Science of the Total Environment 958 (2025) 177528

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Effects of organic mulching and regulated deficit irrigation on crop water status, soil and yield features in an orange orchard under Mediterranean climate

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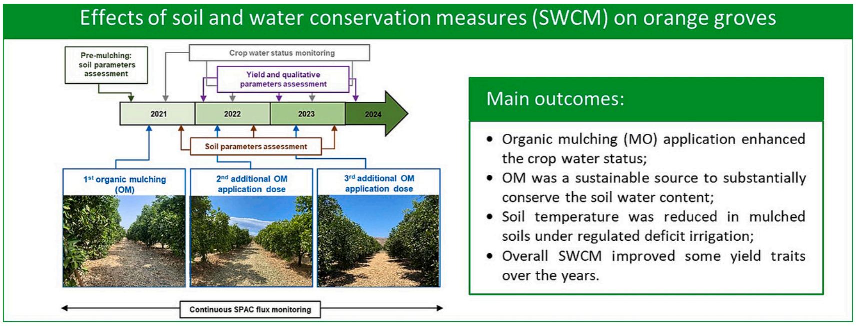
## HIGHLIGHTS

- Soil and water conservation measures (SWCM) were applied in a citrus grove.
- Organic mulching (MO) application improved the crop water status.
- OM was a sustainable source to substantially conserve the soil water content.
- Soil temperature was reduced in mulched soils under regulated deficit irrigation.
- Overall SWCM improved some yield traits over the years.

## GRAPHICAL ABSTRACT



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## ARTICLE INFO

Editor: Manuel Esteban Lucas-Borja

*Keywords:*
Soil-plant-atmosphere *continuum* monitoring
Regulated deficit irrigation
Organic mulching
Sustainable agricultural practices
Citrus groves

## ABSTRACT

The adoption of soil and water conservation measures (SWCM) is essential for improving the use of natural resources and making the agro-systems more resilient to climate change. In this context, a three-years trial was carried-out in an orange orchard characterized by different soil management (SM, i.e., bare and organic mulched soils) and water regimes (WR, i.e., full irrigation, FI, and regulated deficit irrigation, RDI). In response to the applied SWCM, crop water status (CWS), soil and yield main features were explored using multiple soil-plant-atmosphere *continuum* (SPAC) monitoring approaches.

Overall average water saving of 24 % was achieved under RDI in comparison to FI. The stem water potential revealed a year-dependent behaviour in accordance to the patterns of the main ancillary physiological indicators. The adoption of additional plant-based measurements provided continuous information on the CWS, both in terms of trunk water potential (TWP) and sap flow fluxes, resulting in higher absolute values of TWP ($-0.93 \pm 0.01$ MPa versus $-0.83 \pm 0.00$ MPa) and lower transpiration rates ($0.64 \pm 0.00$ mm $d^{-1}$ versus $0.88 \pm 0.01$ mm $d^{-1}$) in mulched compared to bare soils. The soil water content showed higher rates under mulched soils than in bare soil condition, both in FI (up to 15 %) and RDI (up to 27 %) at 0.75 m from the tree trunk to the inter-row.

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https://doi.org/10.1016/j.scitotenv.2024.177528
Received 6 August 2024; Received in revised form 8 October 2024; Accepted 10 November 2024

Soil temperature was lower in mulched soils under RDI. However, a great time-variability was observed for most of the soil physical-chemical variables under study. Nevertheless, the application of SWCM improved the yield over the years, resulting in higher fruit weights under mulched FI conditions.

Finally, the study suggests that the adoption of SWCM can serve as an efficient strategy to enhance soil and yield features, highlighting the critical role of using SPAC methodological tools for monitoring the CWS at the field level.

## 1. Introduction

The implementation of sustainable management approaches is pivotal for making more efficient the use of natural resources (i.e., soil and water) in the agricultural sector (Wallace, 2000). In this sense, a number of sustainable agricultural strategies, based on the application of soil and water conservation measures (SWCM), have been proposed in literature for improving, or at least maintaining, high-standard levels of crop productivity at low environmental costs (e.g., Deng et al., 2006; Dimelu et al., 2013; Piñeiro et al., 2020). A general overview on the main effects related to the adoption of SWCM under different agro-ecosystems is provided by Choden and Ghaley (2021), which emphasized that the effectiveness of SWCM varies significantly based on the scale of application, the extent of the SWCM implementation, as well as to external factors variability (such as topography, climate, land use). Thus, case-by-case solutions need to be developed as function of the site-specific characteristics.

Among the available SWCM, soil surface mulching is widely used in arid and semi-arid environments, where the agricultural sustainability is additional threatened by drought, heat waves and the inconsiderate use of limited water resources (Abd El-Mageed et al., 2018; El-Beltagi et al., 2022). This effective water conservation strategy refers to the use of different cover materials of the soil surface for preventing the soil moisture losses due to surface evaporation (e.g., Iqbal et al., 2020). According to Ngosong et al. (2019), further beneficial functions are attributed to the use of mulching, such as the containment of weed populations, the regulation of soil temperature, the minimal losses of nutrients, the reduction of soil erosion and compaction, the improvement of soil hydrological conditions and the promotion of biological activity. In general, the adoption of mulching strategies determines the establishment of a link between soil and agrometeorological variables, which can alter the entire agroecosystem environment (Kader et al., 2019).

The understanding of these phenomena is multifaceted, particularly when mulching is coupled with other SWCM, e.g., deficit irrigation (DI) criteria. Even if mulching and DI strategies have been separately applied in numerous experiments (e.g., Consoli et al., 2014; Liu et al., 2014; Saitta et al., 2021; Tu et al., 2021; Visconti et al., 2024), only few studies have assessed the role of mulching under DI conditions for fruit trees. These studies were mainly focussed on assessing the agronomic and physiological response (e.g., Al-Qthanin et al., 2024; Berríos et al., 2024a, 2024b), the yield, water productivity and fruit quality components (e.g., Abdelraouf et al., 2020; Alhashimi et al., 2023) and/or the soil water content (SWC), and heat changes (e.g., Liao et al., 2021). However, none of them have thoroughly investigated the combined effects of organic mulching (OM) and regulated deficit irrigation (RDI) in citrus groves.

At the light of the above-described state-of-the-art, the objective of this study was to identify the main crop water status (CWS), soil and yield features of orange groves subjected to SWCM under a peculiar regional context, i.e., the Sicilian citrus farming, characterized by high-value crop production and climate-related issues (Toreti et al., 2022). Specifically, the main hypothesis that is behind this study was that the combined application of SWCM, including different soil management (SM) (bare and organic mulched soils) and water regimes (WR; full irrigation, FI, and RDI) may improve the sustainability of these agrosystems. This objective was pursued by exploring the potential of using multiple soil-plant-atmosphere *continuum* (SPAC) monitoring approaches, as follows: *(i)* traditional and plant-based continuous methods for determining the CWS, including stem water potential (SWP), trunk water potential (TWP), sap flow fluxes and ancillary physiological indicators (i.e., net photosynthesis, transpiration rate, stomatal conductance, intercellular carbon dioxide concentration, instantaneous water use efficiency, and maximum quantum efficiency of photosystem in light and dark); and *(ii)* laboratory and field measurements for characterizing the main soil features (e.g., soil physical-chemical variables in lab, and SWC and soil temperature in situ).

## 2. Materials and methods

### 2.1. Description of the experimental set-up

A three-year trial (June–September 2021–23) was carried out in an experimental orange orchard, managed by the Italian Council for Agricultural Research and Agricultural Economics Analyses of Acireale (CREA-OFA), located in Eastern Sicily, (37°20′12.65" N, 14°53′33.04″ E, WGS84) (Fig. 1a). The study area was characterized by dry and hot-summer temperate climate, with annual daily average air temperature ($T_{air}$; °C), cumulative precipitation (mm) and reference evapotranspiration ($ET_0$; mm) of 18 °C, 573 mm, and 1261 mm, respectively, within the period 2002–23 (data provided by an automatic agrometeorological station, managed by Servizio Informativo Agrometeorologico Siciliano-SIAS, located 2 km from the study site).

The orange orchard under study [*Citrus sinensis* (L) Osbeck] 'Tarocco Sciara' C1882 on Carrizo citrange rootstock [*Poncirus trifoliata* (L.) Raf. × *C. sinensis* (L.) Osbeck] was planted in 2010 (Consoli et al., 2014), with a tree spacing of 4 × 6 m (Fig. 1a). Since 2021, sustainable agricultural management strategies, based on SWCM (i.e., the use of OM in combination with DI regimes) were adopted (Guarrera et al., 2024; Longo-Minnolo et al., 2024; Pappalardo et al., 2023) (Fig. 1b). In detail, two different approaches were applied for the SM. The first one consisted in the adoption of traditional practices, based on the maintenance of bare soil, with weeds shredding in spring period. The second approach was based on the application of OM for covering the soil surface (Fig. 1b). The OM was made of crop residues from citrus orchard pruning and intercrop weed residuals. The thickness of the OM layer was variable in the three years under study, mainly as function of the pruning needs, resulting in average (and standard error) values of 2.35 ± 0.12 cm, 7.05 ± 0.34 cm and 5.79 ± 0.24 cm, respectively, in 2021 (light pruning), 2022 (heavy pruning), and 2023 (moderate pruning). The OM layer was applied every year before the beginning of the irrigation season. In addition, the following WRs were implemented at the study site: *(i)* the FI, in which the irrigation volume was applied at the potential rate (i.e., 100 % of crop evapotranspiration, $ET_c$); and *(ii)* the RDI, supplied at 50 or 100 % of $ET_c$, depending on crop phenological stage. Note that the application of DI strategy coincided with the II phenological phase, less sensitive to water stress, in correspondence with fruit growth, i.e., from the days of the year ($DOY_s$) 202, 214 and 212 in 2021, 2022 and 2023, respectively, until the end of each irrigation season.

From the combination of the above-described experimental factors (i.e., SM and WR), four treatments were realized at the study site, in three randomized two-factor blocks, resulting as in the following (Fig. 1a): *(i)* a FI treatment under bare soil condition (FI-BARE); *(ii)* a FI treatment under mulched soil condition (FI-MULCH); *(iii)* a RDI treatment under bare soil condition, irrigated at 100 % of $ET_c$, except for the II phenological stage (irrigation rate equal to 50 % of $ET_c$) (RDI-BARE); and *(iv)* a RDI treatment irrigated at 100 % of $ET_c$, except for the II phenological stage (irrigation rate equal to 50 % of $ET_c$) under mulched soil condition (RDI-MULCH). Each treatment was composed of 3 repetitions, with 12 trees each (Fig. 1a).

The main hourly agrometeorological variables, monitored during the irrigation seasons 2021–23 by the local SIAS station, were used as inputs for calculating the daily $ET_c$ on the basis of the FAO-56 Penman-Monteith approach (Allen et al., 1998). The daily $ET_c$ was determined by multiplying the daily $ET_0$ estimates by the FAO-56 crop coefficient ($K_c$), referring to the citrus species at the middle stage, and, then, adjusted for the site-specific conditions (i.e., 0.7 as observed by Consoli et al., 2006; Consoli and Papa, 2013; Saitta et al., 2021). The irrigation water requirements (IWR) were calculated on a weekly basis using a localization factor ($K_l$) and taking into account the occurrence of rainfall events (P), as follows:

$$IWR = ET_c - P^*K_l \tag{1}$$

where $K_l$ considers the performances of the drip irrigation system in terms of emission uniformity and irrigation efficiency.

The irrigation volumes were applied three times a week during the irrigation seasons under study, using a surface drip irrigation system made of 12 emitters per tree, with flow rate of 4 L $h^{-1}$. Further details on the irrigation set-up are reported in Vanella et al. (2021).

### 2.1.1. *Crop water status monitoring*

The SWP was used as traditional indicator to identify the CWS during the irrigation seasons over the three-year period. More in detail, SWP measurements were performed, on fortnightly basis at midday, using a portable Scholander pressure chamber (Model 3115, Soilmoisture equipment corp., Santa Barbara, CA, USA). For each date of monitoring, mature leaves, fully exposed to sunlight and previously wrapped with aluminium foil (for at least 1 h before the measurements), were collected from 24 sample trees (i.e., two sample trees per treatment in each plot, Fig. 1a). Leaves were immediately placed into the chamber, with the leaf stem exposed outside of the chamber trough a seal, and pressurized with nitrogen until the water appeared at the petiole and the corresponding tension was recorded.

Ancillary physiological indicators, including net photosynthesis (A, μmol $CO_2$ $m^{-2}$ $s^{-1}$), transpiration rate (E, mmol $H_2O$ $m^{-2}$ $s^{-1}$), stomatal conductance (gs, mol $m^{-2}$ $s^{-1}$), intercellular $CO_2$ concentration (Ci, ppm), instantaneous water use efficiency (WUEi, μmol $mol^{-1}$) were monitored using a portable IRGA (Leaf Chamber Analyser - ADC LCA4 Bio Scientific Ltd., Rickmansworth, England). The maximum quantum efficiency of photosystem in light and dark (PSII, expressed as the ratio of variable ($F_V$) to maximum fluorescence ($F_M$)) was determined using a portable chlorophyll fluorimeter (OS30p+, Opti-Sciences Inc., Hudson, USA), on leaves exposed to the sun illuminated with a saturation irradiance pulse of 3500 μmol·$m^{-2}$·$s^{-1}$. Then, the same leaves were dark-adapted for 20 min and again illuminated for the measurement. All these measurements were taken on a monthly basis within the irrigation seasons 2021–23, on the leaves of 12 samples tree.

An expeditious indication of the CWS was obtained by using the plant-based FloraPulse© (Davis, CA, USA) sensors for measuring the water tension in the woody tissue of the tree trunks. In particular, six SDI-12 microtensiometers were embedded into the woody tissues of selected six trees (RDI-BARE and RDI-MULCH treatments, Fig. 1a) for continuous monitoring the TWP on a semi-hourly basis. Data was managed by a datalogger (CR1000, Campbell Scientific, USA). To assess the capability of the FloraPulse© sensors in estimating continuously the CWS, two leaves, from each of the six selected tree, were sampled at diurnal time-steps and analysed with the traditional Scholander method.

In addition, semi-hourly continuously transpiration fluxes ($T_{SF}$) were determined by using custom made sensors (Tranzflo NZ Ltd), based on the compensation heat-pulse technique (Swanson, 1962). Specifically, a linear heater and two temperature probes were inserted radially into the trunks of two samples trees for treatment (Fig. 1a). Data were collected using a CR1000 data logger (Campbell Scientific, USA) and, then, the sap flow was estimated at the tree level according to the procedure provided in Consoli et al. (2014) and Motisi et al. (2012). In this study, only data from RDI-BARE and RDI-MULCH treatments were analysed according to the FloraPulse© observations.

### 2.1.2. *Soil features characterization*

In order to analyse the potential effects of SWCM at soil level, site-specific analyses were conducted in laboratory for determining the main physical and chemical soil characteristics before (on March 2021) and after (on October 2022 and 2023) the application of the OM. Specifically, 12 soil samples (i.e., disturbed and undisturbed) were collected at a 0–30 cm depth and 1 m far from the centre of the tree rows, towards the inter-rows, at the treatments under study (Fig. 1b). Note that in the

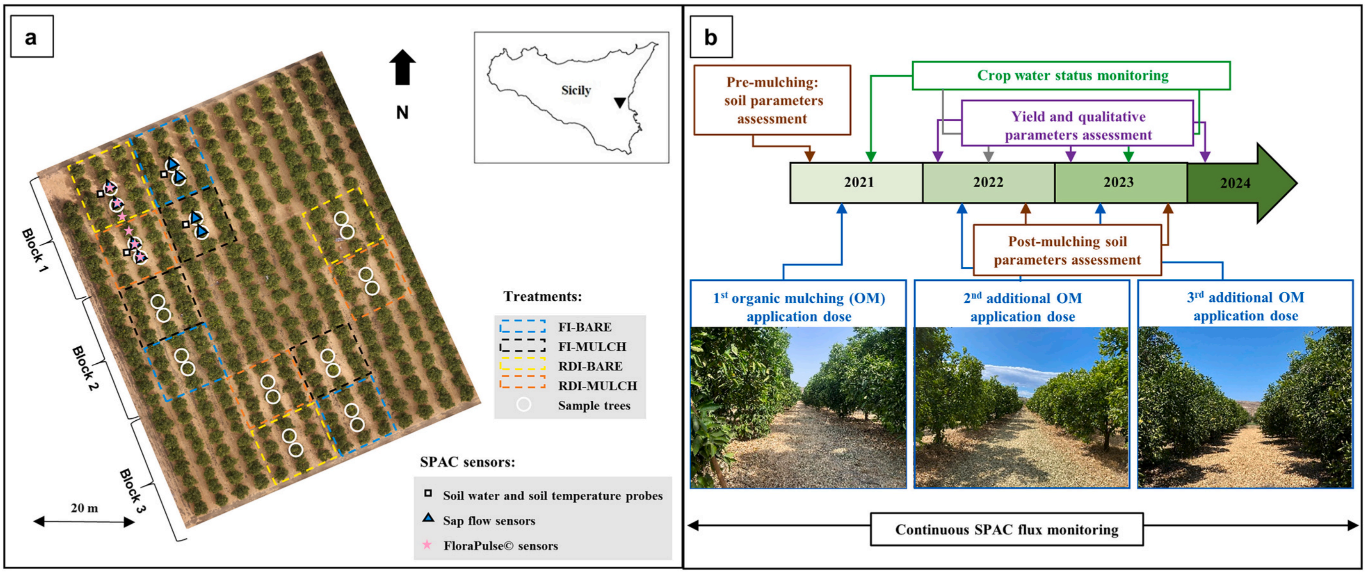

**Fig. 1.** (a) Overview of the study site, including the layout of the treatments, the location of the samples trees and the point-based sensor measurements; and (b) the chronology of the experimental activity conducted at the site during the reference period (2021–23).

two-year period 2021–22, soil sampling was carried out after a rainy period. Differently, in 2023, it was carried out in a drier period, even if at the end of the irrigation season. The selection of the depth for soil sampling depended on the maximum observed root biomass colonization, under zero tillage conditions (Guarrera et al., 2024). The analysed parameters included the main soil physical-chemical variables commonly used for agronomic characterization purposes, as: pH (−), electrical conductivity (CE; mS $cm^{-1}$), total nitrogen ($N_{tot}$; mg kg d.m.$^{-1}$), nitrates ($NO_3^-$; mg $kg^{-1}$ d.m.), total potassium ($K_{tot}$; mg kg d.m.$^{-1}$), potassium ion ($K^+$; mg $kg^{-1}$ d.m.), calcium (Ca; mg kg d.m.$^{-1}$), magnesium (Mg; mg kg d.m.$^{-1}$), phosphate ($PO_4^{3-}$; mg kg d.m.$^{-1}$), sodium (Na; mg $kg^{-1}$ d.m.), total carbon ($C_{tot}$, % d.m.), total organic carbon (TOC; %), soil organic matter (SOM, %), microbial biomass carbon (CMIC, ppm), and ratio CMIC/TOC (%).

