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Addition of compost changed responses of soil-tree system in olive groves in relation to the irrigation strategy

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ABSTRACT

Intensification of olive production could suppose an increase of natural resources consumption as well as an acceleration of soil degradation. Studies of soil and trees combining different strategies of water management and fertilization to solve these drawbacks are scarce and contradictory. The aim of this work was to describe the effect of organic and inorganic fertilization in soil parameters (water availability, physico-chemical properties and greenhouse gas emissions) and tree development (fruit and crown growth pattern) in rainfed and irrigated conditions in two different olive systems (hedgerow and intensive). The solid olive-mill by-product called "Alperujo" compost (AC) was added as organic fertilization in both systems and two irrigation managements (full and deficit) at the hedgerow sites were also considered. The addition of AC tended to increase soil water retention and soil organic matter (SOM), displaying on average about 15% and 20% more respectively in soils treated compared to their controls in both experiments. Irrigation rather than compost addition was the factor controlling the evolution of both fruit and tree growth. However, AC seemed influenced fruit production specially at the hedgerow system that yielded 30% and 41% more for the deficit and full irrigation management with compost than their respective controls. Emissions of GHE did not generally increase with the AC addition and showed a marked seasonal character in both sites. Regardless irrigation, at the hedgerow site, the full irrigation regimen tended to increase CO_2 and CH_4 soil fluxes. The agronomic use of organic wastes combined with a deficit irrigation strategy proved to be an efficient tool for nutrient recycling, and promoting a zero waste circular economy and a water conservation strategy.

1. Introduction

Olive cultivation in Mediterranean areas has been traditionally low-input rainfed systems, with low tree densities located in marginal areas. However, the trend towards olive grove intensification to meet society's needs in these areas characterized by medium to poor soil fertility and water scarcity is having a significant impact on water and soil resources (Gómez-Limón et al., 2012; Kavvadias and Koubouris, 2019; Kostelenos and Kiritsakis, 2017). Although there is no doubt of the environmental problems that this fast and large-scale intensification is causing (i.e. increased rates of soil fertility loss, over-exploitation of water resources, increased use of fertilizers) (Fernández-Lobato et al., 2021; Zipori et al., 2020), there is also a growing recognition of the potential of agricultural practices to somehow palliate and compensate for these adverse consequences. In this sense, fertilization and irrigation control have been pointed out as pivotal management tools to preserve soil fertility and water resources maintaining, in turn, production (Bai et al., 2018; Li et al., 2021).

Soil organic amendments through compost have been postulated as a solid instrument to increase C stocks, potentially constraining at the same time, soil greenhouse gases (GHG) emissions namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in agroecosystems (Calvano and Tamborrino, 2022; de Sosa et al., 2022; Forte et al., 2017; Thangarajan et al., 2013). Soils are closely entangled with atmospheric and climate processes through the C, N, and hydrologic cycles. In fact, new strategies intended to reduce the environmental impacts of olive groves and improve soil quality are focused on enhancing and preserving soil organic matter (SOM) limiting emissions (Brevik, 2012; Brilli

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et al., 2019; Kavvadias and Koubouris, 2019). However, this effective and complex link between nutrient storage- irrigation and reduction of GHG emissions is not well understood. Some studies have showed that depending on the nature of the organic amendment, rate and time of application, soil characteristics, climatic conditions and spreading methods a priming effect of the native SOM can result and also soil-borne GHG emissions can be enhanced compared to mineral fertilizers (Brenzinger et al., 2021; De Rosa et al., 2018; Graham et al., 2017; Thangarajan et al., 2013).

Together with fertilization, the irrigation management can exert a strong influence on nutrient availability and leaching, soil properties and SOM mineralization (Khaliq and Kaleem Abbasi, 2015; Morgado et al., 2022; Zipori et al., 2015). Researches on this field have demonstrated that irrigation management can maximize the agronomic performance of the organic amendments increasing yield and biomass production or improve soil properties (Hirich et al., 2014; Kavvadias and Koubouris, 2019; Mairech et al., 2021; Michalopoulos et al., 2020) while other studies found no significant relation between the irrigation management and significant changes in most of the soil chemical and microbial parameters (Kavvadias et al., 2018). Sanz-Cobena et al. (2017) showed how changes in soil conditions between irrigated and rainfed crops could heavily alter soil microbial processes involved in C (CO_2, CH_4) and N (N_2O) fluxes drastically altering the reserves of these elements in the soil. Likewise, Sapkota et al. (2020) concluded that optimizing irrigation may assist in reducing CH_4 emissions and net global warming potential (GWP). Other studies, however, have pointed to lower the intensification of olive groves (i.e. tree densities and irrigation vs rainfed) as the key to reduce the emission and C footprint (Fernández-Lobato et al., 2021). Therefore, establishing solid nexus between irrigation and soil amendment is of vital importance to promote natural resources conservation and olive groves productivity in systems with different demands especially under a climate change scenario.

Olive trees have showed an enormous capacity to store $CO_{2\text{-eq}}$ mainly in their fruits and through plant growth (Brilli et al., 2019; Proietti et al., 2016). In this sense, some studies have showed the potential of olive wastes derived compost to increase vegetative growth improving, therefore, C sequestration (Proietti et al., 2015). Amendments derived from pomace originated from 2-phase olive oil extraction process called in Spanish “alperujo” (AC) (the major wastes from the oil industry) have been showed to alter the availability of N inorganic and organic forms, P and K content during SOM decomposition (de Sosa et al., 2022; Panettieri et al., 2022). However, this nutrient availability provided by the organic amendment that it is needed to achieve a growth improvement could be restricted under conditions of water stress (Ekinci et al., 2015). It is clear and fully established for obvious reasons the direct repercussion that irrigation has on fruit development and vegetative growth (Caruso et al., 2014; Gucci et al., 2019a). However, the number of studies that integrate the synergetic effects of the organic amendments and irrigation regimens in olive systems with different densities and therefore different nutritional needs is very limited.

The aim of the present study was to evaluate the effect of fertilization and irrigation management in two different systems: traditional rainfed and high density in hedgerow olive systems to identify the potential to carbon sequestration and GWP. Specifically, we aim to assess (1) broad changes in patterns of SOM decomposition over time (2) emissions patterns of GHG emissions after the addition of an exogenous source of C with and without irrigation control (3) fruit and crown growth and yield responses.

2. Materials and methods

2.1. Experimental area and experimental design

Experimental plots were located at the agriculture experimental farm “La Hampa'' of the “Instituto de Recursos Naturales y Agrobiología de Sevilla (IRNAS-CSIC)'' (37°17’01.8"N 6°03’57.4"W). The soil is a calcic Cambisol (IUSS Working Group WRB, 2015) characterized by a sandy clay loam texture, low fertility, and low organic matter content (pH: 7.5; TOC: 8 g kg^{-1}; N: 0.8 g kg^{-1}; Olsen P: 10 mg kg^{-1}; Available-K: 200 mg kg^{-1}). The climate is typically Mediterranean, with 3–5 months of summer droughts and moderately wet cool winters. A summary of the meteorological data of the experimental area can be found in Fig. 1.

Treatments were applied between December 2020 and June 2022 in two olive grove areas with different managing strategies. The first experimental site was set in an area of 0.7 ha of a young olive grove of cultivar Manzanilla, planted in a pattern of 4 m × 1.5 m as a hedgerow system established in 2018. The area was divided into 12 plots (ca. 410 m^2 consisting of 5 lines of trees, 1.666 trees ha-1) and had a completely randomized design with irrigation and fertilization as the main experimental factors as explained in Fig. 1. The second study site was located in an area of 1.2 ha of an adult olive grove of the cv Manzanilla, planted in a pattern of 7 m × 5 m with intensive management under rainfed conditions established in 1997. The plantation has always remained rainfed. The study site was divided into 20 plots (ca. 400 m^2, 285 trees ha^{-1}) of which 8 were selected to carry out the present experiment based on their treatment history (Fig. 1).

