International Journal of Fruit Science

ISSN: 1553-8362 (Print) 1553-8621 (Online) Journal homepage: www.tandfonline.com/journals/wsfr20

Eco-Physiological and Growth Behavior of Two Italian Olive Cultivars Under Two Soil Management Practices

Carmen Arlotta, Giuseppina Las Casas, Alessio Giuffrida, Biagio Torrisi, Elisabetta Nicolosi, Enrico Maria Lodolini, Margherita Amenta & Filippo Ferlito

To cite this article: Carmen Arlotta, Giuseppina Las Casas, Alessio Giuffrida, Biagio Torrisi, Elisabetta Nicolosi, Enrico Maria Lodolini, Margherita Amenta & Filippo Ferlito (2026) Eco-Physiological and Growth Behavior of Two Italian Olive Cultivars Under Two Soil Management Practices, International Journal of Fruit Science, 26:1, 2620206, DOI: 10.1080/15538362.2026.2620206

To link to this article: https://doi.org/10.1080/15538362.2026.2620206

INTERNATIONAL JOURNAL OF FRUIT SCIENCE
2026, VOL. 26, NO. 1, 2620206
https://doi.org/10.1080/15538362.2026.2620206

RESEARCH ARTICLE

OPEN ACCESS

Eco-Physiological and Growth Behavior of Two Italian Olive Cultivars Under Two Soil Management Practices

Carmen Arlotta[a*], Giuseppina Las Casas[a], Alessio Giuffrida[a,b], Biagio Torrisi[a], Elisabetta Nicolosi[b], Enrico Maria Lodolini[c], Margherita Amenta[a], and Filippo Ferlito[d*]

[a]Council for Agricultural Research and Economics, Research Centre for Olive, Fruit and Citrus Crops, Acireale, Italy; [b]Department of Agriculture, Food and Environment, University of Catania, Catania, Italy; [c]Department of Agricultural, Food and Environmental Sciences, Polytechnic University of Marche, Ancona, Italy; [d]Department of Veterinary Sciences, University of Messina, Messina, Italy

ABSTRACT

Conservative Agriculture (CA) encompasses various agronomic practices aiming at enhancing the sustainability of agricultural systems. In terms of soil management, CA involves strategies such as cover crops, zero and minimum tillage, intercropping, and different mulching systems. This study, conducted over three years (2021, 2022 and 2023), was focused on agroecological practices in a young organic olive orchard in the Mediterranean area. The experiment involved two Sicilian double-aptitude olive cultivars, "Nocellara del Belice" and "Nocellara Etnea," planted in blocks with two soil management strategies: "Tillage" and "Zero Tillage." Physiological assessments were conducted on olive leaves, encompassing measurements of stem water potential, leaf gas exchange, and fluorescence. Tree morphological characteristics were examined, including trunk cross-sectional area, plant growth, and canopy volume. The analysis of physiological parameters highlighted the importance of the year and of the day, with climate change having a significant impact on tree well-being. Differences have emerged between cultivars, while concerning soil management, the main parameters differentiate water potential, resulting in less negative effects under Zero Tillage practice. The trees maintained moderate water stress levels during the summer seasons. This research contributes valuable insights into the potential benefits of agroecological practices in olive orchards, emphasizing their role in sustainable agriculture.

KEYWORDS

Mediterranean basin; water stress; gas exchange; conventional tillage; zero tillage; olive growth

Introduction

Spreading on 9.5 million ha (Michalopoulos et al., 2020), olive (*Olea europaea* L.) is among the oldest domesticated species and one of the best-adapted crops in marginal areas with specific climatic conditions well suited to its cultivation, which has great social and economic importance in the Mediterranean region. Even if olive is well-known to be highly adaptable to dry spells and drought and to achieve an acceptable yield under dry farming (Trentacoste et al., 2018), the Mediterranean area might be particularly affected by climate change in the next years, with extensive impacts on ecosystems, tree physiology and productions (Ferlito et al., 2021; Tanasijevic et al., 2014). Among the climate change effects, the increase of drought areas and

---

CONTACT Giuseppina Las Casas giuseppina.lascasas@crea.gov.it Council for Agricultural Research and Economics, Research Centre for Olive, Fruit and Citrus Crops, Acireale 95024, Italy

*These authors contributed equally to this work.

Supplemental data for this article can be accessed online at https://doi.org/10.1080/15538362.2026.2620206 the reduction in water availability are the most worrying (Boussadia et al., 2023). As consequence of the lack of water, the considerable reduction in physiological performance have been reported (Boughalleb and Hajlaoui, 2011; Bacelar et al., 2007; Ben Abdallah et al., 2018). Nowadays, traditional extensive rainfed olive groves are no longer profitable and are progressively abandoned even though their rejuvenation can be very interesting for multifunctional activities or biomass production (Boussadia et al., 2023; Giorgi, 2006). In the Mediterranean olive orchards, mechanical tillage represents the most common technique of soil management (Xiloyannis et al., 2008) for the spontaneous flora control, and for the interruption of the capillarity water rise to reduce the loss of water through the evaporation from soil surface (Ozpinar and Cay, 2006). However, this technique, when performed at the same depth and using the same tillage machine for a long time (i.e. hoeing), can cause soil degradation, reduce water infiltration and induce soil erosion (Abid and Lal, 2009). This management coupled with the temperature increase, mainly in sandy or sandy-loam soils determine a strong soil water potential decrease and the possibility of water absorption by plant's roots is strongly reduced. Aiming to improve the crops income, in recent years, plantation has been extended by growers to irrigated lands requiring an optimization of the water resources also adopting conservative strategies for soil management (Ciaccia et al., 2019; Nicolosi et al., 2016) both in inter-row (zero till-age, minimum tillage, cover crops, cover flattening) and in intra-row (mulching, organic mulching, living mulching) (Giorgi et al., 2022; Las Casas et al., 2022; Lodolini and Ciaccia, 2022). Conservative agriculture has emerged as a key strategy for improving the sustainability and resilience of Mediterranean agroecosystems, where climatic constraints such as prolonged drought and high evaporative demand strongly influence orchard performance (Palese et al., 2014). Several researches have compared conventional tillage to conservation practices including reduced tillage, cover cropping, and Zero-tillage and have reported their effects on soil properties, water availability, and, in some cases, yield in mature Mediterranean olive orchards (Nieto et al., 2012; Palese et al., 2014; Parras-Alcántara and Lozano-García, 2014; Tekaya et al., 2016). However, the relevance and reliability of conservative agriculture research increase with both the duration and scale of the investigation, particularly when multi-year datasets are available and when early orchard development stages are considered. In fact, the establishment phase is widely recognized as crucial for determining long-term orchard efficiency, productivity, and resilience (Fernández et al., 2013). The specific context of young olive trees, whether newly planted or in their first two years of growth, managed under organic and/or conservative systems adds further complexity. Early phases of olive orchards often involve combined organic and inorganic fertilization strategies designed to support initial growth (Roussos et al., 2017). Despite the agronomic importance of this phase, data on the integrative response of young trees to conservative agriculture practices remain limited.

The olive tree efficiency for drought tolerance is due both to morphological adaptations structures in leaves such as enhanced sclerophylly (high density of foliar tissue, presence of thick cuticle and trichome layers) (Bacelar et al., 2004) and to its capacity of stomatal control (Giorio et al., 1999). The anatomical changes, mainly in leaf tissues, play a key role for the maintenance of a high CO_2 flux into the carboxylation sites, so enhancing the net photosynthesis despite the stomatal closure (Evans and Loreto, 2000). Developing this knowledge, an emerging approach involves coupling eco-physiological measurements with biometric assessments to obtain a more comprehensive understanding of plant functioning. This integrative framework links carbon assimilation and stress physiology directly to growth dynamics and canopy development (Roussos et al., 2017). Such combined analyses provide a more robust evaluation of early management success than studies focusing exclusively on structural drought tolerance or on either physiological or growth parameters alone. As Guerfel et al. (2009) highlighted, simultaneous assessment of gas exchange, stress-related metabolites, and growth indicators such as leaf area index (LAI) and early yield components offers a powerful method for evaluating tree performance during establishment.

Being an anisohydric species, olive can reach very low leaf water potentials, maintain full rehydration capacity and guarantee vegetative growth and reproductive activity (Karimi et al., 2018).

We hypothesized that a sustainable management based on zero tillage can allow significant differences in olive trees water status, physiological response and growth. Thus, the aim of this study was to understand the ecophysiological behavior of two Italian olive cultivars, "Nocellara del Belice" and "Nocellara Etnea" subjected to two soil management strategies: the usual periodical tillage vs the conservative zero tillage.

Material and Methods

Site Description, Experimental Design, and Treatments

The study was carried out between February 2021 and December 2023, in the "Long term trial on organic Olive (BiOlea)," within the experimental farm of the CREA, Research Centre for Olive, Tree Fruit and Citrus crops "Palazzelli" (Lentini municipal-ity, Syracuse), Sicily, Italy (latitude 37.17" N, longitude 14.50" E, elevation 45 m a.s.l.). The experiment focused on a young olive orchard: olive trees (*Olea europaea* L.) of two Sicilian double-aptitude cultivars "Nocellara del Belice" and "Nocellara Etnea" grafted onto seedling rootstocks. Trees were planted in June 2019 in North-South oriented rows at a spacing of 6 m between rows and 5 m within the row (333 trees ha^{-1}), so the area pertaining to each tree is 30 m^2. The imposed training system since the first winter pruning season (February 2020), was the polyconic vase with three main branches. During the month of December 2020, an intercropping system was introduced in the row, consociating four agroecological service crop species (ASC) as following: a) Sage, *Salvia officinalis* L.; b) Thyme, *Thymus vulgaris* L.; c) Curry plant *Helichrysum italicum* (Roth) G. Don and d) Lemongrass, *Cymbopogon citratus* (DC) Stapf. These consociating species were compared with a control without ASC maintained by a natural green cover and periodical mechanical strimming. The intercropping system was not considered as a factor for the present research. Trees selected for measurements were chosen where no officinal species were cultivated, but in the control rows where the spontaneous flora grew, located at a sufficient distance from agroecological service crops to avoid any potential effects of competition or microclimatic changes.

