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Research article

Analysis of small-scale soil CO_2 fluxes in an orange orchard under irrigation and soil conservative practices

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ABSTRACT

The quantification of soil carbon dioxide (CO_2) flux represents an indicator of the agro-ecosystems sustainability. However, the monitoring of these fluxes is quite challenging due to their high spatially-temporally variability and dependence on environmental variables and soil management practices.

In this study, soil CO_2 fluxes were measured using a low-cost accumulation chamber, that was realized *ad hoc* for the surveys, in an orange orchard managed under different soil management (SM, bare *versus* mulched soils) and water regime (WR, full irrigation *versus* regulated deficit irrigation) strategies. In particular, the soil CO_2 flux measurements were acquired in discontinuous and continuous modes, together with ancillary agrometeorological and soil-related information, and then compared to the agrosystem scale CO_2 fluxes measured by the eddy covariance (EC) technique.

Overall significant differences were obtained for the soil CO_2 discontinuous fluxes as function of the WR (0.16 ± 0.01 and 0.14 ± 0.01 mg m^{-2} s^{-1} under full irrigation and regulated deficit irrigation, respectively). For the continuous soil CO_2 measurements, the response observed for the SM factor varied from year to year, indicating for the overall reference period 2022-23 higher soil CO_2 flux under the mulched soils (0.24 ± 0.01 mg m^{-2} s^{-1}) than under bare soil conditions (0.15 ± 0.00 mg m^{-2} s^{-1}). Inter-annual variations were also observed as function of the day-of-year (DOY), the SM and their interactions, resulting in higher soil CO_2 flux under the mulched soils (0.24 ± 0.02 mg m^{-2} s^{-1}) than under bare soil (0.15 ± 0.01 mg m^{-2} s^{-1}) in certain periods of the years, according to the environmental conditions.

Results: suggest the importance of integrating soil CO_2 flux measurements with ancillary variables that explain the variability of the agrosystem and the need to conduct the measurements using different operational modalities, also providing for night-time monitoring of CO_2. In addition, the study underlines that the small-scale chamber measurements can be used to estimate soil CO_2 fluxes at orchard scale if fluxes are properly scaled.

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1. Introduction

Soil health is a key component for addressing the global challenge of food safety and simultaneously ensuring environmental sustainability in view of the growing human population [1,2], without compromising the ecosystem services associated to the agricultural systems [3,4]. This challenge is particularly urgent in the Mediterranean irrigated areas that are currently affected by water scarcity issues and are particularly sensitive to impacts related to the predicted climate change scenarios [5]. Under this climate context, a more efficient use of soil and water resources is needed for maintaining high-value crop productions, such as citrus cultivation, that may suffer critical issues due the depletion of soil and water resources, both in qualitative and quantitative terms [6]. In this sense, the adoption of mixed conservative production techniques is required for mutually achieving crop production and environmental objectives [7]. Furthermore, it is imperative to adopt multidisciplinary approaches that integrate several fields, such as biology, engineering, chemistry, to achieve the goal of sustainability in agriculture [8]. Nowadays, even if soil is one of the largest pools in the global carbon cycle and it plays a multifaceted role in enhancing the productivity of agricultural soils (e.g. Ref. [9]), there are still large uncertainties regarding the determination of its flux dynamics (e.g. Refs. [10,11]). In general, the gas flux exchanges from soil to atmosphere interface are attributed to several dynamic phenomena occurring at the soil level.

In most agro-ecosystems, soil carbon dioxide (CO_2) release is a complex process, descriptive of soil activity [12]. The soil CO_2 flux is the main pathway for carbon exchange moving from the agro-ecosystem to the atmosphere [13,14] and represents a major flux in the global CO_2 cycle [15,16]. Small changes in soil CO_2 flux derived by agricultural activities can have a significant impact on atmospheric CO_2 concentrations at higher level [17,18]. For cropland and grazing lands, soil is the dominant carbon pool in the ecosystem in comparison with CO_2 emissions [11], which means that even a small change in soil CO_2 flux may greatly influence the carbon cycle between the ecosystem and the atmospheric carbon change [19,20]. In general, the three major carbon pools that can be recognized as sources of CO_2 flux from soil include: *(i)* the soil organic matter (SOM); *(ii)* the above and below ground dead plant residues; and *(iii)* the rhizodeposits [17,21]. These latter include the organic substances released by living roots, such as exudates, secretions, and sloughed-off root cells [22]. In other words, soil CO_2 flux is defined as the combination of two main biological sources: *(i)* the autotrophic respiration by plant roots together with the associated microorganisms (i.e., rhizosphere respiration), and *(ii)* the heterotrophic respiration, via microbial decomposition of SOM [13,23–25]. In this sense, a fraction of CO_2 flux is related to root microbiome and mycorrhizae activity in rhizosphere [26,27]. In the latter, fungi and bacteria establish a mutual symbiotic association with crop roots [28]. Specifically, as a soil carbon pump, microorganisms using root exudates, can survive and reproduce in rhizosphere while providing nutrients (mainly nitrogen-based molecules) to the plants and releasing CO_2 [29,30], through heterotrophic decomposition [31] and by converting exogenous carbon into microbial residues and store them in soil aggregates (i.e., through anabolism). The other CO_2 flux fraction is related to processes that occur in the first few centimeters of the soil depth, due to leaves litter decomposition or soil management (SM) operations, as soil tilling or the adoption of mulching. Evidence indicates that SOM in the rhizosphere undergoes more rapid decomposition and mineralization than under bare soils [28,32].

Soil CO_2 flux depends on several seasonally and long-term time-varying soil parameters, such as soil texture, soil compaction, soil nutrients, soil aggregates, roots density, available SOM, soil temperature, pH, and soil water content (SWC) [33,34]. [35] showed that the relationship between soil heterotrophic respiration and SWC is consistently affected by soil texture and other physical properties (e.g., soil bulk density). The proportion of soil CO_2 flux from autotrophic and heterotrophic contributions may vary annually and seasonally among the terrestrial ecosystems [23]. Annul soil CO_2 flux trends respond differently depending on latitude and biome, increasing mainly in boreal zones and decreasing in tropical areas [36]; whereas, in semiarid regions such as the Mediterranean, no long-term trends are observed [34].

For the above-mentioned reasons and for the wide variety of the Mediterranean agricultural systems [37], different responses of soil CO_2 flux are expected as function of the crop types and the management regimes. In particular, soil CO_2 flux is strongly affected by the type of the soil and irrigation management at farm level. Under drying conditions, such as under the application of deficit irrigation strategies, soil microorganisms may respond to reduced soil water potentials by dehydrating into a dormant state or accumulating compatible solutes [38–40]. The reduction of water availability decreases substrate diffusion and, hence, substrate accessibility for microorganisms, therefore affecting the availability of nutrients and the soil CO_2 flux [41–44]. Simultaneously, it can increase soil hydrophobicity, especially for soils rich in SOM [45]. At the same time, soil CO_2 flux can be affected by the adoption of soil mulching practices (including organic mulching) because they generally reduce soil compaction, protect the soil surface against erosion, regulate soil temperature, decrease evaporation, and increase SWC [46]. The application of mulch strongly influences the physicochemical properties of the soil and the growth of crops [32] demonstrated that mulching fields increase CO_2 emissions in the soil, especially in the heterotrophic component. In addition, organic mulching can improve soil quality and increases its SOM content [47,48].

