Water use of a super high density olive orchard submitted to regulated deficit irrigation in Mediterranean environment over three contrasted years

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Abstract

The measurement of transpiration at the field level is a challenging topic in crop water use research, particularly for orchards. The super high density olive orchard system is in great expansion all over the world, so these investigations are necessary to assess the trees water use under different irrigation techniques. Here, transpiration at plant and stand scales was measured using the sap flow thermal dissipation method, in an olive orchard (cv. "*Arbosana*") subjected to full and regulated deficit irrigation (RDI) with a withholding irrigation period under Mediterranean climate (southern Italy). The measurement method was used after specific calibration and correction for wound effect, azimuthal and gradient errors. Water use efficiency (WUE) and water productivity (WP) were determined over three complete growth seasons (2019–2022). The seasons were submitted to highly contrasted weathers. Measurements of stem water potential and stomatal conductance showed that the RDI trees were under mild-moderate water stress only during the withholding irrigation period. Results showed that seasonal Tr was not significantly different in the two treatments in all seasons (249 and 267 kgm^{-2}, 249 and 262 kgm^{-2}, 231 and 202 kgm^{-2} for FI and RDI in the three seasons, respectively) and that WUE was greater in RDI treatment without any impact on yield. The main conclusion is that, when the available water in the soil is limited, olive trees decrease transpiration under any atmospheric conditions, but when the water in the soil is amply available, drought conditions lead to a decrease in tree transpiration.

1. Introduction

The current increasing instabilities of precipitation regimes coupled with the steady increase of air temperature due to global warming lead to the need for adaptation to climate change for crops and cropping systems. Irrigation is a common adaptation agricultural technique, even for crops traditionally grown under rainfed conditions, hence, studies to quantify water requirements (WR) and to understand crop water use (WU) must be updated. One such crop is *Olea europaea* L. var. *sativa* Hoff. et Lk., whose WR and WU have been object of several studies in the last decades (i.a., Aganchich et al. 2007; Agüero Alcaras et al. 2016; Fernández et al. 2020), since this fruit tree crop is notably efficient to face drought, being very well adapted to arid and semiarid climates (Tognetti et al. 2009). Olive cultivation is becoming more intensive, with the widespread adoption and the strong increase in Mediterranean region of the super high density (SHD) cropping systems (Godini et al. 2011; Fraga et al. 2021). These mechanized olive groves are characterised by a density over 1,200 trees per hectare cultivated in regular rows (hedgerow orchards). Irrigated SHD orchards show positive environmental impact compared to rainfed traditional olive orchards, both in terms of carbon and water footprint (Pellegrini et al. 2016; Camposeo et al. 2022). Nevertheless, the eco-physiological responses of olive cultivars to water supply are still poorly investigated for entire periods of continuous cultivation (Chebbi et al., 2018), mainly when, in adult orchards, rejuvenation pruning is carried out to restore both trees bearing function and sizes suitable for continuous harvesting machines (Vivaldi et al. 2015; Albarracín et al. 2018).

The Mediterranean region is known to be strongly negatively affected by increases in air temperature and changes in seasonal rainfall distribution (Giorgi 2006; Espadafor et al. 2011; Rana et al. 2016; Katerji et al. 2017). In this important agricultural area, among the different proposed strategies to reduce freshwater use for SHD olive orchards, several studies demonstrated that the regulated deficit irrigation (RDI) can be a suitable strategy for reducing the excessive vigour of the species, through limiting the soil water availability (Iniesta et al. 2009; Fernández et al. 2013; Rosecrance et al. 2015). Iniesta et al. (2009) and Fernández et al. (2020) indicated that RDI allows to save 60% of irrigation water without significantly compromising the oil production and quality. Aganchich et al. (2007) and Agüero Alcaras et al. (2016) showed that typical Mediterranean olive cultivars under RDI optimized water use by decreasing stomatal conductance, stem water potential and relative water content compared to full irrigation (FI) treatment. It has also been extensively demonstrated that in SHD olive orchards the controlled water stress has little effect on oil yield and a positive effect on oil quality (i.a., Tognetti et al. 2006; García et al. 2017).

The crop water use efficiency is defined as the ratio between actual crop evapotranspiration (ET) and the amount of water supplied by irrigation and precipitation (Fernández et al. 2020; Eq. (1) in reported Table 1); from an agronomical perspective the concept of water productivity (WP) is preferable, defined as the ratio between yield and actual transpiration (Bouman 2007; Fernández et al. 2020).

To correctly evaluate the WUE or, in general, the WR of a crop, it is necessary to determine with high accuracy the crop water losses (Katerji et al. 2008), particularly complex for orchards (Rana and Katerji 2000; Scanlon and Kustas 2012; Cammalleri et al. 2013). In fact, the accurate determination of transpiration in orchards is particularly difficult when two or more treatments are compared. The micrometeorological methods generally resulted the best way to measure ET; starting from ET measured by eddy covariance technique, the transpiration can be determined by partitioning methods (Rana et al. 2018). These approaches can estimate transpiration with a suitable accuracy, but measurements must be carried out above large surfaces (Lee et al. 2004). For comparing more treatments, methods to measure transpiration at plant level are preferred, and the most widespread methods to determine it at single plant scale are based on the measurement of sap flow density (Rana and Katerji 2000). The thermal dissipation method (TDM) (Granier 1985; 1987) has been frequently used to determine actual transpiration of olive orchards in different situations (Masmoudi et al. 2011; Cammalleri et al. 2013; Agüero Alcaras et al. 2016; Conceição et al. 2017; Kokkotos et al. 2021).

Due to difficulties in accurately continuous measuring olive transpiration, the total water losses from transpiration in olive orchards on yearly and/or growth seasonal time scale are almost always unknown or affected by large uncertainties. As a result, olive orchard WUE and WP values are often limited to incomplete or reduced/restricted growth seasons (Burgess et al. 2001; Chebbi et al. 2018).

The general objective of this mid–term study was to analyse the eco-physiological behaviour of olive trees (cv. *Arbosana*) grown in an adult SHD orchard subjected to full irrigation *versus* regulated deficit irrigation, to evaluate the impact of water deficit on seasonal WUE and WP, at both the plant and canopy scale. Actual transpiration was monitored using TDM, specifically calibrated and corrected, in three complete growing seasons (2019–2020; 2020–2021; 2021–2022) including a rejuvenation pruning event, in a Mediterranean area (southern Italy). To generalize the agronomic results, relationships between transpiration and water use variables were investigated.

2. Materials and Methods

2.1. The site and the orchard

Measurements were continuously carried out from 1 March 2019 to 28 February 2022 in an olive orchard located at the University of Bari experimental farm in Valenzano, southern Italy (41° 01’ N; 16° 45’ E; 110 m a.s.l.). The soil is sandy clay (sand, 630 g kg^{-1}; silt, 160 g kg^{-1}; clay, 210 g kg^{-1}) classified as a Typic Haploxeralf (USDA) or Chromi-Cutanic Luvisol (FAO). These textural characteristics do not change with the vertical dimension. At a depth of 0.5 m, a parent rock reduces the capacity of the root systems to expand beyond this layer. The site is characterised by a typical Mediterranean climate with a long-term average (1988–2018) annual rainfall of 560 mm, two third concentrated from autumn to winter, and a long-term average annual temperature of 15.6°C.