Trees were irrigated by a drip irrigation system applied early in the morning, three times per week from June to September. Irrigation scheduling was based on the FAO-56 Penman-Monteith (P-M) approach (Allen et al., 1998), adjusted by the crop coefficient (Kc, equal to 0.7) (Girona et al., 2002). Each dripper emitted 2 L h^{-1}, for a total of 8 L h^{-1} per tree, with an operational pressure of 1 bar. Trees were fully irrigated, corresponding to 95–98% of ETc. The electrical conductivity (at 25°C) of the water was 2.02 dS m^{-1} (medium salinity) and the pH was 7.30. Only organic fertilization was applied at the transplanting. A factorial treatment combination was used to conduct the trial over the three consecutive growing seasons from February 2021 to December 2023. The experimental layout was set in four blocks, each one consisting of 10 rows with five trees each, alternating between the cultivars (C) "Nocellara del Belice" (NB) and "Nocellara Etnea" (NE). Each block was divided into two sub-plots (five rows with five trees each). In each sub-plot, two soil (So) management practices were compared: (a) tillage (T), in which two tillage (20 cm depth) were performed at the end of the winter and at the end of summer and (b) zero-tillage (ZT), in which the soil was managed using only a mechanical strimming performed twice per year, at the end of the spring and at the end of summer, respectively. So, the four treatments considered in the present study were: 1) Nocellara del Belice – Tillage (NB-T), 2) Nocellara del Belice – Zero Tillage (NB-ZT), 3) Nocellara Etnea – Tillage (NE-T), 4) Nocellara Etnea – Zero Tillage (NE-ZT). Each physiological measurement was applied to one tree per sub-plot for a total of four plants for thesis, randomly assigned within the orchard to minimize spatial variability. Morphological measurements were applied to two or three trees per sub-plot, for a total of 10 plants for thesis.

Table 1. Main soil physical and chemical properties at the experimental field "long-term trial on organic olive (BiOlea)".

Parameter	Unit	Value
Sand	%	60
Clay	%	19
pH		7.8
Electrical conductivity (1:2.5)	dS/m	0.26
Cation exchange capacity (CEC)	meq/100g	64.98
Total nitrogen (N)	‰	140
Exchangeable phosphorus (P)	ppm P	53
Exchangeable potassium (K)	ppm K	3628
Total organic carbon (TOC)	%	1.47
Organic matter	%	2.69
Total calcium carbonate (CaCO3)	%	0.18
Active calcium carbonate	%	0.06
Microbial biomass carbon (MBC)	ppm	163.61
MBC/TOC	%	1.13

Soil Analysis and Climatic Data

At planting, soil characteristics were analyzed at 20–40 cm depth by three samplings per plot. Regarding physical characteristics, the quantity and distribution of sand, clay, and silt, total nitrogen (N), organic matter (OM), soil extractable phosphorus (mg/kg), soil exchangeable potassium (meq/100 g), cation exchange capacity, pH, and electrical conductivity (EC) were determined as described in previous studies (Ferlito et al., 2020; Torrisi et al, 2021).

In agreement with the United States Department of Agriculture (USDA) scheme, the soil is classified as loamy sand (Klingebiel and Montgomery, 1961), based on its physical properties. Concerning the chemical characteristics, the soil pH is sub-alkaline, and the electrical conductivity can be considered low (Las Casas et al., 2022; Saitta et al., 2020) (Table 1).

Over the past 30 years, the annual mean reference rainfall for the study area was approximately 550 mm and daytime maximum temperatures in summer often exceeded 38–40°C (Ciaccia et al., 2019).

Climatic data registered at the experimental field (i.e. monthly minimum, mean, and maximum air temperature, and rainfall) were collected from an agro-meteorological station located in the experimental farm (Figure 1). During the research, the climate was characterized by mild and wet winters, while the summers were semi-arid, during the first and the third year and dry during the second year, no rainfall was recorded from May to August. The lowest minimum temperatures, in all the three years were recorded in January and February. Mean temperature values were always above 22°C from April to November.

Compared to the past 30 years, from January to April the temperatures were similar, while significant differences in temperatures and rainfall were found in the summer months, particularly from June to August (from July to August in 2021, from June to August in 2022 and in August in 2023). Compared to the previous 30 years, the minimum temperatures were +4.0°C (2021: 4.24, 2022: 4.41, 2023: 3.32), the mean temperatures were +2.64°C (2021: 2.90, 2022: 2.92, 2023: 2.11), the maximum were +1.30°C (2021: 1.55, 2022: 1.43, 2023: 0.91) higher, respectively. The average amount for rain during the summer (June- September) was 15.28 mm (2021: 13.55, 2022: 16.75, 2023: 15.55).

Physiological Measurements

Physiological measurements were executed each season at intervals of 30 days from mid-June to mid-September (between the day 13th and 17th of each month) from 12.00 a.m. to 14.00 p.m. The days of the year (DOY) for these measurements were 166 (June), 196 (July), 226 (August) and 256 (September). Midday-stem water potential (ΨStem) was measured by a Scholander pressure chamber (Soil moisture Equipment Corp., Sta. Barbara, CA, USA) (Matthews et al., 1987; Nicolosi et al., 2021),

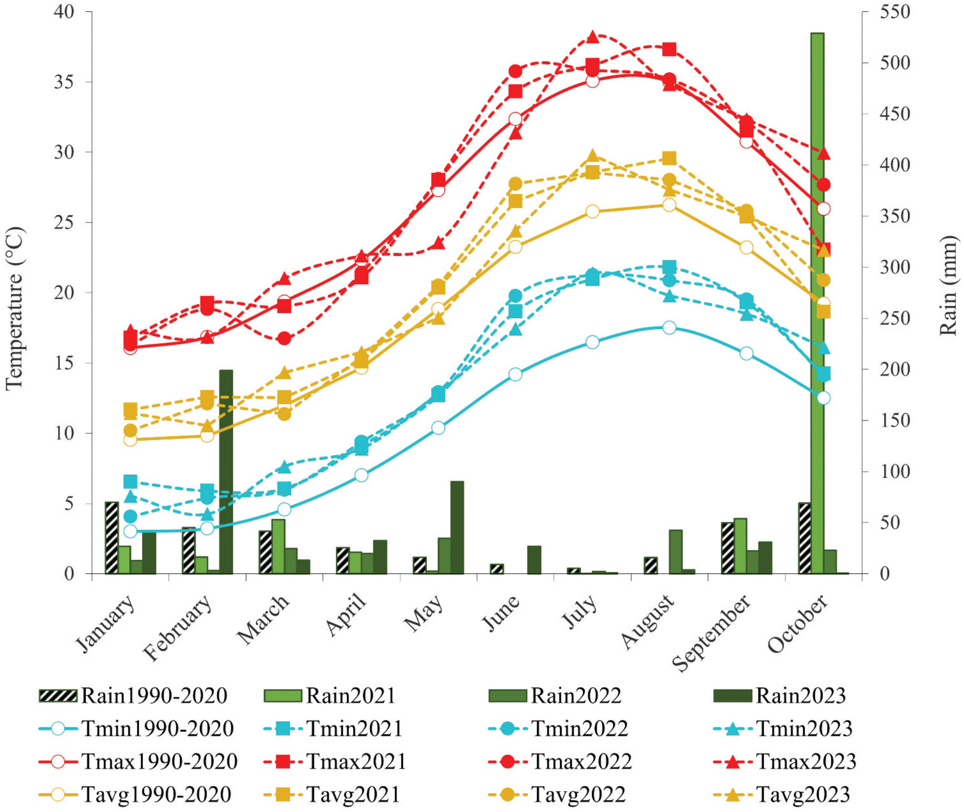

Figure 1. Monthly minimum, average, and maximum air temperature and rainfall registered from 1990 to 2020 and in the three years of the field experimental 2021, 2022, and 2023, in the experimental field "long-term trial on organic olive (BiOlea)".

for a total number of 4 measurements per treatment (1 leaves per tree, 4 trees per treatment). Leaves were closed into a small black hermetic plastic bag covered with aluminum foil for at least 2 h before detaching from the tree.

Leaf photosynthetic parameters, net photosynthesis (A, µmol CO_2 m^{-2} s^{-1}), transpiration rate (E, mmol H_2O m^{-2} s^{-1}) and stomatal conductance (g_s, mol H_2O m^{-2} s^{-1}) of well-exposed mature leaves, were measured when solar radiation was at maximum intensity, with a portable photosynthetic gas exchange, from non-detached young and fully expanded leaves using a portable infrared gas analyzer (IRGA, LCA4, ADC Bio. Scientific Ltd., Herfordshire, UK) with leaf surface area 1 cm^2, ambient CO_2 concentration 370 µmol mol^{-1}, and PPFD 200 µmol m^{-2} s^{-1}. The photosynthetic active radiation (PAR) was determined simultaneously with the measurements of the ecophysiological variables, using the sensor coupled to the porometer chamber, always placed perpendicularly to incident sunlight on the leaf surface throughout each reading. The registered measurements were the PAR on the leaf surface (Qleaf, µmol m^{-2} s^{-1} of photons), leaf temperature (Tl, °C), sub-stomatal CO_2 concentration (Ci, µmol CO_2 mol^{-1}) (Nicolosi et al., 2021). According to Esmaeilpour et al. (2016) A/E ratio was taken as an estimation of instantaneous water use efficiency ($WUE_{inst.}$), the ratio between A/g_s as intrinsic water use efficiency (iWUE) and the ratio A/Ci as instantaneous carboxylation efficiency (ICE). The mean daily vapor pressure deficit ($VPD_{leaf\ air}$, MPa) was calculated from the mean daily vapor pressure and relative humidity (Goldhamer and Fereres, 2001). Photosystem photochemical efficiency (Fv/Fm) was measured using a portable chlorophyll fluorometer (OS5-FL modulated chlorophyll fluorometer, ADC Bio Scientific Ltd. Hoddesdon, Hert, EN11 0 DB England). Minimal fluorescence (F0) was determined by applying weak modulated light (0.4 μmol m^{-2} s^{-1}) and maximal fluorescence (Fm) was induced by a short pulse (0.8 s) of saturating light (8000 μmol m^{-2} s^{-1}). F0 and Fm were used afterward to calculate variable fluorescence (Fv = Fm − F0) and maximum quantum efficiency of PSII (Fv/Fm). Measurements were made from the same leaf used for gas exchange determination, under light and after 20 min of dark adaptation (Maxwell and Johnson, 2000).

Biometric Measurements

Morphological measurements were performed on 10 trees per each variety within each soil management. Tree height and trunk and canopy dimensions were taken annually in February (2021–2022–2023). The trunk cross-sectional area (TCSA) was calculated by measuring the circumference at a height of 20 cm from the ground. The canopy volume was calculated by measuring longitudinal, transversal and diagonal dimensions and assuming a truncated conic shape of the canopy. On the same trees, wood resulting from winter pruning was weighed, considering separately the material coming from branches and from suckers. Shoot vegetative growth was monitored on young lateral shoots throughout all the spring-summer season, with 5 measurements each year, from May to September. Relationships between growth and physiological parameters, were then investigated in the four tested treatments.