Soil CO_2 flux has a dual role by depleting the SOM and serving as a consequential source of CO_2 emissions [21]. Thus, soil CO_2 flux and soil processes are strictly linked, but their understanding is complex to be delineated. Indeed, this link dominates both base rates and short-term fluctuations in soil CO_2 flux. In this sense, many roles of soil CO_2 flux have been suggested as an indicator of ecosystem metabolism, varying also in terms of the type of methods used to detect the soil CO_2 fluxes [13]. Accurate quantification of soil CO_2 fluxes can help better understand ecosystem health and provide feedback on the effects of global warming, as well as evaluate the carbon sequestration potential of different land management practices and the effectiveness of climate mitigation strategies [21]. Numerous methods have been developed to determine soil CO_2 flux from natural and agricultural ecosystems [21,49]. These methods are mainly divided into direct and indirect methods. The indirect methods can be, for example, based on the measurement of CO_2 concentration in soil at different depths with at least two measurement points at different depths. They require to have available the soil gas porosity, that is then used to calculate the soil CO_2 flux at the soil-atmosphere interface. The direct methods adopted for determining soil CO_2 fluxes require dynamic/static together open/closed volume procedures. The static closed volume procedure is normally used for manual gas sampling using a syringe. The dynamic open volume procedures consist in the measurement of CO_2 concentration in a gas mixture obtained from the gas coming out from the soil and a known air flux with a known CO_2 concentration, through an inverted chamber and across a known soil surface [50–52]. All dynamic open volume procedures are affected by possible over pressurization or depressurization into the measurement chamber, depending on the design of the instrumental apparatus and the magnitude of the air flux chosen by the operator [52,53]. The dynamic closed volume procedures for measuring the soil CO_2 consist in determining the rate of increase of the CO_2 concentration inside an inverted chamber placed on the soil surface without using external air dilution while carrying out gas mixing, to avoid gas stratification inside the chamber. This technique, known as the “accumulation chamber method” or “dynamic closed chamber method”, has been successfully applied in agricultural sciences to determine soil CO_2 flux and other soil gaseous species, e.g., N_2O [54–56]. Several authors recognized the accumulation chamber method as the best way to measure soil CO_2 flux, being an absolute method that does not require either assumptions or corrections depending on soil characteristics [52,57,58]. However, the high costs generally associated to the use of traditional accumulation chambers make it necessary to develop low-cost devices to make the monitoring of CO_2 soil fluxes more accessible.

The main hypothesis behind this study was that the combined use of conservative agricultural practices in Mediterranean irrigated orchards may differently affect the CO_2 flux emissions from soil, proving new insights on understanding the soil processes driving the CO_2 mechanisms under these specific agricultural contexts. Thus, the aim of this research work was to characterize the temporal patterns of soil CO_2 fluxes in an adult citrus orchard under different SM practices (bare soil *versus* organic mulched soil) and irrigation water regimes (WR, full irrigation *versus* regulated deficit irrigation). The specific objectives are as follows: (i) To assess the reliability of implementing *ad-hoc* accumulation chambers as easy-to-use on field soil CO_2 efflux monitoring approaches (i.e., continuous and discontinuous measurements) together with ancillary agrometeorological and soil-related information; and (ii) To compare the obtained soil CO_2 emissions with the agrosystem CO_2 fluxes measured by an eddy covariance (EC) system.

2. Materials and methods

2.1. Study site description

The research activity was conducted in the period 2021–23 in an adult orange orchard (*Citrus sinensis* (L.) Osbeck cv “Tarocco Sciara”; [59]) managed by the Italian Council for Agricultural Research and Agricultural Economics Analyses (CREA-OFA) and located in the insular part of Italy (Eastern Sicily, Lentini, SR, 37° 20′ 12.65″ N, 14° 53’ 33.04″ E, WGS84). The study area is characterized by semi-arid Mediterranean climate, with warm and dry irrigation seasons. During the years 2010–21, the mean air temperature, the cumulative annual precipitation and reference evapotranspiration (ET_0) values were 18.2 °C, 587 mm and 1,264 mm, respectively. Agrometeorological data provided from an automatic station located at 2 km from the study site and managed by “*Servizio Informativo Agrometeorologico*” of the Sicilian Region (SIAS).

The experimental set-up at the study site involved conservative agricultural practices (i.e., regulated deficit irrigation (RDI) strategies in combination with the adoption of organic mulching). In particular, the irrigation management included: (i) a full irrigation (FI) regime, where the irrigation volume corresponds to 100 % of the crop evapotranspiration (ET_c); and (ii) a RDI strategy, where irrigation volumes were reduced to 50 % of ET_c during the second phenological phase (i.e., at the end of the physiological fruit drop, from Day of the Year, DOY, 214 and 212, respectively, in 2022 and 2023), when the crop is less sensitive to water reduction.

The ET_c rates was calculated weekly using the Penman- Monteith approach on the basis of the daily ET_0 values, calculated using the hourly agrometeorological data provided by the nearest SIAS station, and the crop coefficients for citrus crops [60,61] adjusted by site-specific coefficients (i.e., 0.7), estimated as the ratio between the canopy cover size (m^2) and the total area pertaining to each tree (24 m^2) [62]. The irrigation season began in early-mid June (DOY 154 and 167, respectively, in 2022 and 2023) and ended on mid-end of September (DOY 259 and 272, respectively, in 2022 and 2023). Irrigation volumes were supplied three times a week, early in the morning, by surface drip lines, located directly close to the trunk, each characterized by a flow rate of 4 L h^{-1} (with an operational pressure of 1 bar) per single-emitter (spaced 0.6 m on each drip line), with a total number of 12 emitters per tree in FI (48 L h^{-1}) [63].

The SM at the study site implied two strategies: (i) the adoption of traditional SM practices (i.e., bare soil, where weeds are shredded in spring) and; the (ii) application of organic mulching (i.e., a conservative SM practice in which the soil surface is covered with the residues from the citrus pruning and spontaneous weeds). At the study site, the main component of organic mulching was the pruning residues. Therefore, the mulching reached an average thickness of 5.1 ± 0.14 cm in the period 2021–23, depending on the pruning needs [64]. Considering the different strategies of soil and water management (i.e., WR and SM), the experimental layout

Table 1
Experimental treatments under study. FI and RDI refer to the full irrigation and regulated deficit irrigation, respectively; BARE and MULCH refer to the bare and mulched soil, respectively; WR and SM denote the water regime and soil management factors under study.

Treatment	WR	SM
FI-BARE	FI	BARE
FI-MULCH	FI	MULCH
RDI-BARE	RDI	BARE
RDI-MULCH	RDI	MULCH

resulted in four treatments arranged in three randomized two-factor blocks, as given in Table 1. The layout of the experimental site, together with the point-locations of the soil CO_2 surveys and ancillary measurements is reported in Fig. 1.

At the study site, the soil is classified as Eutric/Chromic Vertic Cambisol [65,66]. It is characterized by a sandy loam/sandy clay loam texture (i.e., defined considering the SOM) according to the United States Department of Agriculture (USDA) soil classification (sand 56.86 %, silt 23.94 %, clay 19.20 %), with field capacity and wilting point values of 0.46 and 0.25 $cm^3\ cm^{-3}$, respectively.

Site-specific soil analyses were conducted in laboratory for determining the main physical and chemical soil characteristics before (on March 2021) and after (on October 2022) the application of the soil mulching at the different treatments. For this purpose, 12 soil samples (i.e., disturbed and undisturbed) were collected at a 0–30 cm depth and 1 m far from the centre of the tree rows towards the inter-rows. The selection of the depth for soil sampling was obtained on the basis of the maximum observed root biomass colonization, under zero tillage conditions. The analysed soil parameters include the main soil physical-chemical variables commonly used for agronomic characterization purposes, as: dry matter (d.m., %), SOM (%), pH (−), electrical conductivity (CE, mS cm^{-1}), potassium ion (K^+, mg kg^{-1} d.m.), nitrates (NO_3^-, mg kg^{-1} d.m.), phosphate (PO_4^{3-}, mg kg d.m.$^{-1}$), total nitrogen (N_{tot}, mg kg d.m.$^{-1}$), total carbon (C_{tot}, % d.m.), total organic carbon (C_{org}, ppm), microbial biomass carbon (CMIC, ppm), ratio CMIC/C_{org} (%), calcium (Ca, mg kg d.m.$^{-1}$), total potassium (K_{tot}, mg kg d.m.$^{-1}$), magnesium (Mg, mg kg d.m.$^{-1}$), and sodium (Na, mg kg^{-1} d.m.).

