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Soil CO_2 emissions during the winter–summer crop rotation fallow period: Influence of tillage, nitrogen fertilization, and weed growth in a long-term field trial

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A R T I C L E I N F O

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A B S T R A C T

Soil respiration is a key component of the carbon cycle, yet it remains understudied during fallow periods, particularly in Mediterranean cropping systems where fallows can exceed nine months. As the carbon credit market emerges, accurately quantifying CO_2 emissions year-round has become increasingly important. This study assessed soil respiration and its abiotic and biotic drivers, such as soil temperature and water content, weed biomass and composition, under two different tillage management, long-term conventional tillage (CT) and no-tillage (NT), combined with two nitrogen levels (0 and 180 kg N ha^{-1} yr^{-1}). Monitoring was conducted during two fallow periods (2022–2023 and 2023–2024) between durum wheat harvest and maize sowing. Soil temperature and water content followed typical Mediterranean trends, with summer heat peaks and higher winter moisture; NT plots had significantly higher average temperatures and winter soil moisture than CT, regardless of fertilization. Soil CO_2 emissions were low and similar across treatments in winter but diverged in warmer seasons. In 2022–23, NT showed significantly higher emissions than CT (up to +65 %), while in 2023–24, only NT0 exceeded CT180 (+48 %). Emissions were positively correlated, although weakly, with temperature and negatively with moisture, especially under NT. Soil cover, dominated by Poaceae, fluctuated seasonally and was consistently greater in NT, with notable differences in species composition. These results emphasize the relevance of fallow-period emissions in carbon budgeting and the potential role of spontaneous vegetation in carbon dynamics. Incorporating such insights into carbon farming frameworks will be essential for improving the accuracy and integrity of climate-related agricultural policies.

1. Introduction

Carbon farming encompasses a range of management practices aimed at delivering climate mitigation in agriculture. These practices involve the management of land, livestock, and both above- and below-ground vegetation to increase carbon sequestration in living biomass, dead organic matter, and soils (Lal, 2023; Mattila et al., 2022). A key objective of carbon farming is to reduce carbon dioxide (CO_2) emissions from the soil (Paustian et al., 2000), a process commonly referred to as soil respiration (Bond-Lamberty et al., 2024). Soil respiration can be divided into two components: autotrophic respiration, associated with plant root systems, and heterotrophic respiration, driven by the activity of soil micro- and meso-fauna (Tang et al., 2020; Wang et al., 2014). Soil respiration is a key component of the carbon cycle, reflecting the rate at which soil organic carbon is converted back into CO_2 and then released into the atmosphere (Schlesinger and Andrews, 2000). At the same time, it serves as an important indicator of soil fertility and health (Singh et al., 2011).

Soil respiration can be significantly influenced by soil temperature, soil water content, and agricultural management practices (Bond-Lamberty et al., 2024; Ferrara et al., 2022; Oertel et al., 2016). Both soil temperature and water content strongly influence the

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metabolic activities of plants as adequate soil temperature is essential for germination and root development, while water supports critical biological and physiological processes such as nutrient transport, photosynthesis, cellular turgor, and temperature regulation (Cohen et al., 2021; Lewandrowski et al., 2021; Reed et al., 2022). Additionally, soil temperature and water content are known to influence the metabolic activity of the soil microbiome (Jansson and Hofmockel, 2020) and affect the microbial diversity (Rasmussen et al., 2020), thereby shaping its role in biogeochemical cycles of nutrients such as nitrogen and carbon (Basu et al., 2021). Agricultural management practices can also play a fundamental role in soil carbon dynamics (Francioni et al., 2020; Pastorelli et al., 2013). For instance, it is well established that different tillage regimes (varying in depth and intensity) influence soil organic matter content, with deeper tillage typically associated with reduced carbon stocks (Haddaway et al., 2017; Ussiri and Lal, 2009). Conversely, no-tillage practices, widely recognized for their ability to increase organic matter content over the long term, also increase or decrease soil respiration depending on the site-specific soil and climatic conditions (Nazir et al., 2024). Fertilization is another practice known to increase emissions, in this case nitrous oxide (N_2O), which is a greenhouse gas approximately 300 times more potent than CO_2 (Ramzan et al., 2020). Moreover, evidence suggests that fertilization can also lead to higher soil respiration rates due to the enhanced vitality of crop root systems (Chen et al., 2017; Hua et al., 2023; Yan et al., 2021). While the effect of incorporating crop residues and weeds on soil CO_2 emissions is well-studied (Muhammad et al., 2019), much less attention has been given to the contribution of weeds to soil respiration during their vegetative stage. In some cropping systems that adopt winter-summer crop rotations, weeds can persist for long periods (Boutagayout et al., 2023), with a potential impact on the soil carbon pool (Aguilera et al., 2018), and therefore influencing soil respiration dynamics (Freschet et al., 2021).

The Mediterranean basin is considered a climate change hotspot (Bianchini et al., 2025) where alterations in rainfall and temperature patterns will impact not only crop yields but also the soil carbon cycle (Francaviglia et al., 2012). Many Mediterranean agricultural systems are characterized by the alternation of winter crops, such as durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.), spring wheat (*Triticum aestivum* L.), and faba bean (*Vicia faba* L.), with summer crops, such as sunflower (*Helianthus annuus* L.) and maize (*Zea mays* L.), and perennial forage crops like alfalfa (*Medicago sativa* L.) (Francioni et al., 2024; Toderi et al., 2022). In Mediterranean cropping systems, the rotation between a winter crop and a summer crop typically involves two fallow periods. The first is a shorter, 3–4 months period, occurring between the harvest of the summer crop (around September/October) and the sowing of the winter crop (around November/December). The second, often exceeding nine months, extends from the harvest of the winter crop (around June/July) to the sowing of the summer crop (around April). During the fallow periods, the soil often remains bare except for the presence of weeds. Most studies on soil respiration focus on the crop-growing season (e.g., Álvaro-Fuentes et al., 2008; Ferrara et al., 2022), leaving the fallow periods largely unexplored.