Statistical Analysis

Analysis of variance (ANOVA) was performed with STATISTICA software 6.0 (StatSoft Italia srl, 2001). One-way analysis of variance (ANOVA) was carried out on the two cultivars and two soil treatments considering single measurement along the three, separately for each year and for each DOY, and independently for each cultivar. A post-hoc analysis based on the Tukey HSD test (Tukey Honest Significant Differences) was performed at significance levels (p-value) of 0.05, 0.01 and 0.001. For data that did not follow a normal distribution the Kruskal-Wallis test was performed using “kruskal.test” function on R software. The graphs of behavior of $VPD_{leaf\ air}$ and Ψstem, shoot growth rate and weather conditions were performed by Microsoft Excel software. The comparison among treatments was also carried out through the Principal Component Analysis (PCA) of the average data, to summarize graphically the specific responses of the two cultivars and to highlight any similarity or dissimilarity implemented in R software, ver. 4.2.0 (R Core Team, 2022). Moreover, also the physiological data used for the Pearson correlation analysis among all the collected parameters were computed using the “cor” function-implemented in R software. The scatter plots were made by “ggplot2” package (Wickham, 2016).

Results

Physiological Parameters

The results concerning the olive trees physiological response to the applied treatments are reported in table S1. During the first year, a significant difference was observed between the two soil managements in NE, both in July and September (*p* value = 0.009 and *p* value = 0.005), when a less negative midday-stem water potential (Ψstem) was registered in ZT compared to T soil management. For the same parameter, in NB significant differences were observed in August (*p* value = 0.027). On the other hand, NB better responded to T conditions for iWUE, in August. The Ψstem ranged from minimum values of −3.25 MPa to maximum values of – 1 MPa in 2021, from −2.6 to −1.4 MPa in 2022 and from −2.8 to −1.4 MPa in 2023. Figure 2 shows the different ranges of Ψstem during the three years, in the two cultivars and in different soil managements, in relationship with different physiological variables. The Ψstem changed according to the months and the years. Only in the first year (2021), three samples

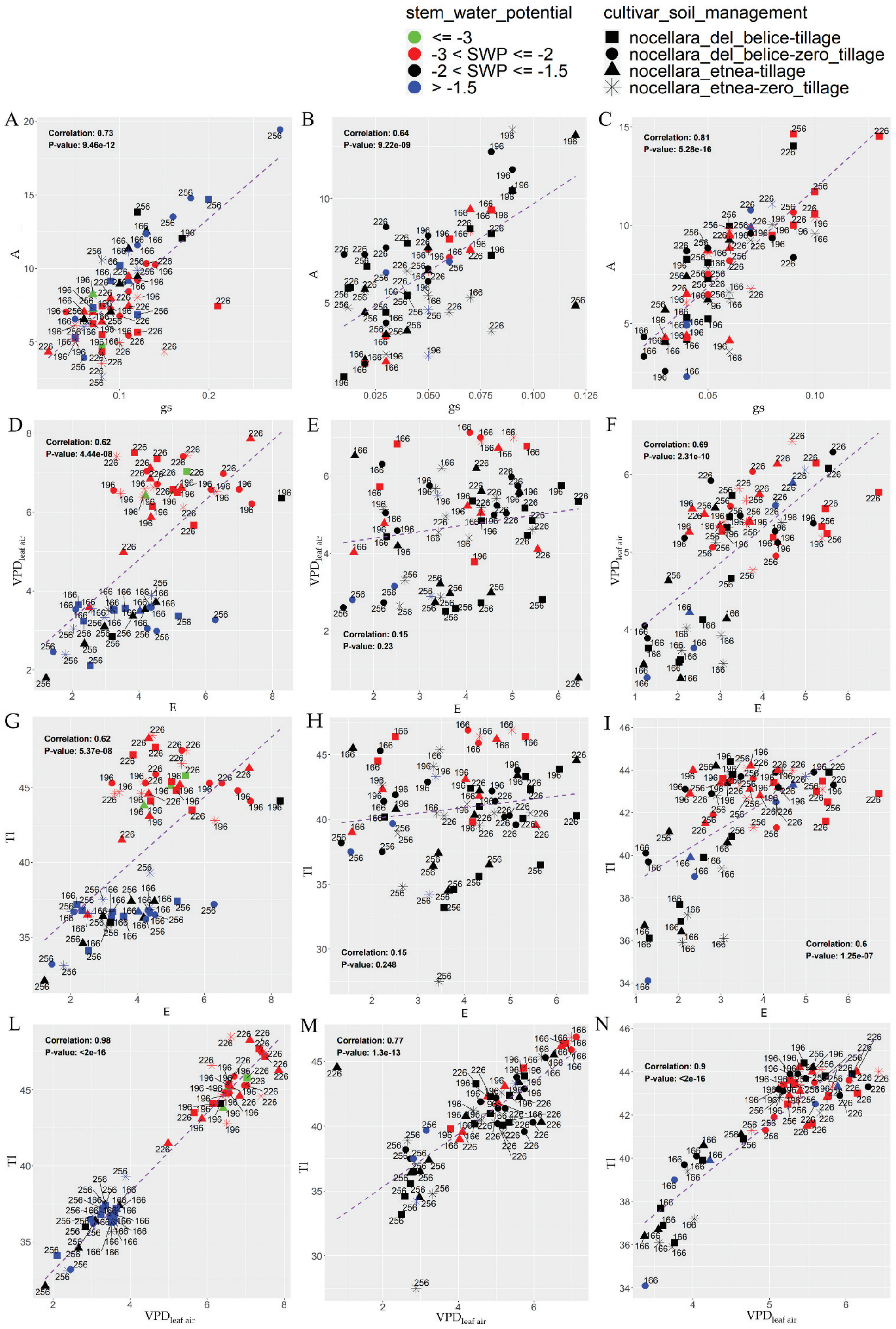

Figure 2. Scatterplot with regression line showing the relationship in years 2021 (A, D, G, L), 2022 (B, E, H, M), and 2023 (C, F, I, N) between g_s (stomatal conductance, mol H_2O m^{-2} s^{-1}) and a (net photosynthesis mol CO_2 m^{-2} s^{-1}) (A, B, C); E (transpiration rate, mmol H_2O m^{-2} s^{-1}) and $VPD_{leaf\ air}$ (leaf air vapor pressure deficit, MPa) (D, E, F); E (transpiration rate, mmol H_2O m^{-2} s^{-1}) and leaf temperature (tl, C°) (G, H, I) and $VPD_{leaf\ air}$ (MPa) and Tl (C°) (L, M, N).

showed Ψstem values below −3 MPa in June and July, in T soil management, as shown in Figure 1 (A, D, G, L). In general, Ψstem values were above −1.5 MPa in June and September during 2021, except in NE-T. In the second year (2022), Ψstem showed values between −3 and −1.5 MPa reaching lower values in June for both soil management and in July only for T. In the third year (2023), Ψstem showed less negative values in June, while more negative in the other months (Figure 2 and Table S1).

Among the studied photosynthetic parameters (A, E and g_s), a general good correlation was found (Figure 2 and Table S2) especially in the third year of the trial. The most frequently correlated parameters were g_s and A for both studied cultivars, that showed significant correlations under T for each year of the trial. Similarly, E and A were positively correlated. Under ZT conditions, g_s and A resulted in a positive correlation for both cultivars especially in NB, while E resulted correlated with g_s in 2021, while with A in 2022. In relation to photosynthetic parameters, except for NB in August 2023 and August and September 2022, when the photosynthetic parameters increased under T condition, in all the other parameters no significant differences were observed between the ZT and T treatments, while between cultivars differences were observed (Table S1).

In Figure 2(A) and in table S2, a high correlation was registered between g_s and A, but no correlation between the latters and the Ψstem was registered. Differences were observed among the years: in 2021, the range of the g_s was wider than in the other two years when the g_s was very low. Regarding E, $VPD_{leaf\ air}$ and Tl in 2021 and 2023, a clear separation was observed between months, as well as for Ψstem values.

An opposite behavior was observed between $VPD_{leaf\ air}$ and Ψstem, when the $VPD_{leaf\ air}$ was higher, during the dry/hot months, the Ψstem was lower, while the opposite occurred during the cool/wet months. This behavior was similar in both cultivars and during the three years depending on the climatic conditions (Figure 3). Across years and tillage systems, the relationship between Ψstem and VPD consistently showed a negative trend, confirming that higher evaporative demand leads to lower stem water potential. In 2021, this correlation was negative and significant in both NE-T and NB-T, indicating a strong atmospheric control on plant water status during that year. In 2022, the correlation in NE-T remained negative but was not significant, suggesting that additional factors (e.g., soil moisture availability or rainfall patterns) may have buffered the effect of VPD on Ψstem. In contrast, 2023 again showed a clear negative and significant relationship in both NE-T and NB-T, reflecting a stronger relation between atmospheric demand and plant hydraulic stress under the climatic conditions of that year. Overall, these patterns support the idea that interannual variability in Ψstem is largely driven by VPD, with the strength of the relationship depending on year-specific climatic conditions and, to a lesser extent, on tillage system.

The limited differences between ZT and T can be explained by the moderate stress conditions during the study period. Although ZT improved soil structure and moisture retention, these benefits were not large enough to generate strong changes in Ψstem or gas exchange. Slightly higher soil water availability under ZT likely contributed to marginally less negative Ψstem and small increases in g_s or A on some dates, but these effects remained subtle because overall drought pressure was low. Notably, in years with higher evaporative demand, the expected advantages of ZT became more evident, suggesting that tillage effects on plant physiology emerge more clearly under stronger water stress.

The factorial analysis (Table 2) over the three years revealed significant differences attributed to both DOY and year, to the contingent weather conditions and temperatures of the respective years as reported in Figure 4. Their interaction is significant for almost all parameters examined. In terms of soil management, the primary statistically significant difference is associated with water potential, with p-value of 0.000, where the cultivar plays a crucial role as well especially in Ψstem with a p-value of 0.000. The cultivar appeared to be a less effective variable compared to the other two factors (year and DOY).