The evaluation of the height of the spontaneous species was obtained at the treatment level, considering 20 random measurement points located within each experimental plot in Fig. 1.

2.2. *Low-cost accumulation chamber: data acquisition and processing*

An *ad hoc* dynamic, closed-volume accumulation chamber was built and used for measuring the soil CO_2 fluxes at the study site. The chamber is a prototype (based also on the research of Chiodini et al., 1998) under development and design by the researchers of *Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo* (INGV-OE) and University of Catania (Di3A). In particular, the accumulation chamber is made by non-transparent PVC (i.e., photosynthetic activity inside the chamber was not considered) with a cylindrical shape, with 10 cm and 20 cm of height and diameter, respectively [67]. The chamber is atmospheric pressure-compensated by a small vent, designed to limit the Venturi effect due to wind. On the top of the chamber, another similar PVC cylinder hosts: the electro-pneumatic sub-systems; the infrared gas analyser IRGA K-30 sensor (Senseair AB, Delsbo, Sweden), with a measurement range of 0–5,000 ppm; and a custom-made data logger (MG2 type from Embenmass, Italy). A pressure-temperature-humidity sensor (BME280, Bosch Sensortec GmbH, Germany) is used to measure temperature, pressure and humidity of the gas flux. Among these three parameters, only pressure and temperature are then used in the soil CO_2 flux calculation. Additional details about the system will be thoroughly described in a separate research paper within a comparison with a commercially available chamber. As a first approximation, the error estimate in obtained CO_2 fluxes, is about ± 5 %; while measurement error on pressure and temperature are about ± 100 Pa and ± 0.5 °C, respectively, and can be neglected.

The soil CO_2 flux monitoring was carried out on a monthly basis, from December 2021 to December 2023, in the morning (between 9:00 a.m. and 1:00 p.m.), for a total number of 18 surveys. Specifically, the soil CO_2 surveys were performed, both in discontinuous and continuous acquisition mode, without using the soil collar (Fig. 1). The discontinuous measurements were conducted at 24 sample points (2 points for each plot, Fig. 1); whereas, two sample points were selected inside the RDI-BARE and RDI-MULCH treatments for

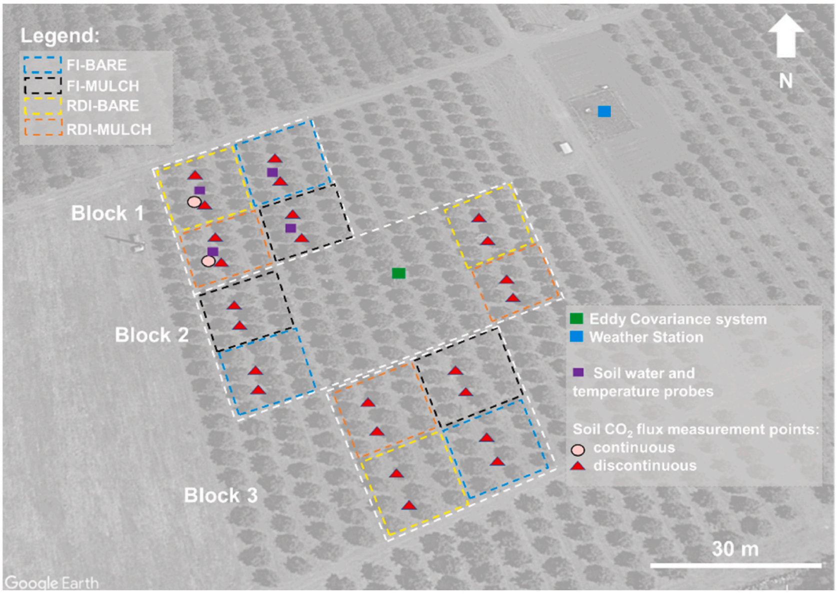

Fig. 1. Layout of the experimental treatments with the point-locations of the soil CO_2 fluxes and ancillary measurements.

the temporal continuous measurements (named in the following as continuous measurements). For all data acquisition, the gas flux chambers were installed at the soil surface in proximity of the root-zone (about 0.75 m from the orange tree trunk, Fig. 1). Note that, retrieved soil CO_2 flux referred to both roots and soil microbial respiration effects as a whole. For both discontinuous and continuous acquisition mode, the duration of the measurements was about 4 h, with 300 s of concentration data every 15 min. At each acquisition time, the gas inside the chamber was flushed using atmospheric air for about 120 s. Then, the CO_2 concentration data (in ppm), along with gas temperature and pressure values inside the accumulation chamber over time was measured and stored on the on-board data logger for a total time of 300 s (in CSV format). The used sampling frequency is 1 Hz. Data can also be read in real time by means of a smartphone, with WiFi connection and a standard web browser [67] (Fig. S1).

For data processing, a custom-made tool (CO2RANSAC Tool, v5.3) was designed with the use of Matlab (v. 2023a, MathWorks®, Massachusetts - USA). This tool implements, for both discontinuous and continuous acquisition mode, different algorithms for calculating CO_2 fluxes using raw concentration data measured in field with the chamber over time. Once the dataset has been loaded, the tool allows to calculating CO_2 flux using different models. In this study, a modified linear regression model [67] based on the RANSAC algorithm [68,69] was used for the whole dataset. Note that RANSAC algorithm is able to automatically discard non-consistent data in the initial dead-band (mainly due to internal pneumatic dead volumes) and different other type of noises and outliers in time series [67]. The tool used the median of a set of temperature and pressure measurements taken inside the chamber (i.e., 300 data); this data was acquired together with the CO_2 concentration. Table 2 reports the main chamber and gas parameters used for the data processing.

2.3. Soil-plant-atmosphere continuum system measurements

Ancillary monitoring data, acquired from an eddy covariance (EC) system, an automatic agrometeorological station, and soil water content (SWC) and temperature sensors were used during the soil CO_2 monitoring (Fig. 1).

The EC system, consisted in 7 m high tower equipped with a three-dimensional sonic anemometer (CSAT-3D, Campbell Scientific Inc.) and an infrared open path gas analyzer (Li-7500, Li-cor Biosciences Inc.), for measuring the turbulent fluxes of sensible heat flux (H), latent heat flux (LE) and CO_2 concentrations at a frequency of 10 Hz. The EC system is integrated with a net radiometer (CNR-1 Kipp & Zonen) and three soil heat flux plates (HFP01SC, Hukseflux), buried at about 0.05 m depth, for measuring the available energy (R_n-G) at a frequency of 30 min. Data was collected by a CR1000 logger (Campbell Scientific Inc., Logan, Utah); the quality control of the EC data was performed according to the EUROFLUX protocol [70], and the CO_2 fluxes were calculated applying the Webb-Pearman-Leuning correction [71]. This information was used to corroborate the temporal evolution of the chamber-based CO_2 measurements. In particular, the soil CO_2 fluxes were compared with the agrosystem CO_2 fluxes measured by EC following the up-scaling methodological approach proposed by Ref. [72]. More in detail, the analysis was performed on the common dates in which CO_2 fluxes were acquired by both the approaches (i.e., 12 dates within the reference period, from December 2021 to December 2023). Then, the EC-based CO_2 fluxes obtained from both methods were aggregated at different time-scales, and, specifically at daily hourly scale (24 h) and at diurnal (from 9 a.m. to 2 p.m.) and nocturnal (from midnight to 5 a.m.) scales. Specifically, in order to refer both CO_2 fluxes (chamber and EC) to the same spatial scale (i.e. orchard level), the soil CO_2 fluxes from the accumulation chambers measured in the different treatments (including both continuous and discontinuous measurements) were up-scaled to the EC footprint [73], considering their individual contribution weighted by the area occupied by each treatment in relation to the total footprint.

Agrometeorological data (i.e., incoming short-wave solar radiation, air temperature, air humidity, wind speed and rainfall) was acquired by the nearest automatic SIAS station, located at 2 km from the field site. The SWC and soil temperature measurements were obtained at semi-hourly basis through 8 TEROS12 probes (Meter Group, Washington – USA), installed at a depth of 30 cm and at two distances from the tree trunks (35 cm and 75 cm) in the FI and RDI treatments with and without mulching located in block 1 (Fig. 1). This location was chosen on the basis of the homogenous soil characteristics observed at the study site.