The upcoming launch of the carbon credit market makes it essential to use sound methods to ensure that CO_2 emissions and removals are measured accurately. This applies whether using direct measurements (e.g., the measure-and-remeasure approach) or modelling, which requires field data for model calibration. If soil respiration (i.e., CO_2 emissions, considered a negative entry in the carbon balance) during the fallow period is overlooked, it could lead to significant gaps in the carbon credit measurement framework—particularly in Mediterranean cropping systems, which constitute a substantial part of European agriculture. In this context, a better understanding of soil respiration dynamics during fallow periods is crucial to improving the accuracy of carbon accounting in Mediterranean agricultural systems.

The objective of this study is to monitor and quantify soil respiration during the fallow period between the harvest of a winter crop (durum wheat) and the sowing of a summer crop (maize), a typical crop rotation in the Mediterranean region. The study aims to highlight how different intensities of soil tillage and long-term nitrogen fertilization (applied over 30 years) influence soil respiration and its associated drivers during the nine-month fallow period. The hypothesis is that long-term management practices (tillage and fertilization) may produce contrasting effects on both abiotic (soil temperature and moisture) and biotic (weed composition) drivers of soil respiration.

2. Materials and methods

2.1. Study site, field management and experimental design

The study was conducted in a long-term field experiment established in 1994 at the 'Pasquale Rosati' experimental farm in Agugliano, Italy (13°22'E, 43°32'N, 100 m a.s.l.). The study site features a clay soil classified as Calcaric Gleyic Cambisol (IUSS Working Group WRB, 2022) and a Mediterranean climate, with an average annual rainfall of 820 mm, predominantly occurring from autumn to spring (24 % of the total precipitation). The annual mean air temperature is 15.3 °C, with monthly averages ranging from 6.2 °C in January to 25 °C in August (Fiorentini et al., 2024; see Fig. 1).

The ongoing long-term field experiment consists of a 2-year rotation between durum wheat and a summer crop: sunflower (from 1994 to 2001), and maize from 2002 onwards. The crop rotation is duplicated in two adjacent fields to ensure that all crops are present each year. Within each field, three tillage treatments (ploughing at 0–40 cm, minimum tillage at 0–10 cm, and no tillage) and three nitrogen fertilization levels (0, 90, and 180 kg N ha^{-1} $year^{-1}$) were tested in the main plots. The trial is arranged according to a split-plot experimental design (1500 m^2 plots and 500 m^2 subplots) with two randomized blocks.

For this study, only the treatments of conventional tillage (CT) and no tillage (NT) at the fertilization levels of 0 and 180 kg N ha^{-1} $year^{-1}$ were selected: CT0, CT180, NT0, and NT180 (Figure S1)—with 180 kg N ha^{-1} chosen as it represents the commonly applied fertilization rate in the study area (Fiorentini et al., 2024; Francioni et al., 2020). The monitoring period corresponds to the time between wheat harvest and maize sowing in two consecutive fallow periods (2022–23 and 2023–24). Both CT and NT plots have a clay content of approximately 44 %, a sand content of 43 %, and a pH of 7.8. However, they differ significantly in terms of soil organic matter (1.3 % in CT vs. 2.2 % in NT) and total nitrogen (1 % in CT vs. 1.4 % in NT) (Fiorentini et al., 2024).

The CT plots were ploughed annually using a mouldboard at a depth of 40 cm in autumn (around October) and the seedbed was prepared with double harrowing before the sowing date for both wheat (between October and November) and maize (between March and April). The soil in the NT plots was left undisturbed, with crop residues maintained, except for no-till seeding and the application of a non-selective herbicide. In the fertilized subplots, 180 kg of N ha^{-1} was applied, split into two applications for wheat (both during the tillering stage) and applied once after crop emergence (approximately at the fourth leaf stage) for sunflower and maize.

This study examined the dynamics of soil CO_2 emissions, temperature, water content, and weed biomass and composition during the fallow period (from the wheat harvest to the seedbed preparation for maize sowing) in the periods from July 25, 2022, to March 30, 2023, and from July 21, 2023, to May 5, 2024.

2.2. Soil temperature, water content and CO_2 emissions

Soil temperature and water content (both at a depth of 10 cm) and CO_2 emissions were measured at intervals of 1–3 weeks during the study period, depending on weather conditions. Soil CO_2 emissions and temperature were measured using a portable infrared gas analyser (EGM-4; PP-Systems, Hitchin, UK) equipped with a soil respiration chamber and a thermometer probe. To measure soil CO_2 efflux, the respiration