SWC and soil temperature were continuously monitored, at the different treatments, through the use of TEROS-12 sensors (Meter Group, Washington-USA). A set of 8 sensors were installed at a depth of 0–30 cm, at two distances from the tree trunks (i.e., 0.35 m and 0.75 m, respectively), in correspondence of selected trees in each treatment (Fig. 1a). Semi-hourly data were acquired using a CR1000 datalogger (Campbell Scientific, USA) and, then, aggregated at the daily scale.

#### 2.1.3. *Yield and fruit quality traits*

Yield and fruit quality characteristics were analysed at the CREA-OFA laboratory during the 2022–24 harvest periods (referring to the irrigation seasons 2021–23). The number of fruits and their average weight, including the skin weight and the percentage (%) of juice, were determined on fruits collected at each sample tree, for a total number of 24 trees (Fig. 1a). The equatorial sections (mm) were measured through a caliber. A number of 10 fruits per tree were selected (2 trees per treatment and replica, for a total number of 24 trees and 60 samples per treatment) for determining the main fruit quality variables, as follows: sugars, acidity, anthocyanin and polyphenol contents.

### 2.2. *Statistical analysis*

Multiple multivariate analyses of variance (MANOVAs) have been carried out on CWS, soil and yield variables using the Statistix software (v.9.0, Analytical Software 2105 Miller Landing Rd Tallahassee, FL 32312). The applied MANOVAs approach allowed us to identify significant differences among the factors under study at different level, i.e., in the long-term among the overall measurements conducted in the same year/irrigation season; in the medium-term among the measurements conducted in different DOYs within a single irrigation season; and in short-term with respect to a single DOY.

In particular, differences in terms of CWS were assessed on the SWP and ancillary physiological indicators, considering as factors: *(i)* the year or DOY (for each irrigation season), *(ii)* the WR, and *(iii)* the SM. The interactions among these factors were determined as well as the difference among the WR and SM at the DOY level. In addition, the relationship between SWP and TWP was evaluated using a linear regression model, based on the coefficient of determination ($R^2$). Linear correlations were also carried out between the ancillary physiological indicators and the SWP.

A three-way MANOVA was performed on the physical-chemical soil data for identifying the differences among the considered factors (i.e., SM and WR), during the years under study (2021–23). To evaluate the effects on the main yield and fruit quality characteristics, a three-way MANOVA was conducted including as factors: *(i)* the SM (bare versus mulched soils), *(ii)* the WR (FI versus RDI); and *(iii)* the different reference years (2022–24).

For all the above-mentioned MANOVAs, the obtained significant differences were separated through the Tukey's honest significant difference (HSD) test with the 95 % of confidence level ($p$-value $<0.05$).

## 3. Results

### 3.1. *Agrometeorological and irrigation features*

The temporal daily evolution of the $ET_0$ and $ET_c$ rates during the period 2021–23 is illustrated in Fig. 2a, together with the observed daily rainfall amounts and the applied irrigation heights. Daily solar radiation (Sr), vapour pressure deficit (VPD) and $T_{air}$ (minimum, average and maximum values) are also given in Fig. 2b-c.

The patterns of the main agrometeorological observations in Fig. 2a-c are typical of the Mediterranean climate conditions, with maximum daily Sr and $T_{air}$ values (i.e., maximum evaporative demand, $ET_0$) during the summer seasons, when less water resources are available for the irrigation practice.

Within the irrigation seasons 2021–23 (June–September), the daily average (± standard deviation) $ET_0$ value was 5.6 ± 0.2 mm $d^{-1}$, with a cumulative amount of 683 mm. In the same irrigation seasons, the cumulative average $ET_c$ and rainfall values were of 334 mm and 61 mm, respectively. The irrigation heights applied at the FI and RDI treatments are given in Table 1, together with the water savings (in %) obtained. Overall, an average water saving of 24 % was obtained under RDI in comparison to the FI conditions.

### 3.2. *Crop water status response*

#### 3.2.1. *Stem water potential, trunk water potential and transpiration fluxes*

Fig. 3 shows the patterns of the average (and standard error) SWP values measured during the irrigation seasons 2021–23 at the treatments under study, resulting in a delayed CWS effect linked to the period of irrigation volume reduction (i.e., 50 % of $ET_c$) and the agrometeorological conditions (i.e., rain events).

The results of the MANOVAs carried out to evaluate the effects of SM and WR practices, year and/or DOY, on the SWP values are showed in Table 2. These results are reported for both the overall monitoring period (2021–23) and at the level of irrigation seasons.

For the overall monitoring period (2021–23), the SWP values showed the highest negative values in 2021 (−1.82 ± 0.03 MPa) and 2023 (−1.78 ± 0.02 MPa) in comparison to 2022 (1.62 ± 0.02 MPa). Overall, the SWP values were affected by the applied WR and the interaction between the year and the WR, resulting in more negative values under RDI conditions (−1.75 ± 0.02 MPa) compared to FI (−1.71 ± 0.02 MPa), with minimum values in 2021 under the RDI regime (−1.91 ± 0.04 MPa).

At the irrigation season level, in 2021, differences in SWP distribution were obtained as function of WR, with more negative values under RDI (−1.91 ± 0.04 MPa) in comparison to FI (−1.73 ± 0.03 MPa), and the different DOYs according to the atmospheric demand (Fig. 2). In 2022, differences in SWP were recorded as function of SM and DOYs, with more negative values under bare soils (−1.63 ± 0.02 MPa) compared to mulched soils (−1.60 ± 0.02 MPa). Similar difference in terms of DOYs were retrieved also in 2023, in relation to the interaction between SM and WR, showing more negative values under RDI-MULCH and FI-BARE treatments (−1.82 ± 0.03 MPa).

According to SWP values measured by the Scholander method, similar trends of TWP values were continuously obtained by the FloraPulse© sensors under RDI conditions (Fig. 4a), resulting in average hourly values of −0.83 ± 0.00 MPa and −0.93 ± 0.01 MPa under bare and mulched soils, respectively. The comparison between the two different methods for estimating the CWS showed more negative values for SWP than for TWP, resulting in a coefficient of determination and root mean square error of 0.77 and 0.9 MPa, respectively (Fig. 4b).

The temporal trend of the $T_{SF}$ fluxes is reported in Fig. 4c, showing higher rates under bare conditions (0.02 ± 0.00 mm $h^{-1}$) than under mulched soils (0.01 ± 0.00 mm $h^{-1}$) in RDI. The daily average $T_{SF}$ fluxes observed under bare and mulched soils in RDI were of 0.88 ± 0.01 mm $d^{-1}$ and 0.64 ± 0.00 mm $d^{-1}$, respectively.

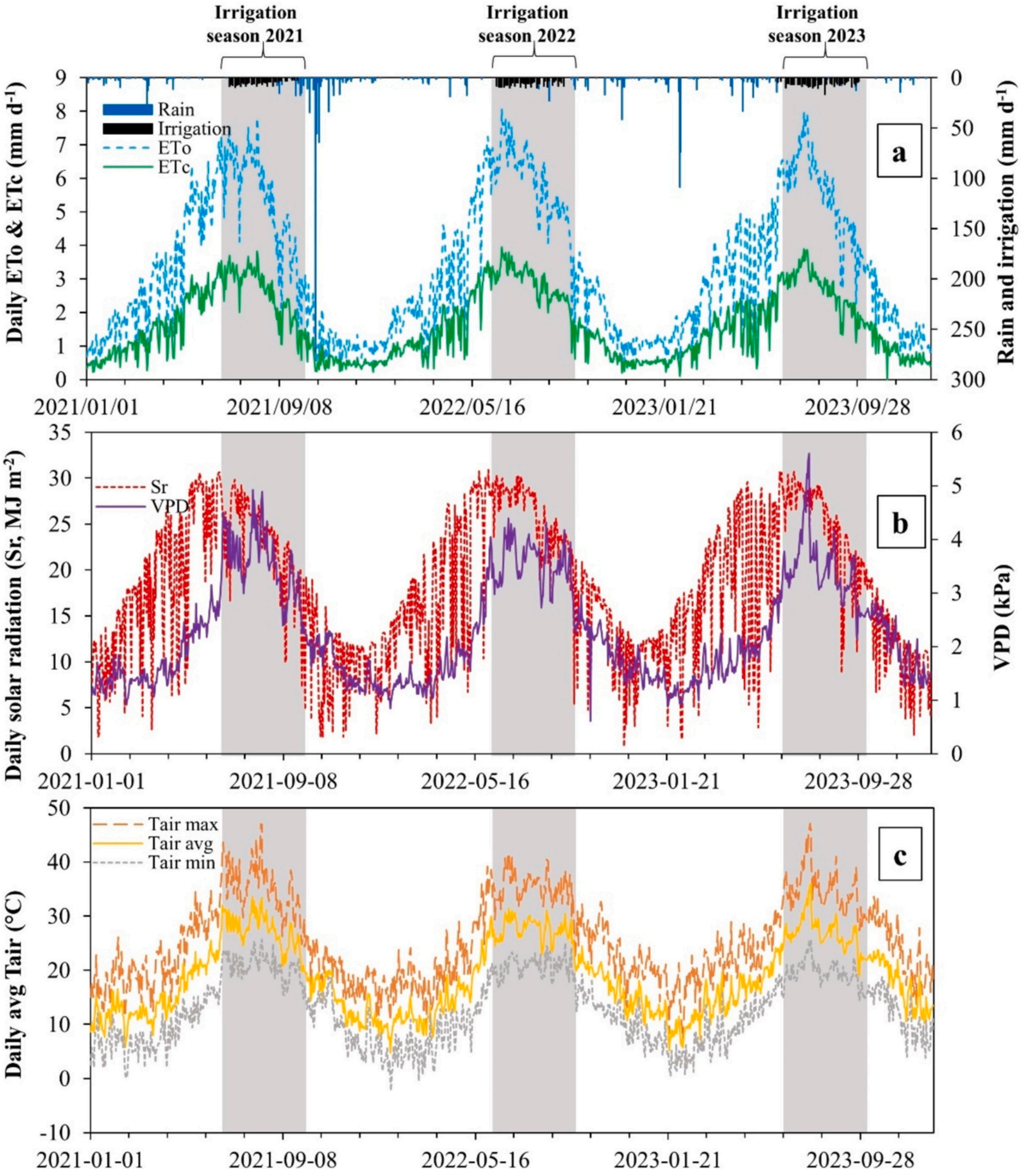

**Fig. 2.** Temporal daily agrometeorological parameters observed during 2021–23: (a) evapotranspiration rates ($ET_0$ and $ET_C$ fluxes), rainfall regime and irrigation heights; (b) solar radiation (Sr) and vapour pressure deficit (VPD); and (c) air temperature, $T_{air}$ (minimum, average and maximum values).

**Table 1**
Irrigation heights (mm) and water savings (%) reached during the three-year trial (FI and RDI refer to full irrigation and regulated deficit irrigation, respectively).

| Irrigation season (June–September) | Water regime | Irrigation height (mm) | Water saving (%)[a] |
|---|---|---|---|
| 2021 | FI | 292 | 26 |
| | RDI | 216 | |
| 2022 | FI | 296 | 19 |
| | RDI | 239 | |
| 2023 | FI | 319 | 26 |
| | RDI | 237 | |

[a] Water saving (%) was defined for each irrigation season (June–September) as [1 – (irrigation in RDI/irrigation in FI)] × 100.

### 3.2.2. Ancillary physiological indicators

The temporal dynamics of the ancillary physiological indicators (i.e., A, gs, Ci, WUEi, PSII in light and dark, and E) observed during the irrigation seasons 2021–23, are showed in Figs. 5–6.

The results of the MANOVAs, used to evaluate the effects over time of SM and WR practices on the same ancillary physiological indicators, are reported in the following Figs. 7–9.

At the physiological level, no significant differences were obtained for A over the three-years period. Conversely, differences were found for A at the DOYs level, where a common increasing trend was found with a peak on September (7.02 ± 0.74 μmol $CO_2$ $m^{-2}$), corresponding to the end of the irrigation season (Fig. 8a-b), characterized by lower stress conditions during the growing period. Influences related to WR were found for the same physiological indicator in the years 2021–22, with higher A values under FI (4.73 ± 0.87 μmol $CO_2$ $m^{-2}$) and RDI (4.86 ± 1.21 μmol $CO_2$ $m^{-2}$) (Fig. 9 a, b). In 2022, interactions were also observed between A, WR and the DOYs, with higher A values recorded under RDI on DOY 257 (Fig. 10a). A triple interaction among A and the WR, DOYs and SM factors was found (Fig. 10b), demonstrating that, even with the same SM, crop growth was more favourable under RDI conditions (10.22 ± 0.47 μmol $CO_2$ $m^{-2}$).

Significant differences were retrieved for gs in the overall monitored period, with higher values in the 2021–22 compared to 2023 (Fig. 7a).

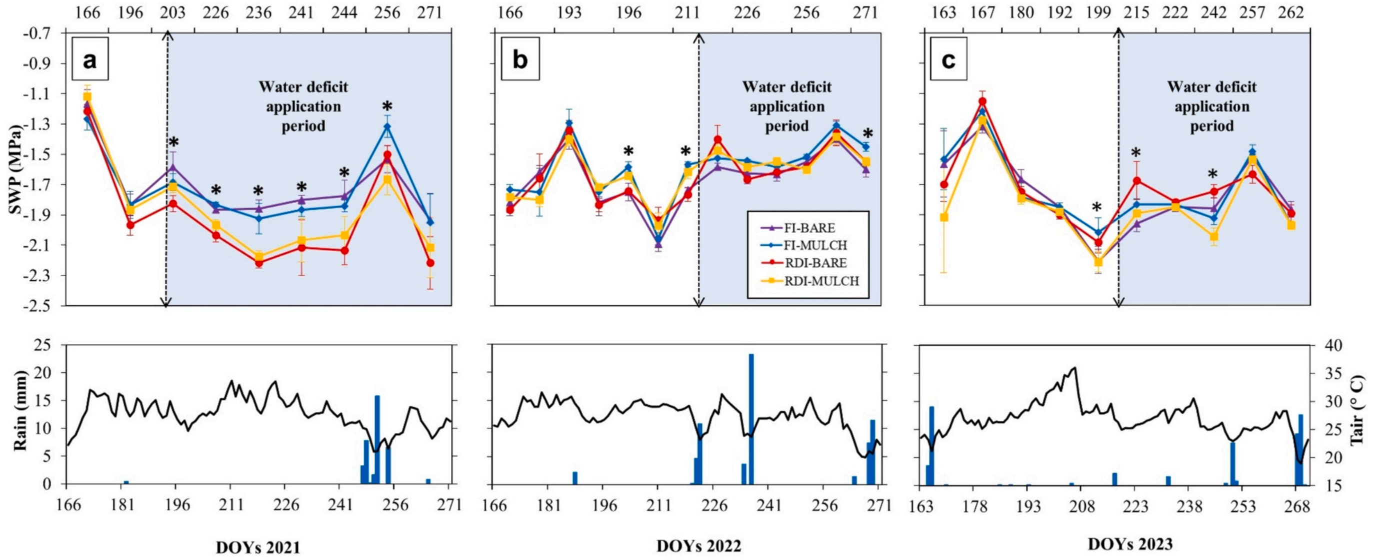

**Fig. 3.** Average stem water potential (SWP, MPa) trends under bare (BARE) and mulched (MULCH) soils in full irrigation (FI) and in regulated deficit irrigation (RDI), together with daily rain and air temperature ($T_{air}$) observed during the irrigation season (a) 2021, (b) 2022, and (c) 2023. Black dashed rows refer to the beginning of water deficit application in RDI. Bars refer to the standard error associated to the SWP values. Asterisks (*) refer to the significant differences obtained at the day-of-the-year level for the factors under study, according to the Tukey test for *p*-value <0.05.

**Table 2**

Effects of soil management (SM, bare versus mulched soil) and water regime (WR, full versus regulated deficit irrigation) on the stem water potential (SWP) for the overall monitoring period (2021–23) and at the irrigation season level. The asterisks refer to the significant differences among the factors (for p-value <0.05). Degrees of freedom (DF) and F-values (F) are also reported in the Table.

| Factor | SWP 2021–23 | | | Factor | SWP 2021 | | | SWP 2022 | | | SWP 2023 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DF | F | p | | DF | F | p | DF | F | p | DF | F | p |
| YEAR | 2 | 42.88 | 0.00* | DOY | 8 | 36.05 | 0.00* | 12 | 29.97 | 0.00* | 9 | 44.56 | 0.00* |
| SM | 1 | 0.10 | 0.75 | SM | 1 | 0.30 | 0.58 | 1 | 5.16 | 0.02* | 1 | 2.15 | 0.14 |
| WR | 1 | 4.88 | 0.03* | WR | 1 | 29.87 | 0.00* | 1 | 0.00 | 0.98 | 1 | 1.59 | 0.21 |
| YEAR*SM | 2 | 1.03 | 0.36 | DOY*SM | 8 | 0.08 | 0.99 | 12 | 1.15 | 0.32 | 9 | 0.85 | 0.58 |
| YEAR*WR | 2 | 4.33 | 0.01* | DOY*WR | 8 | 1.53 | 0.15 | 12 | 0.78 | 0.67 | 9 | 1.26 | 0.26 |
| SM*WR | 1 | 1.66 | 0.20 | SM*WR | 1 | 1.58 | 0.21 | 1 | 1.17 | 0.28 | 1 | 6.03 | 0.02* |
| YEAR*SM*WR | 2 | 1.65 | 0.19 | DOY*SM*WR | 8 | 0.92 | 0.50 | 12 | 0.19 | 0.38 | 9 | 1.20 | 0.37 |
| TOTAL | 647 | | | TOTAL | 151 | | | 215 | | | 191 | | |

Differences for gs were also obtained at the DOYs level (Fig. 8d-f), showing an increasing trend in all the monitored years. Influences of gs related to WR were found in 2021 and 2023, in which the same condition was maintained with higher gs values in FI (0.07 ± 0.02 mol $m^{-2}$ $s^{-1}$and 0.03 ± 0.00 mol $m^{-2}$ $s^{-1}$, respectively) (Fig. 9c-d). In 2022, the interaction between gs and the three factors (DOYs, the SM and WR) is illustrated in Fig. 10c, indicating a positive effect linked to the application of OM under RDI, with higher values compared to the bare condition (0.07 ± 0.03 mol $m^{-2}$ $s^{-1}$ and 0.06 ± 0.02 mol $m^{-2}$ $s^{-1}$, respectively).

