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Determining the water status of olive trees using microtensiometer sensors, on-ground and proximal sensing observations under Mediterranean climate conditions

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ABSTRACT

Determining tree water status in the field is essential for implementing precision irrigation strategies. This study evaluated the performance of microtensiometer sensors (MTs) in a commercial olive orchard located in the province of Castellón, Spain, by comparing MTs readings with multiple ground-based and proximal sensing indicators related to soil–tree water status. MTs were installed in the trunks of olive trees subjected to different irrigation regimes (full irrigation, FI, and deficit irrigation, DI) during the 2022–2024 period. Throughout the study, periodic measurements of stem water potential (SWP) were conducted to characterize tree water status, alongside continuous monitoring of agrometeorological variables and soil water content (SWC). In addition, spatially distributed visible/near-infrared and thermal data were acquired at the field scale using proximal sensing techniques. The results showed that trunk water potential (TWP), measured by MTs, and SWP followed similar temporal patterns (with average values ranging from −0.5 MPa to −2.5 MPa and −2.0 MPa for SWP and TWP, respectively), with a positive correlation observed between the two variables, although this relationship tended to weaken over time (with coefficient of determination (R^2) ranging from 0.50 to 0.21, from 2022 to 2024). The MTs were able to detect significant differences between irrigation regimes (p-value < 0.05, resulting in average values of -0.78 ± 0.20 MPa and -1.09 ± 0.27 MPa under FI and DI, respectively), while thermal indicators and SWP measurements occasionally identified these differences. Moderate relationships were also found between TWP and SWC under both FI and DI conditions in the upper soil profile ($R^2 = 0.45$). However, robust estimation of absolute SWP values requires site-specific sensor calibration across multiple cultivars and water stress levels and MTs sensors usefulness might be limited to a single season.

1. Introduction

Precision irrigation requires reliable and operational indicators of crop water status to optimize water use and sustain productivity under increasing water scarcity (Bwambale et al., 2022; Eslamian and Eslamian, 2023). Achieving this objective requires accurate, field-based measurements of plant water status to effectively assess and interpret plant responses to water stress (Taylor et al., 2015). In this context, several plant-based indicators have been proposed to monitor the water status of Mediterranean perennial tree crops (Fernández, 2014). Among these indicators, stem water potential (SWP) is widely recognized as the reference standard due to its high sensitivity in detecting slight differences in plant water status (Jones, 2007). However, its routine use in commercial orchards is constrained by labour requirements, low temporal resolution, and operator dependency. SWP measurements are traditionally performed at two specific times of the day: (i) pre-dawn,

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when transpiration and plant water stress are minimal, and (ii) at midday, when stress levels are typically at their maximum. Measurements are conducted on selected, previously bagged, leaves, following the procedure described by Scholander et al. (1965), and using a pressure chamber. Over the past decades, research efforts have focused on defining accurate irrigation scheduling criteria and identifying crop-specific SWP thresholds to support the effective implementation of precision irrigation strategies under full irrigation (FI) and/or deficit irrigation (DI) management (Lakso and Intrigliolo, 2022).

Despite the robustness and widespread adoption of SWP measurements, several limitations are associated with this methodology. These include its point-based nature, temporal discontinuity, sample variability, and potential operator-dependent errors. In parallel, proximal and remote sensing approaches provide spatially distributed canopy information that may complement plant-based measurements, although their physiological interpretation still requires benchmarking against robust indicators of plant water status. In this context, vegetation indices derived from visible and near-infrared (VNIR) reflectance, as well as thermal-based metrics obtained from thermal infrared (TIR) domains, have been increasingly used to assess crop water status at the orchard scale (Damm et al., 2018; Rallo et al., 2014; Ramírez-Cuesta et al., 2025). However, although unmanned aerial vehicle (UAV) platforms enable high-resolution tree-level assessments and overcome satellite revisit and cloud-cover constraints, proximal sensing approaches still require further validation before being considered reliable stand-alone tools for crop water status assessment (Carrasco-Benavides et al., 2025). To overcome the temporal limitations of SWP measurements, technologies for automatic and continuous data collection are now available in the market with promising results (i.e., microtensiometers - MTs, osmometers, and psychrometers). However, their relatively elevated costs, reliability, and incompatibility with different crop types hinder their massive adoption (Kisekka et al., 2024). The innovative MTs FloraPulse©, based on a microelectromechanical pressure sensor that is embedded into the trunk, have been developed for continuously register the trunk water potential (TWP). Even if the initial development of MTs was announced in 2008 (Corelli Grappadelli, 2022), the sensors reached the market about 10 years later, and their application in open field conditions is still under experimental evaluation for several crops (refer to the crop validation database by the manufacture). Even if numerous studies have tested their use for perennial tree crops (such as almond, pear, apple, and grapevines), most of them highlighted the difficulty to have representative water status in heterogeneous fields under Mediterranean dynamic environmental conditions (Blanco and Kalcsits, 2021; Kisekka et al., 2024; Lakso et al., 2022; Pagay, 2022). However, evidence remains scarce for olive, a drought-adapted species with marked hydraulic buffering capacity and the ability to reach very low water potential values under severe stress. Villalobos et al. (2024) and Zucchini et al. (2023) evaluated TWP dynamics in potted and field-grown olive trees over a single spring–summer season. Therefore, multi-season assessments under contrasting irrigation regimes are still lacking.

Long-term evaluations under field conditions are needed to determine whether MT-derived trunk water potential can provide robust and operational information for irrigation management in olive orchards. In particular, it remains unclear to what extent the relationship between TWP and conventional SWP is temporally stable across seasons, and whether MT measurements offer complementary value when interpreted together with soil water content and canopy-scale proximal sensing observations. The present study hypothesized that MTs would be able to track relative changes in olive tree water status under contrasting irrigation regimes, but that their agreement with absolute SWP values would vary over time under field conditions. Therefore, the aim of this study was to assess the suitability of MT-derived trunk water potential measurements in a commercial single-cultivar olive orchard over a three-year period. Specifically, we evaluated: (i) the temporal agreement between TWP and SWP, (ii) the ability of MTs to discriminate between full irrigation (FI) and regulated deficit irrigation (RDI) treatments, and (iii) the complementarity between MT measurements and soil- and canopy-based indicators derived from in situ and proximal sensing observations.

2. Materials and methods

2.1. Field site description

The study was conducted in a commercial olive orchard (6-year-old) cv. 'Serrana' (*Olea europea* L.), managed by the Cooperativa de Viver, situated in Viver (Castellón province) in eastern Spain (WGS84 39º 55' 46"N, 0º 36' 48"W) (Fig. 1). The study site is characterized by semi-arid Mediterranean climate, with mean annual reference evapotranspiration (ET_0) and rainfall amount of 998 mm and 427 mm, respectively, during the period 2022–2024. Data was measured by an automatic weather station located on site and managed by "Servicio de Tecnología del Riego" (IVIA). The soil at the site is classified as loam according to the USDA soil texture classification and is composed of 26%, 40% and 34% of clay, sand and silt, respectively.

The olive orchard under study (with tree-spacing of 6 m × 7 m in the row and inter-row, respectively) was supplied by a sub-surface drip irrigation system made of two drip-lines for each tree row, separately by 1.5 m from each side of the trunk, and buried at 30 cm from the soil surface. Each drip-line had emitters with flow rate of 1.75 L h^{-1} and spacing of 0.5 m from each other. The plot was also equipped with automatic control valves and flowmeters to monitor and control irrigation volumes precisely.