2.4. Statistical analysis

The statistical approach allowed to analyse the main effects of SM, WR and/or year, varied in function of the explored parameters (i.e., soil chemical-physical characteristics, soil CO_2 fluxes, spontaneous weed height and mulching thickness).

Specifically, to evaluate the effects on soil chemical-physical main characteristics, a three-way analysis of variance (ANOVA) was conducted including as factors: (i) the SM (bare *versus* mulched soils), (ii) the WR (FI versus RDI); and (iii) the pre and post-mulching application conditions (i.e. different years).

Table 2
Chamber main features and environmental parameters used for the data processing.

Parameters		Value		Unit
		Fixed chamber	Portable chamber	
Chamber	Height	0.09	0.10	m
	Radius	0.10	0.10	m
Gas	Pressure	Variable for each set of measurements		mbar
	Temperature			°C
	CO_2 concentration rate			ppm s^{-1}

Regarding the soil CO_2 fluxes (from both continuous and discontinuous measurements), multivariate ANOVAs were conducted including as factors: (i) the SM (i.e., BARE and MULCH); (ii) the WR (i.e., FI and RDI; only for discontinuous measurements since continuous soil CO_2 fluxes measurements were performed only under RDI conditions; Fig. 1); and (iii) the year (YEAR). Intra-annual differences in soil CO_2 fluxes were also evaluated by performing multivariate ANOVAs including the DOY as a factor.

To evaluate the differences in the height of spontaneous weed species and mulching thickness, a two-way ANOVA was performed considering the factors: (i) SM (i.e., BARE and MULCH); and (ii) WR (i.e., FI and RDI), for spontaneous weed height; and the factors (i) WR (); and (ii) year, for the mulching thickness.

The F-tests together and the degrees of freedom (DF) were calculated for each above-mentioned ANOVA's approach. The mean comparisons were computed using the Honest Significant Difference (HSD) Tukey's test at p-value of 0.05. Statistical analyses were implemented in STATISTIX 2.4 (Analytical Software, Tallahassee, FL, USA).

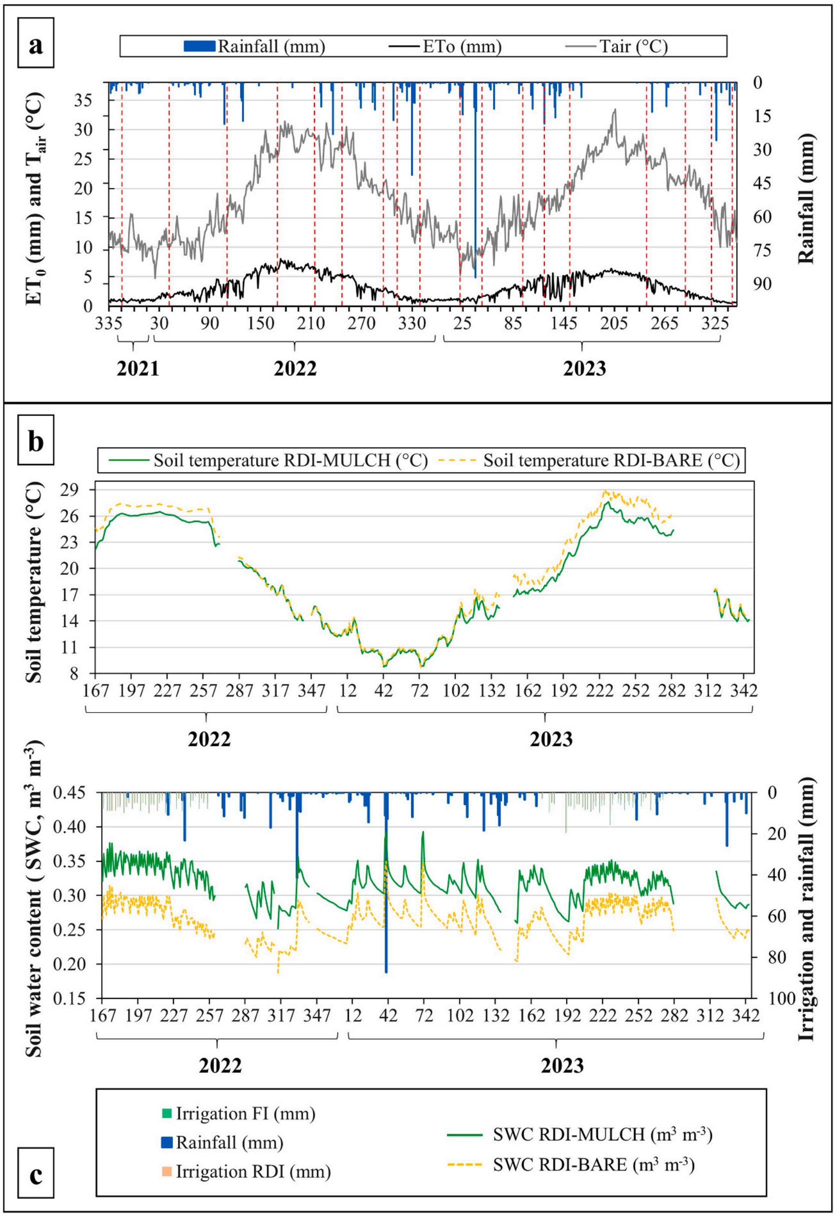

Fig. 2. Time trend of the main variables measured at the study site: (a) air temperature (T_{air}, °C), reference evapotranspiration (ET_0), and rainfall (mm d^{-1}) within the period 2021–23; (b) soil temperature (°C); and (c) soil water content (m^3 m^{-3}) together with the rainfall and the irrigation heights (mm) measured at the treatment level. The red dashed lines in panel (a) indicate the DOYs of the soil CO_2 efflux acquisitions. Gaps in the lines indicate missing data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Three-way analysis of variance (ANOVA) for evaluating the effect of the SM practices and WR on the soil chemical-physical variables. WR and SM denote the water regime and soil management factors. The asterisks refer to the significant differences among the factors and their interactions (for p-value <0.05). F-values (F) are reported in the Table.

Factors	d.m.		SOM		pH		CE		K^+		NO_3^-		PO_4^{3-}		CMIC		CMIC/C_{org}	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
Year	168.6	0.00*	1.91	0.19	226.7	0.00*	1.64	0.22	2.67	0.12	2.46	0.14	1.85	0.20	1.11	0.31	0.46	0.51
WR	0.24	0.63	1.40	0.26	1.02	0.33	1.24	0.28	0.77	0.39	0.04	0.84	0.07	0.79	0.10	0.75	0.33	0.58
SM	0.16	0.70	2.99	0.11	1.18	0.30	3.74	0.07	0.25	0.62	2.51	0.14	0.04	0.84	0.41	0.53	1.18	0.30
Year × WR	0.70	0.42	0.10	0.75	0.51	0.49	0.23	0.64	0.02	0.90	2.40	0.14	0.03	0.87	0.15	0.71	0.12	0.73
Year × SM	0.00	0.98	0.05	0.82	1.53	0.24	0.23	0.64	0.10	0.76	0.00	0.96	0.59	0.46	0.00	0.95	0.09	0.77
WR × SM	0.28	0.61	6.34	0.02*	3.79	0.07	5.41	0.04*	2.00	0.18	2.73	0.12	2.33	0.15	0.04	0.85	0.58	0.46
Year × WR × SM	0.95	0.35	1.84	0.20	0.14	0.71	0.43	0.52	0.02	0.89	1.12	0.31	0.09	0.77	0.56	0.47	0.05	0.83