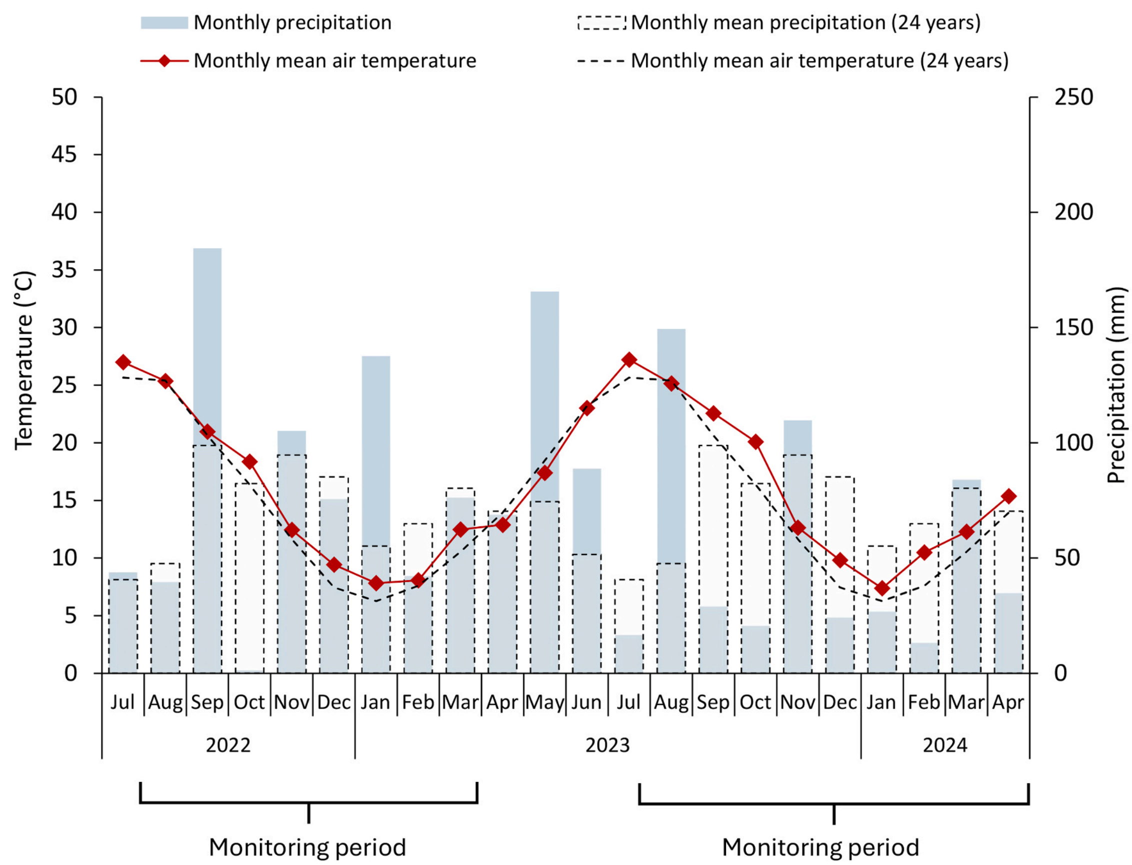

Fig. 1. Monthly precipitation and average air temperature during the study period (July 2022–April 2024) and over the long-term (1998–2022) period for Agugliano (Ancona province, Italy).

chamber was fitted onto 10 × 10 cm PVC collars with perforated walls, which were permanently installed in NT plots. In CT plots, the collars were temporarily removed one day prior to soil tillage and reinstalled the following day. For each subplot, three PVC collars were placed to explore the spatial variability of emissions (Krauss et al., 2017), resulting in a total of 24 collars used for soil CO_2 and temperature measurements (Figure S1). The cumulative soil CO_2 emissions over each monitoring period were calculated by linear interpolation between the two sampling dates and by numerical integration using the trapezoidal rule (Toderi et al., 2022). Soil water content was measured on the same dates as the soil CO_2 measurements and was determined from soil samples collected from the top 10 cm using oven drying at 105 °C to constant weight. Soil CO_2 emissions, temperature, and soil water content were measured 20 times during the 2022–23 monitoring period and 24 times during the 2023–24 monitoring period. In order to standardize the measurements between the two periods, data collection was avoided under particular conditions—specifically, near the time of PVC collar removal in CT and herbicide application in NT—and immediately after significant rainfall events.

2.3. *Weed composition and aboveground biomass*

The weed species composition and aboveground biomass were measured at the end of summer (on 02 September 2022 and 25 August 2023) and during peak development in spring (on 27 March 2023 and 09 April 2024). Both samplings were performed approximately one meter away from the collars used for soil CO_2 measurements, within a 1 × 1 m quadrat. Weed species composition was assessed by estimating percent cover of each species present within the quadrat (Dengler and Dembicz, 2023). Taxonomic nomenclature of each taxon was updated according to the Italian checklist provided by Bartolucci et al. (2018). The aboveground weed biomass was obtained by collecting all weeds within the quadrat, drying them at 65 °C until constant mass, and then weighing them.

2.4. *Statistical analysis*

Statistical analysis was performed using SPSS, version 29 (SPSS Inc., IBM, Chicago, IL, USA). A three-way mixed ANOVA (GLM procedure) was used to determine the effects of tillage (between-factor), fertilization and date (within-factors) and their interactions on soil temperature, water content, and CO_2 emissions. A two-way ANOVA was used to determine the effects of tillage (between-factor), fertilization (within-factor) and their interactions on cumulative soil CO_2 emissions and weed above ground biomass. When the data did not meet normality and/or homoscedasticity assumptions, the Box-Cox transformation was applied. When data did not meet sphericity assumption, the Greenhouse-Geisser correction was applied to adjust the degrees of freedom (Table S1). Linear regression analysis was used to relate the soil CO_2 emissions to the soil temperature and soil water content. Statistical significance was set at $P < 0.05$. Figures in the main text display non-transformed treatment means, with significant differences indicated by the Tukey HSD test. The complete ANOVA tables are available in the supplementary file (Table S2).

3. Results

3.1. *Soil temperature, water content, and CO_2 emissions dynamics*

Table 1 summarizes the results of the mixed ANOVA, which revealed significant within-subjects effects for both soil water content and CO_2 emissions, with most comparisons showing P-values < 0.01, indicating

Table 1
p-values from the three- or two-way mixed ANOVA. The complete ANOVA tables are available in the supplementary file.