In 2021, for both cultivars, replicates were categorized by DOY in both PC1 and PC2 (Figure 5(A, B)). Notably, Ψstem values were higher in June and September and more negative during the peak of summer (July and August) when temperatures were higher (Tmax 36°C and 37°C, respectively) and rainfall was absent. For the physiological data analysis in 2021 for NE, PC1 explained 32.90% of the

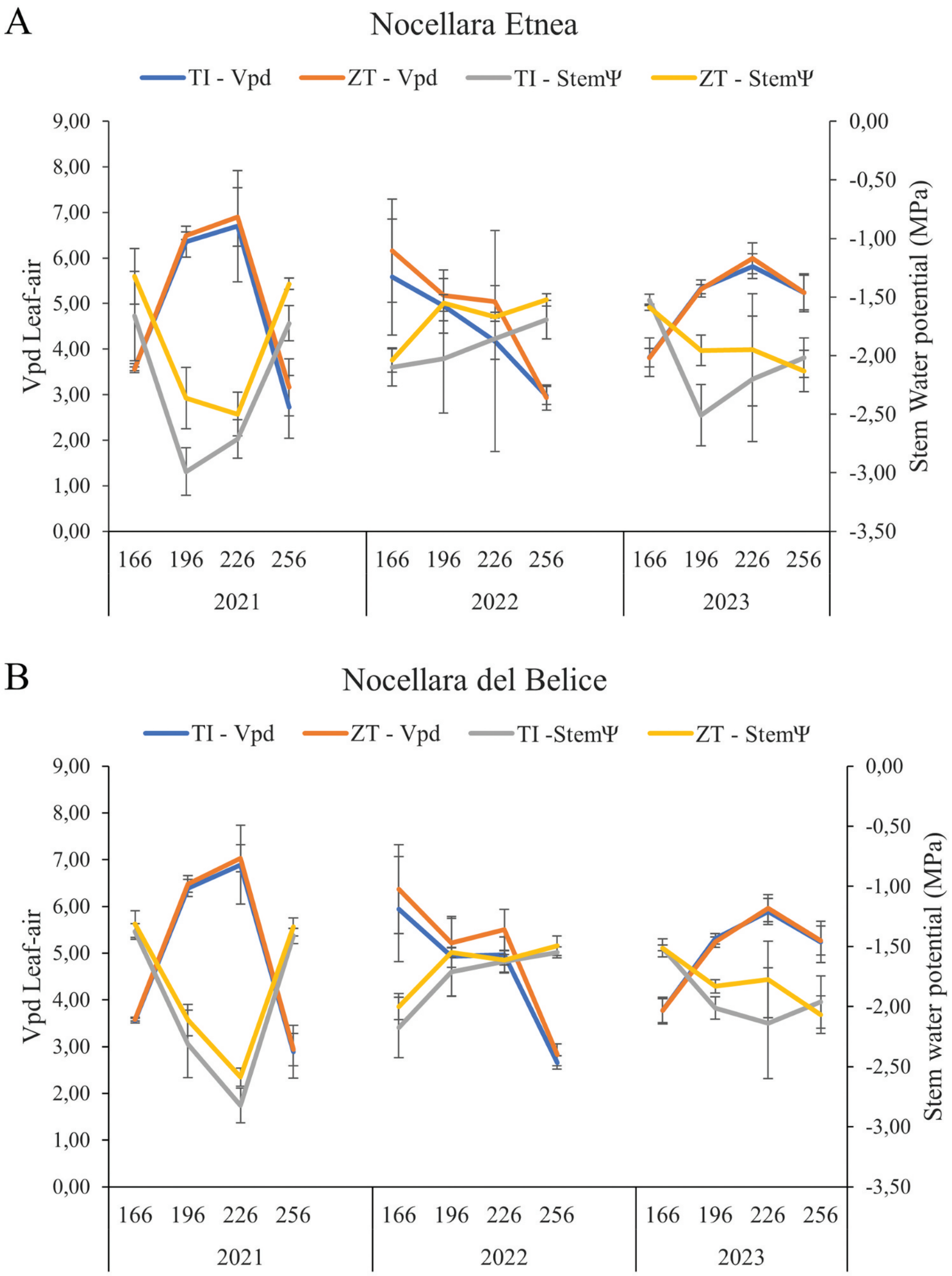

Figure 3. Behavior of $VPD_{leaf\ air}$ and ΨStem in Nocellara Etnea (A) e Nocellara del belice (B) in the summer months during the three years of the analysis.

total variability, while PC2 the explained 23.10%. Samples were divided by DOY. For PC1, the main contributions were attributed to $VPD_{leaf\ air}$, Tl, $WUE_{inst.}$ and Ψstem, while for PC2, the ICE, Ci and DOY played significant roles (Figure 5(A). Regarding NB, the two components of PCA were divided as follows: PC1 and PC2 described the 39.1% and 18.3% of the total variability, respectively. DOY, Ψstem, $VPD_{leaf\ air}$ and Tl showed a greater contribution in PC1, whereas g_s, DOY, A, and maximum quantum yield of PSII in darkness resulted more effective in PC2 (Figure 5(B)).

Table 2. Factorial analysis of physiological data. Values with significant p-values are in bold.

	Degree of freedom	Ψstem	Qleaf	Tl	Ci	E	g_s	A	VPD$_{\text{leaf air}}$	WUE$_{\text{inst.}}$	iWUE	ICE	PSII light	PSII dark
Year (Y)	2	**0.000**	**0.001**	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**	**0.006**	**0.000**	**0.000**	**0.000**	0.409	**0.010**
Doy (D)	3	**0.000**	0.127	**0.000**	0.161	**0.000**	0.221	0.099	**0.000**	**0.000**	**0.005**	0.082	**0.000**	**0.003**
Cultivar (C)	1	**0.000**	**0.045**	0.438	0.539	**0.024**	0.084	**0.022**	0.473	0.110	**0.045**	0.067	0.058	0.250
Soil manag. (S)	1	**0.000**	0.988	0.473	0.723	0.388	0.872	0.942	0.052	0.668	0.815	0.904	0.731	0.962
C*S	1	**0.026**	0.630	0.507	0.115	0.155	0.965	0.184	0.720	**0.001**	0.222	0.116	**0.011**	0.254
C*D	3	**0.008**	0.126	0.878	0.875	**0.045**	**0.04**	**0.016**	0.567	0.349	0.214	0.250	0.083	0.325
S*D	3	**0.002**	0.918	0.951	0.979	0.315	0.794	0.615	0.789	0.398	0.792	0.915	0.401	1.000
C*Y	2	0.543	0.668	0.701	0.649	0.491	**0.001**	0.424	0.672	0.068	**0.001**	0.873	0.082	0.317
S*Y	2	0.191	0.232	0.757	0.466	0.13	0.539	0.782	0.255	**0.019**	0.443	0.586	0.923	0.998
D*Y	6	**0.000**	**0.000**	**0.000**	**0.000**	**0.001**	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**

ΨStem, midday stem water potential (MPa); Qleaf, photosynthetic active radiation on the leaf surface; Tl, leaf temperature (°C); Ci, sub-stomatal CO2 concentration (μmol CO2 mol-1); E, transpiration rate (mmol H2O m−2 s−1); gs, stomatal conductance (mol H2O m−2 s −1); A, net photosynthesis (mol CO2 m−2 s−1); VPDleaf air, leaf air vapour pressure deficit (MPa); WUEinst., instantaneous water use efficiency; iWUE, intrinsic water use efficiency; ICE, instantaneous carboxylation efficiency; PSII light, maximum quantum efficiency of PSII at light; PSII dark; maximum quantum efficiency of PSII at dark; F (F-value), p (p-value ≤ .05).

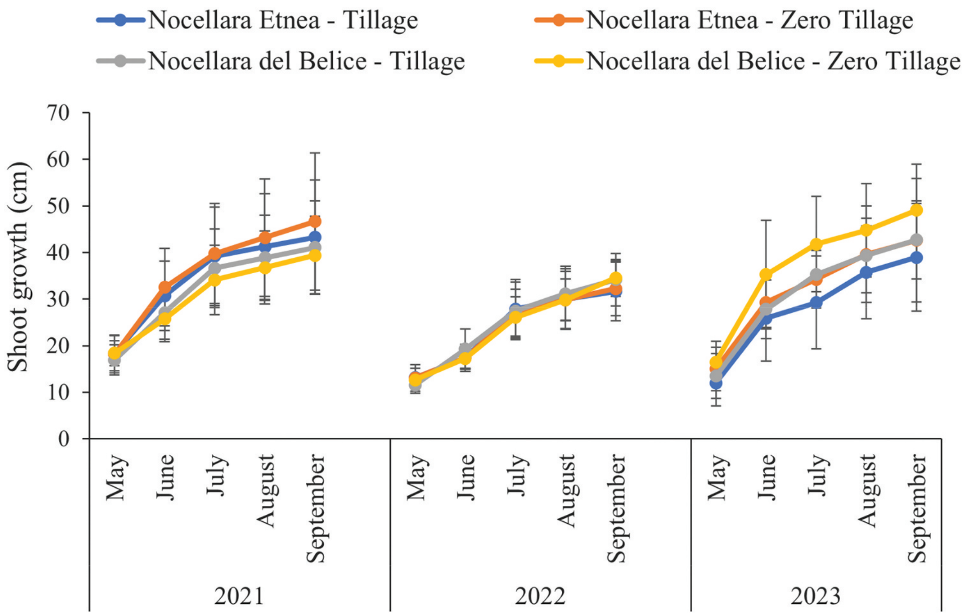

Figure 4. Principal component analysis of biometrical parameters in: A) nocellara etnea 2021; B) nocellara del belice 2021; C) nocellara etnea 2022; D) nocellara del belice 2022; E) nocellara etnea 2023; F) nocellara del belice 2023. Red circles indicate soil management with tillage, while blue circles the zero tillage.

In 2022, both cultivars were divided by DOY for both PC1 and PC2 (Figure 5(C,D)). In the second year, June was warmer than the previous year, as confirmed by the more negative water potential, determined by high temperature and absence of precipitation (Figure 1) as well as for the T treatment in July, similar to the NB cultivar. For the physiological data of NE in 2022, PC1 and PC2 explained 32.7% and 18.3% of the total variability, respectively. ICE, A, and WUE$_{\text{inst.}}$ contributed more to PC1; DOY, VPD$_{\text{leaf air}}$ and iWUE, affected more the PC2 (Figure 5(C)). For NB, PC1 explained 28.6% of the variability, whereas PC2 explained 25.70%. For PC1, the main contributions were attributed to DOY, Tl, VPD$_{\text{leaf air}}$ and Ψstem; for PC2, to ICE, A, and g_s. Comparing the two cultivars, significant