The olive grove was planted in early summer 2006; the self-rooted trees (cv. *Arbosana*) were trained according to the central leader system and spaced 4.0 m × 1.5 m (1,667 trees ha^{-1}) with a North–South rows orientation, according to the SHD cropping system. Routine cultural nutrition, soil management, pests and diseases control practices were set up as described by Camposeo and Godini (2010). During the experimental period, the olive trees were heavily pruned in March 2020, reducing the canopy volume by 65% (from 5.3 m^3 to 2.2 m^3 per tree). This rejuvenation pruning was scheduled at the end of the 14th year after planting. However, the recovery of canopy volume was fairly quick: in fact, in the second year after hard pruning (2022) the canopy regrowth was + 90% with respect to the pruned trees values (from 2.2 to 4.2 m^3 $tree^{-1}$).

Two plots of 180 m^2 surface, 60 m apart, with 35 trees in each one, were subjected to two irrigation regimes: FI versus RDI applied throughout the pit hardening phase, when the tree is least sensitive to water deficit (Goldhamer 1999). During this phenological phase, irrigation was interrupted for about one month per season (19 July – 20 August 2019; 15 July – 18 August 2020; 14 July – 14 August 2021). Irrigation was scheduled according to the ET method, by restoring 100% of actual crop evapotranspiration (*ETc*) lost in each irrigation interval. *ETc* was calculated using Eq. (1) recommended by the FAO56 guideline as:

$$ETc = K_r K_c ET_0$$

1

where K_r is the reduction coefficient (0.86; Allen and Pereira 2009), K_c (K_{cini}=0.5, K_{cmid}=0.6, K_{cend}=0.5) is the crop coefficient, ET_0 is the reference evapotranspiration, calculated by the Penman–Monteith method (Allen et al. 1998). The plots were irrigated by a dripline equipped with 2.5 L h^{-1} emitters, 0.6 m apart.

To be consistent in the comparison of WUE values in different years, the beginning of the olive growth season for the WUE and WP calculations was considered to be March 1st because the end of the dormancy period usually falls in January – February, at least for most olive cultivars in the Mediterranean region (Oteros et. al. 2013; Aguilera et al. 2014; Fernández 2014). Thus, results will be presented for three growth seasons: first, 1 March 2019 to 29 February 2020; second, 1 March 2020 to 28 February 2021; third, 1 March 2021 to 28 February 2022 .

2.2. Weather variables and tree transpiration

Air temperature (*T*, °C) and vapour pressure deficit (*VPD*, kPa) through air relative humidity, global radiation (R_g, MJ m^{-2} s^{-1}) and precipitation (*P*, mm) were collected at a standard agrometeorological station 120 m far from the experimental field. To determine the degree of drought for each year under investigation, the standard precipitation index (*SPI*, Naresh Kumar et al. 2009) was calculated as:

$$SPI = \frac{x_i - x}{s}$$

2

with x_i yearly precipitation, *x* and *s* long-term average precipitation and standard deviation values, respectively. Value of *SPI* lower than − 1 and higher than 1 indicates dry and wet conditions, respectively.

Sap flow density, J_{s0} (g m^{-2} s^{-1}), was measured in a set of selected plants, by means of TDM (Granier 1985; 1987), by the difference in temperature (ΔT) between two probes placed in the conducting xylem of the stem. Commercial 20 mm sap flow probes (SFS2 Type M, UP, Steinfurt, Germany) were installed at 0.30–0.40 m above the ground on the north side of each tree. The probes in each sampled tree were covered by a reflecting radiation screen to protect them from rain. ΔT was continuously monitored by two data loggers (CR10X, Campbell Scientific, Utah, USA) which took measurements every 10 seconds and recorded the average values every 10 minutes. Details on the TDM measurement procedure are reported in Rana et al. (2020). Measurements were carried out in three replicate trees per irrigation treatment and averaged. Trees have been selected to be representative of each plot, considering the similar vigour, according to frequency distribution of trunk diameters and tree size of the whole plot.

The application of the TDM method requires specific local species-specific calibration and may be affected by wounds and inhomogeneities in the sapwood, both radially and azimuthally, due to wood anatomy and soil water availability (e.g., Nadezhdina et al. 2007; Fuchs et al. 2017). Therefore, a specific procedure was followed to obtain accurate transpiration values at tree scale, as summarized in Appendix 1, other details can be found in Rana et al. (2023).

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

$$Tr_{TDM} = A_p \, \overline{Tr}_{tree}$$

where Tr_{TDM} is expressed per unit of projected canopy area, i.e., kg m^{-2} or mm, with $\overline{Tr}_{tree}$ the mean of the monitored trees and A_p the cover fraction, i.e., the area occupied by the mean vertical projection of each tree (Lu et al. 2003). A_p was determined with the aid of images from the European Space Agency's Sentinel 2 satellite; with the application released by ESA, SNAP, the Coverage Fraction (FVC) was calculated (Sentinel 2 ToolBox; Level2 Products; Date Issued: 02.05.2016; Issue: V1.1. https://step.esa.int/docs/extra/ATBD_S2ToolBox_L2B_V1.1.pdf). Determinations on daily time scale was calculated by integrating transpiration at daytime (i.e., when R_g>10 W m^{-2}).

Transpirations at field level in the two irrigation treatments are indicated by Tr_{FI} and Tr_{RDI} (mm).

To estimate transpiration at seasonal and annual scales, a gap-filling strategy was developed by following Peters et al. (2010) and Rana et al. (2020). For each replicate tree, when 10-minutes J_{s0} data were sporadically missing, J_{s0} was calculated by linear interpolation; when more than 50% of daytime 10-minutes data were missing, the whole day was removed. Gaps in daily data were filled by developing a model for the relationship between J_{s0} daily mean, daily mean VPD and daily cumulated R_g. The resulting functions for the two treatments were multivariate, quadratic in VPD and linear in R_g and were built using the procedure described by Rana et al. (2020).

2.3. Physiological variables and soil water content

The olive orchard bearing shoot biomass and leaf surface in the 2020–2021 season was considerably lower than the previous season due to the hard pruning applied in the March 2020; therefore, physiological and yield measurements were not carried out during this second season. Much better bearing shoot biomass and leaf surface of the olive orchard were achieved in the following 2021–2022 season.

During two vegetative growing seasons (2019–2020 and 2021–2022), to determine the difference in the water status of the plants, especially during the RDI period, measurements of stem water potential (Ψ_s) and stomatal conductance (g_s) were carried out at midday (between 11:00 and 13:00 h solar time). These two variables were monitored from mid-June until mid-September, when the atmospheric demand in the region is elevated (Rana and Katerji 2000; Katerji et al. 2017).

Ψ_s was determined using a Scholander pressure chamber connected to a cylinder containing nitrogen. For each treatment, measurements were performed on 10 mature and fully expanded leaves (5 facing East and 5 facing West). The leaves were sealed with an aluminium bag for at least 1–2 hour to prevent transpiration and allow them to reach equilibrium with water potential in stem (Begg and Turner 1976). Subsequently, they were cut near the base of the petiole and immediately measured.