2.1.1. Fertilization

Fertilization treatments included control plots with mineral fertilization and plots treated with AC (60% “alperujo” and 40% pruning wastes and legumes). The main characteristics of the compost can be found in Table S1. The product was supplied by an olive oil cooperative after a composting process for more than 12 months. A chronogram of the compost addition in both sites is provided in Fig. S1.

Specifically, fertilization treatments were applied as follows:

-AC fertilization treatment had several applications (Fig. S1):

- In December 2020, AC was applied only in the intensive plots with a fertilizer spreader in the lanes in between the tree rows and incorporated manually into the soil at a rate of 17 t ha^{-1} with the aim to increase SOC by at least 20% of the initial soil C content.
- In July 2021, the same product with the same dose and procedure to be incorporated into the soil as mentioned above was applied in the hedgerow plots
- In March 2022, AC at the same rate of 17 t ha^{-1} was applied as described before in both sites.

-Mineral fertilization in control plots had a different fertilization plan in each site:

- In March 2022, Nitrofoska perfect (15−5-20) at a rate of 286 kg ha^{-1} at the intensive rainfed site and 105 kg ha^{-1} at the hedgerow site to meet plant needs.
- Hedgerow site was completed with fertirrigation at a variable rate (Table S2) for the treatments of full and deficit irrigation along 2022 season.

Additionally, trees of all treatments were supplemented with three foliar applications of KNO_3 at a rate of 12.5 kg ha^{-1} each time and one application of B (2 l ha^{-1}) before fruit set each year. Phytosanitary treatments consisted of the application of Cu as a fungicide and two applications of dimethoate as an insecticide.

2.2. Irrigation regimes

Irrigation management for the hedgerow system were full irrigation (F) and deficit irrigation (D). The trees water status was characterised with stem water potential (Ψ) and leaf conductance. The water potential was measured at midday in one leaf per tree, using the pressure chamber technique (Scholander et al., 1965). The leaves near the main trunk were covered in aluminium foil at least two hours before measurements were taken every 7–10 days. Leaf conductance was measured at midday in the

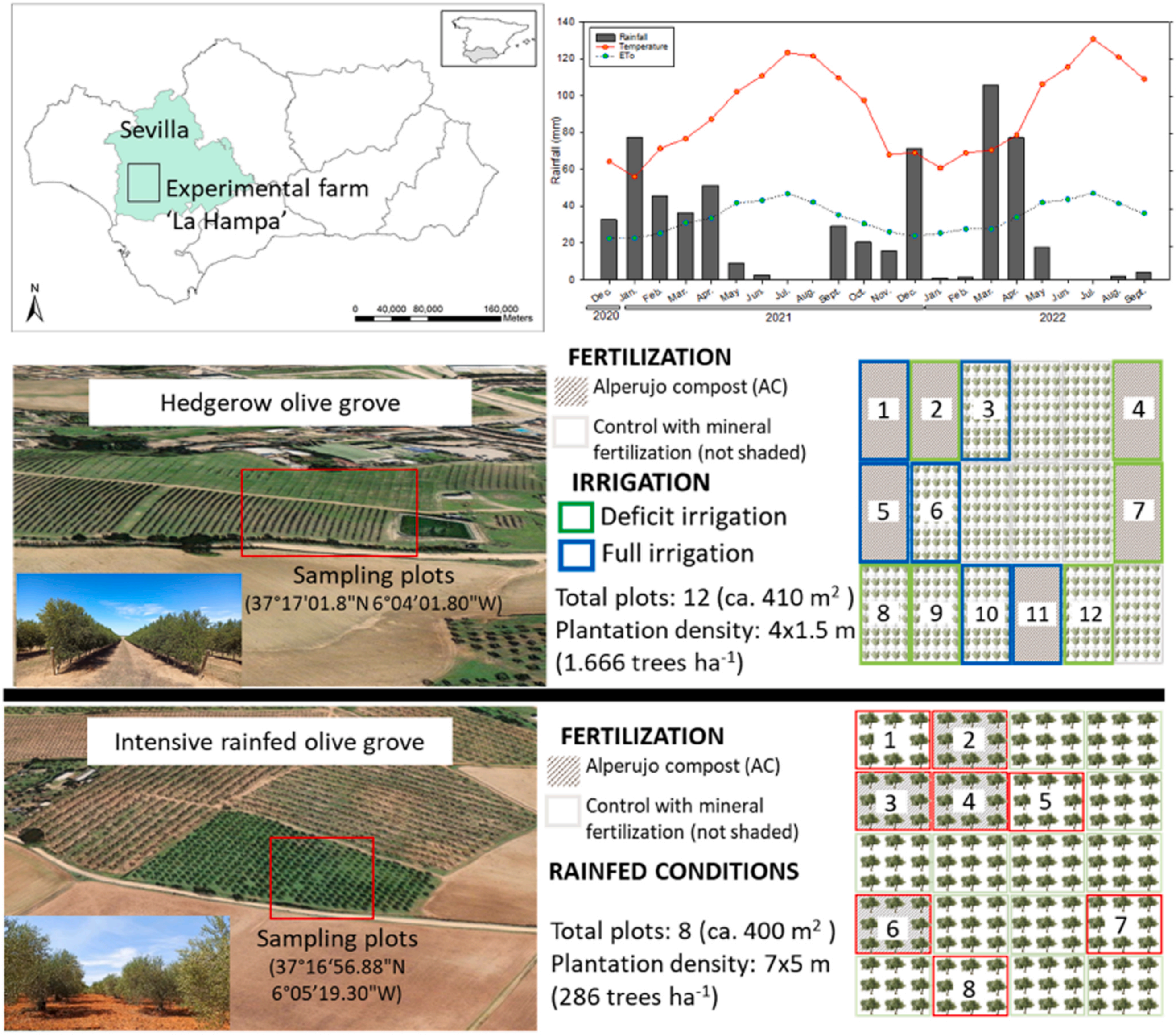


Fig. 1. Experimental sites and climatic conditions in two olive grove areas with different management strategies at the experimental farm 'La Hampa' located in Coria del Río, Seville (Spain).

same trees that water potential with a dynamic diffusion porometer (DC-1, Decagon, UK). Irrigation was carried out during the night by drip, using one lateral pipe per row of trees and three emitters per plant, delivering 2 L h^{-1} each. All the measurements were made on the central tree in the intensive plots or the centre line of trees (out of 5 lines of trees per plot) in the hedgerow plots. Specifically,

(1)The full irrigation regimen was programmed to supply the 100% of the crop evapotranspiration (ETc). This water dose was increased to 125% ETc if the water potential measurements were more negative than those estimated by the baseline established in Corell et al. (2016). The ETc was estimated by means of a soil water balance approach following the FAO methodology (Doorenbos and Pruitt, 1977) in which ETc is calculated as a product of three terms: ETc= ETo x Kc x Kr where ETo is the reference evapotranspiration obtained from the nearest agro weather station, Kc is a crop coefficient set in 0.6 for our case and Kr is the reduction coefficient based on the soil surface covered by the plantation crown set in 1 for our particular case. Same irrigation treatment combined with the compost addition is stated as FC.

(2) Deficit irrigation regimen maintained conditions of low to moderate stress during several phenological stages. The water dose was 1 mm/day along the irrigation season. This applied water was changed accordingly to the water status and phenological stages of the trees. During all the seasons, except the pit hardening period, from mid-June to the end of August, water potential was compared with Corell et al. (2016)'s baseline. Applied water was increased (in 1, 2, 3 mm) when measured values were more negative than expected (10%, 20% 30% more negative). During the pit hardening, the threshold value decreased until − 2 MPa according to Girón et al. (2015). Same irrigation treatment combined with the compost addition is stated as DC.

