) calibration curve also reported in Fig. 2 . The new calibration curve had a slightly steeper slope and higher J_{s0} values along the whole K domain than the original Granier curve (a=118.9, b 1.231). This discrepancy resulted in overall underestimation of actual J_{s0} values by the original Granier curve.

Often, the used methods to calibrate the TDM species-specifically are based on gravimetrically induced flows through a stem segment (Roberts 1977; Vertessy et al. 1997; Bush et al. 2010; Sun et al. 2012). Although these cut-tree methods can be considered as the only way to directly obtain gravimetric measurement of water circulation for large trees at suitable time scale, Merlin et al. (2020) showed that these complex apparatus and studies present many disadvantages and limitations, mainly due to the separation of the crown and stem from the root system, which can much alter the correct evaluation of water uptake by trees. Conversely, weighting lysimeters, which are quite similar to the system pot plus balance here used, can provide suitable TDM calibration (Merlin et al. 2020) for young olive trees.

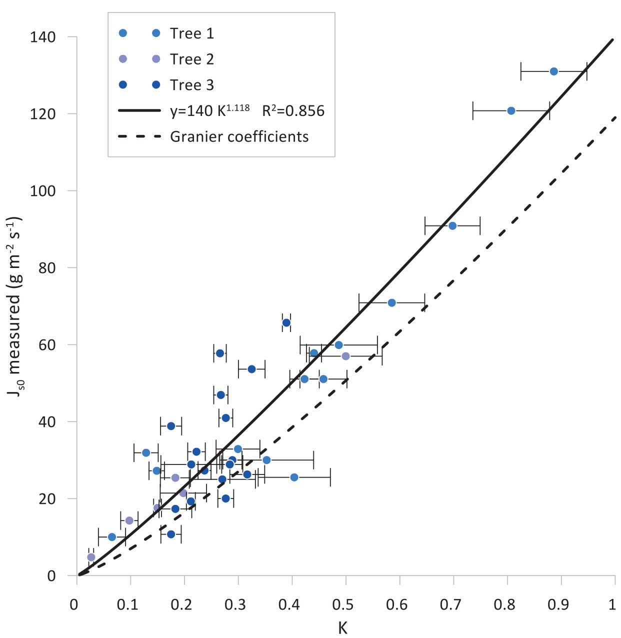

Figure 2. Calibration curve of the Thermal Dissipation Method (TDM). J_{S0} is the sap flow density measured by using eq. (4) in the text. K values have been obtained by TDM and eq. (2) in the text. The original Granier curve (a=118.9, b 1.231) is also reported.

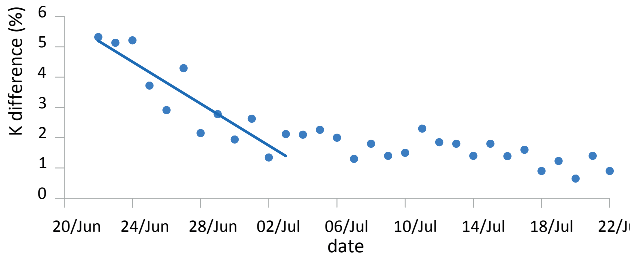

Figure 3. The relative difference between K values (see eq. 2 in the text) measured by the probes just installed and the oldest ones.

3.2 The TDM corrections

Regarding the wound effects, the relative difference between the K variable measured by the probes just installed and the probes installed in the first part of January 2021 is shown in Figure 3, from which a correction factor C_w=1.06 was calculated on K daily values. The correction factor due to wound effects is strongly dependent on the species (Wiedermann et al., 2016): in this case study, the found value is in the range reported by Reyes-Acosta et al. (2012) for another diffuse porous species (*Fagus sylvatica* L.). Moreover, the wound effects seem to vanish in around two weeks (see Fig. 3) against the four weeks reported by Wiedermann et al. (2016).