Stomatal conductance was measured on the same days as Ψ_s determination. Two healthy, well light-exposed leaf per tree (on the West and East side) selected in the middle part of the canopy were used to measure g_s for water vapour ($mol_{H2O}\ m^{-2}\ s^{-1}$) using a portable open gas-exchange system fitted with a LED light source (LI-6400XT, LI-COR, Lincoln, NE, USA). During each measurement and on each side of the canopy, light intensity was maintained constant across the two treatments by setting the LED light source at the natural irradiance detected near the leaf. For each treatment, g_s measurements were performed on the three plants where transpiration was measured by TDM and on two other trees that were similar in dimension, vigour and health state, chosen in correspondence with the soil moisture probes. The data were subjected to one-way ANOVA using SAS/STAT 9.2 software package (SAS/STAT 2010).

Soil water content in volume (θ, $m^3 m^{-3}$) was measured by capacitive probes (5TM, Decagon Devices Inc., USA). For each treatment, three points were monitored: two points along the row (θ_r) and one between the rows (θ_{ir}). At each point, two capacitive probes were installed horizontally into the soil profile and transversely to the row, at − 0.12 and − 0.37 m from the soil surface, to intercept the dynamics of θ below the dripping lines. All sensors were connected to data-loggers (Tecno.el srl, Italy) and data were transferred to a web server via GPRS mode. Integrated soil-water content on a daily basis (θ_i) was determined for the soil profile (0.5 m) by integrating the values measured at each depth, since each probe was supposed to detect the water content in a 0.25 m soil layer (Campi et al. 2019), as:

$$\int_0^{0.5} \theta_i = \theta_{\mathrm{i}(-0.12)} \cdot 0.25 + \theta_{\mathrm{i}(-0.37)} \cdot 0.25$$

4

The θ_i measurements from the three points were pooled to obtain a single average value for each treatment as (Searles et al. 2009; Autovino et al. 2018):

$$\theta = 0.7\ \bar{\theta}_r + 0.3\theta_{ir}$$

5

Where $\bar{\theta}_r$ is the mean of the two θ measured along the rows.

Soil water availability was described through the relative extractable water (*REW*, unitless) calculated using the average soil water content across positions around the tree and soil layers as

$$REW = \frac{\theta - \theta_{min}}{\theta_{max} - \theta_{min}}$$

6

where θ_{min} is the minimum soil water content observed during the experiment and θ_{max} is the maximum soil water content in the area (e.g., at field capacity).

2.4. Water stress and water use efficiency at canopy level

Water stress index (*CWSI*, unitless) at canopy level can be written as an explicit function of the actual and potential transpirations (e.g., Jackson et al. 1981; Stanghellini and De Lorenzi 1994; Rana et al. 2020) as:

$$CWSI = 1 - \frac{Tr}{Tr_p}$$

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where *Tr* is the transpiration measured by TDM as above described and Tr_p is the potential transpiration calculated by a Penman–Monteith method approach (Appendix 2). *CSWI* ranges between 0 (no stress, with $Tr = Tr_p$) and 1 (stress, with $Tr = 0$).

According to Fernández et al. (2020), SHD olive orchard water use efficiency and productivity at seasonal scale can be calculated as:

$$WUE = \frac{Tr}{P + I}$$

8a

$$WP = \frac{yield}{Tr}$$

8b

where *Tr* is total seasonal transpiration in kg_{H2O} m^{-2}, *P* and *I* are total precipitations and water supplied by irrigation in mm (kg_{H2O} m^{-2}), yield is the marketable yield produced (kg m^{-2}). Yield values were determined in first and third seasons (2019–2020 and in 2021–2022) as mean of olives production measured on the same five trees used for physiological measurements. Harvesting times were yearly assessed by using ripening indices as reported by Camposeo et al. (2013).

3. Results and Discussion

3.1. The weather and the actual transpiration

The seasonal time evolution of main agrometeorological parameters (*T*, *VPD*, R_g and *P*) during the three growth seasons is depicted in Fig. 1, while Table 1 reports the seasonal values. The three seasons were characterized by very different weather, including extreme water scarcity conditions during the 2019 and 2021 drought summers and the exceptionally rainy summer in 2020, characterized by few events of high rain intensity. 31 and 23 mm of rain fell in a few minutes on 5 and 7 August 2020, respectively; similarly, more than 100 mm of rain fell in three days between 21 and 23 September 2020. The yearly mean air temperature was 18.1, 16.4 and 17.0°C in 2019, 2020 and 2021, respectively, and was always warmer than in the past (15.6°C). *T* was well above the mean for the period in June 2019; an intense heat wave crossed the experimental field during summer 2021, between the end of July and the beginning of August, when irrigation was withheld in the RDI plot. In summer 2022 mean *T* reached 34°C, and peaks of 42°C were observed during the day. In these periods, *VPD* also reached high values, unusual for the region.

The *SPI* was equal to -1.61, + 0.96 and − 1.45 for years 2019, 2020 and 2021, respectively, indicating that 2020 was extremely wet, while 2019 and 2020 were very dry, according to the cumulated precipitation.

The greatly contrasted weather of the three seasons confirmed the strong variability following climate change in this Mediterranean area (Rana et al. 2016; Katerji et al. 2017).

The actual transpiration trends in the three growth seasons at daily scale are shown in Fig. 2, for FI and RDI treatments. In the three seasons *Tr* values increased from March until June, then slowly decreased until November, after that *Tr* remained quite constant and showed very low values until the end of January, when *Tr* values showed a tendency to increase again. *Tr* ranged between 0 and 2.73 mm for FI and between 0 and 1.95 mm for RDI, the same order as the values reported in other similar studies in the Mediterranean region (Tognetti et al. 2009; Camalleri et al. 2013; Chebbi et al. 2018).

Following an ANOVA, in all growing seasons, *Tr* daily values for the two treatments were significantly not different ($p < 0.01$). Moving from FI to RDI, daily *Tr* was 0.68 and 0.73 mm, 0.68 and 0.72 mm, and 0.63 and 0.55 mm, in the first, second and third season, respectively, despite the RDI orchard received 124, 68 and 170 mm less irrigation water in the three seasons, respectively (Table 2). However, Fig. 2 clearly shows that olive trees under RDI treatment transpired less than FI during the period when irrigation was withheld in the first and in the third season, while the *Tr* values in FI and in RDI were quite similar in second season 2020–2021 because of the rainy summer (see Fig. 1) which effectively annulled the differentiation between the two irrigation regimes. Moreover, the reduction of *Tr* values due to the RDI regime appeared about 10–15 days after the irrigation was stopped. This feature supports the results of Agüero Alcaras et al. (2016) and Corell et al. (2022), who found that transpiration in olive trees did not start to decline until much later than the water withholding.

Total transpirations were quite similar for both irrigation treatments in the three seasons (Table 2).The lowest total transpiration in the 2021–2022 growth season can be attributed to the extreme dry and warm weather conditions during spring and summer 2021 (see Fig. 1); indeed, in hedgerow olive orchards, *Tr* values show a diurnal relation with *VPD*, with a high logarithmic relationship between *Tr* and *VPD* (Zuñiga et al. 2014), which likely induced a reduction of stomatal conductance.

The well-known relationships between the measured *Tr* and weather variables drining crop transpiration (i.e., *VPD* and R_g; Katerji and Rana 2011) showed the usual standard differences in the olive trees' responses to daily weather conditions in the three experimental seasons (data not shown, see for example Tognetti et al. 2009). *Tr* is significantly ($p < 0.001$) related to *VPD* by logarithmic functions in any growth season. While the linear relationships between *Tr* and R_g are significant ($p < 0.01$) in any season, indicating that any solar saturation value is advisable in this type of olive orchard.