A detailed description of the amount of water provided monthly according to the irrigation treatment can be found in Table S3.

The intensive sites were under rainfed conditions noted as R or RC if AC was applied.

2.3. Soil sampling and chemical analysis

Three soil cores (0–10 cm) per plot were taken and merged together to obtain a composite sample in November 2021, March, April and September 2022 in both experimental sites to test the different degrees of AC decomposition. After sieving at 2 mm, soil samples were air dried for chemical analysis.

Sample dry weights were used to calculate soil gravimetric water content (GWC) by the gravimetric method. Soil organic matter was calculated by dichromate oxidation and titration with ferrous ammonium sulphate (Walkley and Black, 1934). Water-soluble carbon (WSC) content was determined using a TOC-VE Shimadzu analyzer after extraction with water using a sample-to-extractant ratio of 1:10.

2.4. Gas sampling

Fluxes of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) were measured using the static closed chamber method. Briefly, a PVC cylinder (15 cm height) was placed into the soil next to the central tree of each plot at the intensive area and in the middle of the center line of trees at the hedgerow plots on a weed-free representative area at an approximately depth of 5 cm, at least one week before measurements. Just before the measurement, the cylinder was gas-tight closed with a septum placed inside. Gas samples were taken at 0, 0.5 and 1 h after cylinder closure using a 10-mL polypropylene syringe (Becton-Dickson, Plastipak™), and 5 mL of gas sample was transferred to an evacuated 4.5-mL Exetainer® borosilicate glass vial (model 048 W, Labco, High Wycombe, UK). Gas samplings were conducted on July, September, November 2021 and on January, March, April and June 2022. At each sampling date, a flux measurement was taken in each of the 12 hedgerow plots (three replications in each of the four treatments, i.e. D, DC, F, FC) and of the 8 intensive plots (four replications of the treatments R and RC). Fluxes of CO_2 were expressed in mg C-CO_2 m^{-2} $h^{-1,}$ N_2O in µg N-N_2O m^{-2} h^{-1} and CH_4 fluxes in µg C-CH_4 m^{-2} h^{-1}.

Concentration of CO_2, N_2O and CH_4 in the air samples was measured by gas chromatography using an automatically injection system (PAL3 autosampler, Zwingen, Switzerland). The gas chromatography systems (Agilent 7890B, Agilent, Santa Clara, CA, United States) was equipped with an electron capture detector (ECD) and a HP-Plot Q column (15 m long, 320 µm in section and 20 µm thick), using He as a carrier gas at 2 mL min^{-1}. The injector and the oven temperatures were set to 50 and 35 °C, respectively. The temperature of the ECD was set to 280 ∘C and a 5% methane in Argon gas mixture at 30 mL min^{-}1 was used as a makeup gas. Ultra-high purity CO_2 and CH_4 standards (Carburos Metalicos, Barcelona, Spain) were used to calibrate the system.

A chronogram of the compost addition, soil and gas sampling, irrigation months performed during the experiment can be found in Fig. S1.

2.5. Profile of soil water content (SWC)

The profile of SWC was measured every 10 cm between the depths of 0.1 and 1 m using a portable profile probe FDR (PR2 y HH2, Delta T, U.K.) connected to a data logger prior to gas sampling (i.e. July, September, November 2021and January, March, April and June 2022). Profile Probes were used within access inserted into augered holes in the soil. The access tubes were placed in the central line of each plot (out of 5 lines of trees) at the hedgerow system and underneath the central tree of the plot in the intensive system and their reading was taken as representative of the water content of the zone. Different depth of soil water distribution (i.e. 0–20 and 0–100 cm) were represented to identify different patterns of SWC within the soil profile. Measurements were performed from July 2021 to June 2022. This period included two different growing season, 2021 with a great fruit load in hedgerow system (data not shown) and 2022 with very small yield. The initial manufacturer's default calibration for this type of soil optimized according to our soil conditions was employed (Delta-T Devices, 2016).

2.6. Olive fruit size, fruit yield and tree growth

Tree growth measurements were performed in March and September 2022 for which three olive trees per plot at the hedgerow system and the central tree of the plot at the intensive system were selected. Tree growth rate was calculated as the difference of tree volume growth between the initial and final measurements, divided by the number of days between them. To determine the crown volume, one vertical and two horizontal diameters of the crown were measured with the same frequency using a measuring pole with marks every 20 cm. It was assumed that the crown shape was similar to a sphere in order to estimate the volume.

Fruit size evolution was monitored during 2022 campaign. To do so, ten olive fruits were randomly selected each time from trees of each experimental plot in both systems and the fruit length, diameter and volume were recorded with a calimeter. Measurements started from day 133 (May 13th 2022, with the fruit formation and finished day 251 (September 8th 2022) just after the harvest for the olive grove in hedgerow and from day 169 (June th 2022) to day 294 (October 21st 2022) in the intensive system. For the regression equation of the intensive plots, it was only considered till day 188 (July 7th 2022) as the final point of the linear growth phase of the fruits, just before the water stress started.

Yield components in relation to the number of inflorescence per shoot and number of fruit per inflorescence was estimated in a sample of ten shoots per plot in both systems at day 237 (August 25th 2022). Olive harvest was carried out in September and November 2022, and the fruit yield was recorded for the total number of trees of each plot and treatment.

2.7. Statistical analysis

A two-way ANOVA was performed for the hedgerow plots to test the effect of compost addition and irrigation on soil physico-chemical parameters, tree growth, olive fruit size, number of inflorescences and fruits, yield and GHG emissions and a one-way ANOVA with compost addition as main factors was performed in the intensive plots. For all statistical tests, $p < 0.05$ was selected as the significance cut-off value. Statistical analysis was performed with SPSS v25 for Windows (IBM Corp., Armonk, NY).

3. Results

3.1. Soil water profile distribution

In general, different patterns of soil water distribution from the portable profile probe were detected along the soil profile (Fig. 2). The irrigation regimen exerted the greatest influence near the surface (0–20 cm, Fig. 2a). Thus, the F irrigation regime displayed on average in the months of July21 to April22 38% more SWC than the D regimen irrespective of the fertilization treatment that had little or no effect. In April22 a punctual reduction of ca. 44% of the SWC for the F treatment compared to FC was detected. In June22, the rise in temperatures and the lack of rainfall exacerbated this difference between the two irrigation regimens causing a reduction of the water content of 86% from the D regime to the F irrigation irrespective of the fertilization treatment.

Regarding the deeper soil layers (0–100 cm, Fig. 2c), the SWC tended to follow a pattern of greater water reduction/consumption in the plots receiving AC (i.e. DC, FC). Thus, in the months of July21, Sept21, November21 and January22 soil amended with mineral fertilization displayed on average 36% more SWC than the ones organically amended whereas in March22 all regimens tended to show quite similar water contents. In April22 and June22 the F irrigation showed on average 27% more SWC than the rest of the treatments amalgamated together.

Patterns of soil water distribution were very similar between the fertilization treatments at the intensive plots (Fig. 2b and d). The total profile showed greater water content in plots treated with AC in March22 and April22 (ca. 15%) whereas in June22 the trend tended to reverse displaying the control plots 9.8% more water than the RC treatment in the deep profile.