To evaluate the azimuthal corrections, the relationship between J_{s0} averaged for all probe directions ($J_{s0\text{-}avg}$) and J_{s0} at north direction ($J_{s0\text{-}North}$) is reported in Figure 4. The slope of this robust linear regression (R^2= 0.999) was used as azimuthal correction (C_a =1.29 in Eq. (6)). López-Bernal et al. (2010) found a variation of azimuthal sap flow density higher (C_a=1.58) in mature olive trees well irrigated; similar azimuthal variations were found in young olive trees by Vandegehuchte et al. 2012. Since azimuthal variability were mainly dependent on the structure of the sapwood (Vandegehuchte et al 2012) and variation of soil water content in the root zone (Fernández et al. 2001), the results of this study, with a lower correction coefficient for azimuthal variations, could be due to the regular structure of the olive orchard and the well localized drip irrigation.

The comparison between the adopted Gaussian function (Eq. 7) and the actual measurements of J_{s0} in the two sampled trees in the two layers (0-10 and 10-20 mm) is shown in Figure 5, using all available data at daily time

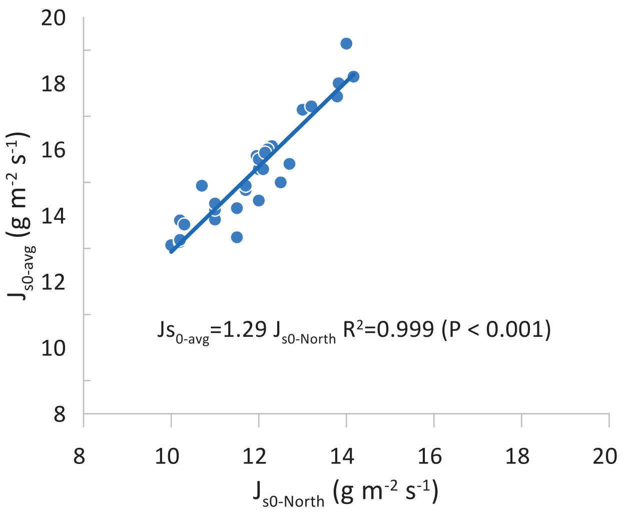

Figure 4. Relationship between sap flow density J_{s0} averaged for all probe directions ($J_{s0\text{-}avg}$) and J_{s0} at north direction ($J_{s0\text{-}North}$).

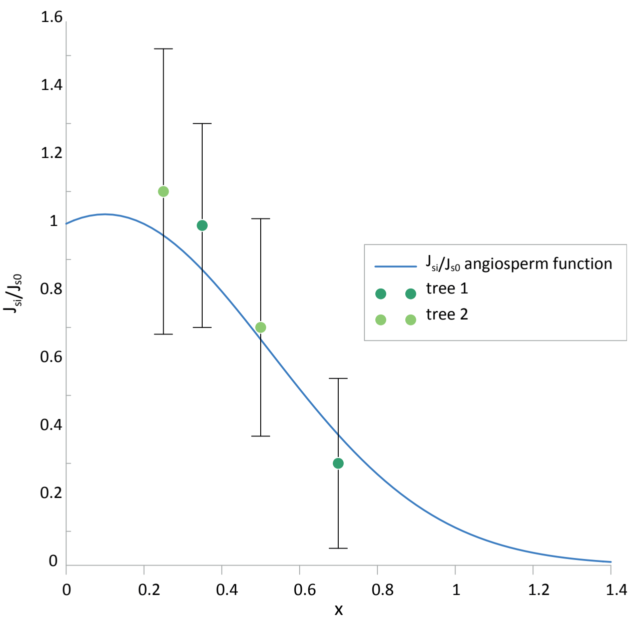

Figure 5. Sap flow density J_{s0} ration in the two sampled trees in the two layers of 0-10 and 10-20 mm vs x, the normalized depth of each sapwood increment.

scale. From this figure it seems clear that the used function to consider the gradient sap flow density over the sapwood works well enough in the present study. These results are supported by Rana et al. (2019), who successfully used the same function in mature olive trees under similar pedoclimatic conditions in urban environment.