Two different water regimes were applied during the period 2022–2024 (June-September). They included the adoption of full irrigation (FI) and regulated deficit irrigation (RDI) strategies. The FI dose was scheduled on the basis of the crop water requirement (ET_c) estimation according to the single crop coefficient (K_c) approach (Allen et al.,1998). Specifically, the daily ET_0 was calculated using the Penman-Monteith equation and the agrometeorological data inputs acquired in situ. According to the canopy ground cover, the seasonal K_c for olive for oil was assumed variable from a minimum of 0.27 in May to a maximum of 0.42 in October, in line with the recommendation provided by https://riegos.gva.ivia.es. Then, the irrigation dose was adjusted based on soil moisture readings from two capacitive sensors (TEROS 10, Meter Group Inc., Pullman, WA 99163, USA) installed at two depths from the soil surface (40 and 100 cm, respectively). One data logger (ZL6, Meter Group Inc.) was used to collect and transmit sensor data via GPRS to ZentraCloud.

The irrigation dose applied at FI (control) corresponded to well-watered trees (100% ET_c). In RDI, a water deficit of 50% ET_c was applied during fruit growth (phase II of fruit growth from approximately mid-July to mid-September) when pit hardening occurred; whereas, FI dose was applied during the rest of the crop cycle. Note that during the irrigation seasons 2022–2024, the water deficit under RDI was applied from 10th July to 22th September, from 10th July to 4th September and from 15th July to 2nd September in 2022, 2023 and 2024, respectively. Fertilization, pest control and pruning practices were managed by the Cooperativa de Viver.

2.2. Tree water status measurements

Tree water status measurements were conducted during the period 2022–2024 using both traditional (SWP) and continuous methods (TWP) on four sample olive trees supplied by FI and RDI, respectively (Fig. 1, refer to Section 2.2.1). Additionally, proximal sensing techniques based on VNIR and TIR data were applied at the olive orchard level (refer to Section 2.2.2). An overview of the applied methodological approach is showed in Fig. 2.

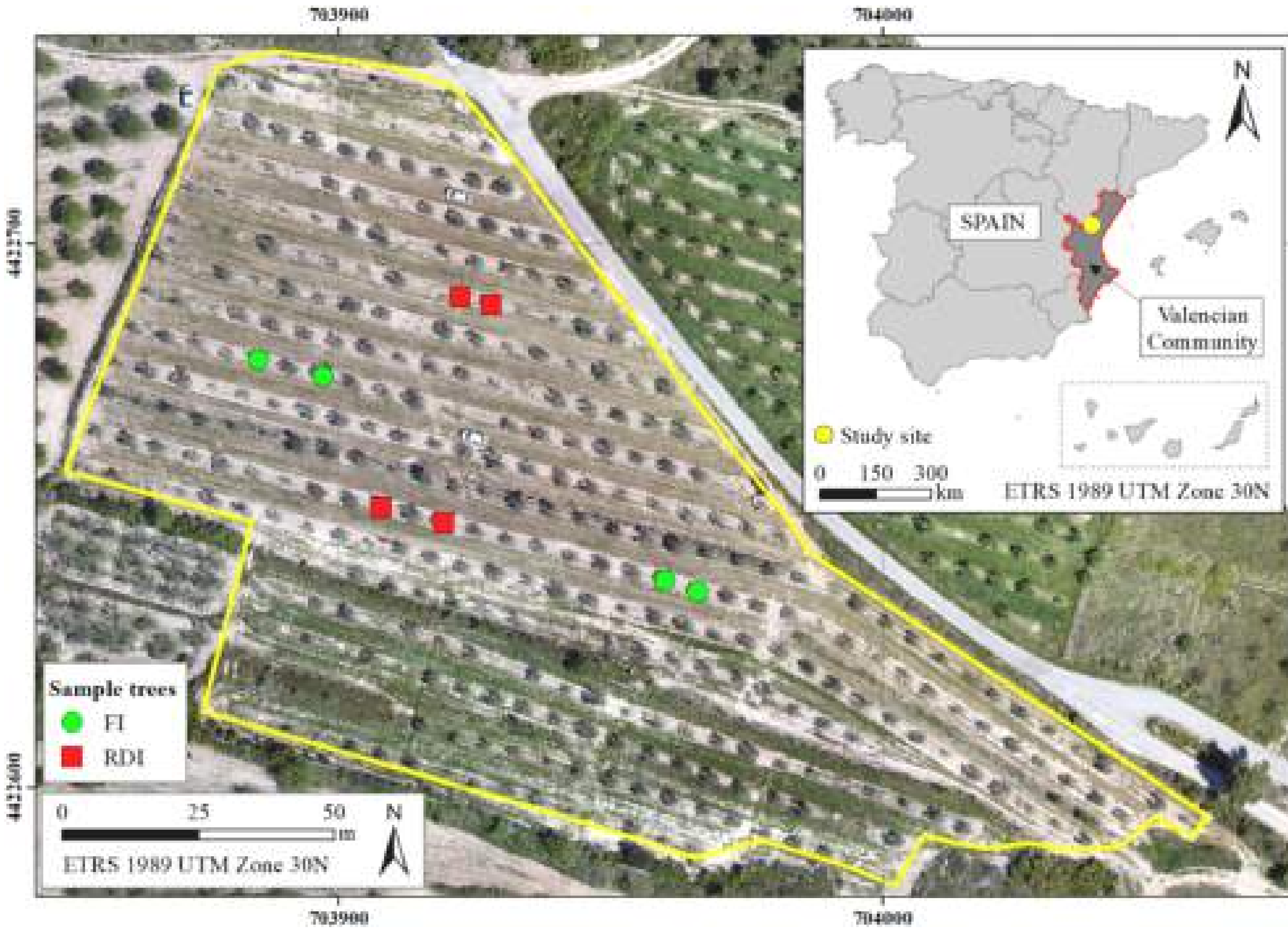

Fig. 1. Orthomosaic obtained on May 2022 at the olive orchard under study with the locations of sample trees (FI: Full irrigation; RDI: Regulated deficit irrigation).

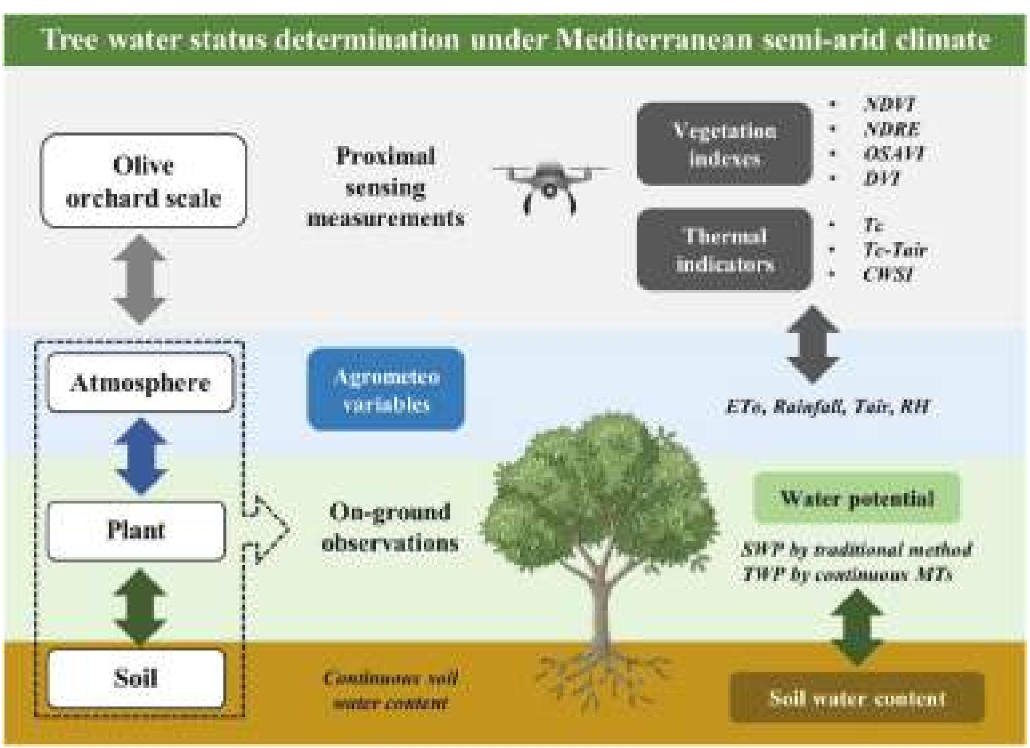

Fig. 2. Flowchart of the methodological approach applied in this study. Reader is referred to the main text for the abbreviation's description.