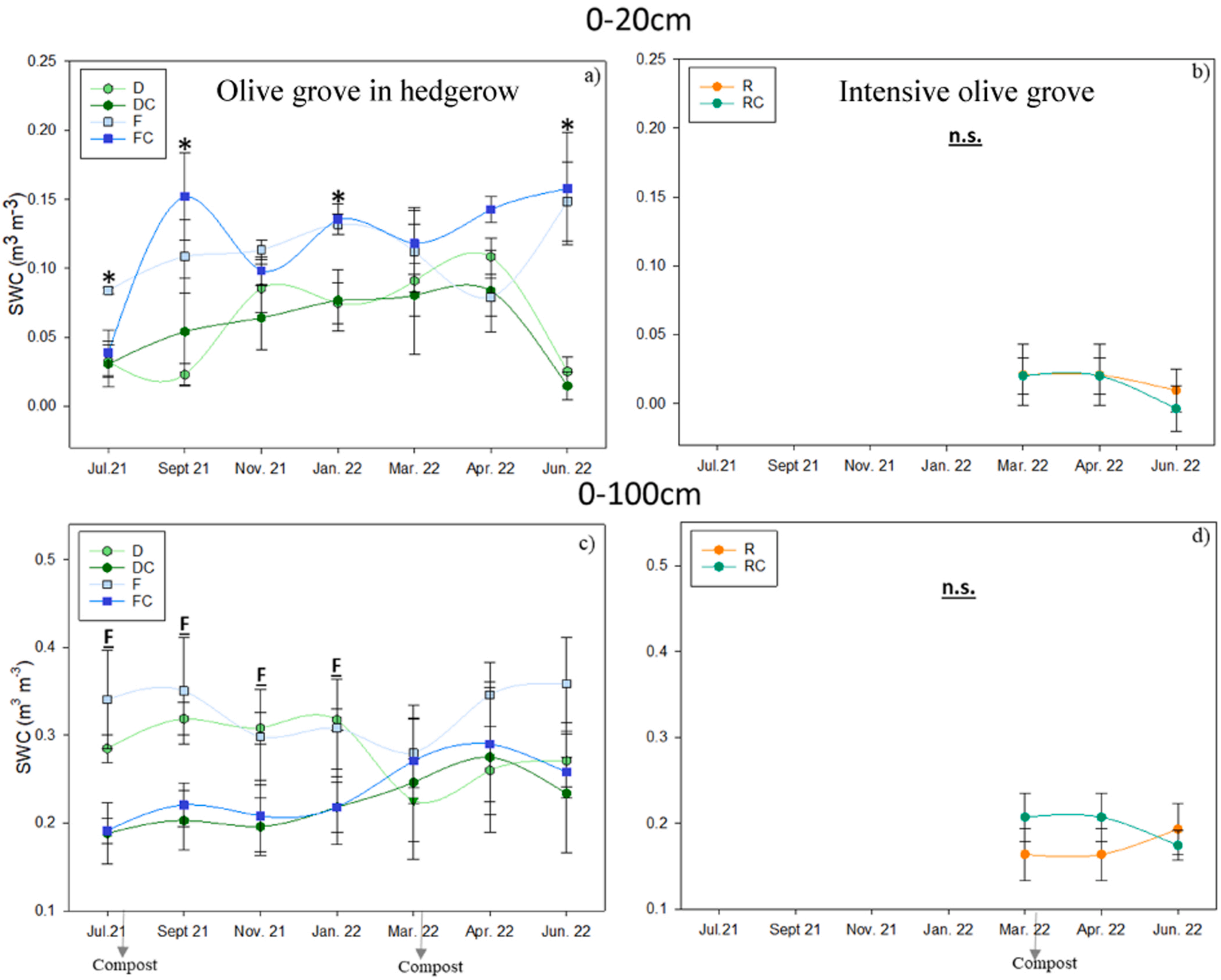


Fig. 2. Soil water content profile from the portable profile probe at the surface (0–20 cm) at the two experimental areas. Graphic on the left (a, c) corresponds to the olive grove in hedgerow with two irrigation regimes (D: deficit and F: full irrigation) and fertilization addition: compost (C) or no letter (Ø) to refer to the inorganic fertilization and graphic on the right (b, d) represents the intensive olive grove under rainfed conditions (R) with the addition of C or no letter (Ø) to refer to the inorganic fertilization at different sampling times. Portable profile probes were installed from March onwards at the intensive sites. The asterisk indicates significant differences ($p < 0.05$) with the irrigation regime within that sample time and significant differences concerning the compost addition are noted by F and no significant differences ($p > 0.05$) were noted by n.s. Data are mean values ($n = 3$ olive grove in hedgerow, $n = 4$ intensive olive grove) ± standard error of the mean (SEM).

3.2. Soil physical and chemical parameters

3.2.1. Hedgerow olive site under fertilization and irrigation management

A great oscillation with time of most of the soil chemical parameters was detected regardless the irrigation and fertilization treatments. The addition of AC rather than irrigation exerted the greatest influence on soil chemical parameters (Tables 1 and S5). Although it was only significant for the first sampling time, compost addition tended to promote soil GWC, displaying on average for all sampling times 20% and 11% more water content in soils with DC and FC treatments respectively compared to their respective controls. The same trend was seen for SOM which was promoted approximately 23% in plots treated with AC. The WSC was significantly affected by the AC addition in all sampling times (Tables 1 and S5, $p < 0.05$). Thus, the treatments with AC showed an average percentage for all sampling times of ca. 30% more than the control irrespective the irrigation regimen. The final balance expressed in % of C loss or store of SOM comparing the absolute values from November21 to September22 was of 8.20, − 14.8, 8.27, − 27.5% for the D, DC, F and FC respectively and for the WSC was 8.5, 12.6, 7.5,

Table 1
Results of ANOVA (F and *p*-value) showing the main significant factors (i.e. compost addition, irrigation or interactions) controlling changes in soil physical and chemical properties at the hedgerow plots. GWC: soil gravimetric water content, SOM: soil organic matter, WSC: water-soluble carbon.

ANOVA results		GWC		SOM		WSC	
		F	*p*	F	*p*	F	*p*
Compost addition	Nov. 2021	7.16	*	ns		18.8	* *
	Mar. 2022	ns		ns		22.7	* *
	Apr. 2022	ns		ns		26.2	*
	Sept. 2022	ns		ns		13.2	* *
Irrigation	Nov. 2021	ns		ns		ns	
	Mar. 2022	ns		ns		ns	
	Apr. 2022	23.5	* *	7.46	*	ns	
	Sept. 2022	21.3	* *	ns		10.5	*
Compost*irrigation	All sampling times	ns					

Significance level: *p < 0.05; * *p < 0.01

− 89.5% following the same order of treatments.

The irrigation effect was mainly detected in April22 in which the F regimen caused an increase of 14% in GWC and a reduction of 14% in SOM irrespective of the fertilization treatment (Tables 1 and S5, $p > 0.05$). In September22, the F irrigation decreased WSC in 17% compared to the D treatment and irrespective of the compost addition.

3.2.2. *Intensive olive grove under fertilization management and rainfed conditions*

The AC effect was very specific to some soil properties and limited to particular sampling times (Tables 2 and S6). On average for all sampling times, soil GWC was enhanced by 20% more in soils with AC than the control although this difference was not significant. The addition of AC also increased SOM and WSC in 20% and 38% on average in April22 and September22 respectively (Tables 2 and S6, $p < 0.05$).

The final balance expressed in % of C loss or store of SOM comparing the absolute values from November21 to September22 was of − 4.3, 12.7% for the R and RC respectively and for the WSC was 3.01, 33.1% following the same order of treatments.

3.3. *Response of yield, fruit and tree gwth*

Irrigation rather than compost addition was the main factor controlling the evolution of both fruit and tree growth (Fig. 3, Table 3). Tree crown growth at the hedgerow plots was driven by the irrigation management both in the initial and final dates (Table 3). The average tree growth rate for the F regimen was 42% higher than the D irrigation regardless of the compost addition. Although the compost effect did not significant influenced the final crown volume, the initial volume was 26% smaller in trees with DC treatment and 10% with the FC management compared to their controls (Table 3). Such differences were decreased in D treatment at the end of the season when DC was only 7% smaller than D because of a greater growth rate along the season. No significant differences were found in the rainfed site (Table 3). Initial and final crown volume were slightly greater at the inorganic fertilization but differences were only around 10%.