According to gs, differences were also found for Ci over the three-years period, resulting in a decreasing trend (Fig. 7b). Significant differences were found for Ci as function of DOYs in 2022–23, with greater interaction in 2022 (Fig. 8r, s). Significant differences were obtained at DOYs level for E during 2021–22, resulting in a decreasing trend over the course of the seasons (Fig. 8p-q). For the same indicator, an interaction between E and WR was detected in 2021 and 2023, showing higher rates in FI compared to RDI (Fig. 9h-i), with average values of 2.52 ± 0.2 mmol $H_2O$ $m^{-2}$ $s^{-1}$and 2.34 ± 0.2 mmol $H_2O$ $m^{-2}$ $s^{-1}$ for FI and RDI, respectively, in 2021 and of 2.17 ± 0.33 mmol $H_2O$ $m^{-2}$ $s^{-1}$ and 2.19 ± 0.3 mmol $H_2O$ $m^{-2}$ $s^{-1}$ for FI and RDI, respectively, in 2023.

The WUEi did not show significant differences in the three monitored years, although dissimilar values were observed among the DOYs in the different years (Fig. 8g-i). Overall, there was an increasing trend in WUEi throughout the irrigation seasons, similar to the trends observed for the other physiological indicators, with a peak in September (3.59 ± 0.37 μmol $mol^{-1}$). Significant differences of WUEi related to WR and SM were found in 2022 as function of DOYs (Fig. 11). Specifically, higher WUEi values resulted in RDI on DOY 257 (Fig. 11a, 4.57 ± 3.23 μmol $mol^{-1}$), while for SM, higher values were retrieved on September for both the soil conditions (Fig. 11b, 3.76 ± 1.88 μmol $mol^{-1}$).

The PSII in light and in dark showed significant differences over the three years with a decrease in 2022 and the re-establishment of the initial condition in 2023 (Fig. 7c-d, respectively). For both the PSII light and dark parameters, there was the same trend at DOYs level over the investigated years (Fig. 8j-l and m-o, respectively). In 2021, an interaction with WR was found in PSII light and dark, with greater efficiency under RDI (Fig. 9-f-g, 0.59 ± 0.02 and 0.70 ± 0.02 under RDI and FI, respectively). In 2022, an interaction was retrieved in PSII light and dark for the SM factor, showing higher values in bare soil (Fig. 12a-b, 0.52 ± 0.03 and 0.63 ± 0.01 under mulched and bare soils, respectively). For PSII light, in 2022 a relationship between the SM and DOYs factors was obtained, showing higher values for the same SM over the course of the irrigation season and at the end of the season (Fig. 12c, 0.63 ± 0.02 and 0.61 ± 0.00, for bare and mulched soils, respectively). In the case of PSII dark, significant differences occurred in the three-years period for WR factor in which the decrease in 2022 is highlighted for both FI and RDI conditions (Fig. 12d). In 2023, for the PSII dark, the interaction between

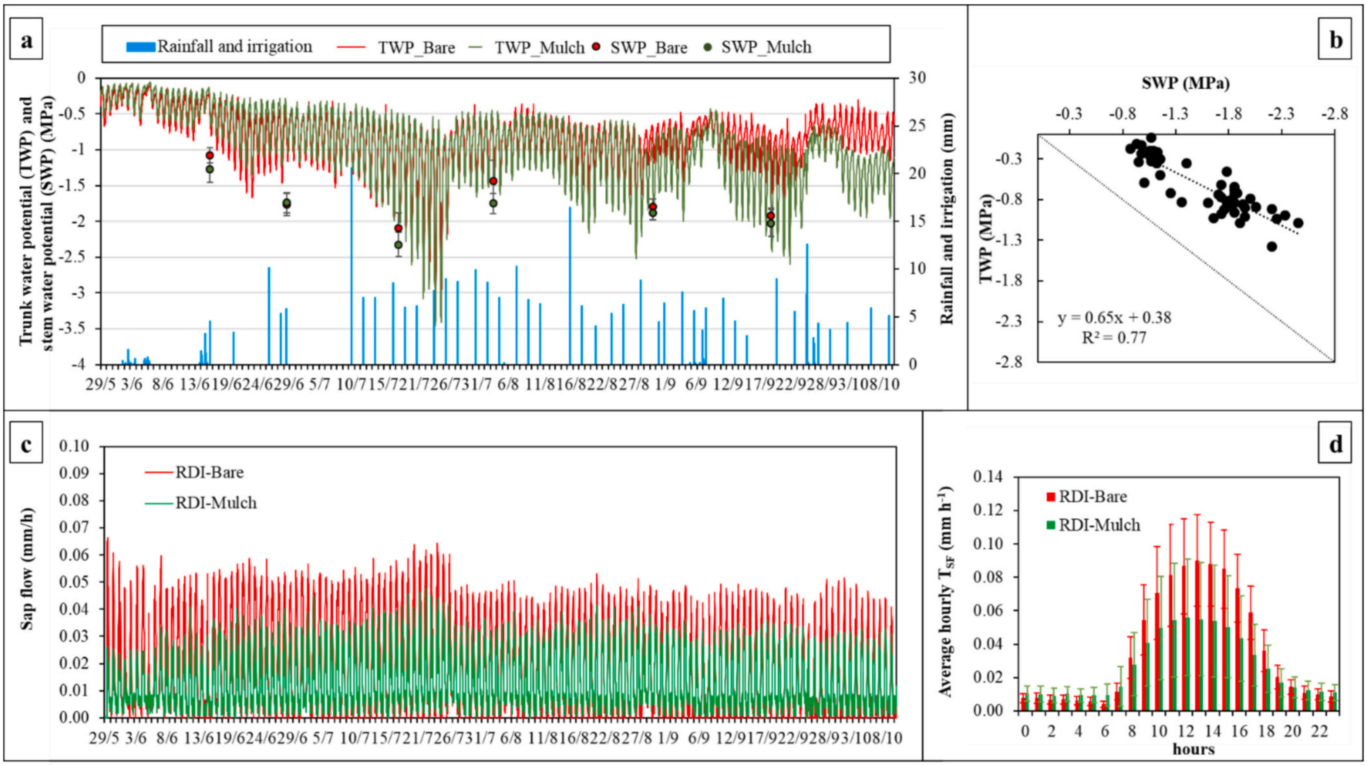

**Fig. 4.** (a) Temporal evolution of the crop water status measured by FloraPulse© sensors (TWP) and Scholander methods (SWP); (b) comparison between SWP and TWP values, (c) temporal dynamics of the transpiration fluxes ($T_{SF}$), and (d) hourly average of $T_{SF}$ fluxes observed in the reference period (June–September 2023) under bare and mulched soils.

the three analysed factors occurred. Specifically, a stress condition was evident near the DOY 192 for all the treatments, with lowest values in the RDI-BARE conditions (0.45 ± 0.10), unlike the other DOYs, where a stable condition was observed for all the treatments (Fig. 12d).

### 3.3. *Soil features characterization*

#### 3.3.1. *Soil physical-chemical main features*

Tables 3 reports the results of the MANOVAs carried out to assess the effects over time of SM and WR practices on the main chemical and physical soil properties.

A significant variability for most of the soil features (i.e., 66 %) was linked to the time factor (years) (Fig. 13). In particular, four types of trends were recognized: *(i)* an increasing pattern for EC (Fig. 13a), Mg (Fig. 13c), K+ (Fig. 13f), Na (Fig. 13g), $NO_{3-}$ (Fig. 13i); *(ii)* a bell-shaped behaviour with a peak in 2022 for $K_{tot}$ (Fig. 13b), $C_{tot}$ (Fig. 13h), $C_{org}$ (Fig. 13j) and pH (Fig. 13k); *(iii)* a decreasing trend for $N_{tot}$ (Fig. 13e); and *(iv)* a parabolic decreasing trend in 2022 for Ca (Fig. 13d). A key factor was WR, for which significant differences were found for Na, $C_{tot}$ and $K^+$ (Fig. 14a, b, and c, respectively). In this case, a common trend occurred, characterized by higher values in RDI (948.95 ± 89.28 mg Kg d.m.$^{-1}$, 1.30 ± 0.24 % d.m, 36.88 ± 3.61 mg Kg d.m.$^{1}$ for Na, $C_{tot}$ and $K^+$, respectively) compared to FI (735.08 ± 58.37 mg Kg d.m.$^{-1}$; 1.43 ± 0.06 % d.m.$^{-1}$; 48.59 ± 23.70 mg Kg d.m.$^{-1}$ for Na, $C_{tot}$ and $K^+$, respectively). Significant differences linked to WR and SM factors were obtained for Mg (Fig. 15b), resulting in higher values under RDI-MULCH (2861.23 ± 267.34 mg kg d.m.$^{-1}$) in comparison to FI-BARE (2581.09 ± 312.82 mg kg d.m.$^{-1}$); while, weak interactions were obtained for Ca (Fig. 15a) and pH (Fig. 15c). For pH, a further interaction was observed between WR and years (Fig. 16a), in which the different WRs presented the same trends with a peak in 2022 (8.24 ± 0.05 and 8.31 ± 0.04, for RDI and FI, respectively); whereas, lower pH values were observed in 2021 (7.60 ± 0.06 and 7.61 ± 0.05, for RDI and FI, respectively). Finally, a significant difference linked to SM was found for Na in the three monitored years, with higher values in mulched soils compared to the bare condition (946.73 89.54 and 737.30 58.43 mg Kg d.m $^{-1}$, respectively) (Fig. 16b).

#### 3.3.2. *Soil water content and soil temperature dynamics*

The daily SWC and soil temperature patterns for FI and RDI treatments under mulched and bare soil conditions, referring to the 0.35 m and 0.75 m tree trunk distances, are represented in Fig. 17 for the period 2022–23, together with the daily rain and irrigation amounts.

Overall, the SWC trends followed the rain and irrigation dynamics, showing a peculiar behaviour at the treatment level as function of the distance from the tree trunk (Fig. 17a-b). Specifically, at the 0.35 m distance (Fig. 17a), the FI treatments were characterized by similar SWC conditions, with average (and standard error) values of 0.40 ± 0.00 m$^3$ m$^{-3}$ and 0.41 ± 0.00 m$^3$ m$^{-3}$ for FI-MULCH and FI-BARE, respectively. Similar SWC trends, but with less magnitude, were detected at the RDI treatments, with values ranging from 0.28 ± 0.00 m$^3$ m$^{-3}$ to 0.29 ± 0.00 m$^3$ m$^{-3}$, for RDI-BARE and RDI-MULCH, respectively (Fig. 17a-b). In the same period, at the 0.75 m distance (Fig. 17b), the SWC showed always higher values under mulched soils compared to bare soil condition both under FI (up to 15 %) and RDI (up to 27 %).

Specific patterns of soil temperature were observed at a distance of 0.35 m and 0.75 m from the trunk, respectively (Fig. 17c-d). In particular, the FI treatments had an almost identical behaviour under bare and mulched soil at 0.35 m (18.54 ± 0.21 °C) and 0.75 m (19.06 ± 0.22 °C) distances, while for the RDI conditions, slight soil temperature reductions (up to 5–6 %) were noted on the mulched soils (18.45 ± 0.20 °C and 18.80 ± 0.21 °C a distance of 0.35 m and 0.75 m from the trunk, respectively) in comparison to the bare soils (19.30 ± 0.22 °C and 19.91 ± 0.25 °C a distance of 0.35 m and 0.75 m from the trunk, respectively).

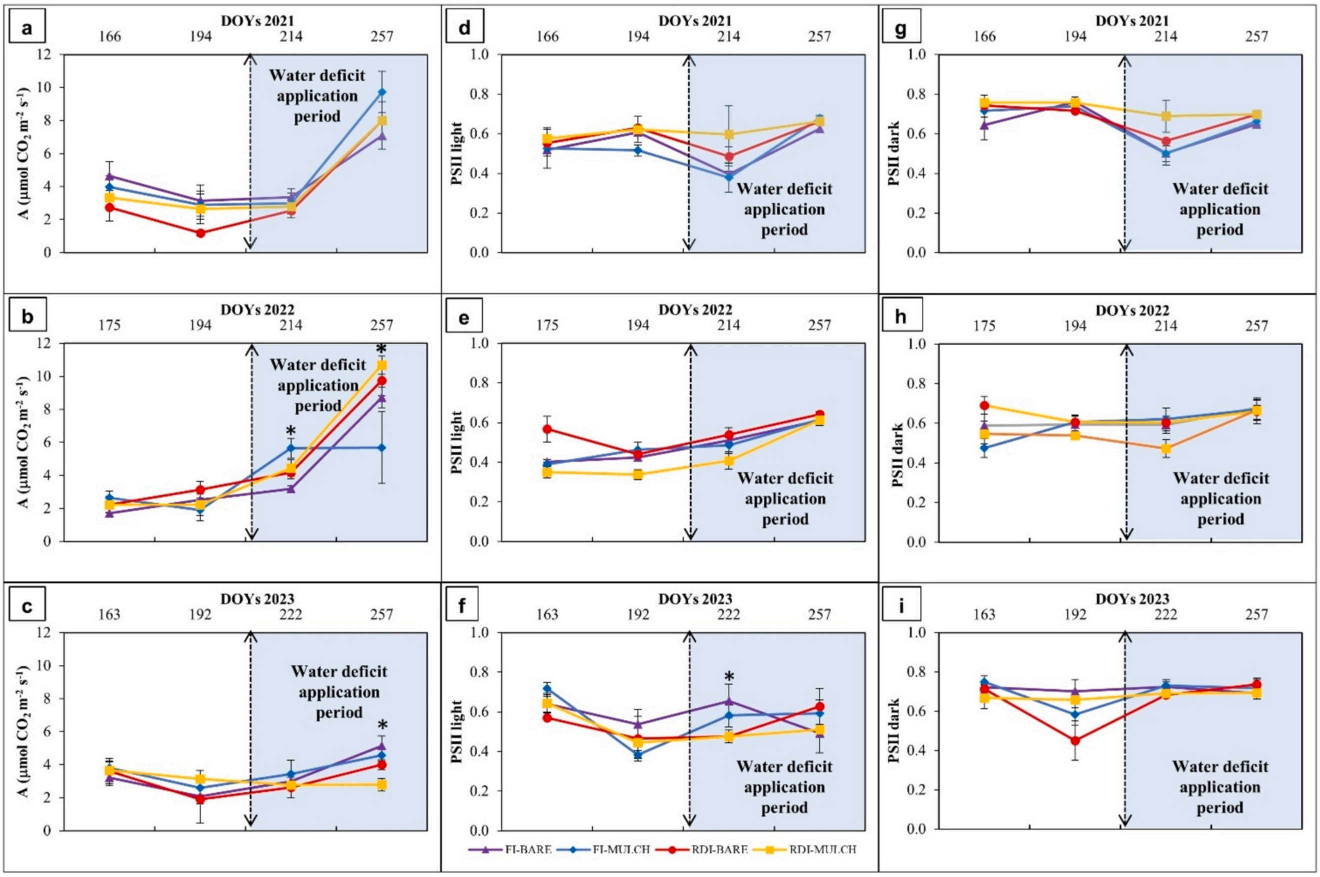

**Fig. 5.** Average trends of (a-c) net photosynthesis (A, µmol $CO_2$ $m^{-2}$ $s^{-1}$) and the maximum quantum efficiency of photosystem (PSII) in (d-f) light and (g-i) dark measured under bare (BARE) and mulched (MULCH) soil in full irrigation (FI) and in regulated deficit irrigation (RDI) during the 2021–23 irrigation seasons. Black dashed rows refer to beginning of RDI. Bars refer to the standard error associated to the average values. Asterisks (*) refer to the significant differences obtained at the day-of-the-year level for the factors under study according to the Tukey test for *p*-value <0.05.

Note that higher soil temperature values were reached under bare soil conditions at 0.75 m far from the tree trunk both for FI (28.70 °C) and RDI (30.80 °C), in comparison to the mulched soils (with values of 28.01 °C and 27.40 °C for FI and RDI, respectively).

### 3.4. *Yield and fruit quality traits*

Table 4 reports the results of the MANOVAs elaborated for evaluating the effects over time of SM and WR practices on the main yield and fruit quality features, such as fruit weight, number of fruits, % of juice, estimated yield, equatorial size, pH, acidity, sugars, anthocyanins and polyphenols.

Fig. 18 shows the significant trends and the interactions obtained for yield and fruit quality as function of the factors under study (Table 4).

Some yield and fruit quality traits (i.e., fruit weight, % of juice, acidity and anthocyanin content) showed a greater variability linked to the time factor (years) (Fig. 18a-d). In particular, there was an increase in fruit weight in 2023 (297 ± 5.58 g), which was maintained in 2024 (285.81 ± 11.60 g) (Fig. 18a). This effect was not associated to the decrease in the % of juice observed from 2022 to 2023, which showed lower values in 2023 (36.88 ± 2.26 %). However, the % of juice recovered a similar condition to 2022 (44.26 ± 1.87 g) in 2024 (43.08 ± 1.10 %) (Fig. 18b). The highest acidity was found in 2023 (Fig. 18c), while the anthocyanin content increased over the three-year period with a peak in 2024 (16.69 ± 1.29 mg/L, Fig. 18d). Ad hoc statistical interactions were found for fruit weight, sugars, and polyphenols (Fig. 18e-g). In particular, the fruit weight showed a triple interaction with the factors SM, WR and years (Fig. 18e). Higher fruit weights were found in 2024 under FI-MULCH and RDI condition (325.28 ± 3.91 g and 292.81 ± 7.97 g, respectively). Significant interaction was obtained between the sugar content and the WR, with higher values in RDI than FI regime (10.99 ± 0.13°Brix and 10.61 ± 0.11°Brix, respectively, Fig. 18f). Polyphenols showed weak interactions related to WR and SM, as given in Fig. 18g.

## 4. Discussion

The innovative aspect of this study was to investigate the coupling response of OM application under different WR in a peculiar regional context, i.e., citrus farming in Sicily, that has an annual estimated production over 1 million tons (data source from https://www.istat.it/). The high economic relevance of the citrus production is certain important under this regional context that is facing with severe problems and crop damages, due to water scarcity and future climate change scenarios, i.e., persistent lack of precipitation and increased $T_{air}$ (Toreti et al., 2022). Thus, investing in SWCM is crucial to mitigate these climate-related impacts on the local agricultural sector as well as it is important to transfer consolidated knowledge on innovative farming management to farmers for achieving economic and environmental improvements. In particular, the effects of the proposed SWCM were assessed on multiple traits, namely, CWS, soil and yield characteristics.