Table 1
Summary of vapour pressure deficit (VPD), air temperature (T), global radiation (R_g) and rain in the three growth seasons.

Growth season	VPD (kPa)		T (°C)		Rg (MJ m^{-2} d^{-1})		Rain (mm)
	range	Mean ± sd	range	Mean ± sd	range	Mean ± sd	
2019–2020	0.1–2.8	0.8 ± 0.6	0.0-27.7	14.6 ± 7.8	5.6–30.5	17.4 ± 6.3	221
2020–2021	0.0-2.3	0.7 ± 0.5	0.0–30.0	15.6 ± 8.6	2.4–29.1	16.2 ± 6.4	695
2021–2022	0.0-4.1	1.1 ± 0.8	0.0-30.3	18.8 ± 7.9	3.0–34.0	17.0 ± 6.6	288

3.2. Water use – soil and canopy scale

The *REW* trends at daily scale in the three growth seasons are shown in Fig. 3, together with irrigations and precipitations, for both treatments. Gaps of values are due to malfunctioning of soil moisture probes. In both treatments, *REW* increased immediately after water supply or rainfall and, conversely, decreased rapidly due to plant transpiration. In the RDI treatment, soil water recovery after the irrigation interruption period occurred on the same day of watering (Fernández 2014).

According to irrigation scheduling, before and after irrigation withholding period, water supply results the same in FI and in RDI. During these periods, FI and RDI trends are almost superimposable. Minor differences are due to the different total water availability in the two plots (0.105 and 0.122 m^3 m^{-3} for FI and RDI, respectively) and to different minimum value of θ in the two soils (0.119 and 0.125 m^3 m^{-3} for FI and RDI, respectively).

Several studies have indicated that when *REW* value fall below 0.4 plants experience increasing water stress, particularly the woody species in arid and semiarid Mediterranean conditions (Bréda et al. 1995; Fernández et al. 1997; Grossiord et al. 2015). In the FI treatment, *REW* values ranged from 0.2 to 0.8 for most of the irrigation season, indicating soil water conditions far from the field capacity, except for short periods immediately after frequent irrigations and/or heavy precipitations. In the RDI treatment, *REW* values decreased when irrigation supply was reduced. The minimum *REW* values in RDI treatment were 0.00, 0.17 and 0.20 in the first, second and third season, respectively.

During the RDI period, *REW* values fell below 0.4 for 8 and 31 days in the first season, 19 and 26 days in the second season and 4 and 30 days in the third season in the FI and RDI treatments, respectively.

In season 2020–2021, *REW* values lower than 0.4 were observed starting in spring: from 4 April 4 until 26 May, values below 0.4 were recorded for 52 and 53 days in the FI and RDI treatments, respectively. Based on these results, it appears that the irrigation in the second season 2020–2021 should have started a month earlier (in April instead of May), and the low *Tr* values during these months could be attributed to the decreased water availability in the soil.

Tr was hardly increasing in spring (see Fig. 2) because the phenological phases in this period (woody buds breaking and shooting) involve intense water uptake by roots. On the contrary, the slight reduction in *REW* values in the fall did not seem to affect *Tr* because similar values were observed in 2020 when *REW* values were much higher than 0.4; in this case *Tr* reduction could be due to the physiological olive tree rest, starting from fruit ripening, inducted by low temperatures (López-Bernal et al. 2020).

Due to the mathematical expression used to calculate *CWSI* (see Eq. (7)), steep oscillations in *CWSI* values were observed when *Tr* and Tr_{pot} values were both close to zero, even though these oscillations did not have any physical significance. Therefore, for clarity, the daily *CWSI* is shown only for the dry months of July and August, during the RDI period in the three growing seasons (Fig. 4).

Focusing on the RDI period, during the first season, the mean *CWSI* value was quite higher for RDI (0.39) than FI (0.20). However, the CWSI values for RDI were generally far from 1, indicating that this olive orchard was never under severe water stress, even when the easily available water, as determined by *REW*, fell below the stress threshold stress value (0.4), especially in the first season. During the second season, the RDI crop was in a water condition closer to that of FI crop (mean *CWSI* equal to 0.21 and 0.26 for FI and RDI, respectively). These results contrast with those reported by Egea et al. (2016) and Agam et al. (2013) who found clearly differentiated *CWSI* values in FI and a similar RDI treatment in a SHD olive orchard in the Mediterranean region, although their *CWSI* was determined by infrared thermometry. Moreover, the mean *CWSI* values at growth seasonal level were quite similar for the FI and RDI treatments (0.51 and 0.58, 0.54 and 0.63, 0.72 and 0.67 in the first, second and third season, respectively), indicating that the water behaviour of this SHD olive orchard is less linked to soil water content and more to atmospheric conditions as expressed by potential transpiration. This insight was supported by the results of Tognetti et al. (2004) and Rana et al. (2023), who found that the large root system of olive trees might buffer reductions in relative extractable water, thus maintaining sufficient water supply with minor consequences on plant water relations.

If the attention is focused on the RDI treatment during the irrigation interruption period, a relationship between *REW* and *CWSI* can be detected (Fig. 5) during the period July - August. *CWSI* and *REW* are well related by statistically significant functions ($p < 0.01$) in the first and third seasons, while the correlation is not statistically significant in the second season, when rainfalls affected the irrigation withholding period. Nevertheless, while in the first season *CWSI* values were high at a *REW* threshold value of 0.4 indicating crop stress, however in the third season *CWSI* values were high only at *REW* threshold values below 0.5–0.6. In this case, it seems that the high evaporative demand of the atmosphere (very high *VPD* and *T*, see Fig. 1) prevails over the water availability of the soil in adapting the olive trees to serve water (Chirino et al. 2011), addressing the plants to decrease the transpiration by stomatal regulation (Fernández et al. 1997; Fernández 2014; Rana et al. 2023).

3.3. Water use – plant scale

Midday water potential and stomatal conductance from mid-June to mid-September are reported in Fig. 6.

In the first season, 2019–2020, Ψ_s for the FI treatment remained almost constant (-1.09 ± 0.12 MPa) throughout the period, while it progressively decreased in the RDI treatment during the irrigation interruption period, reaching the lowest value (-2.21 MPa) at the end of July. In the first three days of 2019–2020 season, as expected, no significant differences in g_s values were found between the treatments. On 31 July and 20 August, when the irrigation was interrupted in RDI, g_s was significantly higher in FI than RDI ($p < 0.004$ and $p < 0.0001$ on 31 July and 20 August, respectively). The RDI treatment showed an increase in g_s when irrigation was resumed, demonstrating a full recovery and even surpassing the FI treatment on 11 September ($p < 0.004$), in accord with Fernández et al. (1997). In the first growing season, g_s for FI treatment roughly increased from June to September, reaching a maximum value of 0.28 $mol_{H2O}\ m^{-2}\ s^{-1}$; g_s for RDI treatment decreased during the irrigation interruption period, reaching a minimum value of 0.07 $mol_{H2O}\ m^{-2}s^{-1}$ in correspondence of the lowest Ψ_s values in mid-August.