Irrigation at the hedgerow site conditioned the fruit development (Fig. 3a). Thus, the F regime yielded greater fruit growth rates during practically all the fruit development. Slope of the regression was greater in F than in D in each fertilization strategy. Moreover, D trees presented several periods of reduction in fruit volume in the second half of the experiment because of water stress conditions. However, just before harvest, the water status recovery of D trees permitted that only the effect of the compost influenced in the final fruit volume ($p < 0.05$). Thus, treatments with inorganic fertilization (i.e. D, F) presented on average an increase in the final fruit volume of 11% compared to the plots treated with AC with no differences between the irrigation managements. At the intensive plots, the compost addition triggered both greater initial fruit growth rates during the linear phase of growth and larger final volumes (ca. 20% increase) although this difference did not result significant (Fig. 3b).

The number of inflorescence per shoot and fruit per inflorescence was not significantly different in any of the systems (Table S4). Number of fruits were almost the same with slightly more than 1 fruit per inflorescence in the hedgerow site, but around 1 in the intensive plots. On the other hand, the number of inflorescence were slightly greater in FC and DC than in their controls. This trend was greater in FC which displayed on average 20% more inflorescences than F, while the increase in DC was only 6%. The intensive system presented the same number of inflorescence per shoot.

Table 2
Results of ANOVA (F and *p*-value) showing the main significant factors (i.e. compost addition) controlling changes in soil physical and chemical properties at the intensive traditional plots. GWC: soil gavimetric water content, SOM: soil organic matter, WSC: water-soluble carbon.

ANOVA results		GWC		SOM		WSC	
		F	*p*	F	*p*	F	*p*
Compost addition	Nov. 2021	ns		ns		ns	
	Mar. 2022	ns		ns		ns	
	Apr. 2022	ns		6.91 *		7.06 *	
	Sept. 2022	ns		ns		14.8 * *	

Significance level: *p < 0.05; * *p < 0.01

Regarding fruit yield no significant differences were detected with respect to the addition of AC and the irrigation regimens in any of the sites (Fig. 4). Although it was not significant, compost seemed to be the most relevant factor influencing fruit production specially at the hedgerow system. Thus, DC and FC treatments yielded 30% and 41% more than their respective controls whereas the addition of AC only caused a 3% yield improvement at the intensive plots. Although in absolute values, the F irrigation induced a 28% of harvest improvement regardless of the addition of compost, there was a great variability among the individual plots (Fig. 4). The yield of the rainfed system was greater than the hedgerow because of the alternate bearing pattern of this latter site. This was likely related with the pruning of the hedgerow which was too strong and increase the alternate bearing of this cultivar. A comparison of an isolated season is not adequate and more data are needed for obtaining some conclusions.

3.4. *Contribution of greenhouse gases*

3.4.1. *Trends of CO_2 fluxes*

Emissions of CO_2 did not generally differ either with the compost addition or irrigation management but they did show a marked seasonal character (Fig. 5a and b). Regardless of the compost addition, in the hedgerow site, the F irrigation regimen tended to increase CO_2 emission raising the fluxes by 38% in July21 and 15% on average in September21 and March22 but this difference was not significant. In November21, DC and FC treatments increased CO_2 emissions by 19% and 70% respectively in comparison with their controls while we detected a certain inhibitory effect on CO_2 emissions at this sampling time for the F treatment. From November22 onward all treatments showed very similar emission patterns (Fig. 5a).

At the intensive plots, the compost addition did not cause significant differences between treated and control plots (Fig. 5b). Nevertheless, plots treated with AC tended to increase by 11% and 35% CO_2 emissions in November21 and March22 respectively. The seasonal pattern of this site was very similar to the hedgerow plots but with a greater reduction during Summer period (Jul21, Sept21, Jun22).

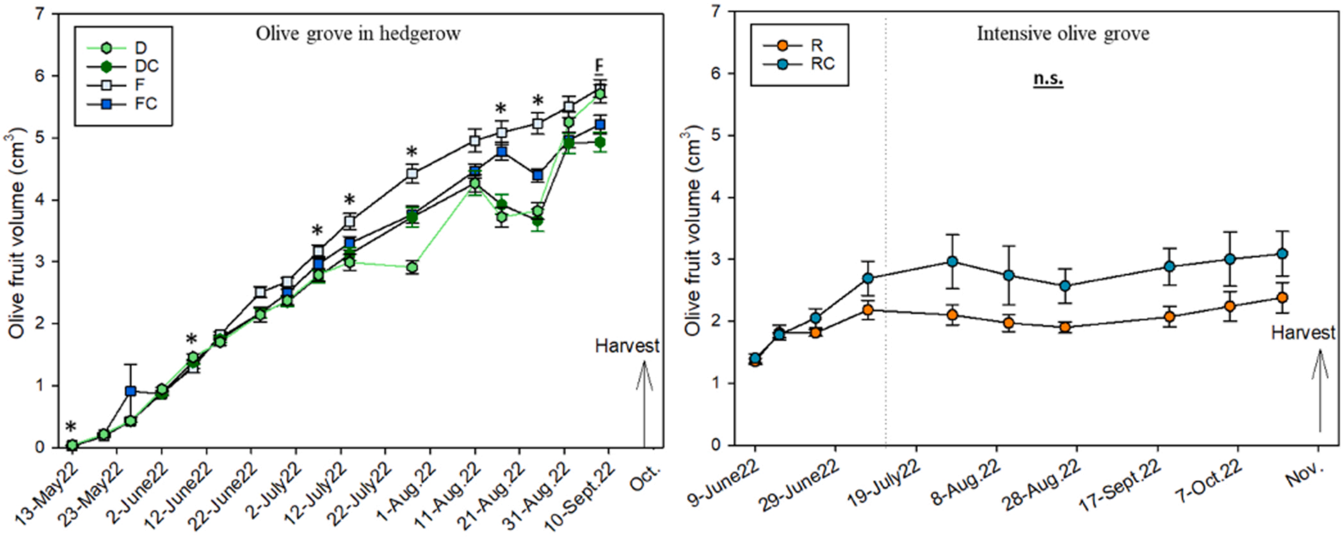
3.4.2. *Trends of N_2O fluxes*

At the hedgerow system, no significant differences were found regarding N_2O patterns emissions and irrigation or fertilization management (Fig. 5c). In general, pulses of N_2O fluxes were detected depending on the treatment and the sampling time and therefore statistical differences were very difficult to detect (Fig. 5c). The F irrigation regimen seemed to enhance N_2O emissions in November21 compared to the rest of the treatments and the greatest variability of N_2O emission patterns among plots of the same treatment was observed in June22. All treatments showed a similar emission behavior during the rest of the sampling times.

At the intensive plots, no effect of the compost addition was detected during the course of the experiment (Fig. 5d) displaying both the organic and the mineral fertilization very low emission rates.

3.4.3. *Trends of CH_4 fluxes*

Different patterns of CH_4 emissions were detected according to the irrigation regimen and the sampling time at the hedgerow system (Fig. 5e). Thus, emissions of CH_4 from the plots receiving F irrigation regardless the compost addition were significantly higher in January and April22 (160% and 52% respectively) compared to the D irrigation



Treatment	Regression equation	R-squared
D	Volume = 0.046 days – 6.067	$R^2 = 0.98$
DC	Volume = 0.0434 days – 5.6331	$R^2 = 0.98$
F	Volume = 0.052 days – 6.8653	$R^2 = 0.98$
FC	Volume = 0.0447 days – 5.7459	$R^2 = 0.98$

Treatment	Regression equation	R-squared
R	Volume = 0.0256 days – 2.6169	$R^2 = 0.85$
RC	Volume = 0.0444 days – 5.6664	$R^2 = 0.98$

Fig. 3. Olive fruit volume (cm^3) evolution as a function of fruit length and diameter at the two experimental areas measured during the campaign 2022.Graphic on the left (a) corresponds to the olive grove in hedgerow with two irrigation regimes (D: deficit and F: full irrigation) and fertilization addition: compost (C) or no letter (Ø) to refer to the inorganic fertilization. Graphic on the right (b) represents the intensive olive grove under rainfed conditions (R) with the addition of C or no letter (Ø) to refer to the inorganic fertilization until the harvest. The dotted line in the graph on the right indicates the end of the linear fruit growth phase for which the regression equation was obtained. The asterisk indicates significant differences ($p < 0.05$) with the irrigation regime within that sample time and significant differences concerning the compost addition are noted by F and no significant differences ($p > 0.05$) were noted by n.s. Data are mean values ($n = 3$ olive grove in hedgerow, $n = 4$ intensive olive grove) ± standard error of the mean (SEM).