Among the general results of the study, with reference to WR, during the 2021–23 irrigation seasons an average water saving of 24 % was achieved in RDI treatments compared to FI conditions. In particular, the effects inherent to the adoption of different WRs have already been evaluated by these authors (e.g., Consoli et al., 2014; Puglisi et al.,

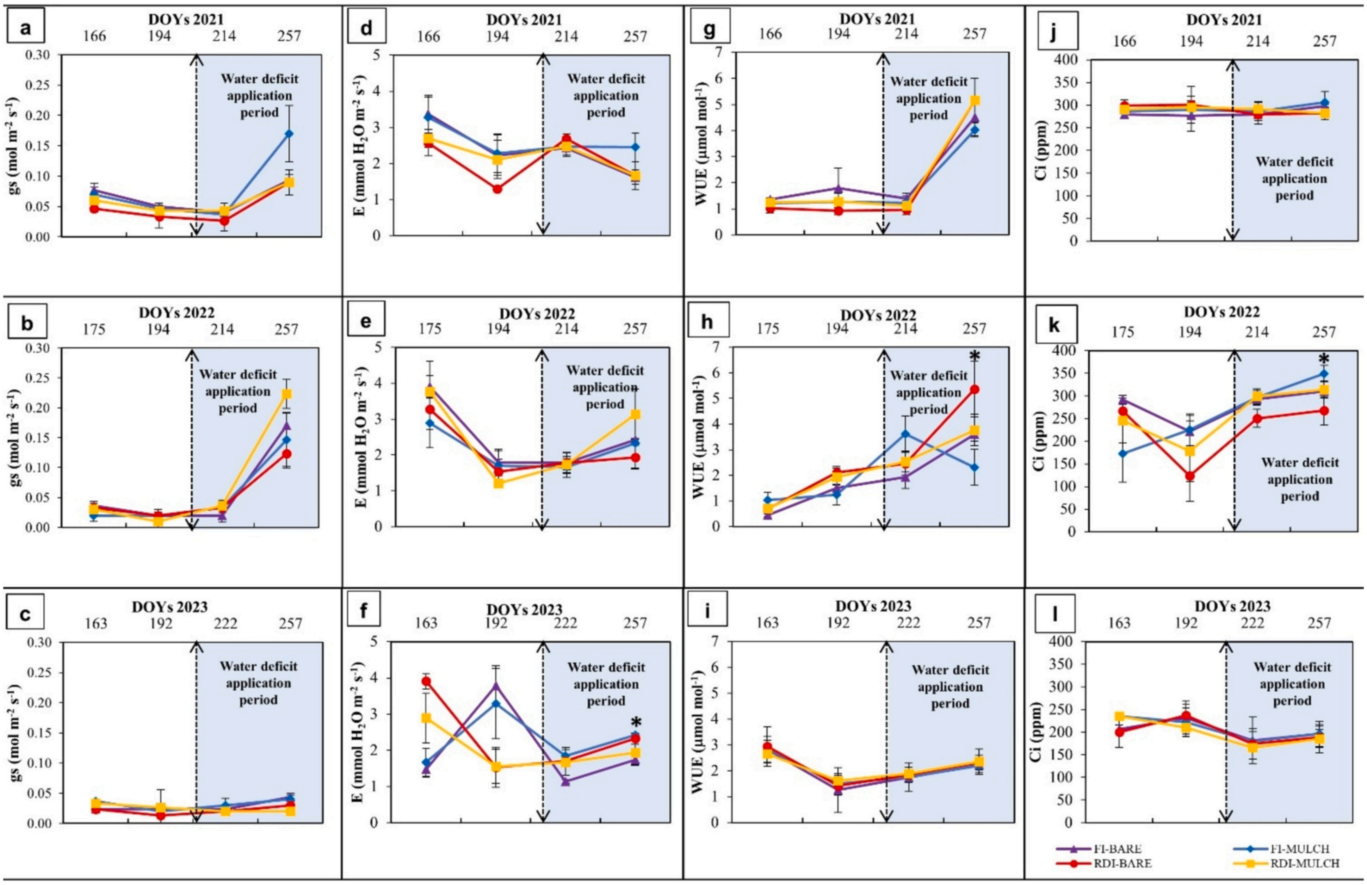

**Fig. 6.** Average trends of (a-c) stomatal conductance (gs, mol $m^{-2}$ $s^{-1}$), (d-f) transpiration rate (E, mmol $H_2O$ $m^{-2}$ $s^{-1}$), (g-i) instantaneous water use efficiency (WUEi, µmol $mol^{-1}$), and (j-l) intercellular carbon dioxide ($CO_2$) concentration (Ci, ppm) measured under bare (BARE) and mulched (MULCH) soils in full irrigation (FI) and in regulated deficit irrigation (RDI), during the 2021–23 irrigation seasons. Black dashed rows refer to beginning of RDI. Bars refer to the standard error associated to the average values. Asterisks (*) refer to the significant differences obtained at the day-of-the-year level for the factors under study according to the Tukey test for $p$-value <0.05.

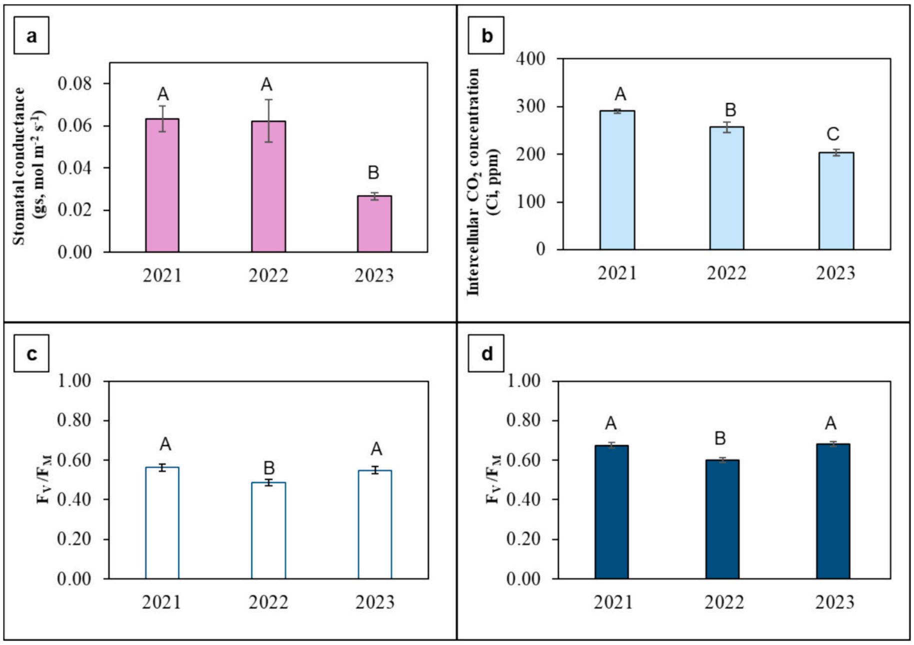

**Fig. 7.** Average values of (a) stomatal conductance (gs), (b) intercellular carbon dioxide ($CO_2$) concentration (Ci), maximum quantum efficiency of photosystem in (c) light and (d) dark (expressed as ratio between the variable and maximum fluorescence, $F_V/F_M$) over the three-years period. Bars refer to the standard error associated to the average values. Different letters refer to significant differences in accordance with the Tukey test for p-value <0.05.

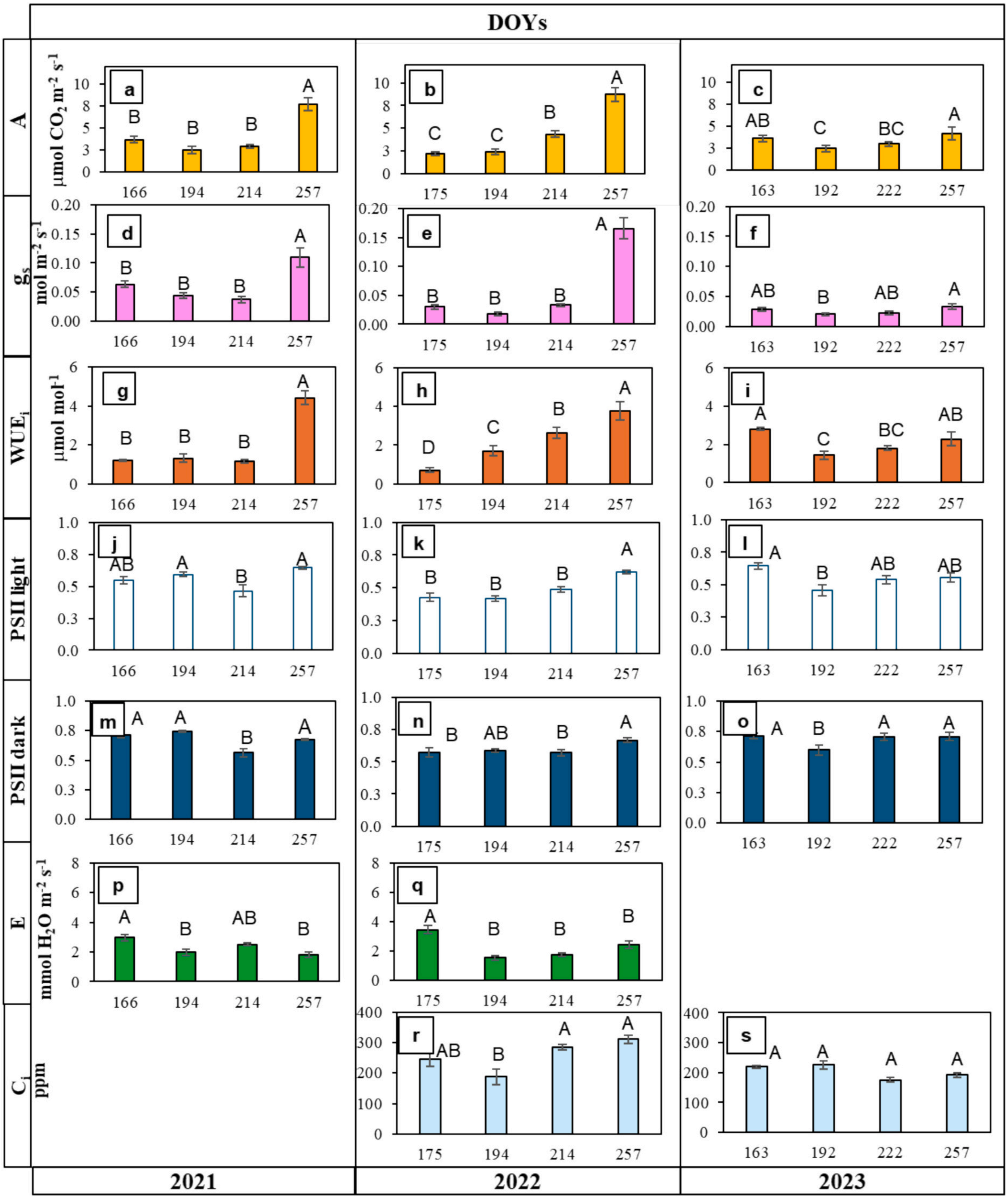

**Fig. 8.** Average values of (a-c) net photosynthesis (A), (d-f) stomatal conductance (gs), (g-i) instantaneous water use efficiency (WUEi), maximum quantum efficiency of photosystem (PSII) in (j-l) light and (m-o) dark, (p-q) transpiration rate (E) and (r-s) intercellular carbon dioxide (CO$_2$) concentration (Ci) for the different DOYs under study over the three-year period. Bars refer to the standard error associated to the average values. Different letters refer to significant differences in accordance with the Tukey test for p-value <0.05.

2019), converging on the fact that the orange trees under Mediterranean conditions developed an adaptive response to long-term water deficit conditions (Saitta et al., 2021; Vanella et al., 2021).

Herein, significant differences in terms of SWP were confirmed in the DI period (i.e., 50 % of ET$_c$), showing a delayed CWS effect also linked to the agrometeorological variability observed across the different years (i.e., rain events, Fig. 3). More in detail, SWP values were affected by the applied WR and the interaction between the year and the WR, resulting in more negative values under the RDI conditions compared to FI, with minimum values in 2021 (i.e., characterized by the lowest mulching thickness dose, Pappalardo et al., 2023). However, the use of OM factor produced multiple effects on the soil-plant system. Specifically, the trees supplied under mulching conditions showed a better water status in 2022, with more positive SWP values in comparison to trees under bare soils. This finding is in accordance with Berríos et al. (2024a, 2024b), which observed that the combined adoption of mulching and irrigation significantly reduced the effect of RDI. In 2023, the interaction between SM and WR showed more stressed conditions under RDI-MULCH and FI-

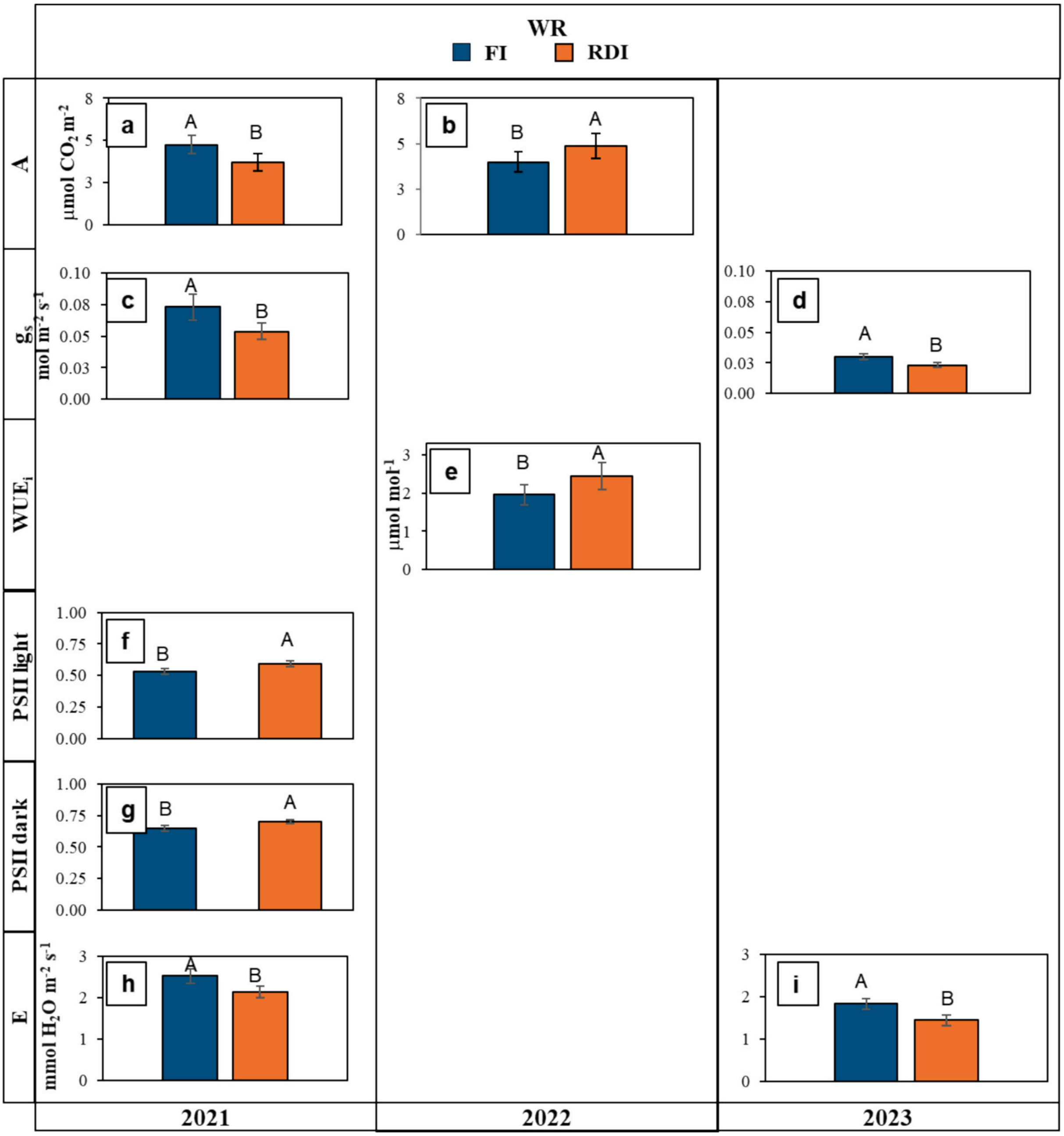

**Fig. 9.** Interactions of (a-b) net photosynthesis (A), (c-d) stomatal conductance (gs), (e) instantaneous water use efficiency (WUEi), maximum quantum efficiency of photosystem (PSII) in (f) light and (g) dark and (h-i) transpiration rate (E) linked to water regime (WR) in the three-years period. Bars refer to the standard error associated to the average values. Letters show the significant differences in accordance with the Tukey test for p-value <0.05.

BARE, indicating an improved capacity of the trees in using the available water.

Although SWP is recognized as a standard indicator of CWS, this study evaluated the implementation of multiple plant-based measures and ancillary physiological indicators. Specifically, the use of sap-flow sensors has permitted to retrieve continuous information about the CWS (Fig. 4), showing lower transpiration rates under mulched soil than in bare soil in RDI conditions (0.64 ± 0.00 mm $d^{-1}$ versus 0.88 ± 0.01 mm $d^{-1}$). In addition, the capability of the automatic sensors FloraPulse© was appraised in comparison to the adoption of the traditional Scholander-based method for continuously providing information on the plant water relationships (Blanco and Kalcsits, 2021).

A moderate discrepancy between SWP and TWP was obtained mainly due to the different point of the tree where the measurement was performed, i.e. the leaf and the trunk, respectively, for the Scholander method and microtensiometers (Gonzalez Nieto et al., 2023; Lakso et al., 2022; Pagay, 2022). The $R^2$ value obtained from the linear regression between SWP and TWP (i.e., 0.77) indicates a reasonable relationship compared to the weak relationship reported by Pagay (2022) (i.e., 0.45). However, additional data are needed to corroborate these findings.