Factors	N_{tot}		C_{tot}		C_{org}		Ca		K_{tot}		Mg		Na	
	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*	F	*p*
Year	37.04	0.00*	5.58	0.03*	1.89	0.19	18.67	0.00*	64.55	0.00*	62.52	0.00*	0.14	0.71
WR	2.53	0.13	2.41	0.14	1.40	0.26	1.66	0.22	0.01	0.94	0.03	0.85	3.29	0.09
SM	0.79	0.39	0.46	0.51	2.96	0.11	0.00	0.97	1.09	0.31	1.77	0.20	1.34	0.27
Year × WR	0.65	0.43	0.02	0.90	0.10	0.75	0.39	0.54	1.61	0.23	0.32	0.58	1.61	0.23
Year × SM	0.28	0.60	0.84	0.37	0.05	0.82	0.23	0.64	0.87	0.37	1.88	0.19	0.84	0.37
WR × SM	0.11	0.75	1.52	0.24	6.30	0.03*	7.60	0.02*	0.39	0.54	6.11	0.03*	0.17	0.69
Year × WR × SM	0.07	0.80	0.00	0.96	1.82	0.20	1.84	0.20	0.72	0.41	0.04	0.84	1.21	0.29

Soil variables: dry matter (d.m.), soil organic matter (SOM), pH (–), electrical conductivity (CE), potassium ion (K^+), nitrates (NO_3^-), phosphate (PO_4^{3-}), microbial biomass carbon (CMIC), ratio CMIC/C_{org}; total nitrogen (N_{tot}), total carbon (C_{tot}), total organic carbon (C_{org}), calcium (Ca), total potassium (K_{tot}), magnesium (Mg), sodium (Na).

Additionally, to the ANOVAs approach, linear regression analyses were performed to evaluate the correlations between the soil CO_2 fluxes, mulching thickness and the main environmental variables (i.e., SWC and soil temperature, see Supplementary material).

3. Results

3.1. Agrometeorological and soil-related data at the study site

Fig. 2(a–c) shows the ancillary variables monitored at the study site during the reference period (i.e., agrometeorological data, irrigation heights, SWC and soil temperature information).

The application of the RDI strategy during the irrigation seasons 2022–23 allowed a water saving up to 13 % and 28 %, respectively, in 2022 and 2023 compared to the FI. The corresponding cumulative irrigation heights were 219 mm (RDI) and 252 mm (FI) in 2022 and 277 mm (RDI) and 200 mm (FI) in 2023. Note that higher soil temperature values were observed in summer under RDI-BARE (up to 2.54 °C) in both the two-year study period. Differently, higher SWC was detected in RDI-MULCH throughout the overall monitoring period.

Table 3 reports the results of the statistical analysis in which the effects of SM, WR and year were ascribed to the soil chemical-physical main characteristics. Specifically, this analysis compared the soil variables before (2021) and after (2022) the application of the organic mulching.

The significance analysis of the results described in Table 3 was reported in details in Table 4. The resulting total degree of freedom (DF) for each analysed soil parameter was 23.

The soil parameters d.m., pH, N_{tot}, C_{tot}, K_{tot}, showed significant differences between the pre- (2021) and post-mulching application (2022), with an increase in their values in 2022, with the exception of N_{tot} which decreased (Table 4). No significant differences were observed in these parameters among the analysed WR and SM treatments.

The interaction WR × SM resulted significant for SOM and C_{org}, even if it was weak for the SOM. In particular, in terms of C_{org}, the highest (15,642 ppm) and lowest (13,603 ppm) values were observed in the RDI treatments under bare and mulched conditions,

Table 4

Average values of physical-chemical soil characteristics before and after the application of the organic mulching (soil sampled on March 2021 and October 2022). WR and SM denote the water regime and soil management factors. Different letters indicate, for each variable, significant differences among factors according to HSD Tukey's test (p-value <0.05). Empty cells refer to not significant differences.

Soil variable[a]	Year	WR[b]	SM[c]	Average value	Unit
d.m.	2021			80.08 b	%
	2022			89.77 a	
pH	2021			7.60 b	–
	2022			8.27 a	
N_{tot}	2021			0.16 a	% d.m.
	2022			0.12 b	
C_{tot}	2021			1.35 b	
	2022			1.56 a	
K_{tot}	2021			2,321.2 b	mg kg d.m.$^{-1}$
	2022			6,527.3 a	
SOM	2021–2022	FI	MULCH	2.46 a	%
			BARE	2.39 a	
		RDI	MULCH	2.34 a	
			BARE	2.70 a	
C_{org}	2021–2022	FI	MULCH	14,243 ab	ppm
			BARE	13,863 ab	
		RDI	MULCH	13,603 b	
			BARE	15,642 a	
CE	2021–2022	FI	MULCH	212.83 b	mS cm^{-1}
			BARE	206.70 b	
		RDI	MULCH	193.85 b	
			BARE	260.67 a	
Ca	2021	FI	MULCH	10,852 a	
	(10,893) A		BARE	9,882 a	mg kg d.m.$^{-1}$
	2022	RDI	MULCH	9,540 a	
	(9,394) B		BARE	10,391 a	
Mg	2021	FI	MULCH	2,140 a	
	(1,682) B		BARE	2,299 a	
	2022	RDI	MULCH	2,510 a	
	(2,783) A		BARE	1,981 a	

[a] Dry matter (d.m.), soil organic matter (SOM), pH (−), total nitrogen (N_{tot}), total carbon (C_{tot}), total organic carbon (C_{org}), total potassium (K_{tot}), electrical conductivity (CE), calcium (Ca), magnesium (Mg).

[b] FI and RDI refer to full irrigation and regulated deficit irrigation, respectively.

[c] BARE and MULCH refer to bare and mulched soils, respectively.

respectively (Table 4). A similar behaviour was observed for the same parameter under the FI treatments both with and without mulching covers. The interaction between WR and SM resulted also significant for the CE, showing greater values for the RDI-BARE during the entire study period (260.67 mS cm^{-1}, Table 4).

For Ca and Mg contents, the obtained response was year-dependent and function of the interaction WR × SM. More in detail, a significant decrease in Ca content was observed from 2021 (10,893 mg kg $d.m.^{-1}$; Table 4) to 2022 (9,394 mg kg $d.m.^{-1}$; Table 5); whereas, the opposite was observed for the Mg content (from 1,682 mg kg $d.m.^{-1}$ in 2021 to 2,783 mg kg $d.m.^{-1}$ in 2022; Table 4). The interaction between SM and WR resulted significant, even if it was weak, due to the higher stability of these elements.

3.2. *Effects of soil management practices and water regime on soil CO_2 respiration fluxes*

The results of the multivariate ANOVAs carried out to evaluate the effects of SM and WR practices, and/or year, on soil CO_2 fluxes (discontinuous and continuous), spontaneous weed height and mulching thickness, are showed in Table 5.

Overall, a similar behaviour was observed for the discontinuous soil CO_2 measurements during the two years of monitoring (2022–23), with statistical differences observed only in terms of WR (Table 5). In general, considering the WR factor, higher mean values of CO_2 were found in FI than in RDI (0.16 ± 0.01 *versus* 0.14 ± 0.01 mg m^{-2} s^{-1}).

At the annual level, as shown in Fig. 3(a–b), significant differences were observed in the soil CO_2 flux over time both in 2022 and 2023 (in terms of the DOY). A common trend, characterized by an increase in the fluxes, can be found during the seasons with greater activity, even if variable within the explored time-period, i.e., late autumn in 2022 and late spring-autumn in 2023. In the second year of monitoring (2023), statistical differences in the soil CO_2 flux were also observed as function of the SM, showing higher mean values of CO_2 under mulched soils than under bare soil conditions (0.16 ± 0.01 *versus* 0.14 ± 0.01 mg m^{-2} s^{-1}).

For the continuous soil CO_2 flux measurements, the response observed for the SM factor varied from year to year (Table 5), indicating for the overall reference period 2022-23 higher soil CO_2 flux under mulched soils (0.24 ± 0.02 mg m^{-2} s^{-1}) than under bare soil conditions (0.15 ± 0.01 mg m^{-2} s^{-1}).