Table 3
Tree crown volume growth (m^3 month^{-1}) calculated as the difference of tree volume between the initial and final measurements (March - Sept. 2022), divided by the number of days between them.

	Vegetative period (days)	Treatments	Initial volume (m^3)	Final Volume (m^3)	Tree volume growth (m^3 month^{-1})
Olive grove in hedgerow	200	D	4.37 ± 0.39	6.55 ± 0.37	0.34 ± 0.11
		DC	3.20 ± 0.25	6.09 ± 0.82	0.45 ± 0.09
		F	4.91 ± 0.16	9.79 ± 0.38	0.72 ± 0.04
		FC	4.39 ± 0.42	8.49 ± 0.15	0.64 ± 0.08
Intensive traditional olive grove	201	R	27.4 ± 1.74	32.4 ± 0.92	0.93 ± 0.25
		RC	24.3 ± 2.15	29.6 ± 1.44	1.06 ± 0.23

ANOVA results							
Olive grove in hedgerow	**Compost**		**Irrigation**		**Intensive traditional olive grove**	**Compost**	
	F	*P*-value	F	*P*-value		F	*P*-value
Initial tree volume	6.85 *		7.16 *			ns	
Final tree volume	ns		32.6 * *			ns	
Tree volume growth	ns		11.3 *			ns	

Significance level: *p < 0.05; * *p < 0.01.

plots that behaved as sinks ($p < 0.05$). Although the addition of compost was not a significant factor in any of the CH_4 emission points, there seemed to be a direct correlation between the intensity of irrigation and the compost application. Thus, in April22 the D irrigation plots receiving mineral fertilization increase in ca. 33% on average CH_4 emission (although there was great variability among plots with the same treatment) whereas the F irrigated plots amended with compost emitted 50% more than its respective control.

In June22, soils of all irrigation regimens acted as CH_4 sinks but with different intensity. While the D regimen captured − 20.76 µg CH_4-C m_2 h^{-1}, the potential of soil CH_4 uptake decreased by 60% for the F regimen.

On the other hand, no significant trends in term of CH_4 emissions were observed after the compost application at the rainfed traditional site (Fig. 5 f). But AC presented lower values in Sept21 and Nov 21. Overall, both treatments followed a very similar emitting/sinking behavior during the course of the experiment.

The seasonal pattern of both sites was very different. At rainfed site, CH4 emission was almost steady and the period of changes was reduced to Sept21 and Nov 21. But, in hedgerow site this pattern was dynamic in all the season and in all treatments.

4. Discussion

4.1. Soil water distribution under different irrigation strategies

The success of irrigation strategies such as deficit irrigation depends largely on the crop ability to handle variability in profile stored soil water in periods of water shortage without compromising yield (Bell

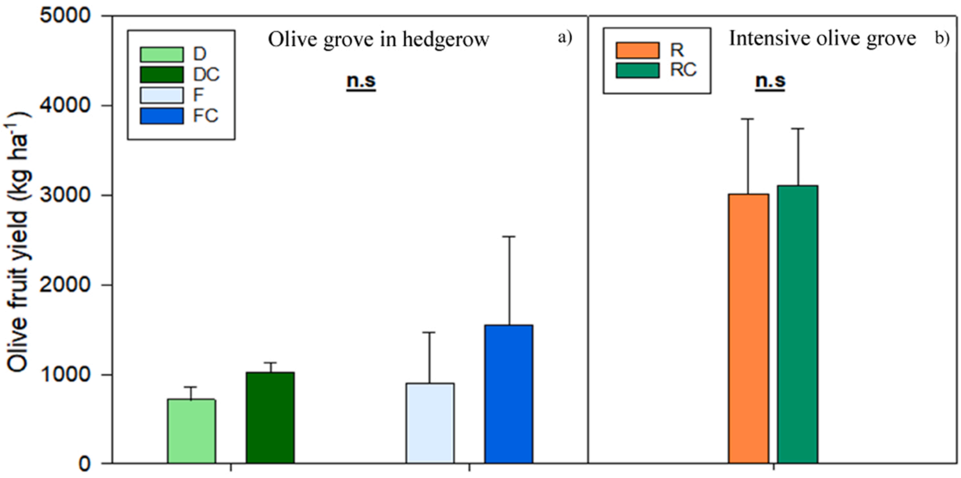


Fig. 4. Olive fruit yield (kg ha^{-1}) during the campaign 2022. Graphic on the left (a) corresponds to the olive grove in hedgerow with two irrigation regimes (D: deficit and F: full irrigation) and fertilization addition: compost (C) or no letter (Ø) to refer to the inorganic fertilization and graphic on the right (b) represents the intensive olive grove under rainfed conditions (R) with the addition of C or no letter (Ø) to refer to the inorganic fertilization until the harvest. No significant differences ($p > 0.05$) were noted by n.s. Data are mean values ($n = 3$ olive grove in hedgerow, $n = 4$ intensive olive grove) ± standard error of the mean (SEM).

et al., 2020). This irrigation regimen is commonly recommended for olive hedgerow orchards with high tree densities because it limits excessive growth and nutrient flushing (Padilla-Díaz et al., 2018). As it was expected, the analysis of the subsurface soil layers (0–20 cm) reflected in general the influence of the irrigation management to store water at surface level. However, it is worth mentioning that although the trend of greater SWC on the first 20 soil centimeters was clear for the F irrigation regimen irrespective of the fertilization treatment, there seemed to be a certain change in soil moisture dynamics and not a general reduction of SWC in April22 in plots with the F strategy. This theory is reinforced by the fact that the analysis of the whole soil profile placed this particular treatment as the one with more SWC in absolute values. This particular event could have been caused by the influence of heterogeneous environmental factors such as antecedent precipitations or soil properties that can exert a strong influence on soil moisture dynamics (Huang et al., 2016).

Regarding the distribution of SWC in deeper soil layers, we did not found a greater root stimulation and soil water extraction at depth as a consequence of the deficit irrigation regimen which contrasts with previous studies (Chai et al., 2016). What is interesting to note is that although fertilization appeared to be a significant factor for the distribution of the SWC at depth, plots receiving the organic treatments showed this natural tendency of greater water consumption prior to the compost addition. This natural trend seemed to be maintained until March22, when more abundant precipitation events were recorded and all treatments tended to equalize the SWC. Due to the great soil spatial variability, this approach to measuring water at depth has a number of limitations as the difficulty to know up to what extent compost addition has modulated this response needing, therefore, widening the variables considered in future research.

Likewise, the effect of the compost at depth at the intensive plots was difficult to determine as in June22 after the second compost addition there seemed to be a change in trend of SWC after the antecedent precipitations. To our knowledge there is no previous study of how the organic amendments can influence water distribution at deeper soil depths in olive orchards so comparing the results is difficult. Further research should be done to investigate this effect over longer period of times and repeated compost application.