With reference to the trend of the main physiological indicators of ancillary type, lower values were observed in the hottest summer months of the years studied (Figs. 5–6). The year-to-year variability can be explained by the role that canopy pruning (which determined the thickness of the OM each year) and the high $T_{air}$ played in the study site, since these conditions have a significant impact on the metabolism of trees and their biological rhythm (Guo et al., 2006; Machado et al., 2005; Ribeiro et al., 2004, 2009). In particular, Li et al. (2021)

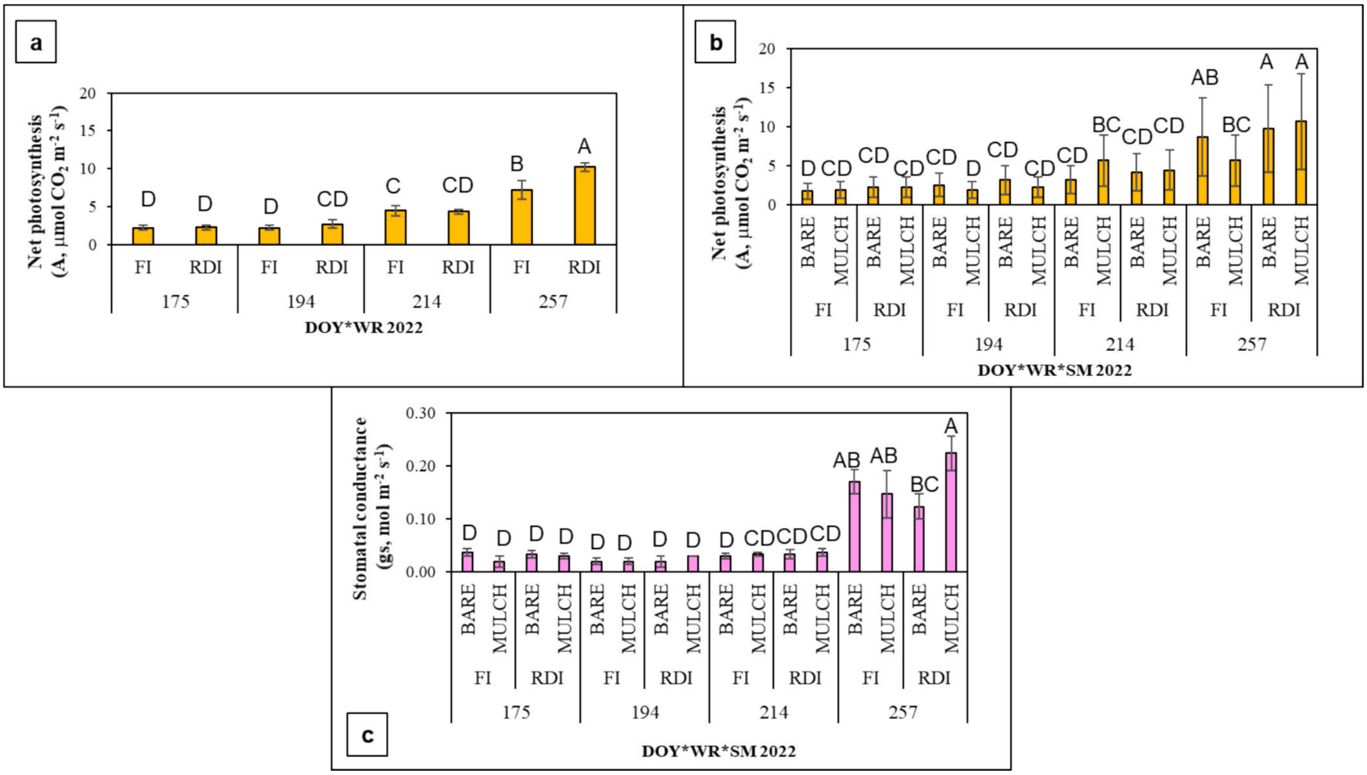

**Fig. 10.** Interactions of net photosynthesis (A) related to WR and DOYs in 2022 (a); and interactions of A (b) and stomatal conductance (gs, c) related to WR, DOYs and SM in 2022. Bars refer to the standard error associated to the average values. Different letters refer to significant differences in accordance with Tukey's test for $p$-value $<0.05$.

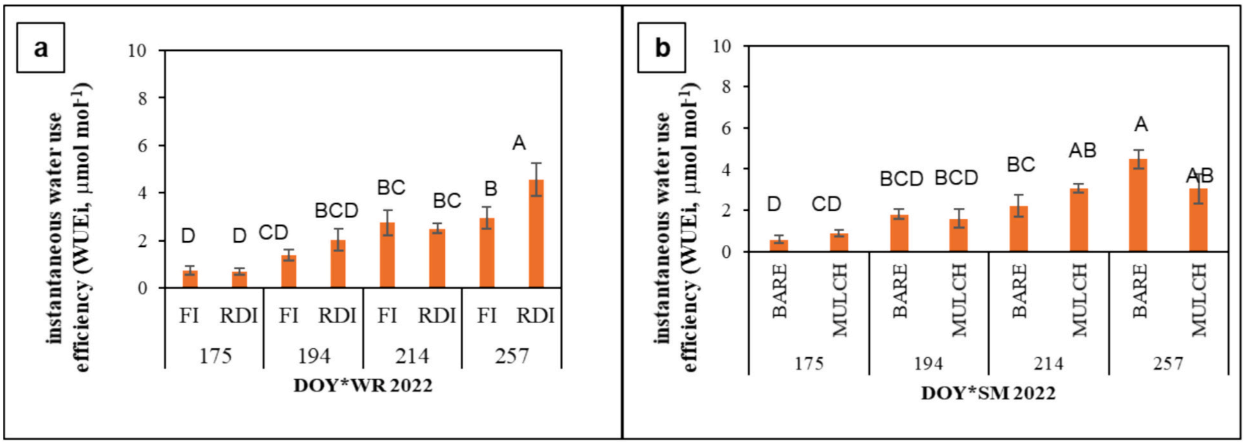

**Fig. 11.** Interactions of instantaneous water use efficiency (WUEi) related to DOYs and WR (a) and DOYs and SM (b) in 2022. Bars refer to the standard error associated to the average values. Letters show significant differences in accordance with Tukey's test for $p$-value $<0.05$.

demonstrated that moderate-heavy canopy pruning can significantly reduce transpiration, increase WUEi (Ma et al., 2019), and induce a sharp decline in photosynthesis until stomata closure (Pérez-Pérez et al., 2007). Note that in our study, the most stressed year in terms of SWP was 2021, characterized by light pruning. The least stressed year was 2022, in which heavy pruning was applied, followed by 2023, in which moderate pruning was applied. Therefore, the observed changes for A, gs, Ci and WUEi suggest that these variables are interdependent (Figs. 6–7). Specifically, the A showed similar increasing patterns among years. Interactions of A with WR appeared relevant in 2021–22 although opposite, as higher values were found in FI and RDI, respectively. This effect may be explained by an adaptation of trees to stress conditions due to external factors, such as seasonal trends and canopy pruning. In this perspective, a role can be ascribed to the OM, which contributed to improve the adaptation of trees to water deficit (Li et al., 2018). Similar to A, an increasing trend was observed for gs at the end of the irrigation seasons. Abad et al. (2019) demonstrated that, in late summer, emerging lateral shoots can compensate for the reduction in total leaf area, due to the canopy pruning, thus increasing gs and A in line with our evidences. In this study, the WUEi did not show significant differences during the three years, thus, this supposes a constant water use efficiency by the trees, even if A increased significantly in some years. In accordance with Liao et al. (2021), these plant mechanisms led to improved yield features, suggesting that OM could serve as an additional practice to irrigation for controlling the crop response (Wang et al., 2015). Generally, due to heat stress, citrus trees tend to show a decrease in Ci (Ribeiro

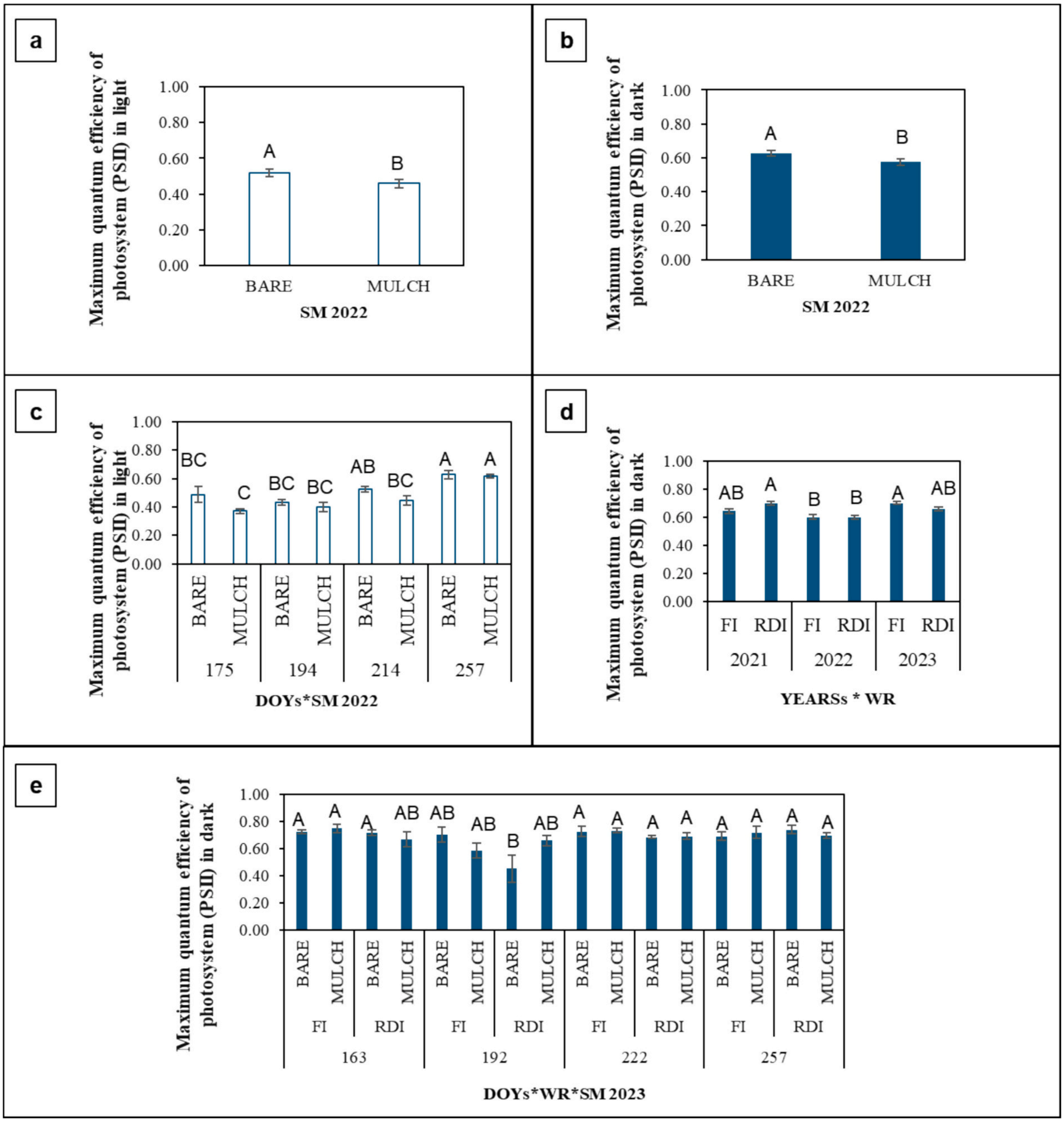

**Fig. 12.** Interactions of the maximum quantum efficiency of photosystem (PSII) in light (a); and dark (b) with SM in 2022; of PSII light with SM and DOYs in 2022 (c); of PSII dark with year and WR in the three-years period (d); and PSII dark with DOYs, WR e SM in 2023 (e). Bars refer to the standard error associated to the average values. Different letters refer to significant differences in accordance with Tukey's test for *p*-value $<0.05$.

et al., 2004; Hu et al., 2007). According with this statement, the observed decrease in Ci corroborates the gs trends, as low values indicate stomatal closure and, therefore, a stress condition. The E exhibited a common trend in the three-years, specifically in 2021 and 2023. An interaction was found for E as function of WR, resulting in a better water status under FI, than in RDI conditions. In agreement with Ribeiro et al. (2009), despite the observed lower gs values, higher E values were observed during the irrigation seasons. These patterns may be linked to different changes occurred at leaf level regulation and in shoot water status (Nobel, 1999), as suggested by the observed SWP values. However, weak correlations were found among the main ancillary physiological indicators under study and SWP. The PSII in light and in dark showed the same trends of SM, with higher values in bare than in mulched soils. Under light conditions, an interaction was observed in 2022 between SM and DOYs. In dark conditions, interactions related to years and WR occurred, with minimum values in 2022 for both FI and RDI; while, in 2023, an interaction was found among the three factors under study. This interaction showed homogeneous conditions among the treatments, except for the lower PSII in dark observed in RDI BARE on DOY 192. Thus, its means that the OM can contribute to mitigate the stress conditions and to avoid damage at the PSII level (Flexas et al., 2004). This observation agreed with Abd El-Mageed et al. (2016), as they showed that mulch application attenuated the negative effects of DI on chlorophyll fluorescence, resulting in similar values to FI regime.

Referring to soil features, several studies have appraised the influence of mulching on the soil physical-chemical characteristics (e.g., Tadayon and Hosseini, 2020; Thakur and Kumar, 2021; Van Dung et al., 2022). Some of these studies have evidenced improvements in nutrients availability, soil porosity and SOM under mulching conditions, and, therefore, an overall improved WUE (Iqbal et al., 2020; Thakur and

**Table 3**

Physical and chemical soil properties (average and standard error values) for the different factors under study. WR and SM refer to water regime (full versus regulated deficit irrigation) and soil management (bare versus mulched soil), respectively. Asterisks indicate significant differences for the factors under study and their interactions at p-value $<0.05$.

| YEAR | WR | SM | pH | EC | $N_{tot}$ | $NO_3^-$ | $K_{tot}$ | $K^+$ | Ca |
|---|---|---|---|---|---|---|---|---|---|
| | | | - | mS cm$^{-1}$ | % d.m. | mg Kg d.m. $^{-1}$ | mg kg d.m.$^{-1}$ | mg Kg d.m. $^{-1}$ | mg kg d.m.$^{-1}$ |
| 2021 | FI | BARE | 7.61 ± 0.11 | 191.50 ± 13.61 | 0.17 ± 0.10 | 29.04 ± 6.07 | 1835.43 ± 164.44 | 36.45 ± 6.75 | 10419.70 ± 530.52 |
| | FI | MULCH | 7.61 ± 0.02 | 200.33 ± 21.74 | 0.18 ± 0.10 | 47.51 ± 12.23 | 2100.47 ± 209.80 | 42.49 ± 6.06 | 12027.55 ± 567.65 |
| | RDI | BARE | 7.70 ± 0.05 | 263.33 ± 33.27 | 0.15 ± 0.09 | 106.10 ± 41.99 | 1773.61 ± 217.21 | 40.00 ± 8.23 | 11183.62 ± 536.27 |
| | RDI | MULCH | 7.49 ± 0.04 | 178.67 ± 21.99 | 0.16 ± 0.09 | 31.13 ± 7.53 | 3575.43 ± 1546.24 | 32.29 ± 6.88 | 9939.81 ± 1301.71 |
| 2022 | FI | BARE | 8.27 ± 0.07 | 221.90 ± 20.17 | 0.12 ± 0.07 | 100.07 ± 40.47 | 6749.59 ± 498.95 | 31.77 ± 6.40 | 9343.57 ± 278.28 |
| | FI | MULCH | 8.35 ± 0.04 | 225.33 ± 6.98 | 0.12 ± 0.07 | 83.95 ± 13.48 | 6926.47 ± 475.15 | 33.82 ± 1.63 | 9675.68 ± 247.77 |
| | RDI | BARE | 8.27 ± 0.02 | 258.00 ± 26.54 | 0.11 ± 0.06 | 87.20 ± 25.23 | 6246.70 ± 514.56 | 32.98 ± 4.86 | 9598.28 ± 430.74 |
| | RDI | MULCH | 8.20 ± 0.10 | 209.03 ± 8.05 | 0.11 ± 0.07 | 50.62 ± 6.67 | 6186.33 ± 890.65 | 23.77 ± 5.39 | 8959.39 ± 125.42 |
| 2023 | FI | BARE | 7.73 ± 0.12 | 519.00 ± 99.46 | 0.10 ± 0.06 | 248.63 ± 114.62 | 1981.17 ± 518.23 | 81.91 ± 19.98 | 11237.51 ± 316.69 |
| | FI | MULCH | 7.77 ± 0.06 | 651.00 ± 123.25 | 0.07 ± 0.04 | 95.44 ± 54.62 | 1527.01 ± 399.98 | 65.09 ± 5.69 | 11133.43 ± 628.16 |
| | RDI | BARE | 7.99 ± 0.04 | 454.00 ± 35.00 | 0.07 ± 0.04 | 113.90 ± 67.15 | 1568.36 ± 315.46 | 57.63 ± 10.78 | 10866.39 ± 1084.62 |
| | RDI | MULCH | 7.87± 0.03 | 464.00 ± 59.18 | 0.08 ± 0.04 | 163.14 ± 90.90 | 1338.15 ± 375.14 | 34.63 ± 7.25 | 10912.03 ± 604.39 |
| **Factors** | | | | | | | | | |
| YEAR | | | * | * | * | * | * | * | * |
| WR | | | | | | | | * | |
| SM | | | | | | | | | |
| YEAR*WR | | | * | | | | | | |
| YEAR*SM | | | | | | | | | |
| WR*SM | | | * | | | | | | * |
| YEAR*WR*SM | | | | | | | | | |

| YEAR | WR | SM | Mg | $PO_4^{3-}$ | Na | $C_{tot}$ | TOC | SOM | CMIC | CMIC/TOC |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | mg kg d.m.$^{-1}$ | mg Kg d.m.$^{-1}$ | mg Kg d.m.$^{-1}$ | % d.m. | % | % | ppm | % |
| 2021 | FI | BARE | 1598.66 ± 229.84 | 12.50 ± 7.21 | 535.70 ± 113.27 | 1.34 ± 0.08 | 1.45 ± 0.11 | 2.50 ± 1.44 | 172.58 ± 34.61 | 1.16 ± 0.67 |
| | FI | MULCH | 1659.95 ± 91.84 | 2.98 ± 2.09 | 602.53 ± 77.50 | 1.48 ± 0.12 | 1.41 ± 0.09 | 2.43 ± 1.41 | 168.07 ± 20.88 | 1.22 ± 0.70 |
| | RDI | BARE | 1389.30 ± 50.67 | 7.79 ± 4.31 | 719.95 ± 185.61 | 1.33 ± 0.06 | 1.58 ± 0.06 | 2.72 ± 1.57 | 141.20 ± 6.55 | 0.91 ± 0.52 |
| | RDI | MULCH | 2080.13 ± 230.96 | 10.66 ± 1.06 | 1138.83 ± 326.32 | 1.23 ± 0.04 | 1.43 ± 0.06 | 2.46 ± 1.42 | 172.59 ± 28.25 | 1.23 ± 0.71 |
| 2022 | FI | BARE | 2999.41 ± 296.68 | 14.09 ± 0.97 | 619.11 ± 90.89 | 1.66 ± 0.11 | 1.32 ± 0.10 | 2.28 ± 1.32 | 132.15 ± 21.04 | 1.04 ± 0.60 |
| | FI | MULCH | 2620.26 ± 104.23 | 11.79 ± 4.55 | 728.07 ± 56.04 | 1.62 ± 0.16 | 1.44 ± 0.03 | 2.48 ± 1.43 | 153.62 ± 7.42 | 1.07 ± 0.62 |
| | RDI | BARE | 2572.60 ± 238.63 | 10.24 ± 1.25 | 763.73 ± 115.36 | 1.61 ± 0.16 | 1.55 ± 0.01 | 2.67 ± 1.54 | 144.04 ± 38.88 | 0.93 ± 0.54 |
| | RDI | MULCH | 2940.47 ± 290.56 | 16.34 ± 8.73 | 710.79 ± 161.38 | 1.36 ± 0.20 | 1.29 ± 0.03 | 2.23 ± 1.29 | 144.20 ± 38.87 | 1.11 ± 0.64 |
| 2023 | FI | BARE | 3145.19 ± 551.61 | 15.79 ± 5.49 | 781.76 ± 79.79 | 1.39 ± 0.07 | 1.58 ± 0.10 | 2.73 ± 1.58 | 157.49 ± 13.58 | 1.00 ± 0.58 |
| | FI | MULCH | 2904.80 ± 195.85 | 9.38 ± 5.44 | 1143.30 ± 131.55 | 1.11 ± 0.10 | 1.56 ± 0.15 | 2.69 ± 1.55 | 136.31 ± 11.10 | 0.90 ± 0.52 |
| | RDI | BARE | 2405.88 ± 236.78 | 12.12 ± 2.04 | 1003.56 ± 186.20 | 1.18 ± 0.04 | 1.53 ± 0.12 | 2.64 ± 1.53 | 144.76 ± 19.62 | 0.97 ± 0.56 |
| | RDI | MULCH | 3563.10 ± 406.91 | 10.01 ± 5.13 | 1356.85 ± 130.70 | 1.10 ± 0.08 | 1.46 ± 0.05 | 2.51 ± 1.45 | 146.15 ± 3.38 | 1.00 ± 0.58 |
| **Factors** | | | | | | | | | | |
| YEAR | | | * | | * | * | | | | |
| WR | | | | | * | * | | | | |
| SM | | | | | * | | | | | |
| YEAR*WR | | | | | | | | | | |
| YEAR*SM | | | | | | | | | | |
| WR*SM | | | * | | | | | | | |
| YEAR*WR*SM | | | | | | | | | | |