Figure 6 presents the comparison between the two methods of determining *Tr* at weekly scale, TDM (species-specific local calibrated and corrected for all the above-mentioned effects) and soil water balance. Generally, both methods agreed in the estimates of transpiration at field scale, with a slight underestimation of the TDM with respect to the soil water balance; the cumulated values were 57.4±3.4 and 60.2±4.1 mm for the TDM and soil water balance, respectively, with an underestimation of about -5% for the cumulated values in the whole considered experimental period. Other publication compared soil water balance and sap-flow methodologies (Oren et al., 1998; Kang et al.,2003; Gong et al., 2007), but without a suitable independent estimation of soil evaporation. López-López et al. (2018), with a similar approach in the separate estimation of soil evaporation, found that the Compensation Heat Pulse sap flow technique applied to an almond crop overestimates the water balance transpiration values of about 10%.

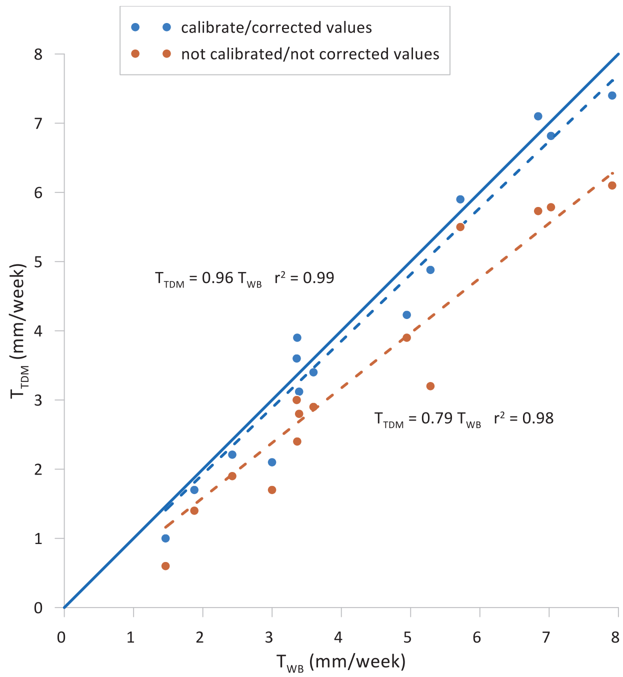

Figure 6. Transpiration by TDM method (T_{TMD}) vs Transpiration by water balance method (T_{WB}). The line 1:1 is also reported.

In Figure 6, also the comparison between Tr determined by TDM without specific calibration and corrections and soil water balance: in this case the underestimation of TDM is quite high, with cumulated value equals to 46.9 mm for the uncorrected and uncalibrated TDM.

4. CONCLUSIONS

This study proved that the thermal dissipation sap flow method applied to a super high-intensive hedgerow olive orchard can be used to quantify the actual transpiration only after several suitable species-specific characterizations. In particular: (i) the species - specific calibration was carried out by comparing TDM transpiration values with those directly measured in pots; (ii) the correction for the wound effects of the probes in the tree trunk was made by measuring the sap flow density with new probes on the same tree; (iii) the correction for the azimuth variability was estimated by measuring the sap flow density at different oriented trunk sectors; and finally (iv) adoption of a suitable Gaussian function to take into account the radial gradient variation of sap flow density over the sapwood area. If any correction nor specific calibration is carried out, the underestimation of the actual transpiration calculated by TDM was of about -18% with respect to the Tr estimated by a suitable water balance method, with the evaporation from the soil modelled by a specific olive orchard method.

The presented results support the widely accepted conclusions that: (i) for thermal dissipation method it should not be assumed that the original calibration is appropriate in all cases; (ii) corrections are necessary to mitigate the invasiveness of the probe use; (iii) the interaction between probes and sapwood could be suitably modelled.

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REFERENCES

Agüero Alcaras LM, Rousseaux MC, Searles PS, 2016. Responses of several soil and plant indicators to postharvest regulated deficit irrigation in olive trees and their potential for irrigation scheduling. Agricultural Water Management, 171, 10–20.