In the third season Ψ_s for the FI gradually and slowly increased from mid-July, being in mean equal to -1.32±0.19 MPa; Ψ_s for RDI treatment decreased during the irrigation interruption period until the minimum value of -2.16 MPa at the beginning of August. In the third season Ψ_s mean value of FI treatment was quite close to the mean value of RDI treatment (-1.35±0.19 MPa) indicating that the two plots were in closer water conditions than in the first season. In the third season, in general, the trend of g_s for the FI and RDI treatments was non-statistically different, indicating similar crop water status, as also reported by the water potential. During the RDI period, stomatal conductance in FI was significantly higher than RDI (4 August, $p < 0.0001$). In the summer of 2021–2022 season, the lowest g_s values in FI and RDI were reached at the beginning of September (0.06 and 0.07 $mol_{H2O}\ m^{-2}\ s^{-1}$, respectively) when the *REW* dropped dramatically, *T* and *VPD* were still high, affecting the stomata regulation as indicated by Zhang et al. (2019).

These results suggest that stomatal conductance measured at the leaf level could be used as water stress indicator (Hernandez-Santana et al. 2016) in *Arbosana* olive cultivar. Both eco-physiological parameters indicate that the olive tree has a good ability to recover from water stress when soil moisture is replenished. Indeed, depending on the severity of the water stress, until − 2.5 MPa of Ψ_s olive eco-physiological recovery occurs within 2–3 days; between − 2.4 and − 4.0 MPa recovery occurs within 20–30 days; it never occurs over − 4.0 MPa (see Angelopoulos et al. 1996; Fernández et al., 1997; Alegre et al. 1999; Moriana et al. 2002; Sofo et al. 2008; Iniesta et al. 2009).

The relationship between stem water potential and canopy conductance is shown in Fig. 7, which includes all available data. This relationship indicates that the RDI orchard was always in a mild-moderate water stress (Ahumada-Orellana et al. 2019). Under these conditions, this SHD olive orchard adjust its water consumption as soon as the thermodynamic conditions of the atmosphere become such as to require a costly increase in transpiration, even at water contents far from the wilting point (0.183 m^3m^{-3}). In this way the olive trees avoid reaching high water potential values that produce a loss of hydraulic conductivity (Tognetti et al. 2009), thus preventing irreversible damage (Vilagrosa et al. 2003; Hernandez-Santana et al. 2016).

3.4. Water use efficiency and water productivity

The WUE and WP values for the three experimental seasons are reported in Table 2: the RDI treatment presents higher WUE and WP values than FI treatment. In 2020–2021 season, the olive orchard did not yield due to necessary hard rejuvenation pruning.

The RDI WUE, which used an average of 83% of the FI water, was 16% higher than the WUE for the FI treatment. The results are consistent with the finding of Fernández et al. (2013), who observed increases in WUE of 20% and 32% for 60% and 30% RDI, respectively, for cv. *Arbequina* in Spain. Padilla-Díaz et al. (2018) also found an increase of 32% in WUE for a 45% RDI treatment with respect to the FI treatment in the same site and olive cultivar. Finally, it is difficult to compare the WP values in this study to those of other investigations in similar hedgerow olive orchards because whole-season measurements of actual transpiration, as were conducted in this study, are rare (Chebbi et al. 2018).

Table 2
Yield, irrigation, transpiration (Tr), water productivity (WP) and crop water use efficiency (WUE) of full (FI) and regulated deficit (RDI) irrigation in the three growth seasons.

Growth season	FI					RDI				
	Yield (kg m^{-2})	Irrigation (kg m^{-2})	Tr (kg m^{-2})	WP (g kg^{-1})	WUE	Yield (kg m^{-2})	Irrigation (kg m^{-2})	Tr (kg m^{-2})	WP (g kg^{-1})	WUE
2019–2020	0.67 ± 0.11	499	249	1.34	0.35	0.62 ± 0.12	375	267	1.64	0.45
2020–2021		306	249		0.25		238	262		0.28
2021–2022	0.41 ± .16	509	231	0.80	0.29	0.51 ± 0.14	339	202	1.50	0.32

4. Conclusions

In this study, the cumulated value of water transpired at growth seasonal scale was compared for a SHD olive orchard under full irrigation *versus* regulated deficit irrigation. The trial was carried out in a Mediterranean site with one the most widely cultivated olive genotype in SHD olive orchards (cv. *Arbosana*).

At the canopy scale, the results showed that olive trees in this cropping system are very sensitive to *VPD*, especially when the soil water availability decreases. The high evaporative demand of the atmosphere prevailed over the water availability of the soil, leading the olive trees to reduce transpiration through stomatal regulation. Moreover, the relative extractable water value of 0.4, usually indicated as stress threshold value, for olive SHD orchard was not an absolute value, but depended on the atmospheric conditions, i.e. its water demand.

At the plant scale, during RDI period, the SHD olive trees adjusted them stomatal conductance as soon as stem water potential was threatened, avoiding high water potential values that could lead to irreversible damage through a loss of hydraulic conductivity. Stomatal conductance at leaf level could be used as water stress indicator due to its strong relationship with stem water potential.

The results of this study indicated that the olive tree has good water recovery ability in SHD orchards under RDI, with stem water potential never exceeding − 2.5 MPa and eco-physiological recovery occurring within a few days after water supply is restored.

Finally, RDI regime applied to SHD olive orchard reduced water requirements, did not affect olive yields and improved water use efficiencies. The 38% reduction in irrigation water applied to the RDI, compared to FI, had a weak or null effect on the physiological response of olive trees at seasonal time scale. Therefore, RDI is a water-saving technique that should further increase the environmental sustainability of SHD olive orchards with well-adapted cultivars. Finally, these are the first eco-physiological data that took into account the rejuvenation pruning of an adult SHD olive orchard, supplying more insights on the behaviour of the well-adapted cultivars.

Declarations

Author Declarations

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Conflicts of interest/Competing interests

The authors, Rossana Monica Ferrara, Maria Roberta Bruno, Pasquale Campi, Salvatore Camposeo, Gabriele De Carolis, Liliana Gaeta, Nicola Martinelli, Marcello Mastrorilli, Anna Francesca Modugno, Teresa Mongelli, Mariagrazia Piarulli, Sergio Ruggieri, Gianfranco Rana declare no conflict of interest.

Ethics approval/declarations

Not applicable

Data are available under request to the authors. Pictures and description of used equipment are available under request.

Code availability

Not applicable.

Authors' contributions.

Conceptualization: G.R.; Methodology: G.R., R.M.F.; Investigation: G.R., M.R.B, P.C., L.G., S.R., G.D., N.M., A.F.M., T.M., M.P.; Formal analysis: G.R., R.M.F., C.S.; Writing - original draft preparation: G.R., R.M.F.; Writing - review and editing: G.R., R.M.F., S.C.; Funding acquisition: M.M.