4.2. Role of organic amendments and water inputs in the soil in olive groves with different management

Developing sustainable strategies to preserve and enhance SOM are much needed to palliate the environmental impacts of olive groves intensification as well as climate change. Previous research has provided evidence that organic amendments are a feasible solution to enhance soil C stocks as we also found if we compared treated plots with controls (Farooqi et al., 2018; Regni et al., 2017). However, the ability to store C in the soil, especially with high tree densities, was positive but limited. Similarly, Regni et al. (2017) found a low amount (but higher than the control plots) of C sequestered in the soil following the application of olive pomace and Sánchez-García et al. (2016) did not detect a significant increase of SOM if not in WSC after the addition of AC which was attributed to the easily degradable compounds that triggered the mineralization processes. In our case due to the easily degradable character of the compost, WSC was the parameter that best reflected the positive effect of AC. Although WSC only accounts for a small portion of total organic C in soils, it has been established as a good indicator of soil quality (Wang et al., 2019; Xu et al., 2011) and there was no doubt that its increment was related to the compost addition. It is interesting to note how the RC treatment was the only one that reflected a positive significant increment of SOM throughout time reveling the importance of the agronomic practices (i.e., tree density, organic amendment dose) in maintaining or enhancing the soil C sink function.

Irrigation, however and contrary to expectations, did not have a strong effect on most of the soil chemical parameters. We hypothesized that this lack of effect could be related to the complex interaction of precipitation events and irrigation that somehow mask a clear trend with the irrigation control. This theory is supported by a close analysis to SOM losses throughout time. Accounting for the SOM loss from November21 to March22 (four months) and the one between March22 and April22 (one month) is noteworthy that the loss intensity in most of the treatments was much higher in just one month that the previous period and this loss occurred more intensely with full irrigation. Therefore, there must be a joint effect of a heavy precipitation event (182 mm) that probably played an important role in runoff generation and soil erosion and the irrigation regime. Likewise, Kavvadias et al. (2018) found challenging to identify an irrigation effect due to the effect of high precipitations or Arampatzis et al. (2018) that observed a greater impact on soil moisture due to the sampling seasonality or the soil management rather than the irrigation regimens.

4.3. Fruit, yield and growth evolution in olive groves with different management

It is generally assumed that irrigation can greatly help to improve a better vegetative and reproductive growth (Caruso et al., 2014; Gucci et al., 2019b; Patumi et al., 2002). In this sense, deficit irrigation is a common practice in orchards to improve water use efficiency without compromising yield (Gucci et al., 2019). The results of this experiment are in good agreement with those statements, allowing us to make several key assumptions. Firstly, irrigation was the determinant factor

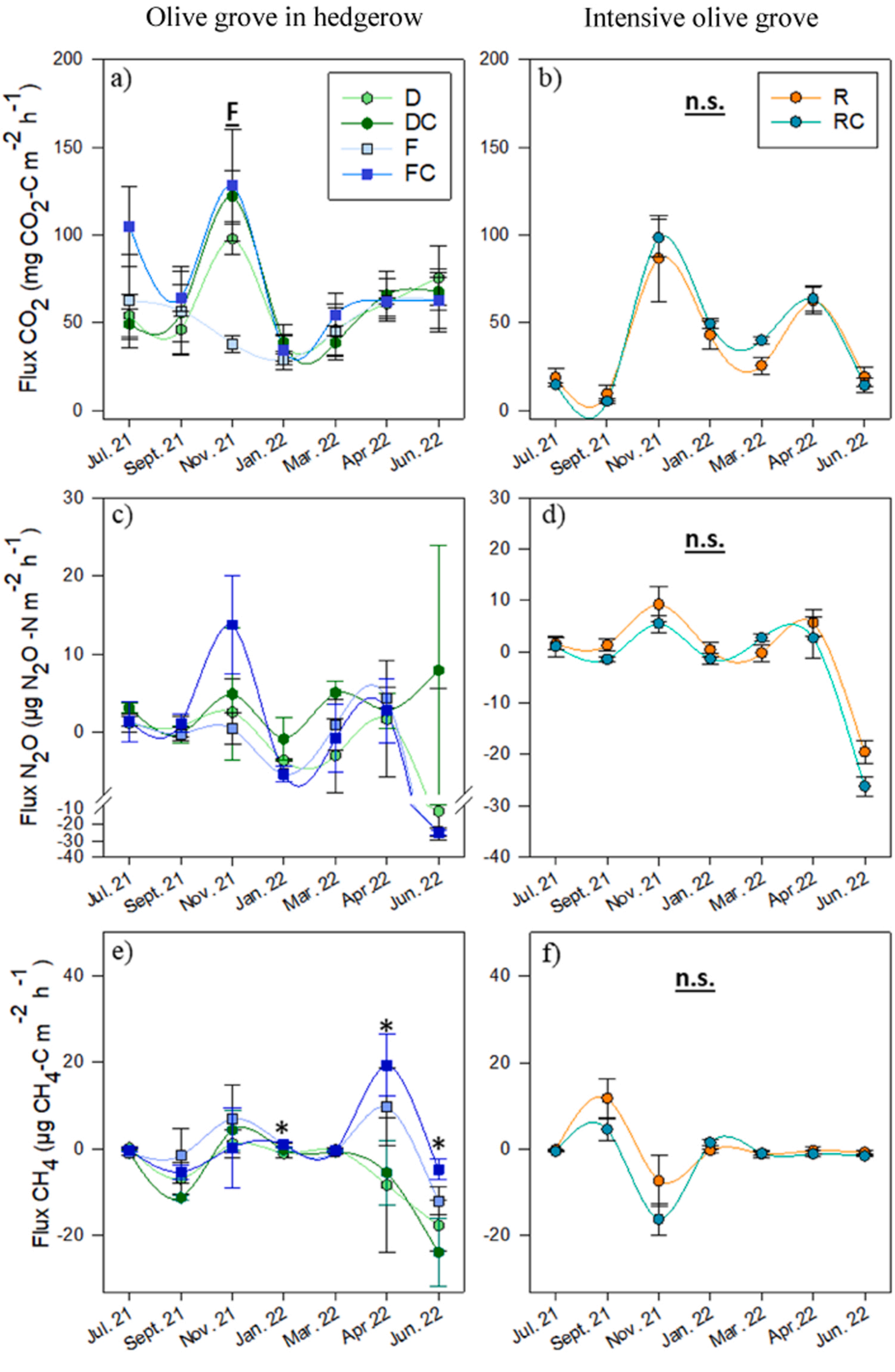


Fig. 5. Fluxes of greenhouse gases (CO_2, N_2O, CH_4) at the two experimental areas. Graphic on the left corresponds to the olive grove in hedgerow with two irrigation regimes (D: deficit and F: full irrigation) and fertilization addition: compost (C) or no letter (Ø) to refer to the inorganic fertilization and graphic on the right represents the intensive olive grove under rainfed conditions (R) with the addition of C or no letter (Ø) to refer to the inorganic fertilization at different sampling times. The asterisk indicates significant differences ($p < 0.05$) with the irrigation regime within that sample time and significant differences concerning the compost addition are noted by F and no significant differences ($p > 0.05$) were noted by n. s. Data are mean values ($n = 3$ olive grove in hedgerow, $n = 4$ intensive olive grove) ± standard error of the mean (SEM).

for tree growth and secondly trees from the D irrigation regimen could perfectly recover from the ups and downs of water shortage but moderately reducing yield. Such yield reduction in D treatment was likely related with the initial lower crown volume of this treatment and have to be better evaluated in a multi-seasonal experiment. Likewise, Fernández et al. (2013) found that although a deficit irrigation strategy meant a moderate decrease in oil yield, it managed the best balance between water saving, tree vigor and oil production and García et al. (2017) also added that this effects can be over ride by autumn precipitations. Moreover, Girón et al. (2015) concluded that an adequate rehydration after a water stress period during pit hardening would eliminate any differences between full and deficit irrigation in quantity and quality of the yield. it is interesting to note that a fruit volume decrease in the FC treatment was detected whereas, for the F treatment, the fruit volume was not reduced, being the amount of water supplied for both treatments practically the same. We hypothesized that this event could be related to two factors. First that the amount of irrigation could be less than the trees needed because of the increase of ETo as the irrigation scheduling was performed the week before. However, in our opinion, this decrease is most related to a possible drawback of the methodology to estimate the fruit volume. As ten fruits were randomized selected each week, changes between weeks could increase. Even considering that, the trend of FC was to decrease in fruit volume from June onwards. In addition, the seasonal pattern is almost linear, the last 4 data in F and FC treatments suggested that there is a decrease in the fruit growth at the end of the experiment. Then, the decrease in fruit volume in FC could be related to variations in the measure that confirm these tendencies.