Source	ST	SWC	CO_2	Σ CO_2 2022–23	Σ CO_2 2023–24	Weed Sep. 22	Weed Apr. 23	Weed Aug. 23	Weed Apr. 24
Within-Subjects Effects									
Date	< 0.01	< 0.01	< 0.01	-	-	-	-	-	-
Date × Till.	0.11	0.00	< 0.01	-	-	-	-	-	-
Date × Block	0.03	< 0.01	< 0.01	-	-	-	-	-	-
Fert.	< 0.01	< 0.01	0.15	0.94	0.02	0.43	0.83	0.04	0.96
Fert. × Till.	0.09	< 0.01	0.85	0.67	0.68	0.11	0.85	0.54	0.95
Fert. × Block	0.87	0.01	0.54	0.84	0.12	0.15	0.89	0.33	0.96
Date × Fert.	0.02	0.00	0.03	-	-	-	-	-	-
Date × Fert. × Till.	0.06	0.00	0.42	-	-	-	-	-	-
Date × Fert. × Block	0.19	0.03	0.52	-	-	-	-	-	-
Between-Subjects Effects									
Till.	< 0.01	< 0.01	< 0.01	< 0.01	0.02	0.89	0.04	0.41	0.07
Block	0.00	0.23	0.13	0.05	0.04	0.70	0.14	0.13	0.02

ST = soil temperature; SWC = soil water content; Σ = cumulative

pronounced temporal variation. Cumulative CO_2 emissions for 2023–2024 showed a significant difference ($P = 0.02$) in one comparison, whereas no significant effects were observed for the 2022–2023 period. Among the between-subjects effects, significant treatment differences emerged for soil water content and CO_2 emissions ($P < 0.01$), as well as for cumulative CO_2 emissions in both years ($P < 0.01$ for 2022–2023; $P = 0.02$ for 2023–2024). A significant effect on weed cover was detected only in April 2023 ($P = 0.04$), with no

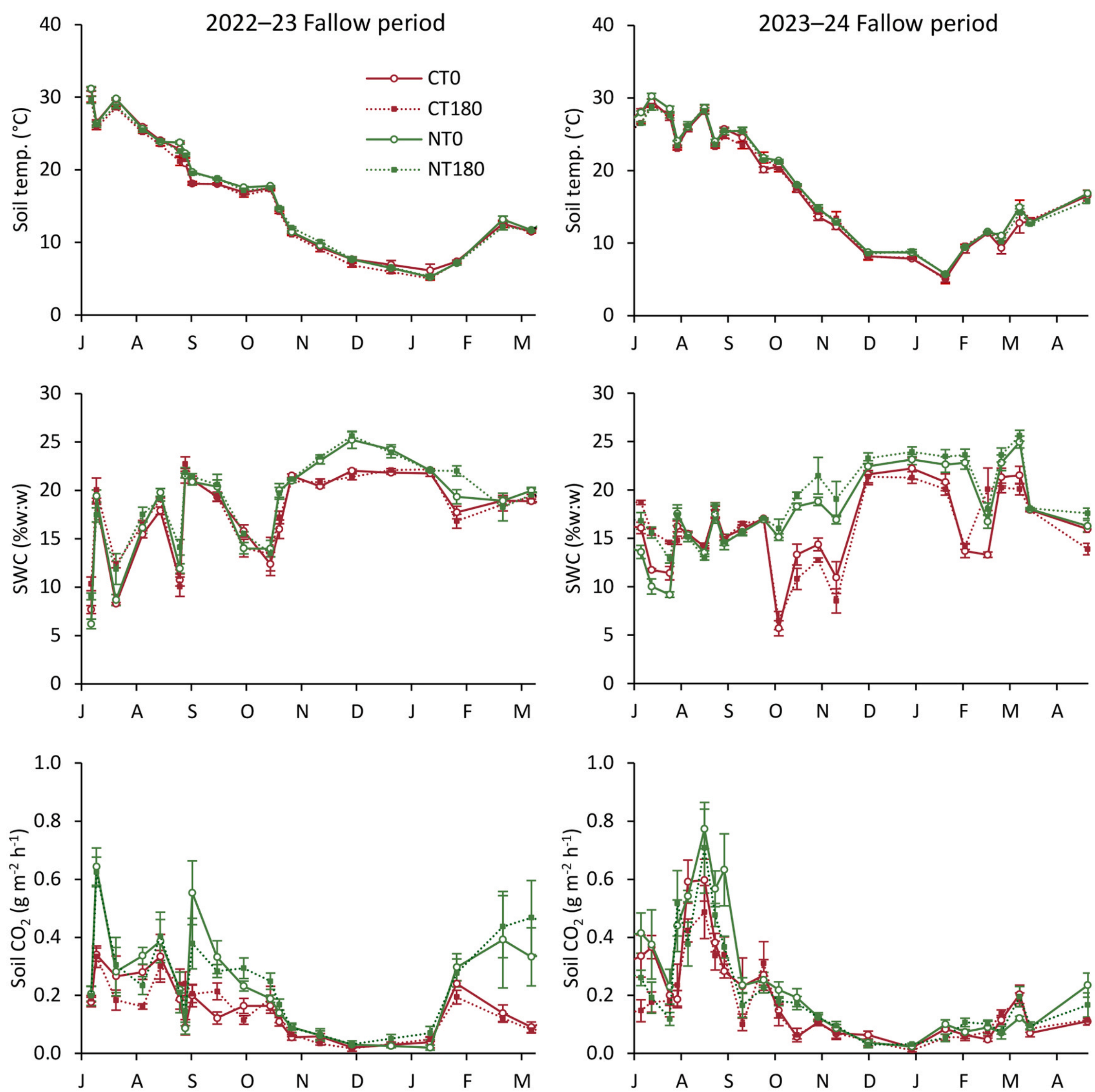

Fig. 2. Seasonal variations of soil temperature (10 cm depth), soil water content (SWC) (10 cm depth) and soil CO_2 emissions during the two monitoring periods (From July 2022 to March 2023, and from July 2023 to May 2024). Data are means ± standard errors. CT0: conventional tillage with 0 kg N ha^{-1} year^{-1}; CT180: conventional tillage with 180 kg N ha^{-1} year^{-1}; NT0: no tillage with 0 kg N ha^{-1} year^{-1}; NT180: no tillage with 180 kg N ha^{-1} year^{-1}.

differences observed in September 2022.

The dynamics of soil temperature and soil water content in both monitoring periods followed the typical patterns observed in Mediterranean environments, where high temperature peaks occur in summer and, in winter, along with the low temperature peak, the soil water content is higher (Fig. 2). The soil temperature dynamics followed a highly similar pattern across all treatments in both monitoring periods, though significant effects of both tillage (NT > CT) and fertilization (higher at 0 kg N than 180 kg N) emerged, and no interaction was detected in terms of average temperature and soil water content (Table 1).