2.2.1. Ground-based measurements

Continuous TWP measurements were acquired, since March-April 2022, using both digital and analogical MTs (FloraPulse®, Davis, USA) installed into the main trunks of the sample olive trees in Fig. 1. Separate data-loggers (CR1000 Campbell Scientific) were used for storing and managing the continuous voltage data with a frequency of 10 min. Then, the voltage data was converted in TWP values using the calibration parameters provided by the manufacturer. During the monitoring period, battery failures occurred which resulted in TWP data gaps in the time series for some sensors.

Periodically within the same monitoring period, traditional on site SWP measurements were taken from mature 2–4 leaves (bagged branches in aluminium foil for, at least, 1 h before the measurement), collected from the outer canopy, at the sample olive trees, for a total number of 92 measurements within the period April 2022- July 2024 (Fig. 1). A portable pressure chamber (model 3000; Soil Moisture Equipment. Corp., Santa Barbara, California, USA) was used for this purpose in the field.

2.2.2. Proximal sensing measurements

VNIR and TIR UAVs flights were conducted with a quadcopter DJI Matrice 350RTK at the olive orchard under study in 12 dates over the reference period as given in Table 1.

VNIR imagery was acquired with a RedEdge-M multispectral camera (Micasense). This camera acquires 5 spectral bands in the blue (B), green (G), red (R), red edge (RE) and near infrared (NIR) spectral domains, with center wavelengths of 475 nm, 560 nm, 668 nm, 717 nm and 840 nm, respectively. A Micasense RedEdge-M calibration panel was captured from directly above immediately before and after each flight to make appropriate reflectance data corrections. The camera spatial resolution is 1280 × 960 pixels, and the field of view (FOV) is 47.2° and 35.4°, respectively, horizontal and vertical.

The TIR information was captured using a Vue Pro R640 camera (Flir Systems, Inc., Wilsonville, OR, USA). The TIR sensor acquires images in the 7.5–13.5 μm spectral range with a spatial resolution of 640 × 512 pixels, and an optics focal length of 13 mm that yields an angular FOV of 45°. UAV-based TIR images were mosaicked using Pix4D software (Pix4D, Lausanne, Switzerland).

The main VNIR-based indices, including the difference vegetation index−DVI (Richardson, Weigand, 1977), normalized difference vegetation index−NDVI (Rouse et al., 1974), normalized difference red edge index −NDRE (Fitzgerald et al., 2010), and optimized soil-adjusted vegetation Index −OSAVI (Rondeaux et al., 1996) were calculated by combining in raster calculator the UAV-based multispectral bands of interest. TIR-based indexes, based on canopy temperature (T_c), were also determined as the difference between the T_c and T_{air} ($T_c - T_{air}$) and the calculation of the crop water stress index (CWSI, Idso et al., 1981). CWSI allows quantification of water stress by positioning the crop within a range defined by two extreme water conditions (baselines), including the absence of water stress (lower baseline) and non-transpiring conditions (upper baseline). In this study, the upper baseline was assumed constant and equal to 5ºC (Ben-Gal et al., 2009); whereas, a dynamic lower baseline dependent on the hour of the flight and the period of the year was used for the olive trees under study (Egea et al., 2017).

Table 1
Time-step of the drones multispectral and thermal acquisitions during the experimental period 2022–2024.

Year	Date (month, day)					
2022		May, 11		July, 13		
2023	April, 20		June, 29		August, 8	August, 31
2024	April, 4	May, 14	June, 28	July, 17	August, 2	September, 12

All the outputted VNIR and TIR indicators were extracted at the tree level according to the methodological protocol described in Ramírez-Cuesta et al. (2025). In brief, for each image, the olive canopies were manually digitalized in GIS (geographic information system) environment. Then, for each one of the resulting polygons (i.e., olive tree canopies), the main statistics (i.e., average, standard deviations, counts, minimum and maximum values and data range) were extracted for further data analysis.

2.3. Statistical analysis

Linear regression analysis on the acquired SWP and TWP datasets was carried out with the software Statistix 9 (Analytical Software, Tallahassee, USA). A previous outlier identification procedure was performed through boxplots and distributional analyses in order to discard anomalous data that could strongly influence the statistical analysis. No data points were excluded unless a clear justification related to data quality or measurement error was established (e.g., operator measurement errors or petiole breaks prior to SWP measurement). One-way analyses of variances were implemented to assess differences on the olive water status indicators under the adopted water regimes. More on detail, the influence of the water regime (FI and RDI) was analysed on each derived tree water status variable (i.e., SWP, TWP, DVI, NDVI, NDRE, OSAVI, T_c, $T_c - T_{air}$ and CWSI). Then, a *post-hoc* significance analysis based on Tukey honest significant differences (HSD) test was performed at significance level ($p\text{-value} < 0.05$) of 0.05.

The sensitivity analysis of the considered indicators for estimating the olive tree water status (i.e., TWP, SWP, VNIR and TIR-based indices) was performed in this study under the experimental water regimes (FI *versus* RDI) by applying the signal-to-noise (S/N) methodology, as described in Fereres and Goldhamer (2003). The tree-to-tree variability of the obtained variables was also quantified in terms of coefficient of variation (CV).

3. Results

3.1. Agrometeorological data and irrigation levels

During the 2022–2024 irrigation seasons (June–September), similar environmental conditions were observed at the study orchard (Fig. 3). The maximum average (T_{air}) reached 41.5 °C in 2023. No rainfall events were recorded during the irrigation seasons, except in 2024, when a cumulative precipitation of 20 mm was registered. The applied irrigation depths under FI and RDI treatments are reported in Table 2, together with the resulting average water savings of 23%, 27% and 17% in 2022, 2023 and 2024 respectively.

3.2. Comparison between stem and trunk water potential measurements

Fig. 4 shows the temporal evolution of the SWP and TWP for each sample olive tree under the water regimes of interest (FI and RDI) during the reference period 2022–2024.

Over the reference period, the SWP and TWP followed similar trends with decreased values from the beginning to the end of the irrigation season, resulting in values ranging from −0.5 MPa to −2.5 MPa and −2.0 MPa for SWP and TWP, respectively (Fig. 4). Extreme TWP were reached in several events, reaching values between −3.0 and −4.5 MPa in 2023 and 2024. In general, across the period 2022–2024, TWP provided less negative values (ranging from –0.1 to −2.4 MPa) than SWP (ranging from −0.6 to −2.9 MPa), being the range of variation observed for both methodologies in the olive orchard equal to −2.3 MPa. A general better water status was observed under FI than for trees under RDI (Table 3). Additionally, a positive significant relationship was obtained between the water potential values measured via the pressure chamber and MTs methods, which allows correlating measurements taken on the leaves and on the trunk ($TWP = 0.90 \times SWP + 0.15$) with coefficient of