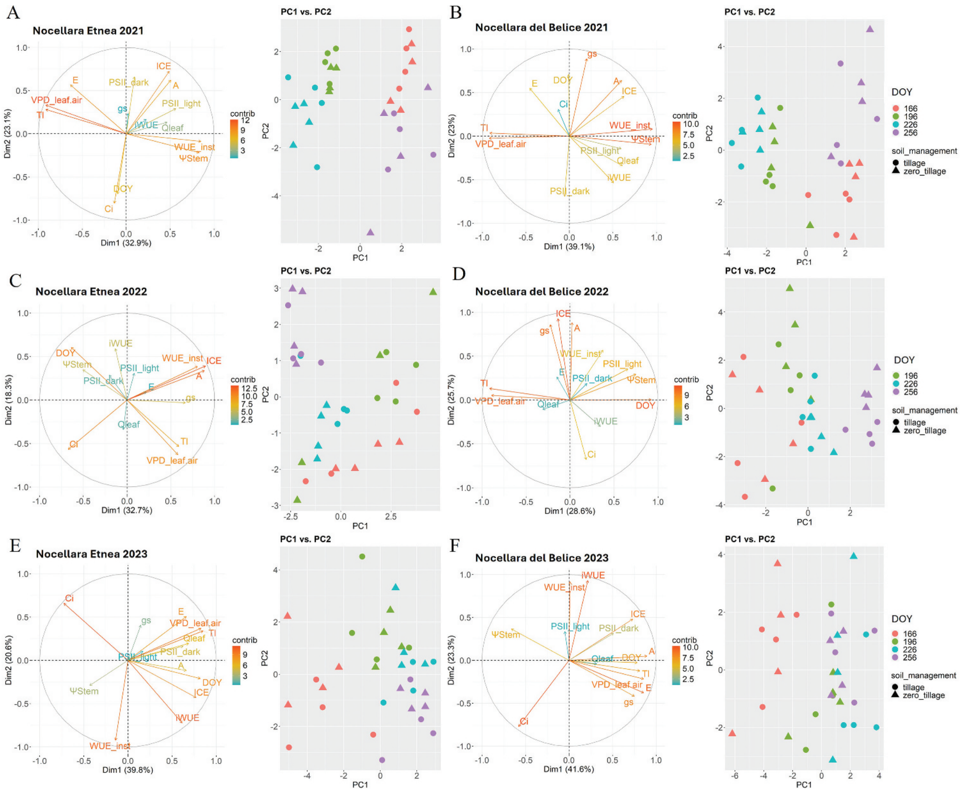

Figure 5. Shoot growth rate of Nocellara Etnea and Nocellara del belice in two different soil management systems (tillage and zero tillage), during the three years of the study.

differences were seen mainly in August and September for the ZT treatment, where NB showed higher values of A, $WUE_{inst.}$ and ICE in both months (Table S1). In September, NB showed significant values with ZT treatment, Tl and higher $WUE_{inst.}$ and lower E values compared to T one.

In 2023, both cultivars seemed to be separated by DOY and not by treatment, with warmer months in July and August. For NE, PC1 explained 39.80% of the total variability, whereas PC2 explained 20.5% (Figure 5(E)). The main contributions for component 1 were attributed to DOY, Tl, $VPD_{leaf\ air}$, and ICE, while PC2 to $WUE_{inst.}$ iWUE, and Ci. For NB, PC1 explained 41.50%, with a greater contribution from Ψstem, DOY, Tl, and $VPD_{leaf\ air}$. In comparison, PC2 explained 23.30%, with the main contributions from $WUE_{inst.}$, iWUE and Ci (Figure 5(F)).

Statistically significant differences (Table S1) were observed in NE cultivar in early summer, when less negative water potential values were found in T in June and ZT in July, in this latter month also for NB. Significant differences were also found in June and August for iWUE, with higher values in NE-T while g_s was significantly higher in NE-ZT. Regarding NB, in August, significant values were observed for T in g_s and A. Observing the two cultivars, NE in the ZT treatment showed higher values for g_s and E in June, while in T, NE had more negative water potential values in July compared to NB. In August, NE had lower values for E, g_s, and A in T compared to NB, while higher values in iWUE.

Biometric Measurements

Concerning the biometrical parameters, the factorial analysis (Table 3) showed significant differences for all considered factors, in order: year, cultivar, and soil management. Among the analyzed factors the interaction cultivar × year and cultivar × soil management were the most evident.

Table 3. Factorial analysis of morphological data. Values with significant p-values are in bold.

	Degree of freedom	TCSA	Plant height (cm)	Canopy height (cm)	Average canopy volume (m^2)	Average canopy surface (m^3)	Pruning weight (g)	Sucker weight (g)
Year (Y)	2	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
Cultivar (C)	1	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
Soil management (S)	1	**0.034**	**0.002**	**0.006**	**0.022**	0.057	0.301	**0.000**
C*S	1	**0.026**	0.101	0.307	**0.019**	**0.002**	**0.009**	0.541
C*Y	2	**0.007**	0.443	0.379	**0.000**	**0.002**	**0.000**	**0.000**
S*Y	2	0.295	0.615	0.753	0.0676	0.157	0.162	**0.012**

TCSA, Trunk cross sectional area.

The observed differences between ZT and T highlight contrasting growth strategies with important agronomic implications. In 2021 ZT promoted sturdier trees with higher TCSA, likely reflecting enhanced root anchorage and better resource allocation to trunk and structural growth. In contrast, T favored taller trees with more suckers, suggesting a shift toward vertical growth and vegetative proliferation at the expense of structural robustness. These patterns have clear implications for orchard sustainability: sturdier trees under ZT may be more resilient to mechanical stress and better able to support fruit load, while T trees may require more management interventions to control height and sucker development. Additionally, the allocation patterns observed under ZT could contribute to improved carbon sequestration in woody biomass, highlighting the potential of reduced-tillage practices for both tree stability and long-term orchard carbon balance.

The principal component analysis for 2021 showed that the two soil management systems are distinguished by PC2, explaining the 18.7% of the total variability in NE and the 16.3% in NB (Figure 5 (A,B)). Morphological parameters related to TCSA, pruning and sukers with significant differences ($p \leq 0.05$) are reported in Table 4, while morphological parameters referred to the canopy are reported in table S3.

The PC1 of the NE cultivar explained the 48.4% of the total variability, with significant differences between the two soil managements for trunk cross-sectional area (TCSA) with p-value of 0.033, canopy height with a p-value of 0.034 and sucker fresh weight with a p-value of 0.021. With T, the trees grew taller but less robust, with a major number of suckers. This can be observed also in the PCA, where TCSA increased with ZT (Figure 6(A)). For NB, the PC1 explained the 55.8% and major contributes were attributed to average canopy volume and suckers for PC2 that explained the 16.3% of variability. Indeed, as reported in Table 4 and S3

Table 4. Morphological parameters of two olive cultivars Nocellara Etnea (NE) and Nocellara del belice (NB) under two soil managements tillage (T) and zero tillage (ZT), in the 3 years of analysis.

Year	Cv	Soil management	TCSA			Pruning weight (g)			Suker weight (g)		
2021	NE	T	6.49 ± 1.87	B		0.77 ± 0.30		a	1.50 ± 0.36	A	
		ZT	8.98 ± 2.84	A	a	0.83 ± 0.13		a	1.15 ± 0.26	B	a
	NB	T	6.42 ± 3.14			0.48 ± 0.11		b	1.11 ± 0.48	A	
		ZT	4.12 ± 1.75		b	0.37 ± 0.18		b	0.49 ± 0.07	B	b
2022	NE	T	22.92 ± 6.98			0.57 ± 0.02		a	0.72 ± 0.22		
		ZT	22.06 ± 6.82		a	0.68 ± 0.21		a	0.72 ± 0.41		
	NB	T	20.49 ± 10.44			0.24 ± 0.08		b	0.67 ± 0.37		
		ZT	12.36 ± 6.41		b	0.38 ± 0.28		b	0.67 ± 0.32		
2023	NE	T	40.46 ± 9.51		a	5.81 ± 1.21			1.76 ± 0.55	A	a
		ZT	39.32 ± 12.32		a	6.47 ± 1.85		a	1.27 ± 0.39	B	a
	NB	T	30.65 ± 8.71	A*	b	5.02 ± 1.62	A		0.93 ± 0.80		b
		ZT	21.90 ± 12.14	B*	b	3.09 ± 1.52	B	b	0.44 ± 0.18		b

Data are expressed as mean ± SD. Significant differences ($p \leq .05$) are indicated by different letters. Uppercase letters indicate anova between the two cultivars within the soil management, lowercase letters indicate anova between cultivars within the same soil management. The asterisk indicates the analysis performed with the krustal Wallis test.

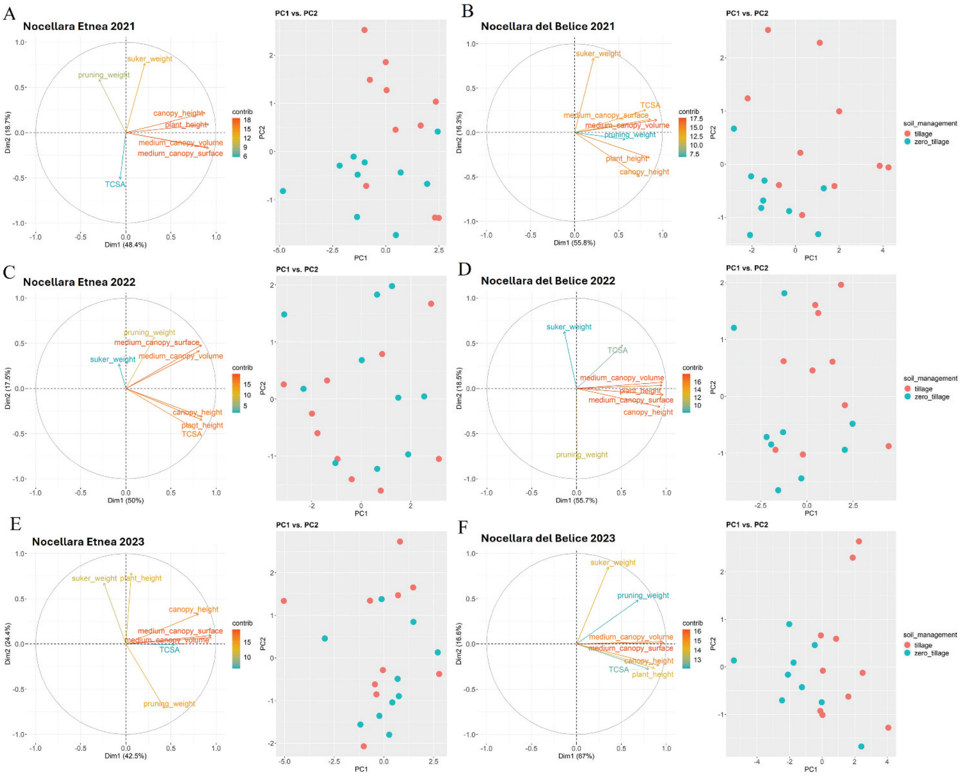

Figure 6. Principal component analysis of the physiological parametrs in: A) nocellara etnea 2021; B) nocellara del belice 2021; C) nocellara etnea 2022; D) nocellara del belice 2022; E) nocellara etnea 2023; F) nocellara del belice 2023.

the significant differences were found for average volume of canopy and sucker fresh weight for T treatment. Comparing the two cultivars, it was observed that NE has significant higher values than NB, developing more in height with T but being sturdier with ZT, with a p-value of 0.000 for TCSA-ZT and with a p-value of 0.003 for Canopy high-T.