Alarcón JJ, Ortuňo MF, Nicolás E, Torres R, Torrecillas A, 2005. Compensation heat-pulse measurements of sap flow for estimating transpiration in young lemon trees. Biologia Plantarum, 49(4), 527-532.

Albuquerque R.W., Matsumoto M.H., Calmon M., Ferreira M.E., Vieira D.L.M., Grohmann C.H., 2022. A protocol for canopy cover monitoring on forest restoration projects using low-cost drones. Open Geosciences 2022; 14: 921–929. https://doi.org/10.1515/geo-2022-0406

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration, guidelines for computing crop water requirements. Paper No. 56. Rome, Italy, 300 pp.

Reyes-Acosta, J.L., Vandegehuchte, M.W., Steppe, K., Lubczynski, M.W., 2012. Novel, cyclic heat dissipation method for the correction of natural temperature gradients in sap flow measurements. Part 2. Laboratory validation. Tree Physiol., 32, 913–929.

Bonachela S, Orgaz F, Villalobos FJ, Fereres, E, 1999. Measurement and simulation of evaporation from soil in olive orchards. Irrig. Sci. 18, 205–211.

Bonachela S, Orgaz F, Villalobos FJ, Fereres E, 2001. Soil evaporation from drip-irrigated olive orchards. Irrig. Sci. 20, 65–71.

Bush SE, Hultine KR, Sperry JR, Ehleringer JR, 2010. Calibration of thermal dissipation sap flow probes for ring- and diffuse-porous trees. Tree Physiology 30, 2010, 1545–1554. doi:10.1093/treephys/tpq096

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.

Campi P, Gaeta L, Mastrorilli M, Losciale P, 2020. Innovative Soil Management and Micro-Climate Modulation for Saving Water in Peach Orchards. Frontiers in Plant Science, Vol. 11, Article number 1052 DOI: 10.3389/fpls.2020.01052

Camposeo S, Godini A, 2010. Preliminary observations about the performance of 13 varieties according to the super high density olive culture training system in Apulia (southern Italy). Adv. Hortic. Sci. 24 (1), 16–20.

Clearwater MJ, Meinzer FC, Andrade JL, Goldstein G, Holbrook NM, 1999. Potential errors in measurement of nonuniform sap flow using heat dissipation probes. Tree Physiol. 19, 681–687. https://doi.org/10.1093/treephys/19.10.681.

Cohen Y, Cohen S, Cantuarias-Aviles T, Schiller G, 2008. Variations in the radial gradient of sap velocity in trunks of forest and fruit trees. Plant Soil, 305, 49–59. DOI 10.1007/s11104-007-9351-0

Conceição N, Tezza L, Häusler M, Lourenço S, Pacheco CA, Ferreira MI, 2017. Three years of monitoring evapotranspiration components and crop and stress coefficients in a deficit irrigated intensive olive orchard. Agricultural Water Management, 191, 138–152.

Fernández JE, Palomo MJ, Díaz-Espejo A, Clothier BE, Green SR, Girón a IF, Moreno F, 2001. Heat-pulse measurements of sap flow in olives for automating irrigation: tests, root flow and diagnostics of water stress. Agricultural Water Management, 51, 99–123.

Flo V, Martinez-Vilalta J, Steppe K, Schuldt B, Poyatos R, 2019. A synthesis of bias and uncertainty in sap flow methods. Agricultural and Forest Meteorology, 271, 362–374.

Ford CR, McGuire MA, Mitchell RJ, Teskey RO, 2004. Assessing variation in the radial profile of sap flux density in Pinus species and its effect on daily water use. Tree Physiology 24, 241–249.

Fuchs S, Leuschner C, Link R, Coners H, Schuldt B, 2017. Calibration and comparison of thermal dissipation, heat ratio and heat field deformation sap flow probes for diffuse-porous trees. Agricultural and Forest Meteorology, 244–245, 151–161.

Fujime N, Kumagai T, Egusa T, Momiyama H, Uchiyama Y, 2021. Importance of calibration in determining forest stand transpiration using the thermal dissipation method. Agricultural and Forest Meteorology, (301-302), 108356.