On the other hand, there is evidence of the beneficial role that organic amendments play in crop productivity (Hale et al., 2021; Regni et al., 2017). However, contrasting results are often presented. Regni et al. (2017) found that 8 years of organic amendment produced a higher fruit yield than the control plots and Tejada and Benítez (2020) reported positive results in plots organically amended. Conversely, other studies stated that the positive effect of the application of organic materials on vegetative activity and fruit yield can be dependent of the rate of substrate mineralization and the timing of nutrients release, stating that in some cases the productivity levels of systems with or without an extra source of C can be comparable (Fernández-Hernández et al., 2014; López-Piñeiro et al., 2011; Oldfield et al., 2018). In our case, the study of fruit size development and yield led to different conclusions. On the one hand, the analysis of the fruit size indicated that the compost addition slightly reduced the fruit size but being this still widely within the caliber of table olives (Girón et al., 2015). On the other hand, in terms of productivity, trees from organic amended soils invested more energy and resources in increasing olive production and probably differences in yield will come significant after repeated applications of the AC for a longer period of time (Regni et al., 2017; Tejada and Benítez, 2020). Then, the slight decrease in fruit size, could not affect the final farmer profit if the increase in yield would be confirmed.

4.4. Role of organic amendment application on greenhouse gas emission from soil

It is well established that the addition of organic amendments can lead to GHG emission by processes such as priming effect, methanogenesis, nitrification, and denitrification (Forte et al., 2017; Thangarajan et al., 2013; Walling and Vaneeckhaute, 2020). In our case, the addition of AC caused very punctual pulses of CO_2 and N_2O that was probably inferred by processes such as microbial activation or growth before easily available SOM (Thangarajan et al., 2013). As in Sánchez-García et al. (2016) losses associated to GHG emissions after the compost addition had a prominent seasonal character mainly affected by the temperature and the water fill pore space. In terms of fertilization, November21 sample point represents a particular case. It is difficult to establish solid patterns as gas emissions did not correlate with any of the soil variables measured which it is not uncommon due to the existence of multiple, simultaneous, and intertwined relationships between the soil-plant system and the atmosphere gaseous phase (Brevik, 2012; Oertel et al., 2016). It is interesting to note that at the November21 sampling point a certain inhibitory effect of CO_2 emission was detected for the full irrigation regimen with mineral fertilization whereas for the rest of the treatments SOM decomposition seemed to be enhanced. Previous studies have reported a certain inhibitory effect of CO_2 emissions at specific times usually linked to the addition of nutritional treatments (for example N application). Maris et al. (2015) attributed this inhibition to the fact that N application could reduce extracellular enzyme activity and the fungal population, resulting in a reduction in the CO_2 flux. This was also observed by Ding et al. (2006) while Xiao et al. (2005) found an enhancement of CO_2 fluxes after N fertilization and Lee et al., 2007 found no effect at all, displaying contradictory patterns of emissions. We hypothesize that this inhibitory effect could be related to the strong coupling of C:N ratio that directly affects to SOM decomposition (Santos et al., 2021). The lowest C content found for this treatment together with the mineral fertilization could have induced changes in nutrient stoichiometry being a limiting factor for emission in this specific case but further research is needed to reach sound conclusions. For the rest of the treatments, it seemed that when there is more C available the C/N relation increased and more N is needed to maintain microbial optimal growth and therefore N mineralization is enhanced providing a source of inorganic compounds whose final end can turn into N_2O emissions as seen in the months of November21 (Mullen, 2015; Reich et al., 2006).

Although emissions of N_2O were extremely low for all treatments during the whole experiment, it is worth mentioning that DC treatment exhibited a complete different behavior than the rest of the treatments in June22. As water soluble N usually follows the same patter as WSC, we hypothesized that this pulse of N_2O could be related to a greater N and C availability in this treatment although this overall impact on N_2O emissions was insignificant as it has been showed before with this type of compost (Sánchez-García et al., 2016; de Sosa et al., 2022). Other studies however have pointed to the contrasting soil moisture and temperature conditions that drive autotrophic nitrification and heterotrophic denitrification as the responsible for these pulses (Barton et al., 2008; Butterbach-Bahl et al., 2013; Sapkota et al., 2020). However, this trend should be confirmed over time.

Several studies have also identified a greater increase in CH_4 emissions after the addition of organic amendments than from mineral fertilizer soils (Lee et al., 2010; Yang et al., 2010) but this is usually associated with poorly aerated soils and high rates of liquid organic fertilizer which it is not our study case. Thus, regarding compost addition, we did not detect any change in the CH_4 emission patterns neither in the hedgerow system nor in the intensive plots.

There is evidence that supports that irrigation practices can change emission patterns due to the influence on microbial process and relocation of nutrient supply (Oertel et al., 2016, Fares et al., 2017, Sapkota et al., 2020). In our study the effect of irrigation control was apparently no significant as studies such as Maris et al. (2015) and Franco-Luesma et al. (2019) have identified before. Nonetheless, we did observe a raise of CO_2 fluxes with the full irrigation management independently of the fertilization strategy in some of the hottest months that could be attributed to an acceleration of microbial respiration of SOM mediated by the increase in SWC (Sapkota et al., 2020).

Under rainfed conditions, however, the low water availability in these months became the rate-limiting factor for CO_2 and N_2O emissions being in absolute values lower than those of the irrigated plots. This leaves evidence that at least under water stress conditions irrigation rather than compost addition exerted a clear influence on CO_2 and N_2O emission patterns.

Irrigation played also a pivotal role controlling patterns of CH_4 emissions. The production of CH_4 is a strictly anaerobic microbial process named methanogenesis but that is usually negligible in non-flooded soils because they are well aerated. If the soil acts as a sink or source of CH_4 will depend on the balance between the CH_4 production by methanogens and the consumption by methanotrophs that in turn it is controlled by shifts in water regimes that change the redox potential and the microbial activity (Jiao et al., 2006, Thangarajan et al., 2013). Previous studies have stated that reduced irrigation practices can decrease CH_4 emissions and although our emission factor was negligible compared to other crops, we did observe how the D irrigation regimen tended systematically to reduce CH_4 fluxes (Oertel et al., 2016; Sapkota et al., 2020). In the case of the intensive site, it was the conditions of soil moisture that modulated the function of the soil as a CH_4 source or sink by enhancing or not the CH_4 oxidation (Hernández, 2010).

5. Conclusions

Soil application of organic matter from organic residues can be an alternative to increase soil fertility and efficiency of irrigation. The agronomic use of organic wastes from agricultural activities presented important benefits towards closing nutrient cycles, enhancing the circular economy, and adding extra value to the food produced. The results obtained indicated that the deficit irrigation strategy accompanied by the addition of alperujo compost maintained soil fertility and did not increase the risks of greenhouse gas emissions in hedgerow olive groves. Although future research is necessary, the contribution of compost would allow considerable savings in irrigation water without compromising crop production under these conditions. Traditional rainfed agriculture was also favoured by the inclusion of alperujo compost, improving soil fertility and maintaining sustainable yield production comparable to or even higher than those obtained with mineral fertilization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mireia Corell reports financial support was provided by Government of Andalusia.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108328.

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