In 2022, for the NE cultivar (Figure 6(C)), the samples were uniformly distributed between the two soil managements. Although NB (Figure 6(D)) showed difference between the two soil managements, as regard PC1 and PC2, growing more in T, but no significance differences were found between the two soil managements in both cultivars. Comparing the two cultivars in both treatments, NE had a greater vegetative growth mainly with ZT, with a p-value of 0.000 for Average canopy surface and for Average canopy volume. In 2023, while no differences emerged for NE in the two soil management systems (Figure 6(E)), on the contrary, the development of the NB cultivar stood out significantly with T, as expressed in PC1 (Figure 6 (F)). Comparing the two cultivars, with ZT, NE grew significantly more than NB, with p-value of 0.000 for Average canopy surface and Average canopy volume, but showed more material removed with pruning and suckers (p-value of 0.000).

The shoot growth is shown in Figure 4 and no significant difference was detected between the T and ZT soil management practices for the investigated cultivars.

Discussion

Our research was carried out in a young organic olive orchard (Las Casas et al., 2022) located in a typical Mediterranean area. The recorded soil characteristics highlighted the absence of any limiting factors based on physical and chemical parameters. However, in a sandy loam soil under Mediterranean conditions, the conventional soil management based on tillage didn't work well as dry farming technique (Palese et al., 2014). On the contrary, the adoption of sustainable management techniques, can promote autumn – winter rainwater storage in the soil, because of the presence of a vegetation cover and of a good soil structure allowed an efficient rain capture (Palese et al., 2014). Indeed, this study revealed that plant growth under both T and ZT managements, but with significant differences between and within the cultivars.

Despite very high temperatures were registered during the summer periods, the scheduled irrigation at 95–98% of the ETc was effective to maintain moderate the water stress during the irrigation season in both soil managements. This result is very interesting considering that the soil had a limited water retention capacity (daily soil water content range from 0.16 to 0.25 cm^3 cm^{-3}) and this limit can lead to water stress for the trees in summer, as reported in Vanella et al. (2021). Although the irrigation regime in our experiment was relatively high, this does not imply that differences between ZT and T were entirely buffered, considering that the two soil management systems induced consistent differences in soil physical properties, including bulk density, porosity, and effective field capacity, which directly influence water storage and release in the root zone. Therefore, even under near-full irrigation, plants in T and ZT encounter distinct soil water dynamics. As regards the climatic conditions, overall, the study highlights the impact of changing climatic conditions and the need for adaptative measures to face water stress in semi-arid climatic conditions.In any case, the on-going climate change affected rainfall patterns with concentrated precipitation in October and scarcity, until absence, during the dry/hot months (summer). Even traditionally drought-resistant species, as the olive, which take on challenges due to elevated temperatures, require irrigation to ensure an adequate water supply leading to the established irrigation rate. As reported in Brito et al. (2019) olive trees are highly resilient and tolerant to various environmental stresses, but climate change and prolonged periods of water scarcity may negatively impact their productivity and oil quality. Young olive trees are strongly stressed in an environment with high evaporative demand (1,268 mm average per year), especially concentrated during summer (Vanella et al., 2021). Research on the cultivar "Koroneiki" has shown that organic or conservation management can significantly enhance leaf area index (LAI), carbon assimilation rate, and yield. This response likely reflects both the high acclimation capacity of the cultivar (Chartzoulakis et al., 1999) and its strong inherent growth potential (Roussos, 2017). In this context, the success of conservation systems through improved water and nutrient availability appears to optimize the intrinsic drought tolerance of the studied cultivars, enabling them to perform similarly to other drought-resilient Mediterranean varieties.Recent studies suggested that maintaining Ψstem values within the range of −2.5 to −3.5 MPa is crucial for ensuring optimal yield and quality of olive oil (cv. Arbequina) (Ahumada-Orellana et al., 2019; Trentacoste et al., 2018). Marino et al. (2018) characterized three levels of water stress: non-stressed trees (Ψstem greater than −2.0 MPa), moderately stressed trees (Ψstem ranging between −2.0 and −3.5 MPa), and highly stressed ones (Ψstem below −3.5 MPa), suggesting that for optimal irrigation efficiency and to avoid harmful water stress levels, the olive Ψstem should be maintained between 2 and 3.5 MPa. In contrast, studies on mature "Chemlali" trees indicate that conventional tillage can increase stomatal conductance and chlorophyll fluorescence parameters relative to no-tillage systems, which tend to accumulate stress metabolites (Tekaya et al., 2016). However, very young "Chemlali" trees, known for superior drought tolerance, possess anatomical adaptations, such as thicker palisade parenchyma and higher stomatal/trichome density, that distinguish them from less tolerant cultivars like "Chétoui" (Guerfel et al., 2009). Similarly, other Mediterranean cultivars adapted to arid conditions, including "Cobrançosa," "Manzanilla," "Negrinha" (Bacelar et al., 2009) and Tunisian varieties such as "Besbessi" and "Sayali" exhibit physiological mechanisms that maintain photosynthetic performance under water deficit. For example, "Besbessi," "Chemchali," and "Sayali" maintained higher photosynthetic efficiency and Performance Index (PI) under drought compared to "Jarboui" and 'Chétoui (Bboussadia et al., 2023)

Roussos et al. (2017) confirmed that, in young olive trees, conservation agriculture and organic management improve both biometric indicators and eco-physiological parameters (e.g., carbon assimilation, leaf water status), highlighting that these management systems function optimally even during the early establishment phase. This integrative response linking physiological performance with canopy development is particularly relevant for young trees and represents a central original contribution of our study. It demonstrates that favorable management can harness the inherent drought resilience of specific cultivars, ensuring rapid establishment and potentially long-term productivity under Mediterranean conditions.

Sofo et al. (2019) highlighted as sustainable management, evidenced in parallel research on mature olive trees (cv. “Maiatica”), where sustainable management significantly up-regulated secondary metabolism in the xylem sap, resulting in higher concentrations of metabolites involved in plant chemical defense and growth regulation compared to conventional management. This reinforces the conclusion that the shift toward conservation practices enhances the entire physiological status of the tree, providing both environmental and plant health benefits.

Our data on average showed in 2021 a range between −1.38 and −2.99 MPa for T and between −1.31 and −2.59 MPa for ZT. In 2022 in T soil management Ψstem was between −1.55 and −2.18 MPa, while in ZT from −1.49 to −2.04 MPa. Indeed in 2023, Ψstem was between −1.51 and −2.51 MPa in T and from −1.51 to −2.13 MPa in ZT. Therefore, our study showed that only in the first year, three replicates showed values below −3 MPa, indeed trees were moderately stressed in the warmer months with values between −1.5 and −3 MPa, this depends on year and weather conditions during the months, temperature significantly influences plant water stress (Frank et al., 1973). In 2021 (DOY 196, DOY 226 and DOY 256) and 2023 (DOY 196) ZT was responsible for an increase (less negative) of Ψstem. In particular, between the two cultivars, NE highlighted a significant different in Ψstem for the soil managments (Ψstem less negative under ZT). During 2021 (DOY196 and DOY 256) and 2023 (DOY 196) NB-T showed less negative Ψstem. During 2023, only for DOY 166, NE-T showed a significant less negative Ψstem. It appears that T negatively affected the Ψstem of olive, thus providing values which are generally more negative than those reported for ZT. Similar results were previously found by Pittarello et al. (2024).

No-tillage is widely accepted as a practice for sustainable management in agroecosystems, including Mediterranean woody crops and resulted in the highest stomatal conductance and photosynthetic rate moreover reduce the negative effects of poor soil and lack of irrigation, making it easier for olive orchards to cope with tough conditions (Pittarello et al., 2024). Tillage negatively affected plant physiology, including the photosynthetic rate, stomatal conductance, and transpiration rate, especially in acid clay soil under rainfed conditions (Pittarello et al., 2024). Our results concerning the photosynthetic parameters (A, E, gs) not fully agree with those obtained by Tekaya et al. (2016) for olive as concern T, but similar values were obtained in ZT in June, period observed by the authors. Regarding the fluorescence of the leaf chlorophyll, our findings agree with those of Boussadia et al. (2008)that reported an increase of these parameters (both in light and dark conditions) under different stress levels. These parameters reflect the protective or regulatory mechanism to avoid photo damage of the photosynthetic system. He argued that the best performance under T is due to a better soil aeration thermal condition, infiltration etc. Probably under our conditions this soil characteristics are maintained also under ZT. The only case in which the A increased under T mainly for NB was during August 2023 that followed the hottest period during the three years. The results of Tekaya et al. (2016) were obtained in an irrigated sandy-loam soil similar to our experimental conditions. The soil of our experimental olive orchard indicated a higher content in organic matter (2.69 vs 0.75, respectively) and mineral nitrogen (140‰ vs 0.07‰, respectively) in comparison with that one of Tekaya et al. (2016), that could be responsible for the better tree conditions. The organic content and total nitrogen are key indicators of physical fertility, power supply of nutrients and biological activity of the soil, reacting quickly to any disturbance of the soil environment (Quideau et al., 2000).

Our results are strengthened by the fact that, excluding September (DOY 256) in 2023, in all of the treatments under ZT management, the trees were not subjected to an environmental higher stress that affected PSII efficiency while a decrease in Fv/Fm was not observed. This result demonstrates that the electron transport rate for the activation of the photosynthetic rate was not reduced. In table S1 we observed that our values of g_s are similar to those reported by different authors (Giorio et al., 1999; Guerfel et al., 2009) in rainfed conditions (T0) and irrigated with 66% of ETc (T66). Moreover, values of A and Ψstem are also similar to those reported by Giorio et al. (1999) in the T66. Compared to other previous studies (Giorio et al., 1999; Guerfel et al., 2009; Marino et al., 2018) we didn't observe a correlation between Ψstem and g_s. This aspect was previously reported by Fernández et al. (1997) and, in our case, the correlation was observed only in NE-T in 2023. The scattered pattern observed in this context may be attributed to the stomatal response to various environmental factors, as suggested by Jarvis et al. (1999). In all three years of study, high correlation and high significance were observed between g_s and A ($R = 0.74$, 0.64, and 0.81; p-value < 0.0001); $VPD_{leaf\ air}$ and Tl ($R =$ 0.98, 0.77, 0.9; p-value < 0.0001), while only in 2021 and 2023 a good correlation and high significance were observed between E and $VPD_{leaf\ air}$ ($R = 0.62$ and 0.69; p-value < 0.0001) and E and Tl ($R = 0.62$ and 0.6, p-value < 0.0001).