Soil water content dynamics exhibited more abrupt fluctuations over time in both monitoring periods (Fig. 2). Despite a relatively similar pattern among treatments in summer, in winter higher soil water content clearly emerged in NT compared to CT treatments, regardless of fertilization level. Notably, this effect persisted from October through March 2023–24 (Fig. 2).

Soil CO_2 emissions followed different patterns across the two monitoring periods, with very low and similar dynamics across treatments during winter, but clear differences in summer and spring (Fig. 2). In 2022–23, emissions were generally higher for NT treatments than CT in summer and spring. In summer 2022, soil CO_2 showed two peaks, one at the end of July and another in the third week of September, with NT treatments significantly differing from CT treatments. Similarly, in spring 2023, soil CO_2 emissions from NT treatments were significantly higher than those from CT treatments, although more widely dispersed around the mean. The 2023–24 period displayed different dynamics from 2022–23, with a single CO_2 peak between August and September, after which emissions gradually declined and nearly flattened out during winter, then increased again gradually in spring without showing significant differences between treatments (Fig. 2).

The cumulative soil CO_2 emissions in 2022–23 were significantly higher in NT treatments compared to CT, showing an increase of 65 % (Fig. 3), and no significant effect attributable to fertilization or its interaction with tillage (Table 1). In 2023–24, only the cumulative soil CO_2 emissions of NT0 were significantly higher than CT180 (+48 %), while the other two treatments showed intermediate values (Fig. 3). In this case, both fertilization and tillage had significant effects, but not their interaction (Table 1).

3.2. Relationship among soil CO_2 emission, temperature, and water content

In general, positive relationships emerged between soil CO_2 emissions and soil temperature, and negative relationships between soil CO_2 emissions and soil water content, though these were relatively weak and observed only for NT treatments (Fig. 4). Soil temperature explained 54 % and 50 % of the CO_2 variation in CT0 and CT180, respectively, and 45 % and 31 % of the CO_2 variation in NT0 and NT180 ($P < 0.01$). Soil water content was not a good predictor of soil CO_2 variation in CT treatments but explained 16 % and 18 % of the CO_2 variation in NT0 and NT180 ($P < 0.05$) (Fig. 4).

3.3. Weed composition and aboveground biomass

Soil cover exhibited significant fluctuations throughout the monitoring period, with a clear dominance of species belonging to the Poaceae family (Table 2). By late summer 2022, soil cover in NT was approximately double that observed in CT. However, the soil was more than half-covered in NT0 and nearly fully covered in NT180 by late March 2023, prior to maize sowing. While the two CT treatments were dominated by *Setaria italica* and, to a lesser extent, *Sorghum halepense*, the NT0 and NT180 treatments exhibited *S. halepense*, but also substantial amounts of *Convolvulus arvensis* and *Kickxia elatine* (Table S2). *Polygonum aviculare*, nearly absent in NT0, was abundant exclusively in NT180. By late summer 2024, soil cover exceeded 50 % across all treatments, with dominance by *S. halepense* and *S. italica*. Additionally, *C. arvensis* was abundant but only in NT180. Conversely, in spring, soil cover was minimal across treatments, with only sparse occurrences of *S. halepense* and *Digitaria sanguinalis* in NT0 and NT180 (Table S2).

In both monitoring periods, weed aboveground biomass was higher in late summer than in spring (Fig. 5). In September 2022, weed biomass was significantly higher in CT0 compared to CT180 (+32 %), with other treatments showing intermediate values (Fig. 5). In April 2023, biomass in NT treatments was higher than in CT treatments, although the difference was not significant. In August 2023, weed aboveground biomass in NT0 was 93 % higher than in CT180. By April 2024, there was no biomass present in CT treatments (Fig. 5).

4. Discussion

In this open-field study, soil CO_2 emissions (the sum of autotrophic and heterotrophic soil respiration) and their main drivers (soil temperature, water content and weeds) were monitored and quantified during the nine-month fallow period between the harvest of a winter crop and the sowing of a summer crop. The study highlighted that soil temperature was influenced by both soil tillage practices and fertilization. Soil water content showed the most significant differences between NT and CT during the winter months. The study also revealed that soil CO_2 emissions are not negligible during the fallow period, and that weather

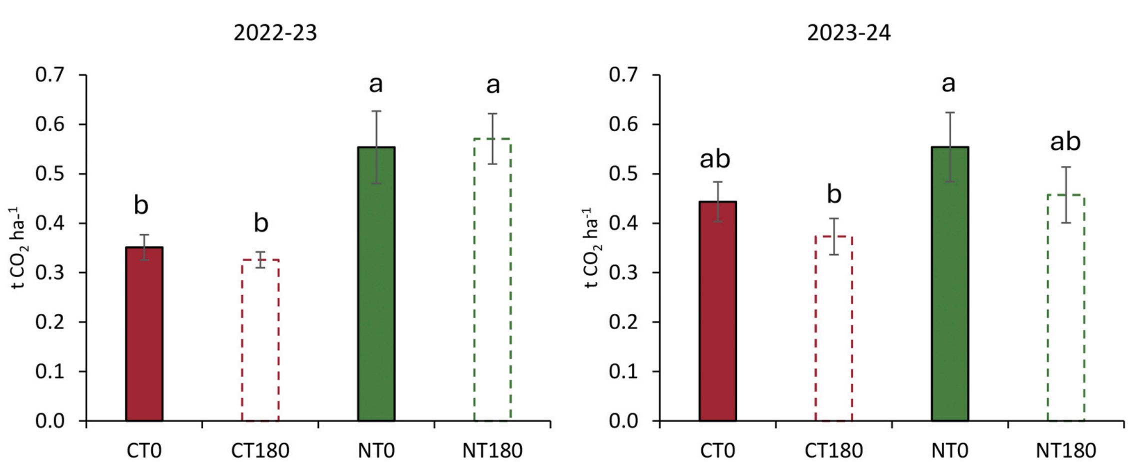

Fig. 3. Cumulative soil CO_2 emissions during the two monitoring periods (from July 2022 to March 2023, and from July 2023 to May 2024). Data are presented as means ± standard errors. Different letters denote significant differences at $p < 0.05$. CT0: conventional tillage with 0 kg N ha^{-1} $year^{-1}$; CT180: conventional tillage with 180 kg N ha^{-1} $year^{-1}$; NT0: no tillage with 0 kg N ha^{-1} $year^{-1}$; NT180: no tillage with 180 kg N ha^{-1} $year^{-1}$.