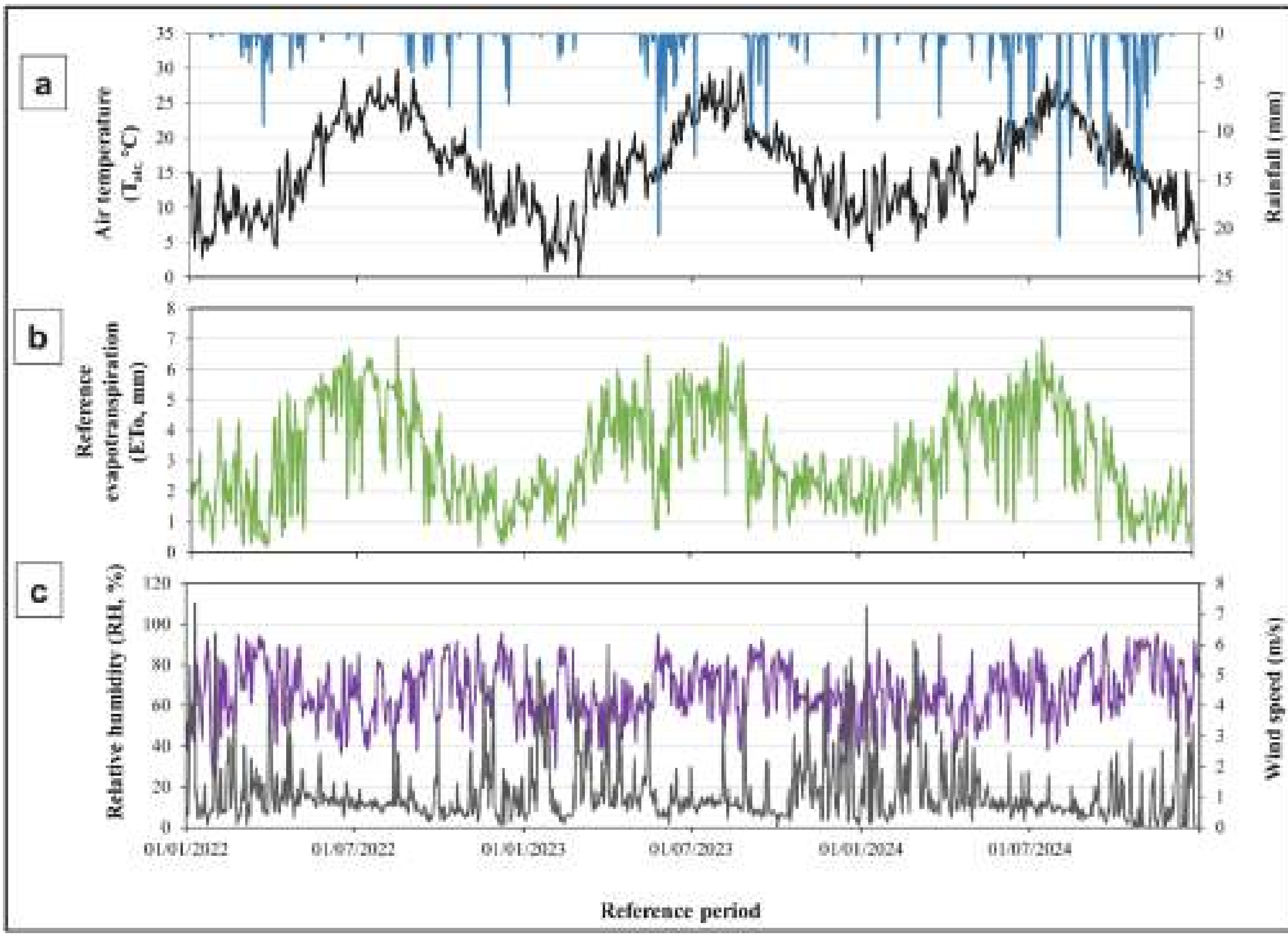

Fig. 3. Environmental conditions at the olive orchard during the experimental period 2022–2024.

Table 2
Reference evapotranspiration (ET_0), annual rainfall, annual irrigation water applied and percentage of water saving compared to the control treatment (%) during 2022–2024.

Irrigation season	ET_0 (mm)	Rainfall (mm)	Irrigation water applied (mm)		Water savings (%)
			FI	RDI	
2022	975	464	113	87	23
2023	1037	279	111	81	27
2024	983	537	166	137	17

determination (R^2) of 0.53 (p-value<0.001) and root mean square error (RMSE) value equals to 0.43 MPa (Fig. 5a).

Importantly, the obtained relationship tended to be weaker along the monitored years, indicating decreasing R^2 values from 0.50 to 0.21 from 2022 to 2024. Thus, the strength of this relationship varies by year, being strongest in 2023 ($R^2 = 0.64$) and weakest in 2024 ($R^2 = 0.21$). The slopes range from 0.72 to 1.01, indicating that tree response to SWP was generally proportional but not constant over time.

3.3. Complementary olive tree water status methodologies

3.3.1. Plant-based measurements

The signal-to-noise (S/N) analysis indicated comparable sensitivities for TWP and SWP over the reference period, with mean values of 5.87 and 9.14, respectively. The corresponding average coefficients of variation (CV) were 0.25 for TWP and 0.14 for SWP (Table 3). Notably, TWP exhibited higher sensitivity than SWP in discriminating between FI and RDI treatments on the evaluated dates (Table 3).

3.3.2. Multispectral indicators

The VNIR-derived indicators presented increased average S/N values for DVI, OSAVI, NDRE and NDVI, with values of 8.31, 13.08, 13.34 and 20.08, respectively (Table 4); and CV values of 0.06 for NDVI, 0.09 for NDRE−OSAVI, and 0.16 for DVI. No differences were observed in terms of the analysed multispectral indicators between the FI and DI conditions.

3.3.3. Thermal-based indicators

The sensitivity of the thermal-based indicators is given in Table 5, indicating higher average S/N ratios for T_c (25.74) than for T_c-T_{air} (4.25) and CWSI (0.67). Note that sporadic statistical differences were observed among FI and RDI treatments in terms of T_c, T_c-T_{air} and CWSI values within the evaluated dates (Table 5).

3.3.4. Soil water content and trunk water potential relationships

The relationships between TWP and SWC measured at 40 cm and 100 cm soil depths are shown in Fig. 6. Overall, tree water status responded more closely to SWC in the upper soil layer (40 cm; $R^2 = 0.45$), resulting in less negative TWP values under higher SWC; while deeper SWC (100 cm) showed a weaker influence to TWP ($R^2 = 0.35$). At both depths, the TWP revealed distinct responses of the sample olive trees under FI and RDI treatments. RDI consistently showed lower SWC