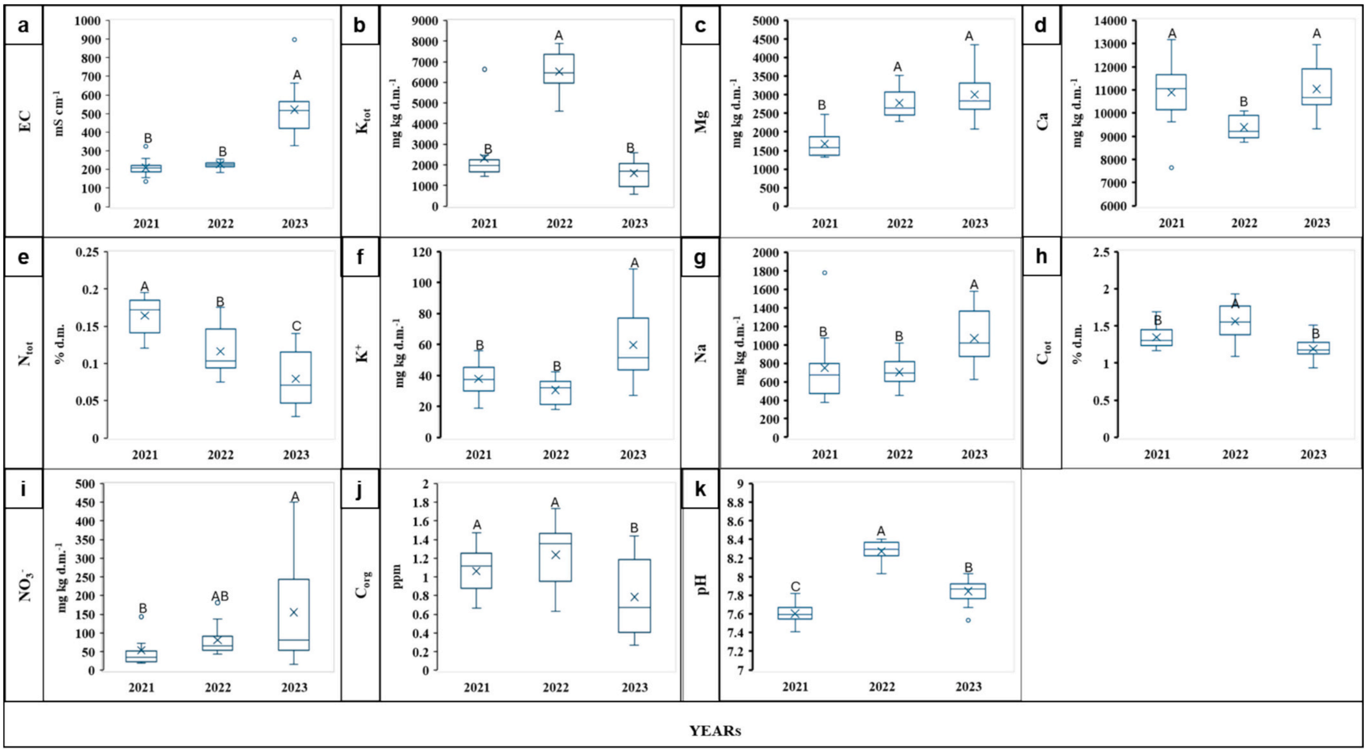

**Fig. 13.** Significant trends over the three-year period of (a) electrical conductivity (EC, mS cm$^{-1}$), (b) total potassium (K$_{tot}$, mg kg d.m.$^{-1}$), (c) magnesium (Mg, mg kg d.m.$^{-1}$), (d) calcium (Ca, mg kg d. m$^{-1}$), (e) total nitrogen (N$_{tot}$, mg kg d.m.$^{-1}$), (f) potassium ion (K+, mg kg d.m.$^{-1}$), (g) sodium (Na, mg kg d.m.$^{-1}$), (h) total carbon (C$_{tot}$, % d.m.), (i) nitrates (NO$_{-3}$, mg kg-1 d.m.), (j) total organic carbon (C$_{org}$, ppm), (k) pH (–). Different letters indicate the significant differences in accordance with the Tukey test for p-value <0.05.

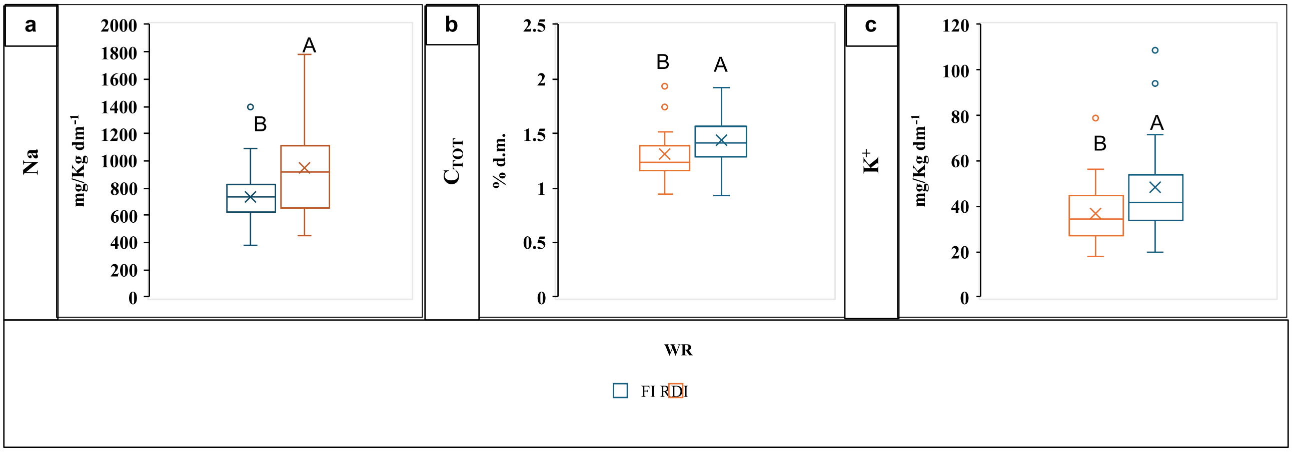

**Fig. 14.** Interactions linked to WR (water management) in the three-years period for (a) sodium (Na, mg kg d.m$^{-1}$), (b) total carbon (C$_{tot}$, % d.m.) and (c) potassium ion (K+, mg kg d.m.$^{-1}$). FI and RDI refer to full irrigation and regulated deficit irrigation. Different letters show significant differences in accordance with Tukey test for *p*-value <0.05.

Kumar, 2021). The behaviour of soil physical-chemical characteristics at the study site was multifaceted, since different aspects have contributed on the response of the soil system (e.g. physical, chemical and biological characteristics), which is also influenced by cultivation practices and agrometeorological conditions. As suggested by Berríos et al. (2024a, 2024b), mulching cannot be considered a stand-alone measure, but part of an agricultural management system. Thus, additional effects on soil physical-chemical and microbial properties may be considered for the effective application of SWCM. Thus, the annual fluctuations observed in soil parameters were the result of complex interactions, that occurred in the investigated soil layer (0–30 cm), due the application of SWCM, the soil biological activity, fertilization and atmospheric conditions. As example, among the traditional cultivation practices, an important influence was determined by the fertilization operations, which may favour specific assimilation mechanisms by the trees. In particular, fertilizations (based on NPK and essential microelements) were performed in the spring over the three-year study period. Thus, it is necessary to consider these practices as partially responsible of the variability observed over time for some soil variables under study (i.e., increasing trends for EC, Na, K$^+$ and bell-shaped patterns for K$_{tot}$, C$_{tot}$). Note that the soil sampling in 2021 was performed in the spring period, before the application of OM and the beginning of the irrigation season (time zero, March 2021). In the two-years 2022–23, the soil sampling campaign was carried-out at the end of the irrigation season, and,

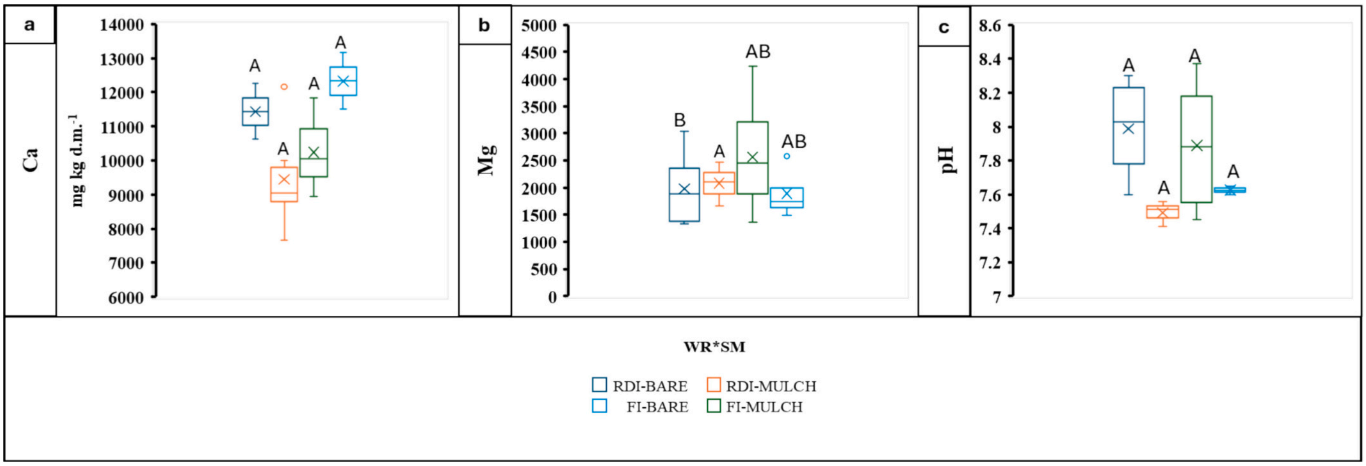

**Fig. 15.** Interactions linked to WR (water management) and SM (soil management) in the three-year period for (a) calcium (Ca, mg kg d. $m^{-1}$), (b) magnesium (Mg, mg kg d.$m.^{-1}$) and (c) pH. FI and RDI refer to full irrigation and regulated deficit irrigation. Different letters show significant differences in accordance with Tukey test for p-value $<0.05$.

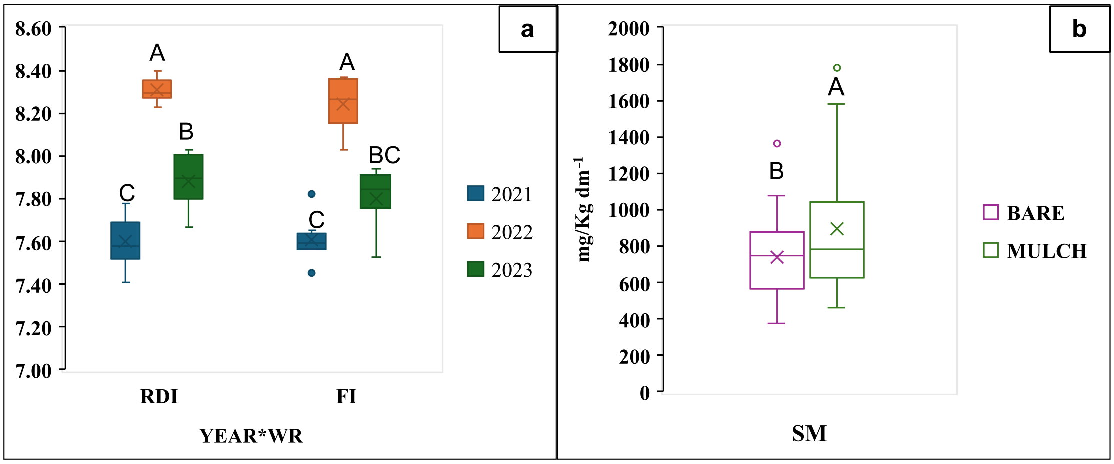

**Fig. 16.** Interactions (a) linked to WR (water management) and years for pH (–), and linked to SM (soil management) for (b) sodium (Na, mg kg d.$m.^{-1}$). FI and RDI refer to full irrigation and regulated deficit irrigation. Different letters show significant differences in accordance with Tukey test for p-value $<0.05$.

therefore, approximately five months after the application of the OM (in October). Based on these assumptions, it cannot be excluded that the field conditions have affected the obtained results. In addition, in the two-years 2021–22, soil sampling was conducted after a rain period (Fig. 2). Differently, in 2023, it was carried out in a drier period, even if at the end of the irrigation season, characterized by a greater solute concentration in the soil. As demonstrated by Durán et al. (2024), soils with different SWC levels have dissimilar microbial biomass and soil enzyme activity, since the SWC favours the population of microorganisms and enzyme activity. These mechanisms may regulate the observed soil variables trends (Fig. 13). Specifically, the EC presented higher values in 2023, when there was a lower rainfall contribution compared to 2021–22. Similar condition was observed for Na, showing a peak in 2023. For this variable, significant interactions were linked to WR and SM, respectively, resulting in higher Na content in RDI compared to FI and in mulched soil compared to the bare soil. As a general rule, the uptake of K by the crops is nearly equal to or even more than N uptake (Kumar et al., 2024). In our study, the most absorbable forms of K and N were $K^{+}$ and $NO_{3-}$, which presented a similar increasing trend over the three-years period. The $K_{tot}$ showed a bell-shaped trend, with a peak in 2022; whereas, the $K^{+}$ became more available over time, with a peak in 2023, as function of the applied irrigation strategy, with higher contents in FI than in RDI. The $N_{tot}$ presented a negative interaction over time with lower values in 2023. Despite this behaviour, the increasing trends of $NO_{3-}$ suggested a greater availability to trees over time. The Mg content showed an increasing trend with similar values in the two-years period 2022–23 compared to 2021. It presented an interaction linked to WR and SM; the influence of these factors determined a greater variability in RDI both in bare and mulched soils, with higher values under mulched soils. The Ca content depicted a parabolic trend, with similar values in 2021 and 2023 and a decrease in 2022. Furthermore, a weak significance of the interaction between WR and SM suggested a reduction of Ca in the RDI-MULCH condition. The application of OM contributed to similar trend of $C_{org}$ in 2021–22 and to a decreasing trend in 2023. This behaviour indicates that, even if additional organic matter were added to the surface of the soil, albeit in varying quantities depending on the pruning needs of the crown, the SOM (not buried in the soil) would require a longer time to be assimilated also as function of the pedo-climatic variability (Jiménez et al., 2017; Özcan et al., 2013). According to Canali et al., (2004), significant variation in SOM and increase in CMIC are expected after many years of organic matter supplying. In our study, the pH was basic with an alkaline tendency, linked to the calcareous components of the soil, showing a bell-shaped trend, as for $C_{tot}$ and $K_{tot}$, within the three-year period. The interaction between WR and years showed similar pH values, with higher values in both RDI and FI in 2022, which were significantly different in 2021, characterized