In 2021, low values of $VPD_{leaf\ air}$ corresponded to low values of Ψstem and E except in NE-T in June and NB-ZT in September (Figure 2). This could suggest that olive trees had a good conservation strategy of the available water, maintaining a low E so that environmental conditions do not determine rapid water loss. A relatively humid environment, a moderate temperature without excessive water stress could indicate that the trees are in a balanced physiological state. On the other hand, in July and August, $VPD_{leaf\ air}$ Tl and E were higher and the Ψstem was more negative, this may contribute to a water stress situation. Indeed, water demand is high (high transpiration) but soil water availability is limited (low water potential). The same situation emerges for 2023 when high temperatures persisted until September. Trees with decreasing water content in the soil reduced respiration activity, however this phenomenon in anisohydric species and especially in olive occurs to a much reduced extent due to the phenomenon of osmotic adjustment that allows the maintenance of cell turgor, which in turn plays a key role in stomatal opening (Gucci et al., 2012). Osmotic adjustment is mainly due to the accumulation of mannitol, glucose and organic acids (Xiloyannis et al., 1999). The $VPD_{leaf\ air}$ values registered an opposite trend compared to the Ψstem (Figure 3), highlighting an increase in E and in iWUE, while a reduction in WUE_{inst}. was observed particularly during the warmest months across the three years. This effect leading to a reduction in $WUE_{inst.}$ was also observed by Testi et al. (2008). Statistically significant differences were observed, with the ZT approach exhibiting higher values in both cultivars. During the dry/hot months, leaves exhibited higher temperatures reaching 45°C at 1.00 p.m. In particular, during the first two years, the hottest periods were registered in the third measurement date (DOY 226). In fact in the period from 10th to 16th of August the highest maximum temperatures reached 39.3 and 35.6°C, in 2021 and 2022 years, respectively. In 2023 the hottest period was registered in the second measurement date (DOY 196) when the average air max temperature registered values of 37.6°C between 10th July and 16th July. Moreover, during this month from 17th to 25th July the average maximum temperature was 44.1°C (peak 47.1°C). Under these conditions, the young olive trees were in conditions of water stress, implementing physiological adaptations to the limitative temperatures. No physical disorders were observed on leaves and stems; therefore, the young trees showed an anisohydric behavior, thus maintaining a transpiration rate during the hottest hours of the day. The maintenance of the transpiration rate represents a plant attempt for the control of the Tl and allow to absorb water to compensate the loss. As reported by Pedraza and Gonzalez-Andujar (2025) in hot, dry conditions typical of Mediterranean climate (high temperatures often exceeding 40°C in July and August), the herbaceous cover naturally dries out, minimizing competition with olive trees for water or nutrients.

NB better responded to biomass production under the ZT treatment compared to NE. Regarding the biometrical parameters, the factorial analysis (Table 3) over the 3 years indicated that cultivar and year followed by soil management had the highest impact on the considered parameters of the young olive trees, infact TCSA and canopy volume under different soil management did not show any difference. On the contrary, NE highlighted a significant variability between the compared soil managements showing a higher canopy surface and volume under ZT, despite produced less material from pruning.

Conclusions

Our study demonstrates the positive impact of conservation agriculture practices on the growth of young olive trees. Both soil management techniques, T and TZ, induced favorable effects including agronomic, ecological, and economic aspects. The decision to minimize the tillage approach in order to reduce the soil disturbance, significantly contributed to enhancing water control, as evidenced by the physiological findings indicating moderate water stress in olive trees during the dryer/warmer periods (summers).

The analysis of physiological parameters highlighted the importance of temporal variables, such as year and DOY. From the results of our study, the interaction between cultivars and soil management emerged, regarding in particular the water potential and the intrinsic water use efficiency.

Although some experiences suggest that reducing soil tillage in a young olive plantation determines negative effect on yields, attributed to the early establishment of permanent cover, our results seem to suggest different effects on the growth in relation to the cultivar. Morphological analysis showed that not always a reduction was observed in plant growth and ZT condition has not provided a negative response in terms of photosynthetic rates when compared to conventional tillage. So, the results emphasized the importance of cultivar selection. Both cultivars showed strengths and weaknesses under the different soil management tested conditions. In particular, NE exhibited similar growth under both soil management methods, whereas NB resulted more stressed under ZT. Furthermore, our results underline that adopting conservation agriculture strategies offers more benefits, not only by promoting plant growth but also facilitating efficient water management and reducing work and cost in agreement with sustainable and ecological agricultural practices.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Italian Ministry of Agriculture, Food Sovereignty and Forestry (Project PERILBIO – "Promozione E Rafforzamento dei dispositivi di Lungo periodo In agricoltura BIOlogica", D.M. 3400 del 20.12.2018 – D. M. 92011 del 21.12.2018) and by European Commission (Project SUPPORT - Supporting UPtake Integrated Pest Management and lOw-Risk pesTicide Use. Grant Agreement Number 101084527 – European Commission Research Executive Agency - Call: HORIZON-CL6-2022-FARM2FORK-01; Topic: HORIZON-CL6-2022-FARM2FORK-01-02; Type of action: HORIZON Research and Innovation Actions).

Data Availability Statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author Bio

Carmen Arlotta: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Giuseppina Las Casas**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Alessio Giuffrida**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Biagio Torrisi**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Elisabetta Nicolosi**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Enrico Maria Lodolini**: Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Margherita Amenta**: Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Filippo Ferlito**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

References

Abid, M., and R. Lal. 2009. Tillage and drainage impact on soil quality: II. Tensile strength of aggregates, moisture retention and water infiltration. Soil Till. Res. 103(2):364–372. doi: 10.1016/j.still.2008.11.004.

Ahumada-Orellana, L., S. Ortega-Farías, C. Poblete-Echeverría, and P.S. Searles. 2019. Estimation of stomatal conductance and stem water potential threshold values for water stress in olive trees (cv. Arbequina). Irrig. Sci. 37 (4):461–467. doi: 10.1007/s00271-019-00623-9.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements FAO, Rome. Irrig. Drain. 56, 300(9):Article D05109.

Bacelar, E.A., C.M. Correia, J.M. Moutinho-Pereira, B.C. Goncalves, J.I. Lopes, and J.M. Torres-Pereira. 2004. Sclerophylly and leaf anatomical traits of five field-grown olive cultivars growing under drought conditions. Tree Physiol. 24(2):233–239. doi: 10.1093/treephys/24.2.233.

Bacelar, E.A., J.M. Moutinho-Pereira, B.C. Gonçalves, H.F. Ferreira, and C.M. Correia. 2007. Changes in growth, gas exchange, xylem hydraulic properties and water use efficiency of three olive cultivars under contrasting water availability regimes. Environ. Exp. Bot. 60(2):183–192. doi: 10.1016/j.envexpbot.2006.10.003.

Bacelar, E.A., J.M. Moutinho Pereira, B. Gonçalves, and C. Correia 2009. Physiological responses of different olive genotypes to drought conditionc. Acta Physiologiae Plantarum 31(3):611–621. doi: 10.1007/s11738-009-0272-9.

Ben Abdallah, M., D. Trupiano, A. Polzella, E. De Zio, M. Sassi, A. Scaloni, M. Zarrouk, N. Ben Youssef, and G.S. Scippa. 2018. Unraveling physiological, biochemical and molecular mechanisms involved in olive (*Olea europaea* L. cv. Chétoui) tolerance to drought and salt stresses. J. Plant. Physiol. 220:83–95. doi: 10.1016/j.jplph.2017.10.009.

Boughalleb, F., and H. Hajlaoui. 2011. Physiological and anatomical changes induced by drought in two olive cultivars (cv Zalmati and Chemlali). Acta. Physiol. Plant. 33(1):53–65. doi: 10.1007/s11738-010-0516-8.

Boussadia, O., F. Ben Mariem, B. Mechri, W. Boussetta, M. Braham, and S.B. Hadj. 2008. Response to drought of two olive tree cultivars (cv koroneki and Meski). Sci. Hortic. 116(4):388–393. doi: 10.1016/j.scienta.2008.02.016.

Boussadia, O., A. Omri, and N. Mzid. 2023. Eco-physiological behavior of five Tunisian olive tree cultivars under drought stress. Agronomy 13(3):720. doi: 10.3390/agronomy13030720.

Boussadia, O., A. Omri, and N. Mzid 2023. Eco-physiological behavior of five Tunisian olive tree cultivars under drought stress. Agronomy 13(3):720. doi: https://doi.org/10.3390/agronomy13030720.

Brito, C., L. Dinis, J. Moutinho-Pereira, and C. Correia. 2019. Drought stress effects and olive tree acclimation under a changing climate. Plants 8(7):232. doi: 10.3390/plants8070232.

Chartzoulakis, K., A. Patakas, and A. Bosabalidis. 1999. Changes in water relations photosynthesis and leaf anatomy induced by intermittent drought in two olive cultivars. Environ. Exp. Bot. 42(2):113–120. doi: 10.1016/S0098-8472(99)00024-6.

Ciaccia, C., A. La Torre, F. Ferlito, E. Testani, V. Battaglia, L. Salvati, and G. Roccuzzo. 2019. Agroecological practices and agrobiodiversity: A case study on organic orange in southern Italy. Agronomy 9(2):85. doi: 10.3390/agronomy9020085.

Esmaeilpour, A., M.C. Van Labeke, R. Samson, P. Boeckx, and P. Van Damme. 2016. Variation in biochemical characteristics, water status, stomata features, leaf carbon isotope composition and its relationship to water use efficiency in pistachio (*pistacia vera* L.) cultivars under drought stress condition. Sci. Hortic. 211:158–166. doi: 10.1016/j.scienta.2016.08.026.

Evans, J.R., and F. Loreto. 2000. Acquisition and diffusion of CO_2 in higher plant leaves, pp. 321–351. In: R.C. Leegood, T.D. Sharkey, and S. von Caemmerer (eds.). Photosynthesis: Physiology and metabolism. Kluwer Academic, Publishers, Dordrecht.

Ferlito, F., M. Di Guardo, M. Allegra, E. Nicolosi, A. Continella, S. La Malfa, A. Gentile, and G. Distefano. 2021. Assessment of chilling requirement and threshold temperature of a low chill pear (*Pyrus communis* L.) germplasm in the mediterranean area. Horticulturae 7(3):45. doi: 10.3390/horticulturae7030045.

Ferlito, F., B. Torrisi, M. Allegra, F. Stagno, P. Caruso, and G. Fascella. 2020. Evaluation of conifer Wood Biochar as growing media component for citrus nursery. Appl. Sci 10:1618.

Fernández, J.E., F. Moreno, I.F. Girón, and O.M. Blázquez. 1997. Stomatal control of water use in olive leaves. Plant. Soil 190(2):179–192. doi: 10.1023/A:1004293026973.

Fernández, J.E., A. Perez-Martin, J.M. Torres-Ruiz, M.V. Cuevas, C.M. Rodriguez-Dominguez, S. Elsayed-Farag, A. Morales-Sillero, G. García, V. Hernandez-Santana, and A. Diaz-Espejo. 2013. A regulated deficit irrigation strategy for hedgerow oliveorchards with high plant density. Plant. Soil 372(1–2):279–295. doi: 10.1007/s11104-013-1704-2.

Frank, A.B., J.F. Power, and W.O. Willis. 1973. Effect of temperature and plant water stress on photosynthesis, diffusion Resistance, and leaf water potential in Spring wheat 1. Agron. J. 65(5):777–780. doi: 10.2134/agronj1973.00021962006500050031x.