Gong, D., Kang, S., Yao, L., Zhang, L., 2007. Estimation of evapotranspiration and its components from an apple orchard in northwest China using sap flow andwater balance methods. Hydrol. Process. 21, 931–938.

Granier A, 1985. Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Ann. Sci. For. 42, 81–88.

Iida S, Tanaka T, 2010. Effect of the span length of Granier-type thermal dissipation probes on sap flux density measurements. Ann. For. Sci. 67, 408.

Iniesta F, Testi L, Orgaz, F Villalobos FJ, 2009. The effects of regulated and continuous deficit irrigation on the water use, growth and yield of olive trees. Europ. J. Agronomy, 30, 258–265.

Kang, S., Hu, X., Jerie, P., Zhang, J., 2003. The effects of partial rootzone drying on root: trunk sap flow and water balance in an irrigated pear (Pyrus communis L) orchard. J. Hydrol. 280, 192–206.

Katerji N, Mastrorilli M, Rana G, 2008. Water use efficiency of crops cultivated in Mediterranean region: Review and analysis. European Journal of Agronomy, 28(4), 493-507.

Katerij N, Rana G, Ferrara RM, 2017. Actual evapotranspiration for a reference crop within measured and future changing climate periods in the Mediterranean region. Theoret. Appl. Climatol., 129(3–4), 923–938.

Lee X, Massman W, Law BE, 2004. Handbook of micrometeorology: a guide for surface flux measurement and analysis. In: Atmospheric and oceanographic sciences library. Springer Netherlands.

López-Bernal Á, Alcántara A, Testi L, Villalobos FJ, 2010. Spatial sap flow and xylem anatomical characteristics in olive trees under different irrigation regimes. Tree Physiology 30, 1536–1544. doi:10.1093/treephys/tpq095

López-López M, Espadafor M, Testi L, Lorite IJ, Orgaz F, Fereres E, 2018. Water use of irrigated almond trees when subjected to water deficits. Agricultural Water Management, 195, 84–93.

Lu P, Yunusa IAM, Walker RR, Müller WJ, 2003. Regulation of canopy conductance and transpiration and their modelling in irrigated grapevines. Funct. Plant Biol., 30, 689–698.

Masmoudi CC, Masmoudi M, Abid-Karray J, Ben Mechlia N, 2011. Sap flow measurements in young olive trees (Olea europaea L.) cv. Chétoui under Tunisian conditions. Scientia Horticulturae, 129, 520–527.

Merlin M, Solarik KA, Landhäusser SM, 2020. Quantification of uncertainties introduced by data-processing procedures of sap flow measurements using the cut-tree method on a large mature tree. Agricultural and Forest Meteorology, 287, 107926.

McCulloh KA, Winter K, Meinzer FC, Garcia M, Aaranda J, Lachenbruch B, 2007. A comparison of daily water use estimates derived from constant-heat sap-flow probe values and gravimetric measurements in pot-grown saplings. Tree Physiology, 27, 1355–1360.

Molina AJ, Aranda X, Carta G, Llorens P, Romero R, Savé R, Biel C, 2016. Effect of irrigation on sap flux density variability and water use estimate in cherry (Prunus avium) for timber production: Azimuthal profile, radial profile and sapwood estimation. Agric. Water Manage. 164, 118–126.

Oren, R., Phillips, N., Katul, G., Ewers, B., Pataki, E., 1998. Scaling xylem sap flux and soil water balance and calculating variance: a method for partitioning water flux in forests. Ann. For. Sci. 55, 191–216.

Pataki DE, McCarthy HR, Litvak E, Pincetl S., 2011. Transpiration of urban forests in the Los Angeles metropolitan area. Ecol. Appl. 21 (3), 661–677.