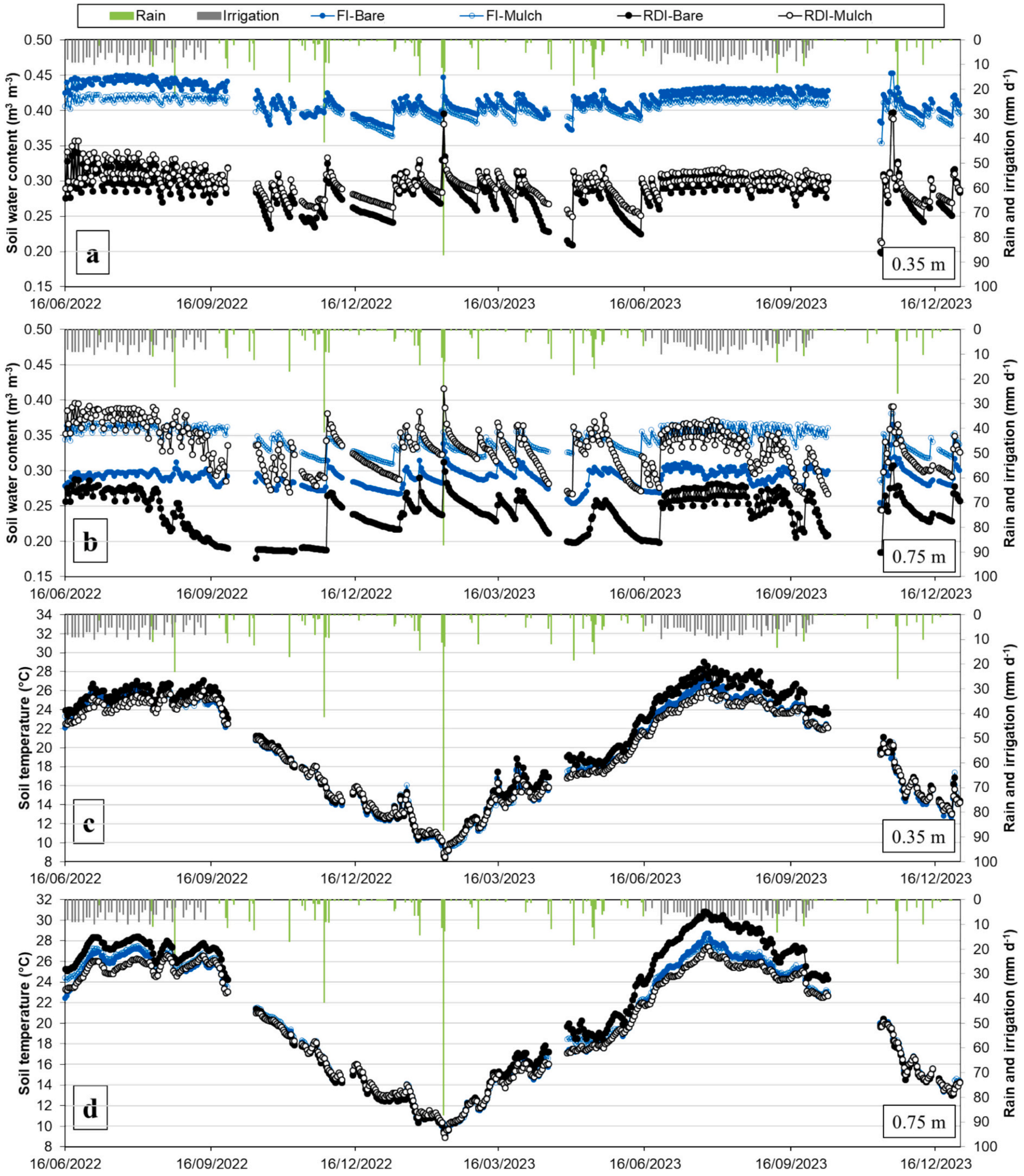

**Fig. 17.** Daily soil water content (SWC) (a, b) and soil temperature (c, d) patters referring to the tree trunk distances (i.e., 35 and 0.75 m) for full irrigation (FI) and regulated deficit irrigation (RDI) under mulched and bare soil conditions, together with daily rain and irrigation amounts, for the period 2022–23.

by the lowest pH values; intermediate condition occurred in 2023. Other weak interactions were retrieved for WR and SM factors, where pH was more favourable under RDI-MULCH conditions. In this study, complex WR*SM interactions were observed for pH and Ca—Mg contents due to the combined use of RDI and OM. This combined effect caused a favourable or stable condition of homogeneity under FI, both with and without OM, and the RDI-MULCH treatments. However, the combined effect of SWCM on soil physical and chemical properties is hard to be fully explained, because it may change over time as function of the specific site-conditions (e.g., Buesa et al., 2021; Yaseen et al., 2014).

The improvement of SWC as well as of water utilization efficiency represents a further added-value associated to OM adoption (Zhang et al., 2023). Herein, the daily SWC continuously measured in the two-years period 2022–23 demonstrated a positive effect of OM on SWC conservation, especially at 0.75 m distance from the tree trunk, i.e., in areas more subjected to soil evaporation. In detail, higher SWC values were detected under mulched soil at this distance, compared to bare soil under both RDI and FI. This evidence agreed with the observations of Visconti et al. (2024), who reported that OM increased the SWC in the inter-row, representing an extra water resource eventually available for the tree root-systems (Cassiani et al., 2015). The lowest SWC values were observed at RDI-BARE. However, the maximum SWC values reached at 0.75 m distance were lower than those recorded at 0.35 m, due to the position of the dripline (i.e., closer to the tree trunk). This distance was

**Table 4**
Three-way analysis of variance for evaluating the effect of SM practices and WR on the main yield parameters during the study period. WR and SM denote the water regime and soil management factors. The values in bold with asterisks refer to the significant differences among the factors and their interactions (for *p*-value <0.05). Degrees of freedom (DF) and F-values (F) are also reported.

| Factors | Fruit weight | | | Number of fruits | | | % of juice | | | Estimate yield | | | Equatorial size | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DF | F | p-value | DF | F | p-value | DF | F | p-value | DF | F | p-value | DF | F | p-value |
| SM | 1 | 2.43 | 0.13 | 1 | 0.44 | 0.52 | 1 | 0.51 | 0.48 | 1 | 0.36 | 0.56 | 1 | 2.61 | 0.12 |
| WR | 1 | 0.56 | 0.46 | 1 | 0.06 | 0.82 | 1 | 1.82 | 0.19 | 1 | 0.06 | 0.82 | 1 | 1.86 | 0.18 |
| YEAR | 2 | 18.02 | **0.00*** | 1 | 0.80 | 0.39 | 2 | 4.95 | **0.01*** | 1 | 0.25 | 0.62 | 2 | 0.84 | 0.44 |
| SM*WR | 1 | 4.23 | 0.05 | 1 | 2.22 | 0.16 | 1 | 0.49 | 0.48 | 1 | 3.05 | 0.10 | 1 | 2.68 | 0.11 |
| SM*YEAR | 2 | 2.84 | 0.08 | 1 | 0.38 | 0.55 | 2 | 0.7 | 0.5 | 1 | 0.45 | 0.51 | 2 | 0.14 | 0.87 |
| WR*YEAR | 2 | 1.78 | 0.19 | 1 | 0.46 | 0.51 | 2 | 2.18 | 0.13 | 1 | 0.14 | 0.72 | 2 | 0.31 | 0.73 |
| SM*WR*YEAR | 2 | 5.5 | **0.01*** | 1 | 0.77 | 0.40 | 2 | 1.12 | 0.34 | 1 | 0.65 | 0.43 | 2 | 0.08 | 0.92 |
| TOTAL | 35 | | | 23 | | | | | | 23 | | | 35 | | |

| Factors | Sugars | | | pH | | | Acidity | | | Anthocyanins | | | Polyphenols | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DF | F | p-value | DF | F | p-value | DF | F | p-value | DF | F | p-value | DF | F | p-value |
| SM | 1 | 0.2 | | 1 | 3.15 | 0.08 | 1 | 0.52 | 0.47 | 1 | 0.5 | 0.48 | 1 | 0.09 | 0.76 |
| WR | 1 | 5.54 | **0.02*** | 1 | 0.69 | 0.41 | 1 | 0.35 | 0.55 | 1 | 2.23 | 0.15 | 1 | 1.72 | 0.21 |
| YEAR | 2 | 2.91 | 0.07 | 2 | 3.39 | 0.05 | 2 | 21.76 | **0.00*** | 2 | 11.85 | **0.00*** | 1 | 0.05 | 0.82 |
| SM*WR | 1 | 0.25 | 0.62 | 1 | 0.07 | 0.79 | 1 | 1.01 | 0.32 | 1 | 0.25 | 0.62 | 1 | 4.94 | **0.04*** |
| SM*YEAR | 2 | 0.18 | 0.84 | 2 | 0.87 | 0.43 | 2 | 0.15 | 0.86 | 2 | 1.57 | 0.23 | 1 | 0.40 | 0.53 |
| WR*YEAR | 2 | 0.47 | 0.62 | 2 | 0.62 | 0.54 | 2 | 0.27 | 0.76 | 2 | 0.13 | 0.88 | 1 | 0.67 | 0.42 |
| SM*WR*YEAR | 2 | 0.42 | 0.66 | 2 | 0.35 | 0.7 | 2 | 0.41 | 0.67 | 2 | 2.53 | 0.10 | 1 | 0.55 | 0.47 |
| TOTAL | 35 | | | 35 | | | 35 | | | 35 | | | 23 | | |

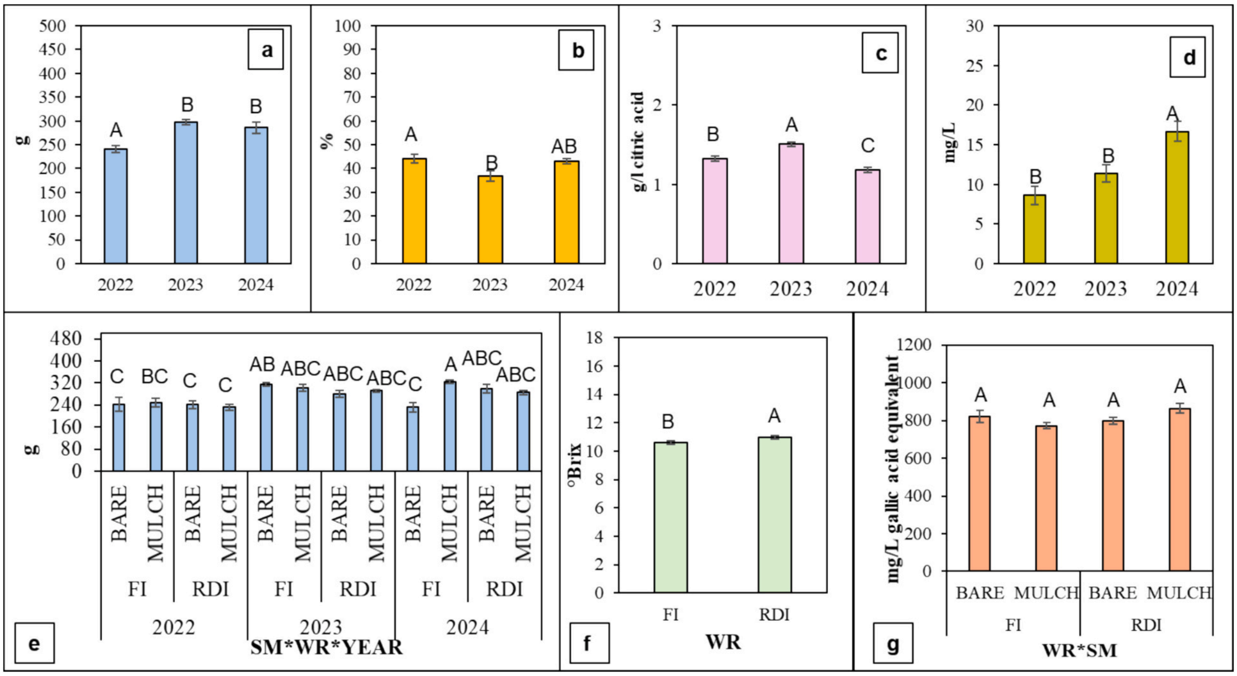

**Fig. 18.** Interactions of (a) fruit weight (g), (b) juice (%), acidity (g/l citric acid) and (d) anthocyanin content (mg/L) with the three-year period; (e) fruit weight linked to SM, WR and years, (f) sugars linked to WR, and (g) polyphenols linked to WR and SM in the three-year period. SM and WR denote the soil management and water regime, respectively. Bars refer to the standard error associated to the average values. Different letters show the significant differences in accordance with the Tukey test for p-value <0.05.

less affected by soil evaporation as it was protected from Sr, due to the shading of the tree crowns. Thus, in the area with a more accentuated root density, at 0.35 m, trees benefit from a greater SWC (Vanella et al., 2018, 2023). Slighter higher SWC were obtained under mulched soils both in FI and RDI at 0.35 m, confirming the critical role of OM in retaining water, as function of its amount or thickness (Liao et al., 2021; Iqbal et al., 2020). Note that OM was more homogeneously distributed further away from the trunk than close to the tree-rows. In this study, the positive effect of OM claimed on soil hydrology, i.e., decreasing water infiltration (e.g., Khurshid et al., 2006; Prosdocimi et al., 2016; Dugan et al., 2024), probably involves a better adaptation of trees to water deficit in mulched conditions, maintaining lower $T_{SF}$ rates compared to the bare soil condition (Fig. 4).

From an economic point of view, the cost of mulching depends on the type of the applied material, mainly divided in organic or synthetic materials (Chopra and Koul, 2020). The use of OM allows significant savings compared to the cost of synthetic plastic material (e.g., 15.000,00 €/ha for the cheapest types in Sicily). Note that OM material can be directly supplied on site, since pruning is an annual operation that is generally applied at the farm level. As short-coming, the OM application requires a phase in which pruning residues are shredded and, subsequently, distributed on the soil surface to make a homogeneous layer (for a total cost of 4.500,00 €/ha). This needs for manpower and, in some cases, the material transport is required from other sites (Kader et al., 2019). Nonetheless, an additional economic benefit associated to the use of OM is the possibility of reusing agricultural residues (i.e., canopy pruning waste as in this study) in accordance to the strategic plans of the European directives of the new common agricultural policy to achieve carbon neutrality objectives (CAP 2023–27; Guarrera et al., 2024).

Benefits associated to the OM application must be evaluated site-by-site in long-term, since the OM degradation timeframe can be quite slow, especially when OM is applied on the soil surface (Li et al., 2021). Mwango et al. (2016) found that long-term mulches were effective in controlling soil and water losses, with reduction rates of runoff and soil losses exceeding 58 %. Other positive aspects of long-term OM application are related to the protection of the soil by extreme high temperatures (Ray and Biswasi, 2016) and the improvement of soil properties and/or biological activities (López et al., 2014; Niswati et al., 2018). However, soil properties changes by mulching might be slower than expected under semi-arid conditions (Jiménez et al., 2016, 2017). Several studies highlighted the positive effects on soil protection from summer heat, with reductions in the maximum daily temperature up to 2 °C under mulched compared to bare soils, which showed notable temperature fluctuations (e.g., Kader et al., 2017; Suo et al., 2019; Liao et al., 2021). In this study, the maximum soil temperature differences between mulched and bare soils were observed under RDI conditions, with values of 2.5 °C and 3.4 °C, respectively, at a distance of 35 and 0.75 m from the tree trunk. Similar soil temperature values were recorded among the FI regimes, characterized by higher SWC compared to RDI. As for SWC, the mulching effect seems to be more intense at a greater distance from the tree, where higher soil temperature discrepancy was observed (up to 5–6 %).

Herein, the overall application of sustainable WR and SM practices improved fruit quality over the year. In particular, fruit weights were affected by the interactions of the three factors under study, showing every year similar values for both FI and RDI in bare and mulched conditions, with higher values in 2024 under mulched soils in FI. Similar evidence was found by Lepaja et al. (2015), whose showed that the mulched soil increased the size of the fruit diameter, without reporting a combined effect due to both RDI and mulching. Differently, Gebeyhu and Markos (2023) found that the combined use of mulching and DI was the most productive for watermelon cultivation. The application of such sustainable SWCM allowed trees to make a better use of the available resources. In this sense, the % of juice was stable in the three-year period, being the decrease occurred in 2023 compensated in 2024. The acidity decreased over the years, even if no relationships were obtained with the other factors under study. Week differences were obtained for the polyphenols as function of the interaction between the WR * SM, resulting in higher values under the mulched soils in RDI (note that this evaluation was conducted only for 2023–24). The effects of RDI application was evident in terms of sugars content, showing higher levels under the RDI treatments (Saitta et al., 2021). However, more complex factors (i.e., fertilization, environmental condition) can influence the drop of acidity and the accumulation of sugars during ripening, linked to the metabolic relationships of trees (Lin et al., 2015; Julhia et al., 2019). In conclusion, from the yield and fruit quality point-of-view, our findings partially agreed with Alhashimi et al. (2023), which recognized the application of OM in combination with DI criteria as a sustainable strategy for improving these traits under arid climatic environments and climate change scenarios. According to Mekonen and Gelagile (2024), smallholder farmers should apply OM under DI to increase yield components and for saving water. Nevertheless, it is important to underline the need of carrying-out additional studies in order to assess definitive results and best advice on the adoption of DI under different mulch levels (Demo and Tsehai, 2024) and/or long-term mulching application (Suo et al., 2019).

## 5. Conclusion and future outlook

The response of different SWCM was assessed in an orange orchard under Mediterranean climate conditions from a multi-perspective point-of-view, including CWS, soil and yield characteristics. The obtained results allowed to accomplish the hypotheses set at the beginning of the study, namely that the combined use of SWCM (i.e., the presence or absence of OM under FI or RDI conditions) can contribute to achieve positive CWS, soil and yield benefits.

At the study site, OM application improved the CWS by maintaining lower SWP values and reducing tree transpiration, demonstrating that OM is a sustainable source to substantially conserve the SWC. Specifically, OM was a beneficial practice for improving the soil water status, resulting in higher SWC values under mulched soils compared to bare soil conditions, both under FI and RDI at 0.75 m from the tree trunk to the inter-row. This behaviour was also translated in terms of soil temperature, revealing reductions up to 5–6 % in mulched soils, in comparison to bare conditions under RDI. However, long-term experiments are needed to provide more insight into the benefits that OM may provide to the soil composition and biology, due to greater time-variability observed for most of the analysed soil physical-chemical variables mainly due to the pedo-climatic conditions (i.e., rain variability during soil sampling) and the OM application for only three years. In this sense, future outlook of this study may be oriented to explore further research areas, such as soil biological activity and the long-term impacts of climate change on the efficacy of OM. In addition, the application of SWCM improved the yield over the years, resulting in higher fruit weights under mulched conditions both in FI and RDI, and significant interactions of WR and WR * SM for sugars and polyphenol content, respectively.

In conclusion, this study suggests that the integration of OM and RDI can serve as an efficient strategy to overall enhance the CWS, soil and yield features. However, several considerations must be addressed before applying this practice. Specifically, growers need to ensure a uniform application of the OM layer across the entire plot. In addition, the role of using multiple SPAC monitoring tools is pivotal to prevent crop damage. In this sense, the use of innovative technologies, such as microtensiometers, can assist growers in managing SWCM under field conditions.

## CRediT authorship contribution statement

**D. Vanella:** Conceptualization, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Writing – review & editing. **S. Guarrera:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **F. Ferlito:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G. Longo-Minnolo:** Writing – review & editing, Investigation, Data curation. **M. Milani:** Writing – review & editing, Methodology, Investigation. **G. Pappalardo:** Writing – review & editing. **E. Nicolosi:** Writing – review & editing, Resources, Methodology, Investigation, Data curation. **A.G. Giuffrida:** Investigation, Formal analysis, Data curation. **B. Torrisi:** Investigation, Data curation. **G. Las Casas:** Writing – review & editing, Investigation, Formal analysis, Data curation. **S. Consoli:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition, 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.

## Acknowledgments

This work was carried out within the framework of the European Union (NextGeneration EU) through the project MUR-PNRR SAMOTHRACE Ecosystem "SiciliAn MicronanOTecH Research And Innovation Center" (E63C22000900006) and the project PRIMA 2020 HANDYWATER "Handy tools for sustainable irrigation management in Mediterranean crops" (PCI2021-121940). Authors wish to thank Pappalardo S., Toscano S. and Vitali F. for their help during the data collection.

## Data availability

Data will be made available on request.