At annual level, the soil CO_2 emissions were significantly different regarding the SM factors, the DOYs and the interaction of the SM factor over time (DOYs) (Fig. 4a–b). More in details, in 2022 an almost constant soil CO_2 flux was observed from DOY 117 to 215 (ranging from 0.07 to 0.14 mg m^{-2} s^{-1}, Fig. 4a). A more evident flux increment (0.39 mg m^{-2} s^{-1}) was progressively recorded between DOY 245 and 294 (2022) under mulched soil; whereas, it was not retrieved under bare soil conditions. This maximum peak under mulch conditions was followed by a soil CO_2 flux decrease (0.42 mg m^{-2} s^{-1}), until reaching similar values to the bare soils (i.e. 0.17 ± 0.01 mg m^{-2} s^{-1} at DOY 341) (Fig. 4a).

In 2023 (Fig. 4b), the soil CO_2 fluxes measured under the different SM conditions were different from DOY 118, being the flux observed under the mulched soil higher than that under bare soil conditions (average difference of about 0.06 mg m^{-2} s^{-1}). Such differences were maximum at DOY 150 (0.20 mg m^{-2} s^{-1}) and lasted until the end of the year (DOY 346).

The temporal evolution of soil CO_2 fluxes during the continuous monitoring period at the RDI treatments in bare and mulched soil conditions are reported in Fig. 5(a–p). Under bare soil, the fluxes were quite stable in a short-time period. Under mulching conditions, a more dynamic behaviour was depicted during DOYs 245–314 in 2022 (Fig. 5d–g) and DOY 150 in 2023 (Fig. 5o).

Further evaluations revealed the different development of the spontaneous weed species (i.e., *Trifolium pratense*, *Agropyrum repens*, *Setaria viridis*) under the experimental conditions (Table 5). Specifically, the height of these species was higher under bare soil conditions than in the mulched treatments (≈44.5 ± 1.6 cm *versus* 32.8 ± 3.9 cm, respectively).

The evaluation of the mulching thickness during the study period is also given in Table 5. In particular, the thickness of the mulching layer significantly varied at annual level accordingly to the pruning needs, reaching in average 9.4 ± 0.02 cm and 7.2 ± 0.05 cm in 2022 and 2023, respectively. Fig. 6 shows the relationship obtained between the average discontinuous soil CO_2 fluxes and the thickness of the mulching layer observed in the period 2022–23, indicating that as the mulching thickness increased, the soil CO_2 flux tended to increase.

At the agrosystem level, the time trend of the continuous small scale soil CO_2 data and of the CO_2 fluxes measured by the EC system

Table 5

Multivariate analysis of variance for evaluating the effect of SM and WR practices on the soil CO_2 fluxes (i.e. both discontinuous and continuous measurements) during the reference period (2022–23). WR and SM denote the water regime and soil management factors. The asterisks refer to the significant differences among the factors (for p-value <0.05). Degrees of freedom (DF) and F-values (F) are also reported in the Table.

Factors	Chamber CO_2 fluxes				Spontaneous weed height		Mulching thickness	
	discontinuous		continuous					
	F	p	F	p	F	p	F	p
WR	7.24	0.00*	–	–	0.22	0.64	2.60	0.11
SM	1.88	0.17	63.52	0.00*	7.81	0.01*	–	–
Year	0.31	0.58	0.12	0.73	–	–	10.06	0.00*
WR × SM	0.02	0.89	–	–	0.00	0.97	–	–
WR × Year	0.72	0.40	–	–	–	–	0.14	0.71
SM × Year	0.08	0.77	4.10	0.04*	–	–	–	–
WR × SM × Year	0.68	0.41	–	–	–	–	–	–
Total DF	500		477		239		214	

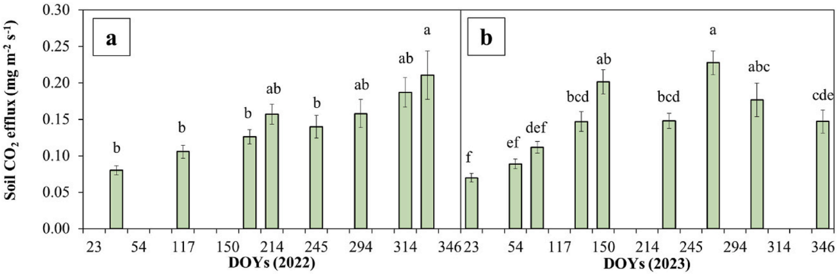

Fig. 3. Annual average temporal dynamics of the discontinuous soil CO_2 fluxes (mg m^{-2} s^{-1}) measured during the observation period (a) 2022 and (b) 2023. Bars indicate the standard errors. Different letters indicate significant differences according to HSD Tukey's test ($p < 0.05$).

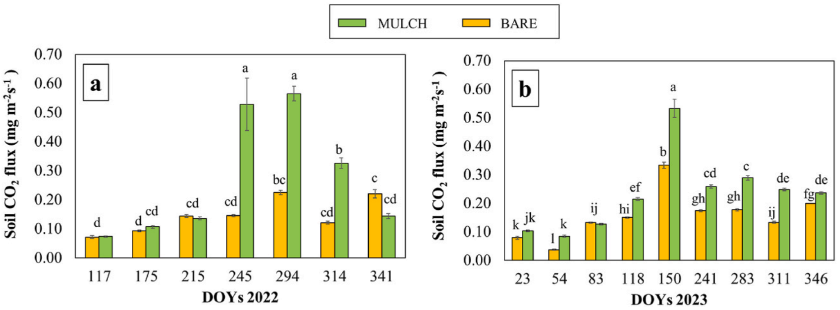

Fig. 4. Annual average temporal dynamics of the continuous soil CO_2 fluxes (mg m^{-2} s^{-1}) measured under different soil management conditions (BARE *versus* MULCH) during the observation period (a) 2022 and (b) 2023. Bars refer to standard errors. Different letters indicate significant differences according to HSD Tukey's test ($p < 0.05$).

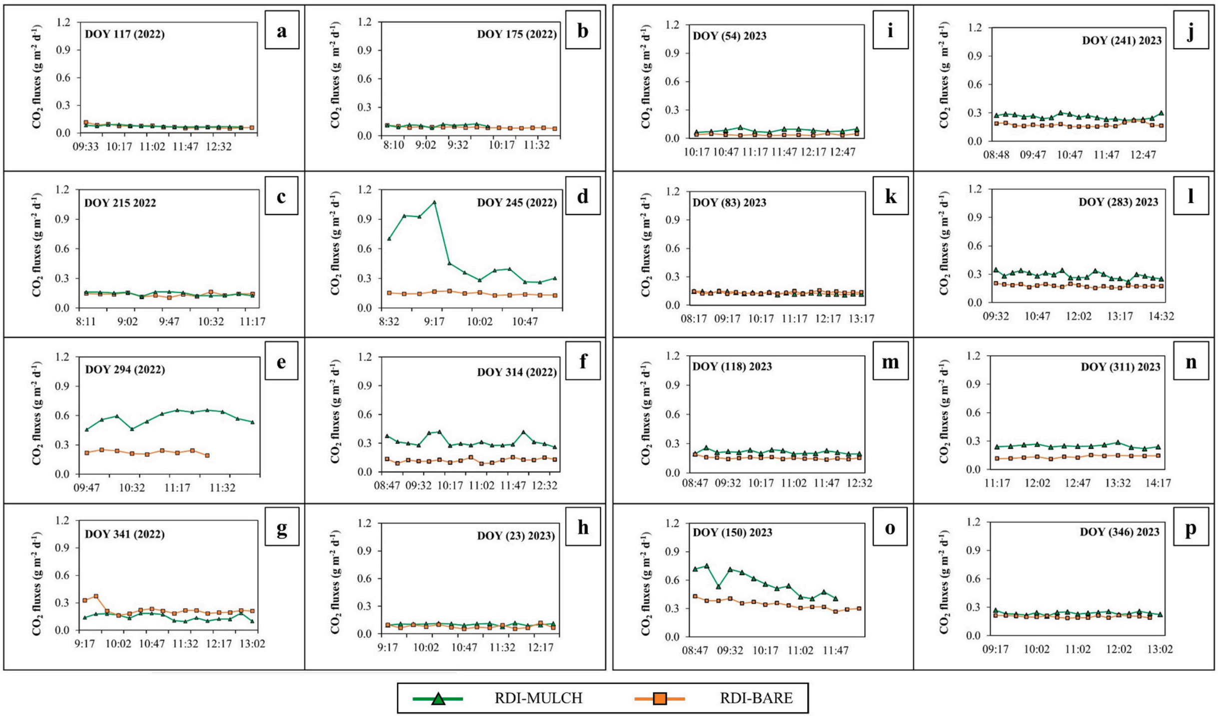

Fig. 5. Continuous temporal dynamics of soil CO_2 fluxes (mg m^{-2} s^{-1}) in regulated deficit irrigation (RDI) treatments under mulched (MULCH) and bare (BARE) soils during the monitoring period (a–g) 2022 and (h–p) 2023.