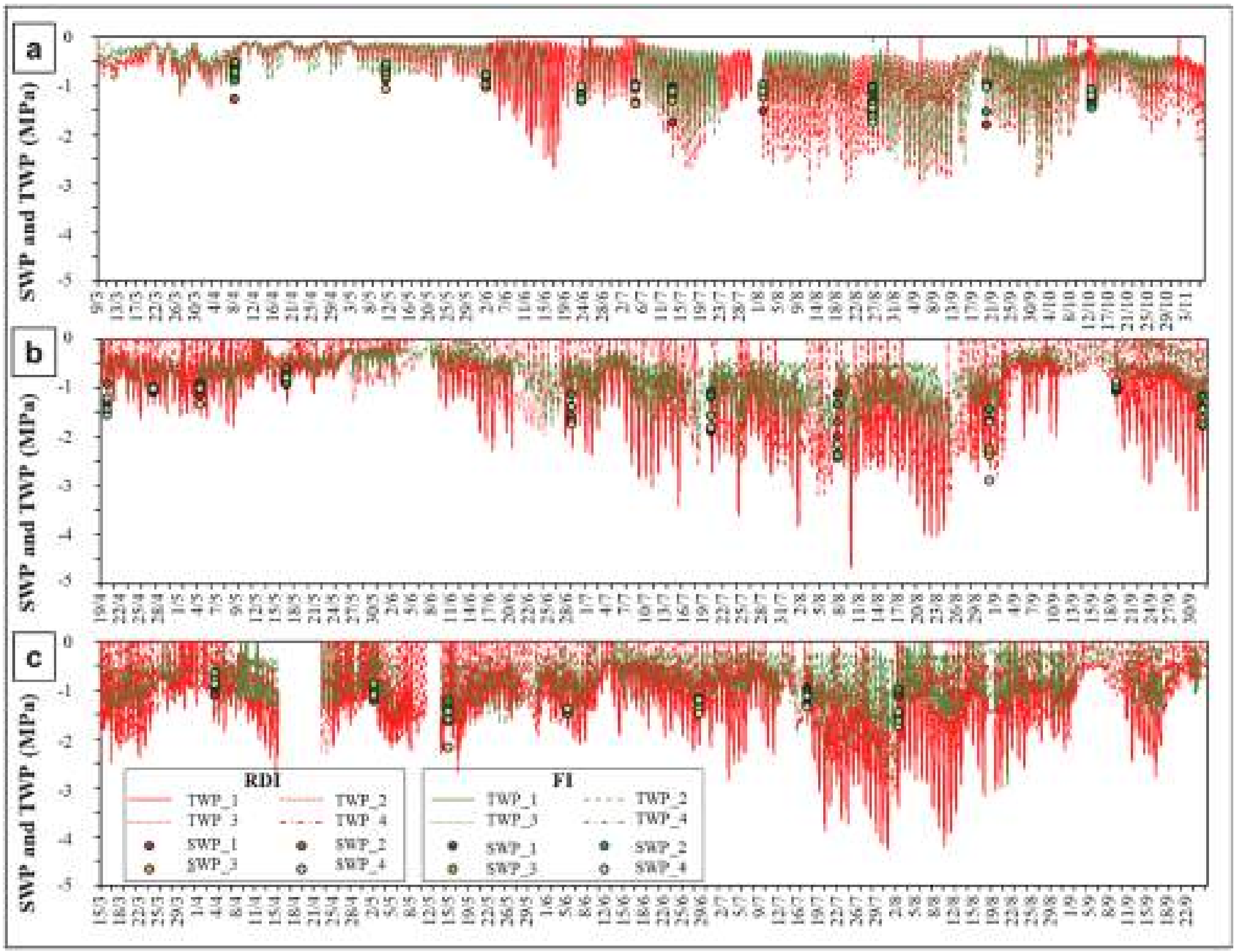

Fig. 4. Temporal evolution of the stem water potential (SWP) and trunk water potential (TWP) values measured during 2022–2024.

(0.10–0.20 cm^3 cm^{-3}) and more negative TWP (down to −3.0 MPa). Conversely, FI maintained higher SWC (0.22–0.35 cm^3 cm^{-3}) and moderate TWP values (generally above −1.5 MPa).

4. Discussion

4.1. Performance of MTs versus SWP method over time

Recent advances in plant-based sensing technologies have opened new opportunities for improving irrigation decision-making by enabling continuous monitoring of crop water status under field conditions. However, the adoption of these technologies in commercial orchards remains limited due to economic constraints, sensor reliability issues, and the difficulty of interpretation sensor-derived indicators in dynamic environmental conditions (Fernandes-Silva et al., 2025). In this context, the present study evaluated the performance of MTs in comparison with traditional stem water potential measurements and complementary soil-plant observations obtained from ground-based and proximal sensing approaches in a commercial olive orchard. Herein, the TWP detected at the sample olive trees showed a less negative trend compared to the SWP observations (Fig. 4), being in the expected range for olive crops (Shackel et al., 2021). Similar TWP trends were also observed by Pagay (2022); Vanella et al. (2022) and Zucchini et al. (2023) in comparison to SWP for grapevine, citrus and mature olive crops, respectively; while, an opposite TWP-SWP behaviour was obtained for pear by Blanco and Kalcsits (2021).

The high dispersion of the TWP-SWP data observed in Fig. 5 can be explained as consequence of the variability existent between the sample olive trees within the orchard and installation uncertainties. Variation in the installers' choice of trunk location and consistency of the installation method (e.g., sleeve insertion, precision drilling of the hole to the xylem, insertion of enough mating compound) are potential sources of expected discrepancy (Lakso et al., 2022). In this study, the installation was performed by the same user, thus systematic errors due to installation can be considered as a constant. Difference in tree anatomy appears to be another source of uncertainty, that can be neglected in this study as fine uniform wood for the trunks of the sample olive trees of interest was found.

The progressive weakening of the relationship between SWP and TWP across the monitored seasons suggests that these water status *proxies* did not remain linearly coupled over time under field conditions. This divergence may be explained by several physiological and methodological factors (Massenti et al., 2022).

From a physiological perspective, olive trees are characterized by relatively high hydraulic resistance and substantial internal water storage capacity, which can buffer short-term fluctuations in plant water status. Trunk tissues may therefore act as hydraulic capacitors, smoothing transient variations in water potential generated by changes in transpiration demand. As trees are repeatedly exposed to DI and high evaporative demand, structural and functional adjustments may also

Table 3
Mean, standard deviation (SD), signal to noise ratio (S/N) and coefficient of variations (CV) values of trunk and stem water potential (TWP and SWP) measured for each date with the microtensiometer sensors and the pressure chamber under full irrigation (FI) and regulated deficit irrigation (RDI) during the observation period 2022–24. Different letters in bold indicate, for each date, statistical differences between treatments or methodologies according to Tukey's test ($p < 0.05$).

		TWP				SWP			
Date	W*R*	mean (MPa)	SD (MPa)	S/N	CV	mean (MPa)	SD (MPa)	S/N	CV
08/04/2022	RDI	−0.45	0.02	5.88	0.06	−0.75	0.25	4.52	0.33
	FI	−0.42	0.13		0.30	−0.74	0.09		0.12
11/05/2022	RDI	−0.29	0.10	2.54	0.34	−0.74	0.17	5.60	0.24
	FI	−0.29	0.13		0.46	−0.70	0.10		0.14
02/06/2022	RDI	−0.59	0.15	6.74	0.25	−0.87	0.12	8.32	0.14
	FI	−0.48	0.05		0.11	−0.83	0.10		0.12
23/06/2022	RDI	−0.90	0.30	3.99	0.33	−1.21	0.13	9.34	0.11
	FI	−0.87	0.16		0.19	−1.19	0.13		0.11
05/07/2022	RDI	−0.69	0.25	3.98	0.36	−1.23 **b**	0.14	18.25	0.12
	FI	−0.69	0.10		0.14	−0.69 **a**	0.10		0.14
13/07/2022	RDI	−1.23	0.41	4.42	0.34	−1.36	0.26	9.44	0.19
	FI	−1.11	0.18		0.16	−1.11	0.08		0.07
02/08/2022	RDI	−1.28	0.62	4.94	0.48	−1.11	0.17	8.83	0.15
	FI	−0.99	0.03		0.03	−1.07	0.09		0.08
26/08/2022	RDI	−1.38	0.57	4.73	0.41	−1.42	0.30	7.06	0.21
	FI	−0.90	0.21		0.23	−1.21	0.15		0.12
20/09/2022	RDI	−1.25	0.13	8.59	0.11	−1.12	0.23	6.94	0.20
	FI	−0.86	0.20		0.23	−1.13	0.10		0.08
13/10/2022	RDI	−0.52	0.09	7.06	0.17	−1.21	0.07	10.01	0.06
	FI	−0.58	0.05		0.09	−1.27	0.17		0.13
20/04/2023	RDI	−0.88	0.15	6.43	0.17	−1.32	0.29	6.89	0.22
	FI	−0.84	0.13		0.16	−1.28	0.10		0.08
04/05/2023	RDI	−1.19 **b**	0.21	9.38	0.18	−1.13	0.23	9.88	0.20
	FI	−0.89 **a**	0.10		0.11	−0.99	0.03		0.03
17/05/2023	RDI	−0.81 **b**	0.10	9.25	0.13	−0.81	0.15	7.49	0.18
	FI	−0.58 **a**	0.10		0.17	−0.80	0.07		0.09
29/06/2023	RDI	−1.41	0.24	6.92	0.17	−1.66 **b**	0.09	16.83	0.05
	FI	−1.02	0.24		0.23	−1.32 **a**	0.13		0.10
20/07/2023	RDI	−1.71	0.26	6.25	0.15	−1.47	0.53	3.52	0.36
	FI	−1.19	0.37		0.31	−1.43	0.32		0.22
08/08/2023	RDI	−1.91	0.41	5.22	0.22	−2.12	0.34	4.71	0.16
	FI	−1.19	0.47		0.40	−1.75	0.62		0.35
31/08/2023	RDI	−1.92 **b**	0.35	4.59	0.18	−2.16	0.59	5.04	0.27
	FI	−1.09 **a**	0.63		0.58	−1.87	0.35		0.19
19/09/2023	RDI	−0.80 **b**	0.18	7.33	0.22	−0.99	0.07	14.12	0.07
	FI	−0.36**a**	0.14		0.39	−0.95	0.07		0.07
02/10/2023	RDI	−1.51	0.56	4.69	0.37	−1.55	0.19	6.99	0.12
	FI	−0.83	0.34		0.40	−1.38	0.27		0.20
04/04/2024	RDI	−0.86	0.20	4.51	0.24	−0.94	0.13	9.03	0.14
	FI	−0.54	0.26		0.47	−0.78	0.10		0.13
15/05/2024	RDI	−1.11	0.23	5.16	0.21	−1.69	0.35	8.41	0.20
	FI	−0.76	0.27		0.36	−1.37	0.12		0.09
28/06/2024	RDI	−1.44	0.40	6.36	0.28	−1.30	0.14	16.98	0.11
	FI	−0.91	0.20		0.22	−1.20	0.02		0.02
17/07/2024	RDI	−1.05 **b**	0.23	6.10	0.22	−1.20	0.12	12.14	0.10
	FI	−0.65 **a**	0.20		0.31	−1.07	0.09		0.08