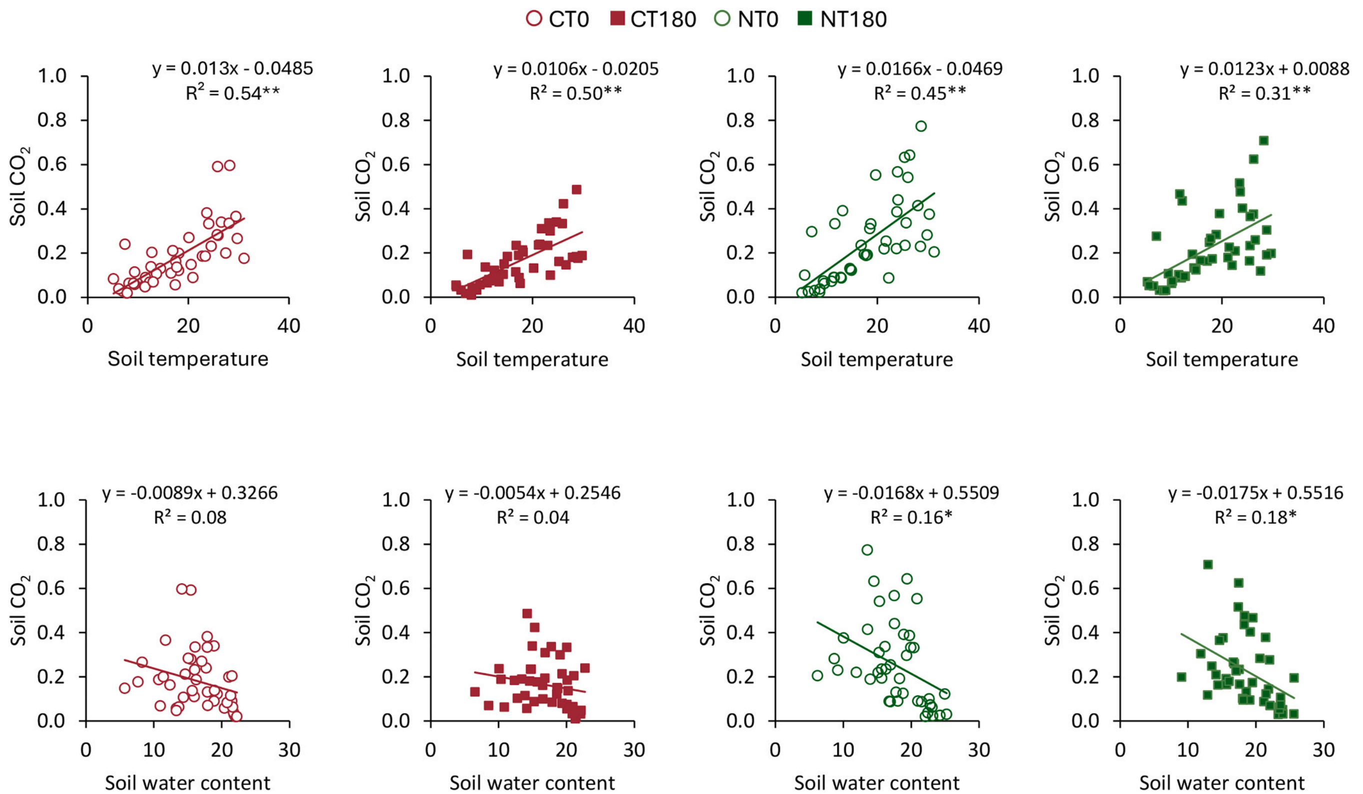

Fig. 4. Relationships between variations in soil CO_2 emissions, soil temperature (10 cm depth), and soil water content (10 cm depth). CT0: conventional tillage with 0 kg N ha^{-1} $year^{-1}$; CT180: conventional tillage with 180 kg N ha^{-1} $year^{-1}$; NT0: no tillage with 0 kg N ha^{-1} $year^{-1}$; NT180: no tillage with 180 kg N ha^{-1} $year^{-1}$. *$p < 0.05$; ** $p < 0.01$.

Table 2
Weed soil cover and percentage abundance of families.

Date	Cover (%)	Treatment	Poaceae (%)	Conv. (%)	Plant. (%)	Polyg. (%)	Others (%)
02/09/2022	23	CT0	82.9	7.9	2.8	0.8	5.5
	28	CT180	65.1	14	9	.	11.9
	46	NT0	56.5	25.1	1.3	14.6	2.5
	42	NT180	22.9	15.2	35.0	25.3	1.7
27/03/2023	.	CT0	.	.	.	.	.
	.	CT180	.	.	.	.	.
	60	NT0	56.7	6.3	.	9.6	27.5
	80	NT180	95.5	.	.	2.7	1.7
25/08/2023	60	CT0	79.4	1.8	10.3	0.2	8.3
	50	CT180	71.2	11.2	11.3	1.7	4.6
	79	NT0	93.5	1.6	2.1	1.3	1.5
	60	NT180	67.3	.	1.2	30.4	1.1
09/04/2024	.	CT0	.	.	.	.	.
	.	CT180	.	.	.	.	.
	7	NT0	50.4	12.6	12.8	.	24.1
	5	NT180	83.9	4.7	.	0.1	11.4

Conv. = Convolvulaceae; Plant. = Plantaginaceae; Polyg. = Polygonaceae

conditions in the spring can play a crucial role. This is because, in addition to soil temperature and water content, weed presence also influences soil CO_2 emissions.