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Figures

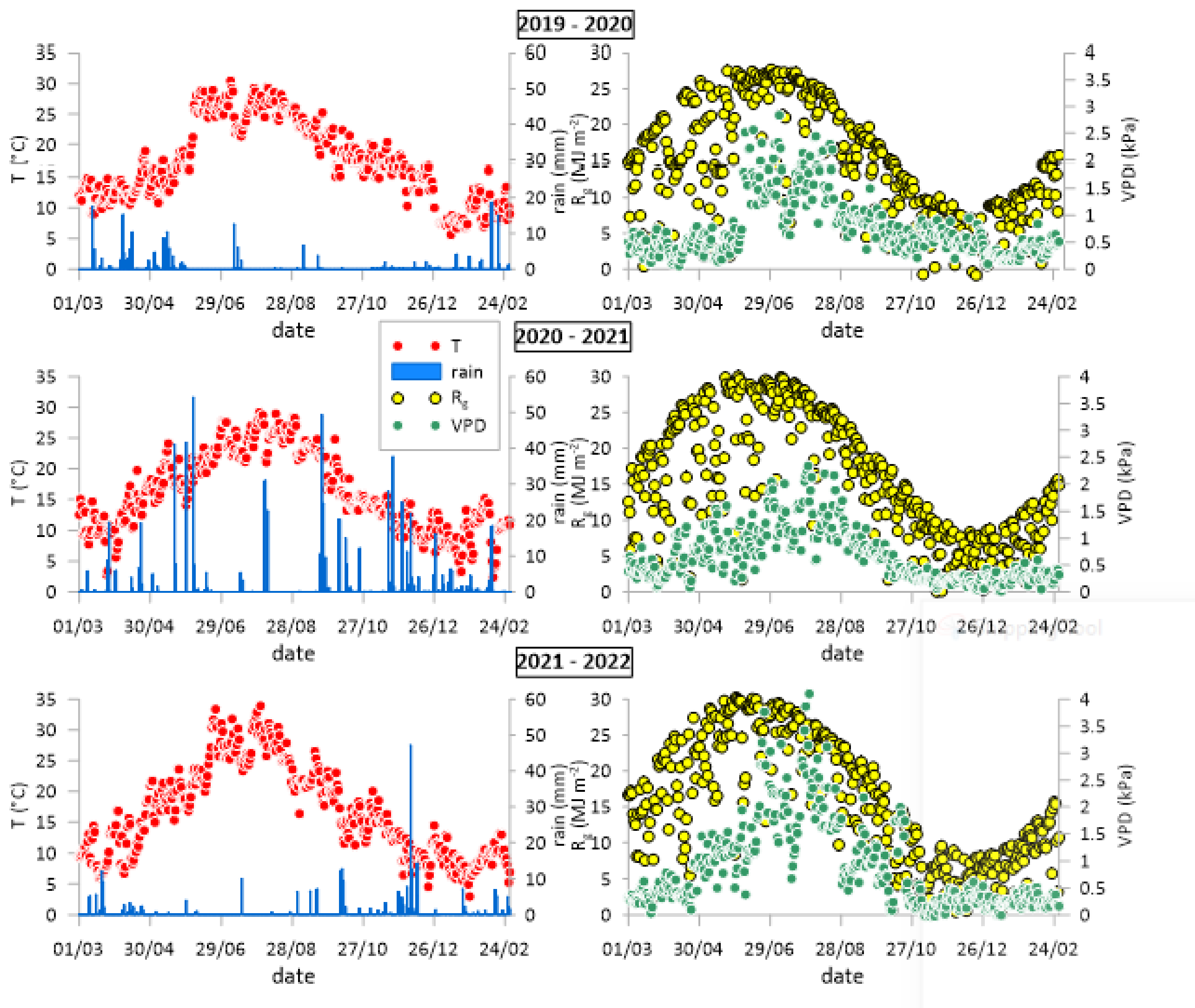

Figure 1

Mean air temperature (T), sum rainfall (rain), sum global radiation (R_g) and mean (VPD) at daily scale in the three growth seasons.

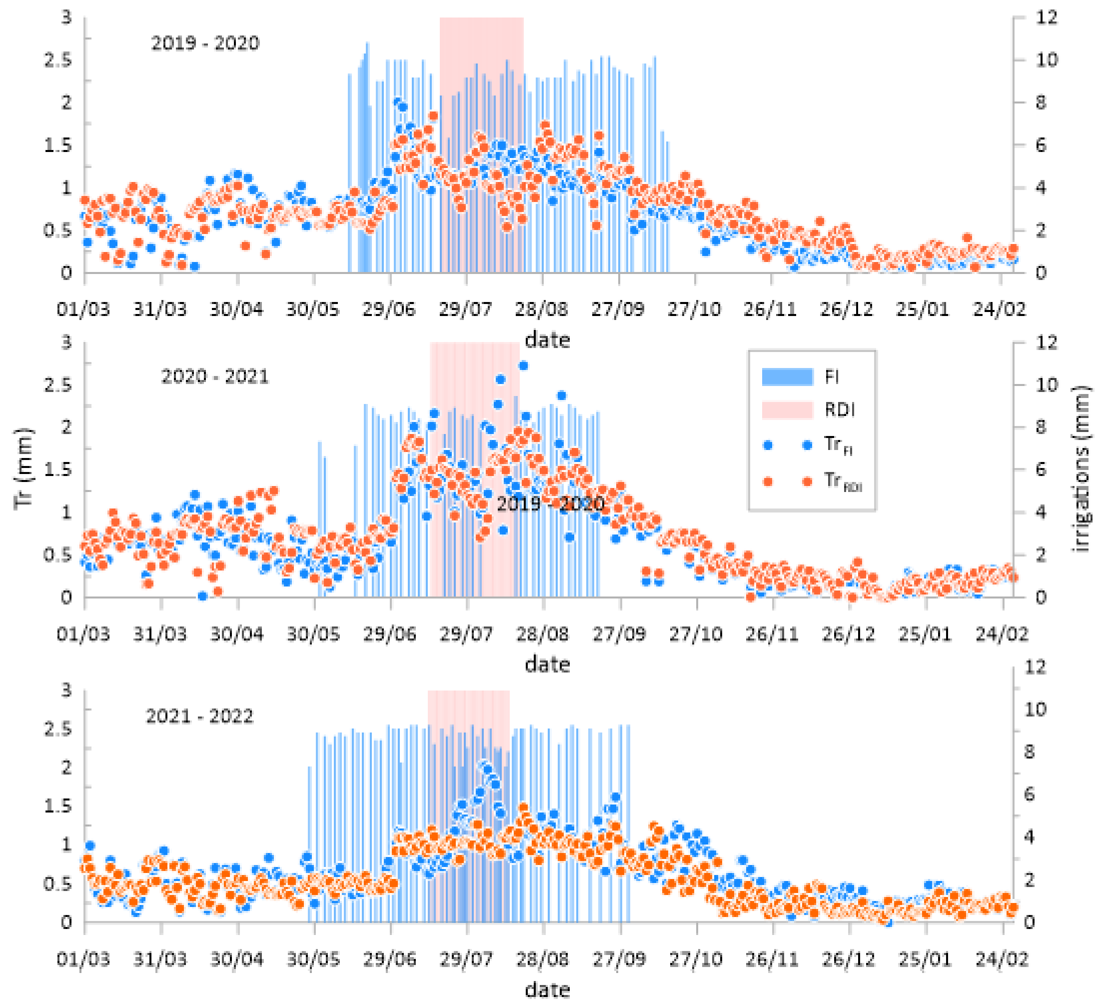

Figure 2

Trends of actual transpiration (Tr) at daily scale, measured in the two treatments full irrigation (FI) and regulated deficit irrigation (RDI) during the three growth seasons, together with irrigation values. The RDI period (irrigation withholding period) is indicated by light pink.