occur, including changes in xylem conductivity, stomatal regulation, and internal capacitance. These adjustments can modify the hydraulic gradient between leaves and trunk, potentially leading to progressive decoupling between SWP and TWP measurements. Note that from a practical standpoint, the declining R^2 values indicate that absolute SWP values cannot be reliably inferred from TWP measurements without periodic re-installation, particularly in multi-season monitoring frameworks. The pronounced reduction in R^2 observed by the third year of the study (2024) suggests that the hydraulic coupling between the trunk xylem and the leaves is not static under field conditions. This divergence may be attributed to the plastic response of olive trees subjected to multi-year DI cycles, where alterations in xylem conductivity or internal capacitance modify water potential gradients. From a technical perspective, the difference between continuous TWP measurements and discrete SWP observations may also contribute to the observed reduction in correlation over the monitoring period (Intrigliolo and Castel, 2004). Additionally, the effect of secondary radial trunk growth cannot be overlooked; the deposition of new functional xylem layers over the MT's tip may have progressively isolated the sensor from the primary transpiration stream.

4.2. Sensitivity of MTs for precision irrigation management

The above-described results emphasise that the use of MTs as a direct surrogate for pressure chamber requires site-specific seasonal validation or sensor repositioning protocols to maintain accuracy in absolute SWP estimations. However, despite the reduced linear agreement over time, TWP maintained its capacity to discriminate between irrigation treatments and to track seasonal water status dynamics, particularly detected by TWP, confirming the sensitivity of the sensor in capturing irrigation-induced stress dynamics. This suggested that MTs may be more suitable as relative indicators of tree water status and for detecting trends and treatment differences rather than for direct substitution of pressure chamber measurements, being MTs highly sensitive in discriminating between irrigation treatments (FI vs. RDI) even in the final season. In this sense, the signal-to-noise analysis highlighted distinct sensitivities among the different plant- and proximal-sensing-based indicators, providing insights into their practical utility for irrigation management (Marino et al., 2021). Although SWP exhibited a higher mean S/N ratio and lower CV compared to TWP, as previously mentioned the latter showed higher sensitivity in discriminating between FI and RDI

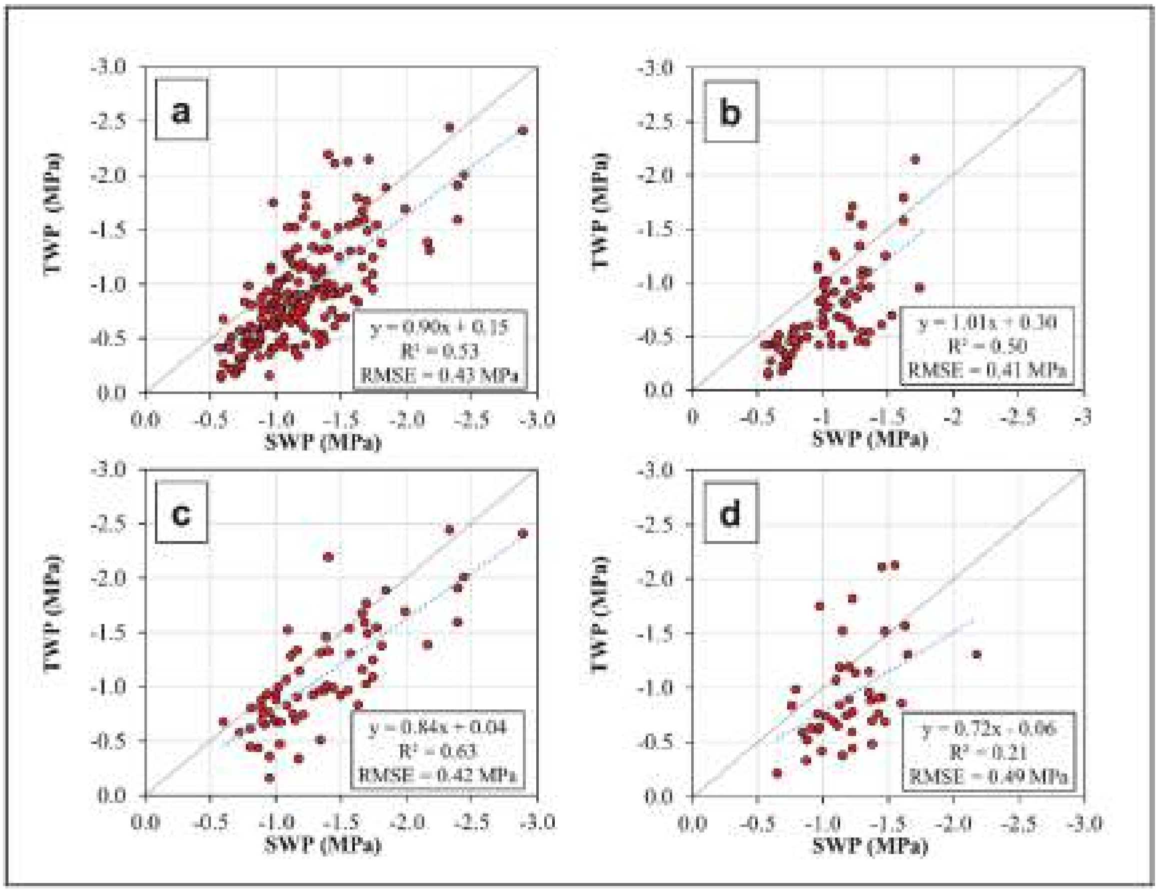

Fig. 5. Relationships between stem and trunk water potential values (SWP *versus* TWP) measured (a) within the overall study period (2022–24) and on annual basis (b-d, referring to years 2022, 2023 and 2024, respectively).

Table 4
Mean, standard deviation (SD), signal to noise ratio (S/N) and coefficient of variations (CV) values of the proximal sensed biophysical indicators (NDVI, NDRE, OSAVI and DVI) under full irrigation (FI) and regulated deficit irrigation (RDI) during the observation period 2022–2024.