Pellegrini G, Ingrao C, Camposeo S, Tricase C, Contò F, Huisingh D, 2016. Application of Water Footprint to olive growing systems in the Apulia region: a comparative assessment. J. Cleaner Prod. 112: 2407-2418. doi: 10.1016/j.jclepro.2015.10.088

Peters EB, McFadden JP, Montgomery RA, 2010. Biological and environmental controls on tree transpiration in a suburban landscape. J. Geoph. Res. 115, G04006. https://doi.org/10.1029/2009JG001266.

Rana G, Katerji N, 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. European Journal of Agronomy, 13(2-3), 125-153.

Rana, G., De Lorenzi, F., Mazza, G., Martinelli, N., Muschitiello, C., Ferrara, R.M., 2019. Tree transpiration in a multi-species Mediterranean garden. Agricultural and Forest Meteorology, 280, 107767, https://doi.org/10.1016/j.agrformet.2019.

Roberts J, 1977. The use of tree-cutting techniques in the study of the water relations of mature Pinus sylvestris l. J. Exp. Bot 28, 751–767. https://doi.org/10.1093/jxb/28.3.751.

Russo G, Vivaldi GA, De Gennaro B, Camposeo S, 2015. Environmental sustainability of different soil management techniques in a high-density olive orchard. J. Cleaner Prod. 107: 498-508. doi: 10.1016/j.jclepro.2014.06.064

Scanlon TM, Kustas WP,2012. Partitioning evapotranspiration using an eddy covariance-based technique: improved assessment of soil moisture and land–atmosphere exchange dynamics. Vadose Zone J. doi:10.2136/vzj2012.0025

Shinohara Y, Tsuruta K, Ogura A, Noto F, Komatsu H, Otsuki K, Maruyama T, 2013. Azimuthal and radial variations in sap flux density and effects on stand scale transpiration estimates in a Japanese cedar forest. Tree Physiol. 5, 550–558.

Sun H, Aubrey DP, Teskey RO, 2012. A simple calibration improved the accuracy of the thermal dissipation technique for sap flow measurements in juvenile trees of six species. Trees, 26, 631–640. DOI 10.1007/s00468-011-0631-1

Tognetti R, Giovannelli A, Lavini A, Morelli G, Fragnito F, d'Andria R, 2009. Assessing environmental controls over conductances through the soil–plant–atmosphere continuum in an experimental olive tree plantation of southern Italy. Agricultural and Forest Meteorology, 149, 1229–1243.

Torres-Sanchez J., Lopez-Granados F., Borra-Serrano I., Pena J.M., 2018. Assessing UAV-collected image overlap influence on computation time and digital surface model accuracy in olive orchards. Precision Agric., 19:115–133. https://doi.org/10.1007/s11119-017-9502-0

Vandegehuchte MW, Braham M., Lemeur R, Steppe K, 2012. The importance of sap flow measurements to estimate actual water use of Meski olive trees under different irrigation regimes in Tunisia. Irrig. and Drain. DOI: 10.1002/ird.1670

Vertessy RA, Hatton TJ, Reece P, O'Sullivan SK, Benyon RG, 1997. Estimating stand water use of large mountain ash trees and validation of the sap flow measurement technique. Tree Physiol. 17, 747–756. https://doi.org/10.1093/treephys/17.12.747.

Villalobos FJ, Fereres E, 2017. Principles of Agronomy for Sustainable Agriculture. Springer. ISBN: 978-3-319-83445-0, XIII+555 pp.

Wiedemann A, Marañón-Jiménez S, Rebmann C, Herbst M, Cuntz M, 2016. An empirical study of the wound effect on sap flux density measured with thermal dissipation probes. Tree Physiology 36, 1471–1484 doi:10.1093/treephys/tpw071.

Wullschleger SD, Childs KW, King AW, Hanson PJ, 2011. A model of heat transfer in sapwood and implications for sap flux density measurements using thermal dissipation probes. Tree Physiol. 31, 669–679.

Zhou S, Liu W, Lin W, 2017. The ratio of transpiration to evapotranspiration in a rainfed maize field on the Loess Plateau of China. Water Science & Technology: Water Supply, 17.1, 221-227. doi: 10.2166/ws.2016.108