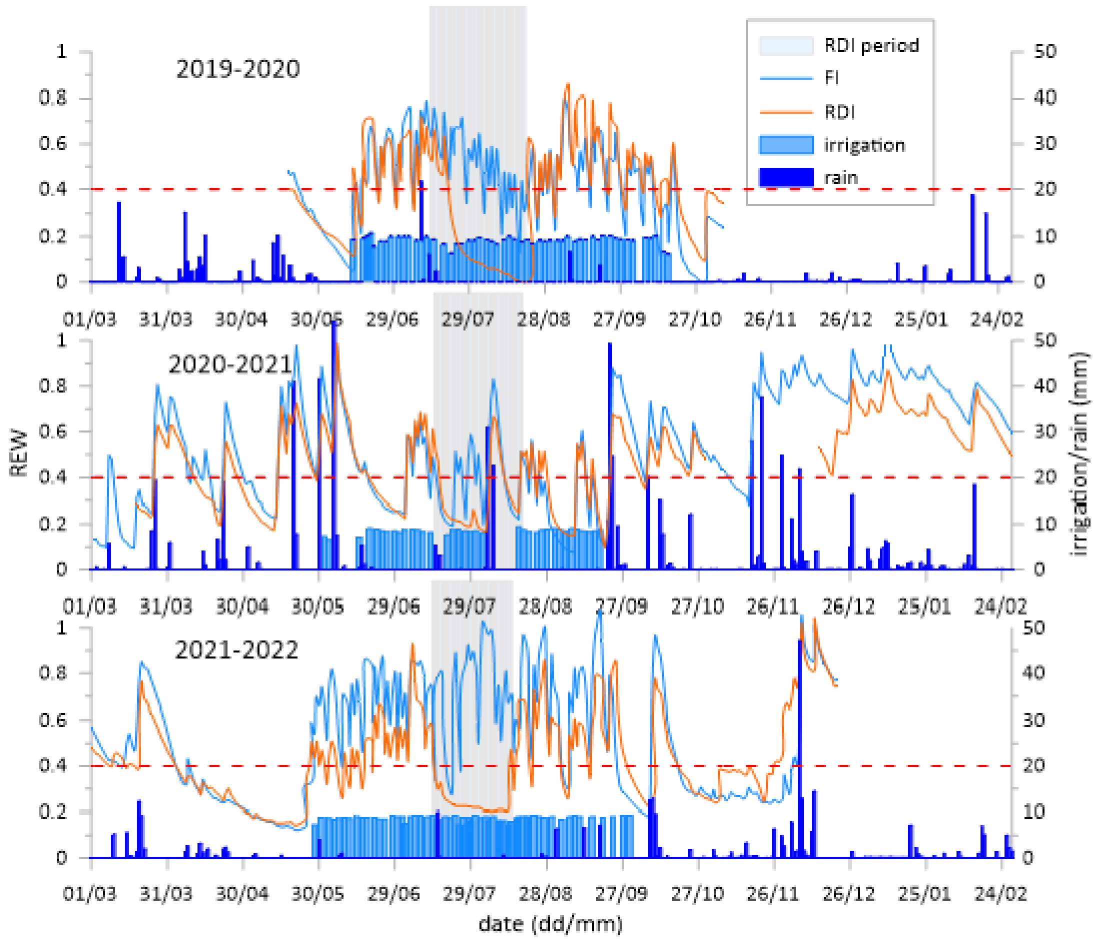

Figure 3

The relative extractable water (REW, unitless) daily trend in the three growth seasons in both full irrigation (FI) and regulated deficit irrigation (RDI) treatments; irrigation and precipitations are also graphed. The horizontal dashed red line at REW = 0.4 indicates threshold for water stress by literature (Bréda et al., 1995; Fernández et al., 1997; Grossiord et al., 2015).

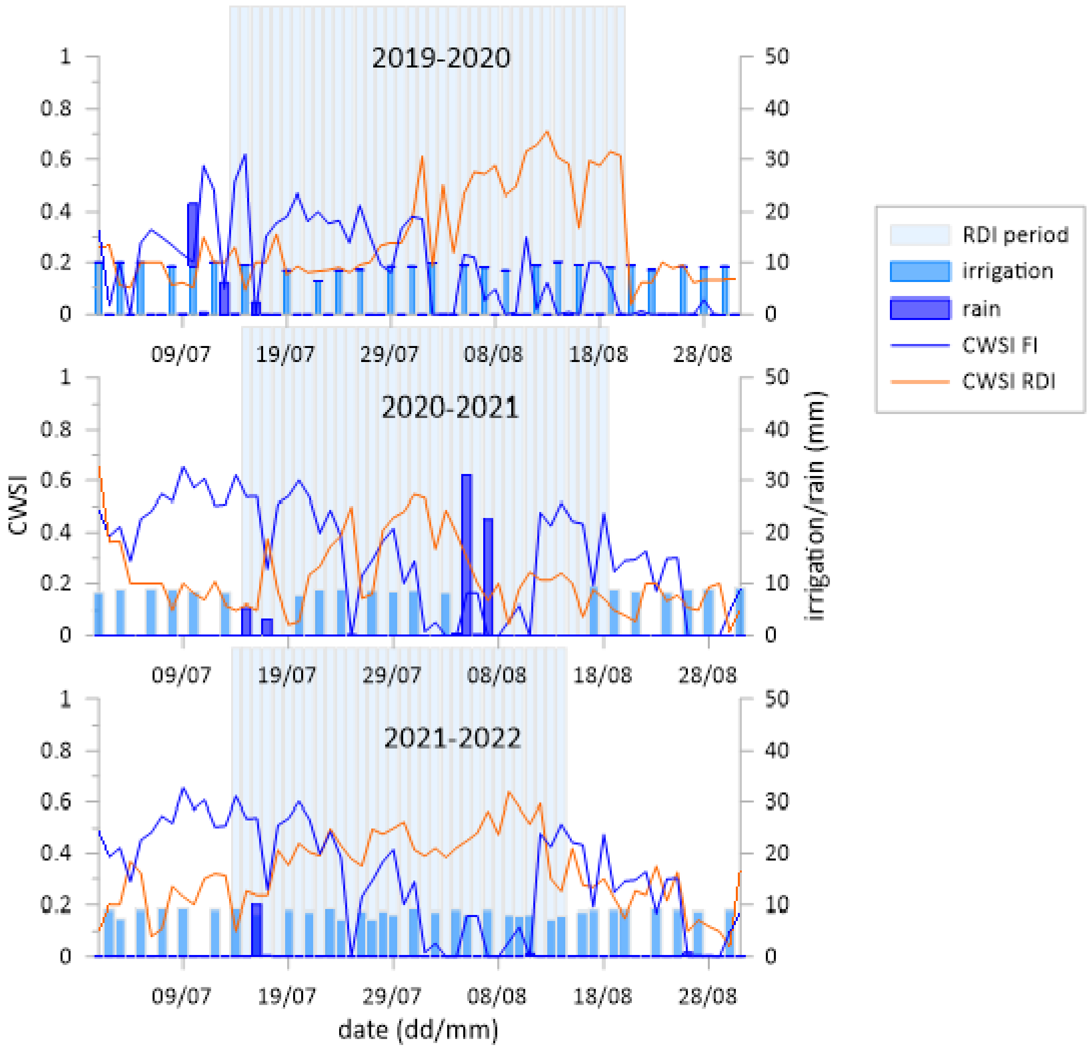

Figure 4

The crop water stress index (CWSI) trend during July and August in the three growth seasons in both full irrigation (FI) and regulated deficit irrigation (RDI) treatments; irrigation and precipitations are also graphed.