## References

Abad, F.J., Marín, D., Loidi, M., Miranda, C., Royo, J.B., Urrestarazu, J., Santesteban, L. G., 2019. Evaluation of the incidence of severe trimming on grapevine (Vitis vinifera L.) water consumption. Agric. Water Manag. 213, 646–653.

Abd El-Mageed, T.A., Semida, W.M., Abd El-Wahed, M.H., 2016. Effect of mulching on plant water status, soil salinity and yield of squash under summer-fall deficit irrigation in salt affected soil. Agric. Water Manag. 173, 1–12.

Abd El-Mageed, T.A., El-Samnoudi, I.M., Ibrahim, A.E.A.M., Abd El Tawwab, A.R., 2018. Compost and mulching modulates morphological, physiological responses and water use efficiency in sorghum (bicolor L. Moench) under low moisture regime. Agric. Water Manag. 208, 431–439.

Abdelraouf, R.E., El-Shawadfy, M., Fadl, A., Bakr, B., 2020. Effect of deficit irrigation strategies and organic mulching on yield, water productivity and fruit quality of navel orange under arid regions conditions. Plant Arch. 20 (1), 3505–3518.

Alhashimi, A., Al-Huqail, A.A., Hashem, M.H., Bakr, B.M., Fekry, W.M., Abdel-Aziz, H.F., et al., 2023. Using deficit irrigation strategies and organic mulches for improving yield and water productivity of mango under dry environment conditions. Agriculture 13 (7), 1415.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-guidelines for computing crop water requirements-FAO irrigation and drainage paper 56. Fao, Rome 300 (9), D05109.

Al-Qthanin, R.N., AbdAlghafar, I.M., Mahmoud, D.S., Fikry, A.M., AlEnezi, N.A., Elesawi, I.E., et al., 2024. Impact of rice straw mulching on water consumption and productivity of orange trees [Citrus sinensis (L.) Osbeck]. Agric. Water Manag. 298, 108862.

Berríos, P., Temnani, A., Zapata-García, S., Sánchez-Navarro, V., Zornoza, R., Pérez-Pastor, A., 2024a. Effect of deficit irrigation and mulching on the agronomic and physiological response of mandarin trees as strategies to cope with water scarcity in a semi-arid climate. Sci. Hortic. 324, 112572.

Berríos, P., Temnani, A., Zapata-García, S., Sánchez-Navarro, V., Zornoza, R., Pérez-Pastor, A., 2024b. Diversified cropping systems effect on the water status of mandarin trees under deficit irrigation. Sci. Hortic. 326, 112724.

Blanco, V., Kalcsits, L., 2021. Microtensiometers accurately measure stem water potential in woody perennials. Plants 10 (12), 2780.

Buesa, I., Mirás-Avalos, J.M., De Paz, J.M., Visconti, F., Sanz, F., Yeves, A., et al., 2021. Soil management in semi-arid vineyards: combined effects of organic mulching and no-tillage under different water regimes. Eur. J. Agron. 123, 126198.

Canali, S., Trinchera, A., Intrigliolo, F., Pompili, L., Nisini, L., Mocali, S., Torrisi, B., 2004. Effect of long term addition of composts and poultry manure on soil quality of citrus orchards in Southern Italy. Biol. Fertil. Soils 40 (3), 206–210.

Cassiani, G., Boaga, J., Vanella, D., Perri, M.T., Consoli, S., 2015. Monitoring and modelling of soil–plant interactions: the joint use of ERT, sap flow and eddy covariance data to characterize the volume of an orange tree root zone. Hydrol. Earth Syst. Sci. 19 (5), 2213–2225.

Choden, T., Ghaley, B.B., 2021. A portfolio of effective water and soil conservation practices for arable production systems in Europe and North Africa. Sustainability 13 (5), 2726.

Chopra, M., Koul, B.J.P.A., 2020. Comparative assessment of different types of mulching in various crops: a review. Plant Arch. 20, 1620–1626.

Consoli, S., Papa, R., 2013. Corrected surface energy balance to measure and model the evapotranspiration of irrigated orange orchards in semi-arid Mediterranean conditions. Irrig. Sci. 31, 1159–1171.

Consoli, S., O'Connell, N., Snyder, R., 2006. Estimation of evapotranspiration of different-sized navel-orange tree orchards using energy balance. J. Irrig. Drain. Eng. 132 (1), 2–8.

Consoli, S., Stagno, F., Roccuzzo, G., Cirelli, G.L., Intrigliolo, F., 2014. Sustainable management of limited water resources in a young orange orchard. Agric. Water Manag. 132, 60–68.

Demo, A.H., Tsehai, K.K., 2024. Effect of irrigation and mulch levels on growth and yield components, yield, and water use efficiency of hot pepper (capsicum annuum L) in eastern Ethiopia. Cogent Food Agric. 10 (1), 2347913.

Deng, X.P., Shan, L., Zhang, H., Turner, N.C., 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. Agric. Water Manag. 80 (1–3), 23–40.

Dimelu, M.U., Ogbonna, S.E., Enwelu, I.A., 2013. Soil conservation practices among arable crop farmers in Enugu–north agricultural zone, Nigeria: implications for climate change. J. Agric. Exten. 17 (1), 184–196.

Dugan, I., Pereira, P., Barcelo, D., Bogunovic, I., 2024. Conservation practices reverse soil degradation in Mediterranean fig orchards. Geoderma Reg. 36, e00750.

Durán, G.A., Sacristán, D., Farrús, E., Vadell, J., 2024. Towards defining soil quality of Mediterranean calcareous agricultural soils: reference values and potential core indicator set. Int. Soil Water Conserv. Res. 12 (1), 145–155.

El-Beltagi, H.S., Basit, A., Mohamed, H.I., Ali, I., Ullah, S., Kamel, E.A., et al., 2022. Mulching as a sustainable water and soil saving practice in agriculture: a review. Agronomy 12 (8), 1881.

Flexas, J., Bota, J., Cifre, J., Mariano Escalona, J., Galmés, J., Gulías, J., et al., 2004. Understanding down-regulation of photosynthesis under water stress: future prospects and searching for physiological tools for irrigation management. Ann. Appl. Biol. 144 (3), 273–283.

Gebeyhu, B., Markos, G., 2023. Assessment of soil mulching field management, and deficit irrigation effect on productivity of watermelon varieties, and AquaCrop model validation. Heliyon 9 (11).

Gonzalez Nieto, L., Huber, A., Gao, R., Biasuz, E.C., Cheng, L., Stroock, A.D., et al., 2023. Trunk water potential measured with Microtensiometers for managing water stress in "gala" apple trees. Plants 12 (9), 1912.

Guarrera, S., Vanella, D., Consoli, S., Giudice, G., Toscano, S., Ramírez-Cuesta, J.M., et al., 2024. Analysis of small-scale soil CO2 fluxes in an orange orchard under irrigation and soil conservative practices. Heliyon 10 (9).

Guo, Y.P., Zhou, H.F., Zhang, L.C., 2006. Photosynthetic characteristics and protective mechanisms against photooxidation during high temperature stress in two citrus species. Sci. Hortic. 108 (3), 260–267.

Hu, L.M., Xia, R.X., Xiao, Z.Y., Huang, R.H., Tan, M.L., Wang, M.Y., Wu, Q.S., 2007. Reduced leaf photosynthesis at midday in citrus leaves growing under field or screenhouse conditions. J. Hortic. Sci. Biotechnol. 82 (3), 387–392.

Iqbal, R., Raza, M.A.S., Valipour, M., et al., 2020. Potential agricultural and environmental benefits of mulches—a review. Bull. Natl. Res. Cent. 44, 75.

Jiménez, M.N., Fernández-Ondoño, E., Ripoll, M.Á., Castro-Rodríguez, J., Huntsinger, L., Navarro, F.B., 2016. Stones and organic mulches improve the Quercus ilex L. afforestation success under Mediterranean climatic conditions. Land Degrad. Dev. 27 (2), 357–365.

Jiménez, M.N., Pinto, J.R., Ripoll, M.A., Sánchez-Miranda, A., Navarro, F.B., 2017. Impact of straw and rock-fragment mulches on soil moisture and early growth of holm oaks in a semiarid area. Catena 152, 198–206.

Julhia, L., Belmin, R., Meynard, J.M., Pailly, O., Casabianca, F., 2019. Acidity drop and coloration in clementine: implications for fruit quality and harvesting practices. Front. Plant Sci. 10, 754.

Kader, M.A., Senge, M., Mojid, M.A., Ito, K., 2017. Recent advances in mulching materials and methods for modifying soil environment. Soil Tillage Res. 168, 155–166.

Kader, M.A., Singha, A., Begum, M.A., Jewel, A., Khan, F.H., Khan, N.I., 2019. Mulching as water-saving technique in dryland agriculture. Bull. Natl. Res. Cent. 43 (1), 1–6.

Khurshid, K.A.S.H.I.F., Iqbal, M., Arif, M.S., Nawaz, A., 2006. Effect of tillage and mulch on soil physical properties and growth of maize. Int. J. Agric. Biol. 8 (5), 593–596.

Kumar, D., Wanjari, R.H., Sinha, N.K., Nagwanshi, A., 2024. Impact of long-term application of fertilizer and manure on phosphorus and potassium balance in Vertisols of India. Indian J. Ferti. 20 (3), 262–270.

Lakso, A.N., Santiago, M., Stroock, A.D., 2022. Monitoring stem water potential with an embedded microtensiometer to inform irrigation scheduling in fruit crops. Horticulturae 8 (12), 1207.

Lepaja, L., Kullaj, E., Lepaja, K., Zajmi, A., 2015. Effects of regulated deficit irrigation, mulching and their combination on fruit diameter growth of young 'William' pears. In Proceedings. 50th Croatian and 10th International Symposium on Agriculture. Opatija. Croatia (Vol. 580, p. 584).

Li, H., Zhao, X., Gao, X., Ren, K., Wu, P., 2018. Effects of water collection and mulching combinations on water infiltration and consumption in a semiarid rainfed orchard. J. Hydrol. 558, 432–441.

Li, R., Li, Q., Pan, L., 2021. Review of organic mulching effects on soil and water loss. Arch. Agron. Soil Sci. 67 (1), 136–151.

Liao, Y., Cao, H.X., Xue, W.K., Liu, X., 2021. Effects of the combination of mulching and deficit irrigation on the soil water and heat, growth and productivity of apples. Agric. Water Manag. 243, 106482.

Lin, Q., Wang, C., Dong, W., Jiang, Q., Wang, D., Li, S., et al., 2015. Transcriptome and metabolome analyses of sugar and organic acid metabolism in Ponkan (*Citrus reticulata*) fruit during fruit maturation. Gene 554, 64–74. https://doi.org/10.1016/j.gene.2014.10.025.

Liu, Y., Wang, J., Liu, D., Li, Z., Zhang, G., Tao, Y., et al., 2014. Straw mulching reduces the harmful effects of extreme hydrological and temperature conditions in citrus orchards. PLoS One 9 (1), e87094.

Longo-Minnolo, G., Consoli, S., Vanella, D., Pappalardo, S., Guarrera, S., Manetto, G., Cerruto, E., 2024. Delineating citrus management zones using spatial interpolation and UAV-based multispectral approaches. Comput. Electron. Agric. 222, 109098.

López, R., Burgos, P., Hermoso, J.M., Hormaza, J.I., González-Fernández, J.J., 2014. Long term changes in soil properties and enzyme activities after almond shell mulching in avocado organic production. Soil Tillage Res. 143, 155–163.

Ma, L., Wang, X., Gao, Z., Youke, W., Nie, Z., Liu, X., 2019. Canopy pruning as a strategy for saving water in a dry land jujube plantation in a loess hilly region of China. Agric. Water Manag. 216, 436–443.

Machado, E.C., Schmidt, P.T., Medina, C.L., Ribeiro, R.V., 2005. Photosynthetic responses of three citrus species to environmental factors. Pesq. Agrop. Brasileira 40, 1161–1170.

Mekonen, B.M., Gelagile, D.B., 2024. Evaluating the effects of deficit irrigation and mulch type on yield and yield components of onion in Fogera, Ethiopia. J. Water Resour. Ocean Sci. 13 (1), 6–22.

Motisi, A., Rossi, F., Consoli, S., Papa, R., Minacapilli, M., Rallo, G., Cammalleri, C., D'Urso, G., 2012. Eddy covariance and sap flow measurement of energy and mass exchanges of woody crops in a Mediterranean environment. Acta Hortic. 951, 121–127.

Mwango, S.B., Msanya, B.M., Mtakwa, P.W., Kimaro, D.N., Deckers, J., Poesen, J., 2016. Effectiveness of mulching under miraba in controlling soil erosion, fertility restoration and crop yield in the Usambara Mountains. Tanzania. Land Degrad. Develop. 27 (4), 1266–1275.

Ngosong, C., Okolle, J.N., Tening, A.S., 2019. Mulching: a sustainable option to improve soil health. Soil fertility management for sustainable development 231–249.

Niswati, A., Yusnaini, S., Utomo, M., Arif, M.A.S., Haryani, S., Kaneko, N., 2018. Long-term organic mulching and no-tillage practice increase population and biomass of earthworm in sugarcane plantation. In: IOP Conference Series: Earth and Environmental Science, Vol. 215, No. 1. IOP Publishing, p. 012034.

Nobel, P.S., 1999. Physicochemical & Environmental Plant Physiology. Academic press.

Özcan, M., Gökbulak, F., Hizal, A., 2013. Exclosure effects on recovery of selected soil properties in a mixed broadleaf forest recreation site. Land Degrad. Dev. 24 (3), 266–276.

Pagay, V., 2022. Evaluating a novel microtensiometer for continuous trunk water potential measurements in field-grown irrigated grapevines. Irrig. Sci. 40 (1), 45–54.

Pappalardo, S., Consoli, S., Longo-Minnolo, G., Vanella, D., Longo, D., Guarrera, S., et al., 2023. Performance evaluation of a low-cost thermal camera for citrus water status estimation. Agric. Water Manag. 288, 108489.

Pérez-Pérez, J.G., Syvertsen, J.P., Botía, P., García-Sánchez, F., 2007. Leaf water relations and net gas exchange responses of salinized Carrizo citrange seedlings during drought stress and recovery. Ann. Bot. 100 (2), 335–345.

Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A.M., Kinengyere, A., et al., 2020. A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. Nat. Sustain. 3 (10), 809–820.

Prosdocimi, M., Jordán, A., Tarolli, P., Keesstra, S., Novara, A., Cerdà, A., 2016. The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci. Total Environ. 547, 323–330.

Puglisi, I., Nicolosi, E., Vanella, D., Lo Piero, A.R., Stagno, F., Saitta, D., et al., 2019. Physiological and biochemical responses of orange trees to different deficit irrigation regimes. Plants 8 (10), 423.

Ray, M., Biswasi, S., 2016. Impact of mulching on crop production: a review. Trends Biosci. 9, 757–767.

Ribeiro, R.V., Machado, E.C., Oliveira, R.F.D., 2004. Growth-and leaf-temperature effects on photosynthesis of sweet orange seedlings infected with Xylella fastidiosa. Plant Pathol. 53 (3), 334–340.

Ribeiro, R.V., Machado, E.C., Santos, M.G., Oliveira, R.F.D., 2009. Photosynthesis and water relations of well-watered orange plants as affected by winter and summer conditions. Photosynthetica 47, 215–222.

Saitta, D., Consoli, S., Ferlito, F., Torrisi, B., Allegra, M., Longo-Minnolo, G., et al., 2021. Adaptation of citrus orchards to deficit irrigation strategies. Agric. Water Manag. 247, 106734.

Suo, G.D., Xie, Y.S., Zhang, Y., Luo, H., 2019. Long-term effects of different surface mulching techniques on soil water and fruit yield in an apple orchard on the loess plateau of China. Sci. Hortic. 246, 643–651.

Swanson, R.H., 1962. An Instrument for Detecting Sap Movement in Woody Plants.

Tadayon, M.S., Hosseini, S.M., 2020. Effect of spread and shallow irrigation wetted area and application of organic mulch on citrus decline amelioration. Adv. Hortic. Sci. 34 (2), 213–222.

Thakur, M., Kumar, R., 2021. Mulching: Boosting crop productivity and improving soil environment in herbal plants. J. Appl. Res. Med. Aromat. Plants 20, 100287.

Toreti, A., Masante, D., Acosta Navarro, J., Bavera, D., Cammalleri, C., De Felice, M., et al., 2022. Drought in Europe July 2022 (GDO Analytic Report).

Tu, A., Xie, S., Zheng, H., Li, H., Li, Y., Mo, M., 2021. Long-term effects of living grass mulching on soil and water conservation and fruit yield of citrus orchard in South China. Agric. Water Manag. 252, 106897.

Van Dung, T., Ngoc, N.P., Hung, N.N., 2022. Impact of cover crop and mulching on soil physical properties and soil nutrients in a citrus orchard. PeerJ 10, e14170.

Vanella, D., Cassiani, G., Busato, L., Boaga, J., Barbagallo, S., Binley, A., Consoli, S., 2018. Use of small scale electrical resistivity tomography to identify soil-root interactions during deficit irrigation. J. Hydrol. 556, 310–324.

Vanella, D., Ferlito, F., Torrisi, B., Giuffrida, A., Pappalardo, S., Saitta, D., et al., 2021. Long-term monitoring of deficit irrigation regimes on citrus orchards in Sicily. *Journal of*. Agric. Eng. 52 (4).

Vanella, D., Ramírez-Cuesta, J.M., Longo-Minnolo, G., Longo, D., D'Emilio, A., Consoli, S., 2023. Identifying soil-plant interactions in a mixed-age orange orchard using electrical resistivity imaging. Plant Soil 483 (1), 181–197.

Visconti, F., Peiró, E., Pesce, S., Balugani, E., Baixauli, C., de Paz, J.M., 2024. Straw mulching increases soil health in the inter-row of citrus orchards from Mediterranean flat lands. Eur. J. Agron. 155, 127115.

Wallace, J.S., 2000. Increasing agricultural water use efficiency to meet future food production. Agric. Ecosyst. Environ. 82 (1–3), 105–119.

Wang, H., Wang, C., Zhao, X., Wang, F., 2015. Mulching increases water-use efficiency of peach production on the rainfed semiarid loess plateau of China. Agric. Water Manag. 154, 20–28.

Yaseen, R., Shafi, J., Ahmad, W., Rana, M.S., Salim, M., Qaisrani, S.A., 2014. Effect of deficit irrigation and mulch on soil physical properties, growth and yield of maize. Environ. Ecol. Res. 2 (3), 122–137.

Zhang, J., Wei, J., Guo, C.L., Tang, Q., Guo, H., 2023. The spatial distribution characteristics of the biomass residual potential in China. J. Environ. Manag. 338, 117777.