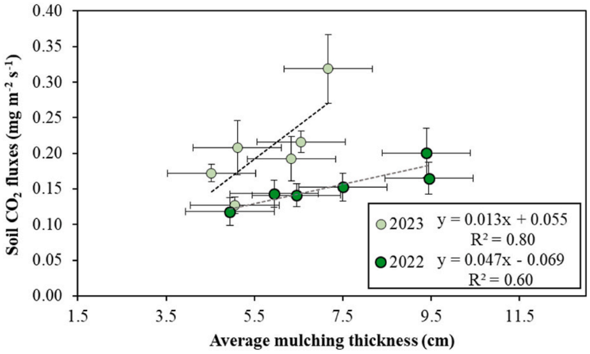

Fig. 6. Linear regression between average discontinuous soil CO_2 fluxes (mg m^{-2} s^{-1}) and mulching thickness in 2022 and 2023, respectively; bars refer to the standard error values.

is reported in Fig. 7 for the period June 2022–December 2023.

By comparing the CO_2 fluxes derived from the accumulation chamber with those directly measured by the EC technique, it is found that the closer agreement among the measurements was obtained in night-time period (mean absolute seasonal discrepancies of about 0.12 mg m^{-2} s^{-1}; Fig. 7). During the nocturnal period, in fact, the photosynthetic activity of the orange trees is minimum being the soil CO_2 fluxes the main contributor to the total agrosystem CO_2 flux. Contrarily, during the diurnal periods, both soil and agrosystem CO_2 fluxes reached the maximum separation (absolute differences ranging from 0.67 to 1.19 mg m^{-2} s^{-1}) because of the key role of the photosynthetic activity on the agrosystem CO_2 flux.

4. Discussion

In the study, the effects of conservative agricultural practices, based on different water regimes (WR) and soil management (SM) strategies application, have been identified on soil CO_2 fluxes emissions in order to determine the reliability and the sustainability of their adoption in a selected Mediterranean agrosystem. Thus, this study contributes to facilitate the predictions of the impacts of mulching measures on soil CO_2 emissions [32]. This assessment was corroborated by the determination of ancillary variables that allowed to better characterize the complex soil CO_2 dynamics (i.e., soil physical-chemical characteristics, agrometeorological, SWC and soil temperature data, EC fluxes).

Regarding the soil physical-chemical characterization, overall the 67 % of the analysed parameters showed significant differences between the pre- (2021) and post-mulching application (2022), e.g., for the pH confirming the presence of calcareous soils rich in Mg and Ca. Significant differences were found from the interaction between the conservative agricultural practices (i.e., SM and WR) and the analysed soil parameters for the 31 % of the whole dataset (e.g., in terms of CE, C_{org}) (Tables 3 and 4). This behaviour may vary under the different plant development stages (e.g., as function of the unit root length and distribution), causing different root-water uptake patterns for specific elements according to the ET_0 demand (Fig. 2a [74]). Furthermore, the complex soil-plant dynamics (e.g., water and nutrient distribution in the root-zone, soil CE variability, microbial activity) could have an extra impact on the response of the analysed site-specific soil physicochemical and microbial features [75]. In this sense, additional differences could be noticed in the long-term [6], especially in terms of CMIC and in CMIC over C_{org} (Table 3), considering that the ratio CMIC/C_{org} has a transient behaviour. Multi-years agricultural experiments are needed to link the effects on the rise in CMIC over C_{org} in relation to the soil CO_2 emissions under conservative agricultural practices [76,77].

In general, the study of soil CO_2 emissions is important for understanding the effects of climate change on the global CO_2 cycle [13, 14]. Several authors have explored the role of soil CO_2 flux under different agriculture practices. As example [78], suggested that the

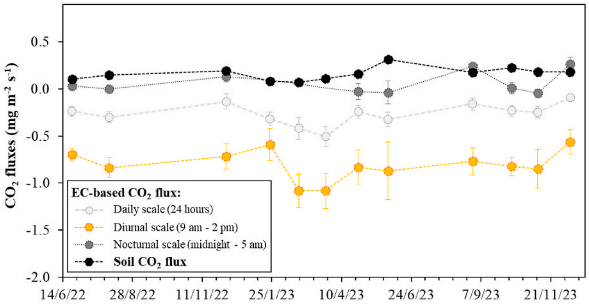

Fig. 7. Time trend of the continuous soil CO_2 fluxes (mg m^{-2} s^{-1}) measured by the accumulation chambers and the CO_2 fluxes measured by the Eddy Covariance (EC) system at the study site; bars refer to the standard error values.

influence of SM (no-till *versus* tillage) on soil CO_2 fluxes is significantly different as function of the soil and agrometeorological conditions [79] reported that the use of organic mulching improves crop yields, with economic benefit in average up to 13.5 %, and increases the soil CO_2 activity in average of 24 %. Herein, *ad-hoc* low-cost accumulation chambers were used to identify the environmental impact of different conservative agricultural practices in terms of CO_2 emissions within a two-year study period (Dec. 2021–Dec. 2023).

In absolute terms, note that the different magnitude of soil CO_2 fluxes derived in discontinuous and continuous mode (Figs. 3–4) may be related to the different location and temporal scale of the applied operational modalities (Fig. 1). Specifically, significant differences were found in the soil CO_2 discontinuous measurements related to the different WR applied at the study site (Table 5). In this sense, higher CO_2 fluxes were obtained in FI (up to 13 %) than in RDI treatments, as consequence of the higher irrigation levels applied (Fig. 2). These results contribute to highlight the relevant role of the environmental and agrometeorological variables, including water availability and land-use systems, in affecting the soil CO_2 flux seasonal change. There is a consensus on the recognition of the main climate factors that control the soil CO_2 fluxes in forest environment (e.g. Refs. [80,81]). Specifically, soil temperature and SWC are recognized as the most important factors influencing the soil CO_2 activity [82–86]. However, this phenomenon is less notorious under Mediterranean agro-ecosystems, where SWC and temperature changes are affected by different water inputs (rainfall and irrigation), varying in a wide and concurrent mode, respectively [87]. Under the experimental conditions, the results of the linear regressions performed between the soil CO_2 fluxes and the key soil variables (soil temperature and SWC) at the RDI treatments under bare and mulched soil conditions did not show a significant correlation (Fig. S3). This may be caused by *(i)* the misalignment between the locations where the ancillary measurements were conducted (the point-based SWC and soil temperature probes were placed at a depth of 0–30 cm from the soil surface, whereas the soil CO_2 flux measurements were performed at the soil surface); and *(ii)* the limited range of variations of the analysed variables. The integration of the SWC and soil temperature probes is planned to be released in a new prototype of the accumulation chamber.