Date	WR	NDVI				NDRE				OSAVI				DVI			
		mean	SD	S/N	CV	mean	SD	S/N	CV	Mean	SD	S/N	CV	mean	SD	S/N	CV
11/05/2022	RDI	0.52	0.02	18.27	0.03	0.25	0.01	11.11	0.04	0.39	0.01	19.01	0.04	0.25	0.01	16.42	0.06
	FI	0.53	0.04		0.07	0.27	0.03		0.12	0.39	0.03		0.06	0.24	0.02		0.07
13/07/2022	RDI	0.52	0.03	21.77	0.06	0.30	0.01	20.47	0.04	0.39	0.03	18.51	0.07	0.25	0.03	12.47	0.12
	FI	0.54	0.01		0.03	0.31	0.02		0.05	0.40	0.01		0.03	0.24	0.01		0.05
20/04/2023	RDI	0.56	0.03	18.93	0.06	0.32	0.04	11.30	0.11	0.42	0.03	16.12	0.07	0.27	0.03	10.12	0.10
	FI	0.55	0.03		0.05	0.30	0.02		0.08	0.41	0.02		0.06	0.26	0.03		0.10
29/06/2023	RDI	0.64	0.05	17.93	0.08	0.36	0.03	12.79	0.09	0.40	0.04	10.70	0.09	0.17	0.03	5.07	0.19
	FI	0.62	0.02		0.03	0.36	0.02		0.07	0.38	0.04		0.10	0.16	0.04		0.23
31/08/2023	RDI	0.51	0.05	12.33	0.11	0.29	0.04	9.87	0.12	0.38	0.05	9.82	0.12	0.24	0.04	6.00	0.18
	FI	0.56	0.02		0.04	0.32	0.02		0.06	0.42	0.02		0.06	0.27	0.03		0.12
04/04/2024	RDI	0.56	0.06	14.01	0.11	0.30	0.04	9.87	0.14	0.42	0.04	13.06	0.10	0.27	0.03	9.79	0.09
	FI	0.51	0.02		0.05	0.27	0.02		0.09	0.39	0.02		0.06	0.28	0.03		0.10
14/05/2024	RDI	0.50	0.06	8.89	0.12	0.26	0.04	6.61	0.17	0.39	0.05	8.05	0.14	0.27	0.05	6.07	0.19
	FI	0.51	0.05		0.10	0.27	0.03		0.13	0.39	0.04		0.11	0.28	0.04		0.14
28/06/2024	RDI	0.51	0.06	9.16	0.12	0.27	0.04	6.86	0.16	0.39	0.05	8.27	0.13	0.28	0.05	6.18	0.18
	FI	0.51	0.05		0.10	0.27	0.03		0.13	0.39	0.04		0.11	0.28	0.04		0.14
17/07/2024	RDI	0.73	0.02	30.38	0.03	0.50	0.03	17.97	0.07	0.53	0.06	13.15	0.10	0.33	0.14	2.48	0.41
	FI	0.71	0.02		0.03	0.45	0.03		0.06	0.56	0.02		0.04	0.42	0.10		0.23
02/08/2024	RDI	0.52	0.02	22.57	0.03	0.34	0.02	13.22	0.07	0.40	0.01	21.60	0.03	0.29	0.02	13.95	0.05
	FI	0.65	0.03		0.04	0.43	0.02		0.05	0.50	0.02		0.05	0.34	0.02		0.07
12/09/2024	RDI	0.74	0.02	46.64	0.03	0.51	0.03	25.54	0.05	0.43	0.09	5.59	0.21	0.18	0.09	2.81	0.47
	FI	0.74	0.01		0.02	0.51	0.01		0.03	0.42	0.07		0.16	0.16	0.05		0.33

treatments, reflecting its strength in capturing temporal and treatment-induced variations in tree water status. This apparent discrepancy may be attributed to the intrinsic differences between discrete and continuous measurements. SWP represents a point-based assessment performed at specific times of the day, potentially limiting its ability to capture dynamic differences in tree water status recovery and cumulative stress (Shackel et al., 2021). In contrast, TWP continuously reflects trunk water status and integrates diurnal fluctuations,

Table 5
Mean, standard deviation (SD), signal to noise ratio (S/N) and coefficient of variations (CV) values of canopy temperature (T_c), T_c-T_{air} and CWSI under full irrigation (FI) and regulated deficit irrigation (RDI) during the observation period 2022–24. Different letters in bold indicate, for each date, statistical differences between treatments or methodologies according to Tukey's test ($p < 0.05$).

Date	WR	T_c				T_c-T_{air}				CWSI			
		mean	SD	S/N	CV	mean	SD	S/N	CV	mean	SD	S/N	CV
11/05/2022	RDI	25.48	1.54	20.08	0.06	1.88	1.54	0.84	0.82	0.07	0.46	0.24	6.41
	FI	25.40	1.00		0.04	2.88	2.12		0.74	0.05	0.30		6.42
13/07/2022	RDI	28.84 b	0.81	61.27	0.03	1.86	0.81	13.66	0.44	−0.09 b	0.13	−0.89	1.41
	FI	30.28 a	0.09		0.00	0.42	0.09		0.20	0.14 a	0.01		0.10
20/04/2023	RDI	29.30	1.28	20.09	0.04	6.40	1.28	4.44	0.20	1.28	0.25	4.51	0.20
	FI	29.09	1.64		0.06	6.19	1.64		0.27	1.23	0.32		0.26
29/06/2023	RDI	31.74	1.25	39.08	0.04	5.54	1.25	7.45	0.23	1.17	0.40	5.22	0.34
	FI	31.00	0.40		0.01	4.80	0.40		0.08	0.93	0.13		0.14
08/08/2023	RDI	25.17	1.43	25.29	0.06	3.57	1.43	5.01	0.40	0.61	0.39	4.33	0.64
	FI	23.52	0.66		0.03	1.92	0.66		0.34	0.16	0.18		1.14
31/08/2023	RDI	25.91 **a**	1.23	30.48	0.05	3.21 **a**	1.23	8.37	0.38	0.60 **a**	0.27	−8.57	0.45
	FI	23.13 **b**	0.60		0.03	0.43 **b**	0.60		1.42	−0.01 **b**	0.13		9.17
04/04/2024	RDI	20.45	1.46	17.70	0.07	1.21	0.76	1.26	0.63	−0.08	0.35	−0.45	4.69
	FI	22.70	0.69		0.03	2.14	0.58		0.27	0.04	0.17		4.53
14/05/2024	RDI	22.68	1.16	13.38	0.05	2.19	0.72	1.68	0.33	0.03	0.36	0.06	11.40
	FI	22.70	2.22		0.10	2.14	1.90		0.89	0.04	0.69		18.84
28/06/2024	RDI	21.65	1.16	12.57	0.05	1.16	0.72	0.72	0.62	−0.29	0.36	−0.78	1.26
	FI	22.70	2.22		0.10	2.14	1.90		0.89	0.04	0.69		18.84
17/07/2024	RDI	22.35	2.03	11.96	0.09	1.75	0.36	4.94	0.21	−0.28	0.46	0.79	1.63
	FI	22.68	1.68		0.07	1.45	0.41		0.28	−0.21	0.38		1.84
02/08/2024	RDI	24.40	0.64	21.48	0.03	1.68	0.64	1.54	0.38	0.39	0.11	2.01	0.29
	FI	30.27	1.47		0.05	1.87	1.47		0.79	0.45	0.26		0.58
12/09/2024	RDI	26.35	0.56	35.53	0.02	0.95	0.56	1.02	0.58	−0.33	0.17	1.59	0.51
	FI	25.71	0.94		0.04	1.59	0.94		0.59	−0.42	0.20		0.48

thereby enhancing its responsiveness to irrigation-induced variations. Moreover, the hydraulic buffering capacity and drought tolerance of olive trees may reduce midday SWP contrasts under moderate DI conditions; whereas, continuous TWP measurements are able to detect slight divergences in water status dynamics between treatments.

4.3. Role of proximal sensing indicators for olive water status

A step forward of this study was that observations from MTs were supplemented with multiple olive tree water status measurements, including UAV mapping tools and SWC observations. According to Zucchini et al. (2023) the main advantage of using UAV spatial distributed information is a useful approach for depicting patterns of water stress at the entire orchard scale even than in a single time-point, as SWP determinations. These authors concluded that the adoption of combined multi-scale and multi-source approaches is the key for implementing more efficient irrigation criteria in the near future. Herein, VNIR-derived indices, particularly NDVI and NDRE, showed high S/N values and low variability, indicating their robustness in capturing canopy spectral properties. However, these indices did not discriminate between irrigation treatments, likely because structural and pigment-related canopy traits are less sensitive to moderate water deficits in olive trees (Carrasco-Benavides et al., 2025). Consequently, VNIR indices may be more suitable for monitoring canopy development or long-term stress responses rather than short-term variations in plant water status.