4.1. The effect of tillage and nitrogen management on soil CO_2 abiotic and biotic drivers

It is well known that both soil temperature and water content are key drivers of soil CO_2 emissions (Ferrara et al., 2022; Oertel et al., 2016). This study found that long-term tillage practices lead to significant alterations in both soil temperature and soil water content, but with seasonal variation. The monitored soil temperature was generally higher in NT plots compared to CT and, regardless of tillage, was higher in fertilised plots. Soil water content was found to be higher in NT plots only during autumn and winter. The dynamics of soil temperature and water content observed in this study are typical of Mediterranean environments, where the peak of temperatures occurs in the summer months (i.e., after winter crops are harvested), while the lowest temperatures correspond to the highest soil water content (Francioni et al., 2020; González-Ubierna and Lai, 2019; Mancinelli et al., 2010).

Studies monitoring soil water content dynamics have observed higher soil water content under to no-tillage (Bescansa et al., 2006; Copec et al., 2015; Francioni et al., 2020). In this study, NT management showed a greater water retention capacity in the top 0–10 cm, but this was not associated with an increase in soil CO_2 emissions. This can be attributed to three reasons: i) winter soil temperatures are well below

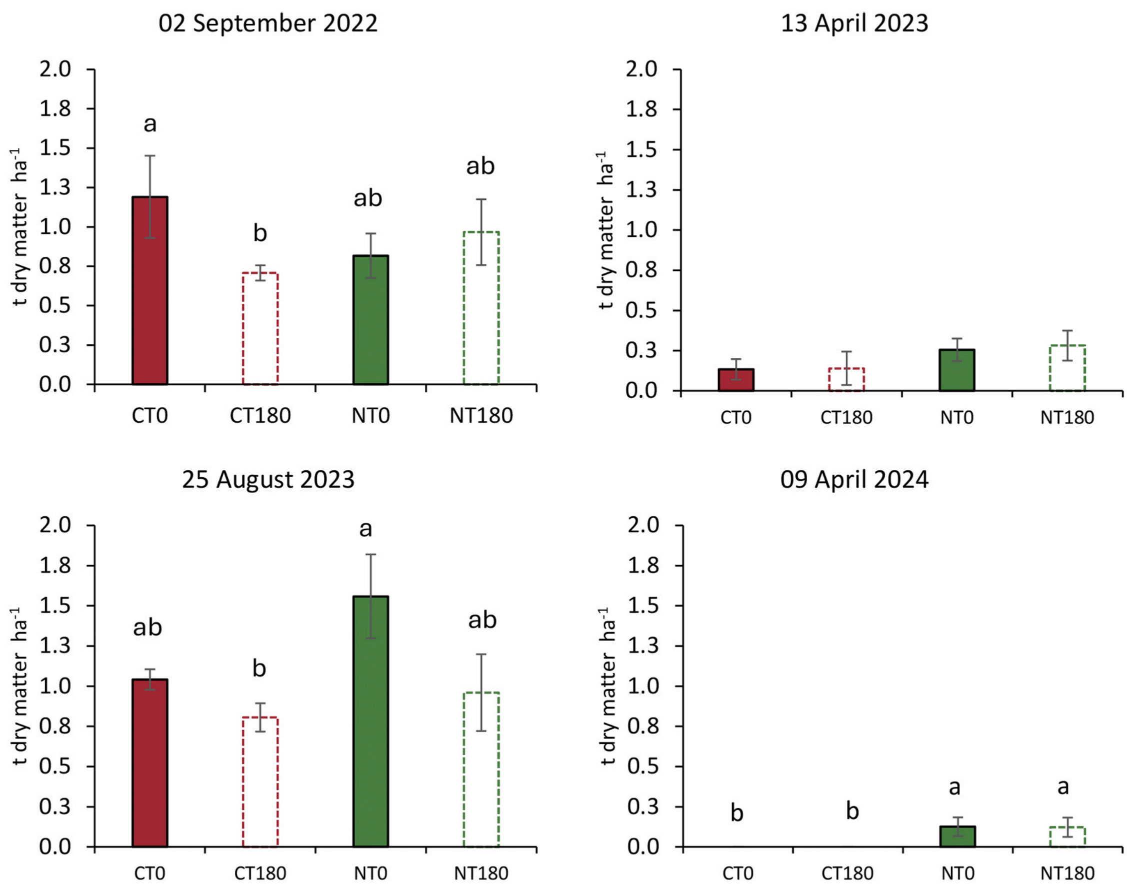

Fig. 5. Weed aboveground biomass. Data are presented as means ± standard errors. Different letters denote significant differences at $p < 0.05$. CT0: conventional tillage with 0 kg N ha^{-1} $year^{-1}$; CT180: conventional tillage with 180 kg N ha^{-1} $year^{-1}$; NT0: no tillage with 0 kg N ha^{-1} $year^{-1}$; NT180: no tillage with 180 kg N ha^{-1} $year^{-1}$.

the optimal range for the mineralization of organic matter by soil microorganisms (Liu et al., 2018); ii) the water content above the field capacity may have favoured anaerobic conditions that inhibited the activity of certain microorganisms (Borowik and Wyszkowska, 2016); iii) high soil water content impedes the diffusion of CO_2 in soil (González-Ubierna and Lai, 2019). During summer, the Mediterranean climate experiences prolonged drought periods. Although soil temperatures remain high and within the optimal range for organic matter mineralization, the process does not occur due to lack of moisture (Francioni et al., 2020). When precipitation follows these extended dry periods, a rapid increase in soil CO_2 emissions, known as 'respiration pulses' or the 'Birch effect,' is triggered (Singh et al., 2023). This phenomenon occurs due to renewed mineralization and the availability of easily decomposable materials for reactivated microbial metabolism (Oertel et al., 2016). In this study, this effect was evident following precipitation events in June and September, but only in NT. This is likely because the organic matter content in CT was too low to produce a detectable emission peak by infrared gas analysers which in clay soils are driven primarily by changes in bacterial abundance (Singh et al., 2023).