Regarding on the differences retrieved on the soil CO_2 continuous measurements due to the interaction of the SM over time (Table 5), two different patterns were found for the bare and mulched soil, respectively, being the CO_2 fluxes higher in mulched soils than in bare conditions as shown in Fig. 4. These results may be explained by the direct correlation retrieved between the soil CO_2 activity and the thickness of the organic mulching (Fig. 6) that could determine a twofold effect. From one hand, the mulching favors the soil CO_2 fluxes in the hotter summer period because it reduces the heating of the soil surface and the soil evaporation, keeping more water in the soil (Fig. 2). On the other hand, the mulching layer contributes to the weed management [88,89]. Specifically, mulch constitutes a physical barrier to the development of the surface litter by preventing the sunlight and limiting the growth of the spontaneous species and seed germination. Note that in the study site, the spontaneous weed species reached the maximum height under bare soils (Table 5), highlighting the role of mulching in inhibiting their growth. This was translated in an increase of the soil CO_2 flux dynamics under mulched soils compared to the bare conditions in certain periods of the years, according to the environmental drivers. As example, in agreement with the results of [84,86], the different peaks of soil CO_2 flux observed in Fig. 4 under mulched soils can be linked to the occurrence of irrigation events or rain (in autumn and late spring in 2022 and 2023, respectively) and more favorable temperatures (Fig. 2).

At the agrosystem scale, the temporal evolution of the soil CO_2 fluxes, averaged at the treatment levels within the EC footprint, together with the CO_2 fluxes measured by the EC system, denotes that the small-scale chamber measurements (footprint of 0.03 m^2) can be used to estimate soil CO_2 fluxes at orchard scale if fluxes are properly scaled [72] (Fig. 7). In addition, the more negative sign of the EC fluxes observed at the daily/diurnal scale in comparison to the night-time fluxes (more similar to the soil CO_2 fluxes) suggested the central role of the agrosystem in absorbing CO_2, acting as a sink source (Fig. 7). Similar findings were reported by Ref. [90] that observed the highest monthly average rates of net ecosystem exchange flux at midday in the summer period. At seasonal level [91], reported that the photosynthetic activity of the citrus orchards shows a typical trend of evergreen species with maximum values in the periods May–June and August–September. Nevertheless, additional data and long-term observations, such as information about the amount of carbon exported in the form of harvested crops and the carbon imported in the form of organic fertilization, are needed to properly quantify the single CO_2 flux component and determine the overall CO_2 budget of the agrosystem.

Several advances have been carried out into the development of CO_2 chamber techniques since long time [52,92]. The dimensions of the soil CO_2 flux system used in this study, in terms of diameter and height of the chamber, are quite similar in comparison to other commercial equipment, i.e., LI-8250 LI-COR Environmental (USA), WestSystems (Italy) and ADC BioScientific (UK). Analogous characteristics also refer to the accuracy of the used infra-red spectrometer for CO_2 determinations, with errors of about 3 % (except for LI-COR spectrometer in which the accuracy improves to 1.5 %). Moreover, the specifications of the gas temperature and pressure sensor mounted on the soil CO_2 flux system are better in comparison to the above-mentioned commercial systems. However, as limitations of this study, sources of uncertainty related to the design of the accumulation chamber and the operational modality used for conducting the soil CO_2 flux surveys cannot be excluded, i.e., using a collar for fixing the accumulation chamber at the soil surface, performing measurements during diurnal campaigns. Note also that non-continuous measurements have limitations regarding statistical replication, temporal dependency, annual budgets, and the related level of uncertainty [93]. In this study, point-based soil CO_2 flux surveys were performed without using the collar for fixing the accumulation chamber to the soil surface, which is commonly used for this type of measurement. This choice was based on the findings retrieved by Refs. [94,95], which reported negative effect on the soil CO_2 flux fluxes using the collar. Indeed, the total diurnal flux of soil CO_2 flux is often underestimated because the insertions of the collar into the soil by cutting the roots lead to the lack of the autotrophic component. To overcome this shortcoming, future research will be focused on updating the accumulation chamber adopting fixed (as commonly used in previous studies) and perforated collars to do not alter the roots activities.

It is well-known that the frequency of the fluxes collection has a direct influence on the soil CO_2 temporal resolution. The best would be to have a redundant number of measurements to reduce the uncertainty caused by soil CO_2 flux variations; however, this is a complicated task to be accomplished in an operational mode [95]. The main advantage of using low-cost accumulation chambers was to carryout multiple and concomitant soil CO_2 flux surveys improving the efficiency of data acquisition time. In addition, the use of *ad hoc* designed tools has facilitated the data acquisition and processing steps thanks both to the visual web interface (Fig. S1) and the Matlab tool based on RANSAC algorithm, which allows immediately discarding noisy measurements (Fig. S2). This latter can be further implemented with other algorithms (including non-linear models) in order to identify the best range of data for each survey in an automatic way.

Finally, the implementation of sustainable agronomic practices (i.e., organic mulched soil and sustainable WR) represents a valid strategy to manage more efficiently the crop production and face the climate change. The use of organic mulching can be a practical solution for the farmers to recycle the pruning residues in the field, according to the strategic plans of the European Directives of the new common agricultural policy [96], which provides additional incentives for farmers who implement these practices aiming at reaching carbon neutrality goals. In this sense, the reuse of these residues will make easier and eco-friendly their disposal providing a solution both in terms of improving the working efficiency, because the residues management takes place on site, and the sustainability of the crop production.

5. Conclusion

This study contributes to improve the understanding about the soil CO_2 fluxes as affected by the adoption of sustainable SM and WR choices in citrus orchards. Specifically, it demonstrates the importance of applying organic mulching in agricultural soils as suitable conservation agriculture practice. Finally, the main findings of this study are listed as follows.

- The application of organic mulching in combination with FI or RDI criteria has influenced some of the analysed soil chemical-physical characteristics within the reference period, showing overall increasing in terms of d.m., pH, C_{tot}, K_{tot}, and Mg contents; whereas, Ca and N_{tot} contents decreased. Moreover, maximum CE and C_{org} values were obtained under RDI-BARE treatment;
- Overall significant differences were obtained for the soil CO_2 flux discontinuous fluxes as function of the WR (0.16 ± 0.01 and 0.14 ± 0.01 mg m^{-2} s^{-1} under FI and RDI, respectively);
- For the continuous soil CO_2 flux measurements, the response observed for the SM factor varied from year to year, indicating for the overall reference period 2022-23 higher soil CO_2 flux under the mulched soils (0.24 ± 0.01 mg m^{-2} s^{-1}) than under the bare soil conditions (0.15 ± 0.00 mg m^{-2} s^{-1});
- At annual level, differences were obtained for both soil CO_2 continuous and discontinuous fluxes as function of the interaction between SM and DOY, with maximum fluxes under mulched soils;
- Direct relationships were retrieved between the soil CO_2 activity and the thickness of the organic mulching (R^2 of 0.60 and 0.80 in 2022 and 2023, respectively). Furthermore, the development of the spontaneous species was favored under bare soil conditions (average height of 44.5 ± 1.6 cm), rather than in the areas covered by the organic mulching (average height of 32.8 ± 3.9 cm);

In conclusion, the study provides innovative insights both on understanding the role of soil CO_2 emissions in agricultural context and on the use of low-cost accumulation chambers and automatic tools for soil CO_2flux data processing. In addition, the comparison of the soil CO_2 emissions with the agrosystem CO_2 fluxes measured by eddy covariance (EC) technique revealed that the small-scale chamber measurements can be used to estimate soil CO_2 fluxes at orchard scale if fluxes are properly scaled. Future outlooks of this research are needed to solve the sources of uncertainty related to the architecture of the accumulation chamber and to the operational modality for conducting soil CO_2flux surveys.

Declarations

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The soil CO_2 dataset analysed during the current study are available at https://doi.org/10.5281/zenodo.10557780.

CRediT authorship contribution statement

S. Guarrera: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D. Vanella:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S. Consoli:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **G. Giudice:** Software, Methodology, Investigation, Data curation. **S. Toscano:** Investigation, Data curation. **J.M. Ramírez-Cuesta:** Writing – review & editing, Validation, Methodology, Investigation. **M. Milani:** Writing – review & editing, Investigation. **F. Ferlito:** Writing – review & editing, Investigation. **D. Longo:** Writing – review & editing, Software, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Co-author member of the journal's editorial team (S.C.).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e30543.

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