TIR-based indicators, especially T_c, exhibited the highest S/N values, and sporadic differences between FI and RDI were detected, confirming that thermal metrics are highly responsive to short-term fluctuations in transpiration and water stress (Ramírez-Cuesta et al., 2025). These findings suggest a complementary role of the different indicators. TWP and TIR-based metrics were more suitable for monitoring dynamic responses to irrigation regimes at the tree level, while VNIR indices provided consistent information on canopy status, but may be less sensitive to moderate water deficits. Integrating these measurements can therefore enhance precision irrigation strategies by combining continuous physiological monitoring with canopy-scale observations.

4.4. Comparison of MTs versus SWC observations

At the soil-plant level, the observed relationships between TWP and SWC at both 40 cm and 100 cm soil depths (Fig. 6), further support the sensitivity of TWP to irrigation-induced variations. Trees under FI consistently maintained higher SWC and less negative TWP values, while RDI trees experienced lower SWC and more negative TWP. Notably, the relationship was evident at both shallow and deeper soil layers, suggesting that TWP integrates the hydraulic response of the root-soil system rather than reflecting only local soil moisture conditions. From a physiological point-of-view, this indicates that olive trees redistribute water between soil layers to buffer short-term deficits, yet TWP can capture cumulative stress under DI. These results reinforce the potential of MTs as continuous indicators of tree water status, capable of guiding precision irrigation in Mediterranean olive orchards by reflecting both short-term atmospheric demand and longer-term SWC variations.

4.5. Limitations and future research outlook

Although this study provides relevant insights on olive tree water status, additional studies are necessary to understand the impact of long-term physiological responses across different olive cultivars and more severe water stress conditions on MTs readings, and to develop irrigation guidelines based on those readings. The high variability observed in TWP measurements highlights the need for local calibration and broader evaluations across different varieties and locations with different environmental conditions, to ensure robust absolute determinations of tree water status. The weakening of the MTs vs SWP correlation over time suggests that annual check of MTs performance should be considered. Such calibration implies their removal from the tree, and their calibration in the laboratory using the water-filled caps provided by the manufacturer. As an alternative to the MTs calibration procedure, the difficulties associated to the MTs tree removal and the relatively low cost of the sensor, could support their replacement by new ones.

In addition, the development of correction algorithms, incorporating key agrometeorological drivers (e.g., VPD and T_{air}) with thermal indicators, is recommended to improve the temporal stability of the

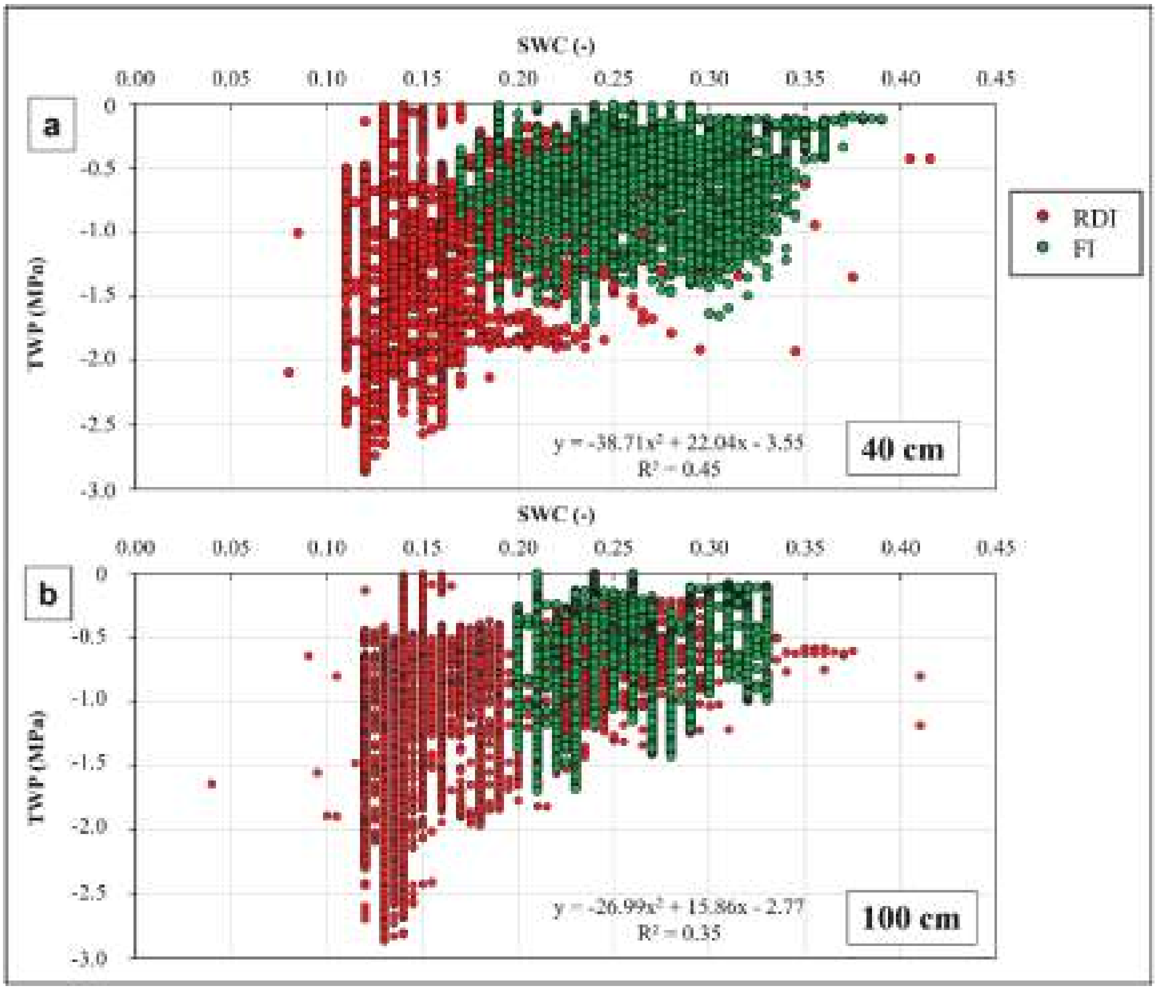

Fig. 6. Relationships between trunk water potential values (TWP) and soil water content (SWC) measured at (a) 40 cm and (b) 100 cm soil depths within the study period (2022–2024) for sample trees under full irrigation (FI) and regulated deficit irrigation (RDI).

method. In conclusion, MT-based TWP monitoring should not be considered a replacement for pressure chamber measurements, but rather a complementary and operational tool for continuous irrigation management, particularly when integrated with multi-scale sensing approaches.

5. Conclusion

In conclusion, while TWP stands out as a superior operational tool for continuous monitoring and real-time stress trend detection, the multi-year drift in its correlation with SWP indicates that the MT's primary value lies in its role as a relative diagnostic indicator rather than a provider of universal absolute values. The success of its commercial implementation in olive orchards will depend on the integration of correction algorithms that account for both the stress history and the physiological maturation of the tree. Furthermore, the synergy between continuous trunk sensing and UAV-based thermal metrics offers a robust framework for precision irrigation, balancing high-frequency physiological data with orchard-scale spatial representativeness.

CRediT authorship contribution statement

Juan Miguel Ramírez-Cuesta: Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniela Vanella:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Juan Gabriel Pérez-Pérez:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Diego S. Intrigliolo:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Luis Bonet:** Writing – review & editing, Resources, Methodology, Investigation, Data curation, Conceptualization. **Maria Tasa:** Writing – review & editing, Methodology, Investigation, Data curation. **Eduardo Badal:** Writing – review & editing, Resources, Methodology, Formal analysis, Data curation. **Maria Amparo Martínez-Gimeno:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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