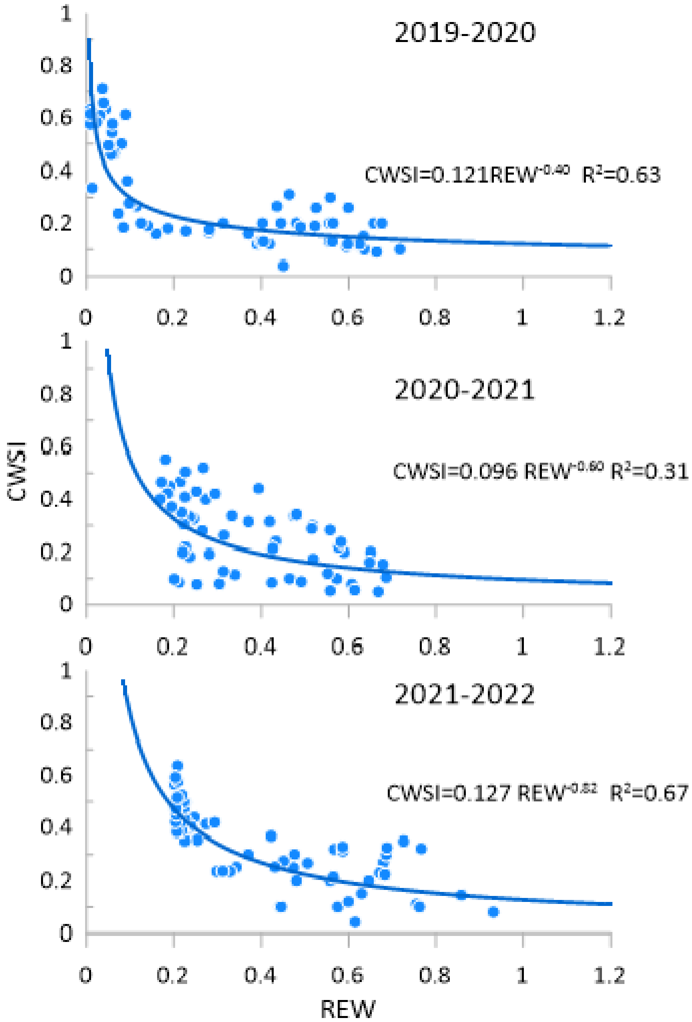

Figure 5

Relationships between crop water stress index (CWSI) and relative extractable water (REW) in the period July-August for the regulated deficit irrigation (RDI) treatment in the three growth seasons.

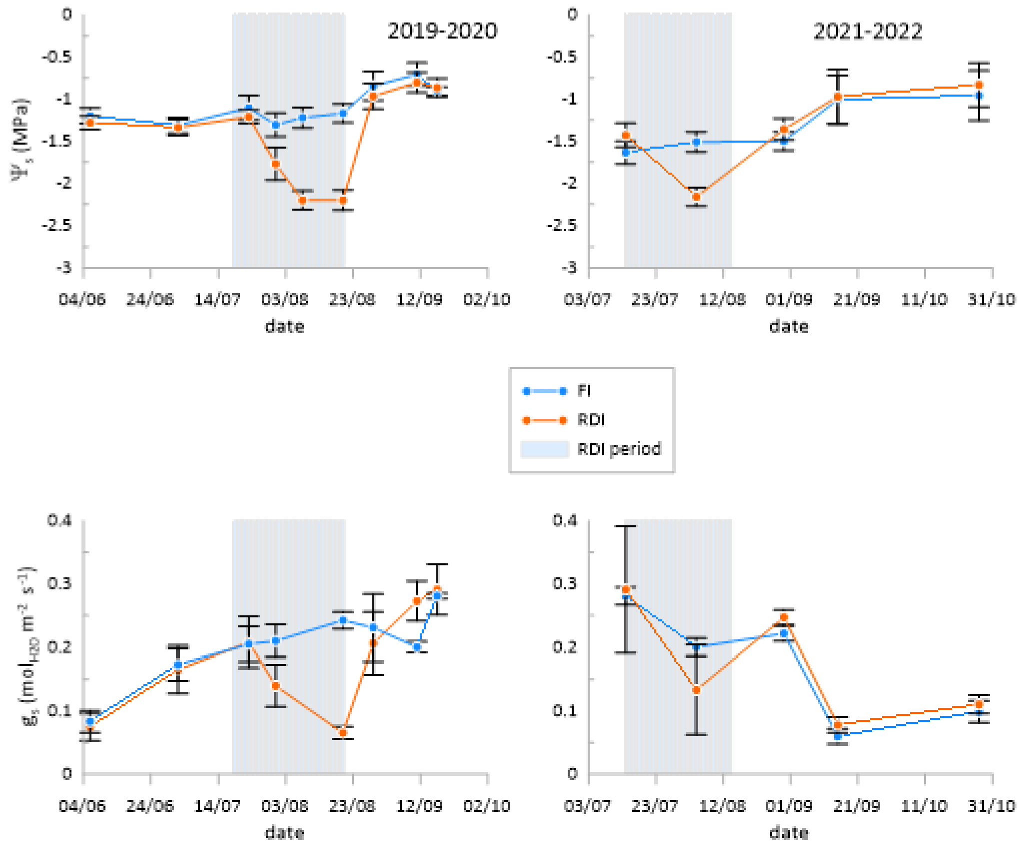

Figure 6

Stem water potential (Y_s) and stomatal conductance (g_s) measured at midday in the first (2019-2020) and third season (2021-2022) in full irrigation (FI) and regulated deficit irrigation (RDI) treatments.

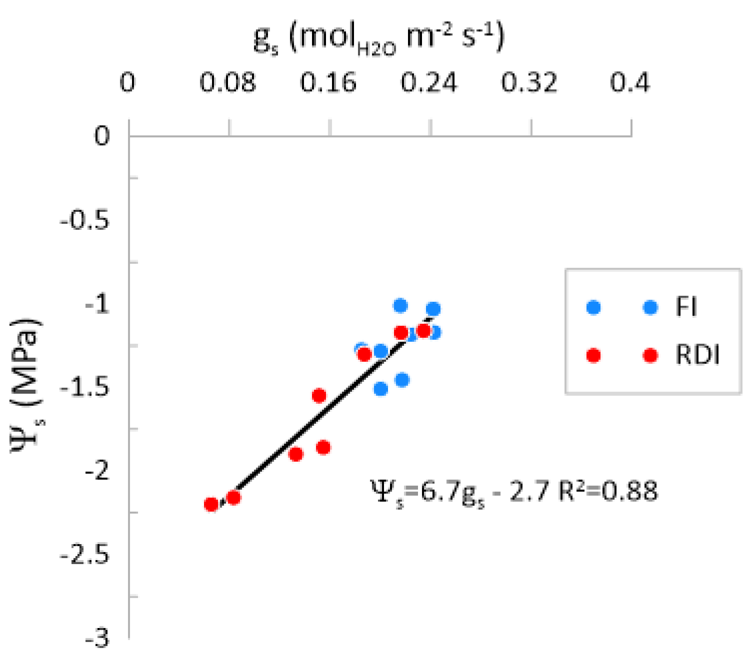

Figure 7

Relationship between stem water potential (Y_s) and stomatal conductance (g_s) measured at midday in full irrigation (FI) and regulated deficit irrigation (RDI) treatments; all available measurements are plotted.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendix.docx