Giorgi, F. 2006. Climate change hot spots. Geophys. Res. Lett. 33(8):L08707.

Giorgi, V., S. Crescenzi, L. Marconi, M. Zucchini, G. Reig, and D. Neri. 2022. Living mulch under the row of young peach orchard. Acta Hortic. 1352(1352):193–198. doi: 10.17660/ActaHortic.2022.1352.26.

Giorio, P., G. Sorrentino, and R. d'Andria. 1999. Stomatal behaviour, leaf water status and photosynthetic response in fieldgrown olive trees under water deficit. Environ. Exp. Bot. 42:95–104.

Girona, J., M. Luna, M. Arbones, J. Mata, J. Rufat, and J. Marsal. 2002. Young olive trees responses (*Olea europea*, cv "Arbequina") to different water supplies. Water function determination. Acta Hortic. 568(586):277–280. doi: 10.17660/ActaHortic.2002.586.53.

Goldhamer, D.A., and E. Fereres. 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig. Sci. 20(3):115–125. doi: 10.1007/s002710000034.

Gucci, R., G. Caruso, C. Bertolla, S. Urbani, A. Taticchi, S. Esposto, M. Servili, M.I. Sifola, S. Pellegrini, M. Pagliai, et al. 2012. Changes of soil properties and tree performance induced by soil management in a high-density olive orchard. Eur. J. Agron. 41:18–27. doi: 10.1016/j.eja.2012.03.002.

Guerfel, M., O. Baccouri, D. Boujnah, W. Chaïbi, and M. Zarrouk. 2009. Impacts of water stress on gas exchange, water relations, chlorophyll content and leaf structure in the two main Tunisian olive (*Olea europaea* L.) cultivars. Scientia. Hortic. 119(3):257–263. doi: 10.1016/j.scienta.2008.08.006.

Jarvis, A.J., T.A. Mansfield, and W.J. Davies. 1999. Stomtal behaviour, photosynyhesis and transpiration under rising CO_2. Plant. Cell. & Environ. 22(6):639–648.

Karimi, S., M. Rahemi, A.A. Rostami, and S. Sedaghat. 2018. Drought effects on growth,Water content and osmoprotectants in four olive cultivars with different drought tolerance. Int. J. Fruit Sci. 18(3):254–267. doi: 10.1080/15538362.2018.1438328.

Klingebiel, A.A., and P.H. Montgomery 1961. Land Capability Classification, p. 21. USDA Agricultural Handbook n. 210. Soil Conservation Service. US Government Printing Office, Washington, DC.

Las Casas, G., C. Ciaccia, V. Iovino, F. Ferlito, B. Torrisi, E.M. Lodolini, A. Giuffrida, R. Catania, E. Nicolosi, and S. Bella. 2022. Effects of different inter-row soil management and intra-row living mulch on spontaneous Flora, beneficial insects, and growth of young olive trees in southern Italy. Plants 11(4):545. doi: 10.3390/plants11040545.

Lodolini, E., and E. Ciaccia. 2022. Inter-row weed management in a young high-density olive orchard Acta Hortic. 1354. Acta Hortic. (1354):41–48. doi: 10.17660/ActaHortic.2022.1354.6.

Marino, G., T. Caruso, L. Ferguson, and F.P. Marra. 2018. Gas exchanges and stem water potential define stress thresholds for efficient irrigation management in olive (*Olea europea*. Water. 10(3):342. doi: 10.3390/w10030342.

Matthews, M.A., M.M. Erson, and H.R. Schultz. 1987. Phenological and growth responses to early and late season water deficits in cabernet franc. Vitis 26:147–160.

Maxwell, K., and G.N. Johnson. 2000. Chlorophyll fluorescence a practical guide. J. Exp. Bot. 51(345):659–668. doi: 10.1093/jexbot/51.345.659.

Michalopoulos, G., K.A. Kasapi, G. Koubouris, G. Psarras, G. Arampatzis, E. Hatzigiannakis, V. Kavvadias, C. Xiloyannis, G. Montanaro, S. Malliaraki, et al. 2020. Adaptation of Mediterranean olive groves to climate change through sustainable cultivation practices. Climate 8(4):54. doi: 10.3390/cli8040054.

Nicolosi, E., F. Ferlito, M. Allegra, A. Cicala, F. Trovato, and S. La Malfa. 2016. Influences of aspect and tillage on two winegrape cultivars on Mount Etna. New Zealand J. Crop Hortic. Sci. 44(2):83–102. doi: 10.1080/01140671.2016.1147472.

Nicolosi, E., V. Iovino, G. Distefano, M. Di Guardo, S. La Malfa, A. Gentile, A. Palliotti, G. Las Casas, and F. Ferlito. 2021. Mid-term effects of conservative soil management and fruit-zone early leaf removal treatments on the performance of nerello mascalese (*Vitis vinifera* L.) grapes on Mount Etna (southern Italy). Agronomy 11(6):1070. doi: 10.3390/agronomy11061070.

Nieto, O.M., J. Castro, and E. Fernández. 2012. Sustainable agricultural practices for Mediterranean olive groves. The effect of soil management on soil properties. Span J. Soil Sci. 2:70–77. doi: 10.3232/sjss.2012.v2.n1.05.

Ozpinar, S., and A. Cay. 2006. Effect of different tillage systems on the quality and crop productivity of a clay–loam soil in semi-arid north-western Turkey. Soil Till. Res. 88(1–2):95–106. doi: 10.1016/j.still.2005.04.009.

Palese, A.M., N. Vignozzi, G. Celano, A.E. Agnelli, M. Pagliai, and C. Xiloyannis. 2014. Influence of soil management on soil physical characteristics and water storage in a mature rainfed olive orchard. Soil Tillage Res. 144:96–109. doi: 10.1016/j.still.2014.07.010.

Parras-Alcántara, L., and B. Lozano-García. 2014. Conventional tillage versus organic farming in relation to soil organic carbon stock in olive groves in Mediterranean rangelands (southern Spain). 2014. Solid Earth 5(1):299–311. doi: 10.5194/se-5-299-2014.

Pedraza, V., and J.L. Gonzalez-Andujar. 2025. Integrated weed management in olive orchard: The effect of spontaneous grass cover crops on weed community, olive production and soil fertility. Eur. J. Agron. 169:127706. doi: 10.1016/j.eja.2025.127706.

Pittarello, M., A. Dattola, G. Gullo, G. Badagliacca, M. Monti, and A. Gelsomino. 2024. Olive tree physiology and productivity responses under No-tillage or digestate amendment in an acid clay soil. Soil Syst. 8(1):13. doi: 10.3390/soilsystems8010013.

Quideau, S.A., M.A. Anderson, R.C. Graham, O.A. Chaddwick, and S.E. Trumbore. 2000. Soil organic matter processes: Characterization by 13C NMR and 14C measurements. For. Ecol. Manag. 138(1–3):10–27. doi: 10.1016/S0378-1127(00)00409-6.

R Core Team. 2022. R-4.2.0 for windows. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://cran.r-project.org/bin/windows/base/old/4.2.0/.

Roussos, P.A., D. Gasparatos, K. Kechrologou, P. Katsenos, and P. Bouchagier. 2017. Impact of organic fertilization on soil properties, plant physiology and yield in two newly planted olive (*Olea europaea* L.) cultivars under Mediterranean conditions. Scientia. Hortic. 220:11–19. doi: 10.1016/j.scienta.2017.03.019.

Saitta, D., D. Vanella, J.M. Ramírez-Cuesta, G. Longo-Minnolo, F. Ferlito, and S. Consoli. 2020. Comparison of orange orchard evapotranspiration by eddy covariance, sap flow, and FAO-56 methods under different irrigation strategies. J. Irrig. Drain Eng. 146(7):05020002. doi: 10.1061/(ASCE)IR.1943-4774.0001479.

Sofo, A., A.N. Mininni, C. Fausto, M. Scagliola, C. Crecchio, C. Xiloyannis, and B. Dichio. 2019. Evaluation of the possible persistence of potential human pathogenicbacteria in olive orchards irrigated with treated urban wastewater science of the total environment 658. Sci. Total Environ. 658(2019):763–767. doi: 10.1016/j.scitotenv.2018.12.264.

StatSoft Italia srl. 2001. STATISTICA (sistema software di analisi dei dati), versione 6. www.statsoft.it.

Tanasijevic, L., M. Todorovic, L.S. Pereira, C. Pizzigalli, and P. Lionello. 2014. Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. Agric. Water. Manag. 144:54–68. doi: 10.1016/j.agwat.2014.05.019.

Tekaya, M., B. Mechri, O. Dabbaghi, Z. Mahjoub, S. Laamari, B. Chihaoui, D. Boujnah, M. Hammami, and H. Chehab. 2016. Changes in key photosynthetic parameters of olive trees following soil tillage and wastewater irrigation, modified olive oil quality. Agric. Water. Manag. 178:180–188. doi: 10.1016/j.agwat.2016.09.023.

Testi, L., F. Orgaz, and F. Villalobos. 2008. Carbon exchange and water use efficiency of a growing, irrigated olive orchard. Environ. Exp. Botany 63.1(3):168–177.

Torrisi, B., M. Allegra, M. Amenta, F. Gentile, P. Rapisarda, S. Fabroni, and F. Ferlito 2021. Physico-chemical and multielemental traits of anaerobic digestate from Mediterranean agro-industrial wastes and assess-ment as fertiliser for citrus nurseries. Waste Manag. 131:201–213.

Trentacoste, E.R., O. Contreras-Zanessi, V. Beyá-Marshall, and C.M. Puertas. 2018. Genotypic variation of physiological and morphological traits of seven olive cultivars under sustained and cyclic drought in Mendoza, Argentina. Agric. Water. Manag. 196:48–56. doi: 10.1016/j.agwat.2017.10.018.

Vanella, D., F. Ferlito, B. Torrisi, A. Giuffrida, S. Pappalardo, D. Saitta, G. Longo-Minnolo, and S. Consoli. 2021. Long-term monitoring of deficit irrigation regimes on citrus orchards in sicily. J. Agric. Eng. 52(4):23. doi: 10.4081/jae.2021.1193.

Wickham, H. 2016. ggplot2: Elegant graphics for data analysis. pp. 189–201. Springer-Verlag New York. https://ggplot2.tidyverse.org. ISBN 978-3-319-24277-4.

Xiloyannis, C., B. Dichio, V. Nuzzo, and G. Celano. 1999. Defence strategies of olive against water stress. Acta Hortic. 474(474):423–426. doi: 10.17660/ActaHortic.1999.474.86.

Xiloyannis, C., A. Martinez Raya, C. Kosmas, and M. Favia. 2008. Semi-intensive olive orchards on sloping land: Requiring good land husbandry for future development. J. Environ. Manage. 89(2):110–119. doi: 10.1016/j.jenvman.2007.04.023.