4.2. The effect of abiotic drivers on soil CO_2 emissions

Many studies have reported exponential relationships between soil CO_2 emissions and soil temperature, while also highlighting negative relationships between soil CO_2 emissions and soil water content. Some studies have described non-linear (parabolic or Gaussian) models between soil temperature and soil CO_2, showing that high soil temperatures do not necessarily correspond to increased soil CO_2 emissions (González-Ubierna and Lai, 2019; Mancinelli et al., 2010). In fact, reduced moisture, as well as thermal stress, can decrease the activity of micro- and mesofauna - key contributors to heterotrophic soil respiration - by both lowering CO_2 flux and inducing mesofauna migration (Tsiafouli et al., 2005). Other studies have attempted to identify threshold values of soil water content, below which water becomes the limiting factor, thereby driving CO_2 emissions regardless of temperature increases (González-Ubierna and Lai, 2019). Unlike previous studies, attempts here to determine thresholds or apply a Gaussian function did not improve the coefficient of determination between soil temperature and/or water content and soil CO_2 emissions. Instead, positive and significant relationships were observed across all management practices between soil temperature and CO_2 emissions. However, only NT management showed significant negative relationships between soil water content and soil CO_2 emissions. This might be attributed to temporary anoxic conditions induced by the high clay content, which retained more water under NT management (Bescansa et al., 2006; Borowik and Wyszkowska, 2016), unlike CT, where mechanical disturbance disrupted soil aggregates, temporarily increasing porosity and improving water infiltration (Bescansa et al., 2006; Weidhuner et al., 2021).

4.3. The effect of biotic drivers on soil CO_2 emissions

Weeds also played a key role in soil CO_2 emissions. Plant root respiration varies by species and is influenced by intrinsic factors such as root system type, developmental stage, and the availability of photosynthetic assimilates (Freschet et al., 2021). Specifically, the higher emissions observed in NT during spring 2023 were largely attributable to the increase in autotrophic respiration caused by the presence of weeds (mainly *S. italica* and *S. halepensis*). This was linked to a season with high temperatures and abundant rainfall until March, which was particularly favourable for weed development. Interestingly, these spring weeds, despite having an aboveground biomass significantly lower than that of the late summer weeds, generated a soil CO2 emission peak far greater in the NT plots than in the CT plot.

Grasses, including *S. italica* and *S. halepensis*, are characterized by fast-growing root systems. *S. italica* is among the most problematic weed species globally. Compared to *S. halepense*, it has shorter and more superficial rhizomes. Nevertheless, the success of *S. italica* lies in its efficient seed dispersal and rapid growth, which are well supported by the temperatures and humidity typical of Mediterranean climates (Dekker, 2003; Dyer et al., 2022). *S. halepense* is also known as one of the six most persistent weeds in global crops. It produces vigorous perennial roots with rapidly spreading rhizomes, capable of withstanding frequent drought conditions (Peerzada et al., 2023). Both species are highly tolerant to herbicides and efficient at accessing nutrients, which were largely available in NT plots (Pastorelli et al., 2013). Moreover, due to the sparser and less dense wheat canopy during the growing season in NT—caused by increased soil compaction linked to repeated machinery traffic during harvesting and treatments—these weeds faced less competition (Pastorelli et al., 2013).

Conservation agriculture and reduced tillage can increase weed abundance and shift communities from annual dicots to grassy annuals and perennials (Derrouch et al., 2021; Scherner et al., 2016), as observed in this study. Deeply buried weed seeds may fail to emerge, as was the case in CT plots, whereas low-disturbance tillage accumulates seeds near the surface, thereby promoting light-dependent germination and increasing seed predation (Baraibar et al., 2009; El Titi, 2002). As a result, cumulative respiration was significantly higher in the NT plots during the 2022–23 fallow period, with the presence of weeds in full vegetative development during spring playing a key role in this increase.

4.4. Limitation and implication of the study and future research directions

The dynamics and magnitude of soil CO_2 emissions observed during the fallow periods are consistent with those reported in other studies conducted under similar climatic conditions (Francioni et al., 2020; Laudicina et al., 2014; Radicetti et al., 2019). However, the observed cumulative soil CO_2 emissions during the fallow period were much lower than other studies that in similar pedo-climatic conditions reported 8.2 t CO_2 ha^{-1} during the wheat growing season (Ferrara et al., 2022). These values obviously include both the heterotrophic and autotrophic components of respiration because the root activity of crops significantly contributes to emissions. Hanson et al. (2000) observed significant variability (ranging from 10 % to 90 %) in the contribution of the heterotrophic component to total respiration. These values were later refined by a recent meta-analysis conducted by Jian et al., (2022), which indicates a global average contribution of 42 %. In this study, the autotrophic component of soil respiration (by plant roots) was not separated from the heterotrophic component because most of the monitoring period occurred during the winter months, when soil temperatures are low and any weeds present are likely dormant. Other studies that have separately measured the heterotrophic and autotrophic components of soil respiration have estimated in similar environments that the contribution of autotrophic respiration to heterotrophic respiration was about 36 % during wheat growing period (December to June) but dropped below 7 % during the fallow period (July to April) (Francioni et al., 2020). For this reason, the non-partitioning of total respiration into the two components was not considered a major limitation of the study. However, it is important to acknowledge that the inability to distinguish between heterotrophic and autotrophic respiration may introduce some uncertainty, especially when interpreting seasonal patterns or evaluating the effects of management practices—such as fertilization and tillage—that may differentially influence root activity and microbial decomposition. Additionally, since weed cover was present during the fallow period, some degree of autotrophic respiration likely occurred, although its magnitude was presumably low compared to microbial-driven processes.

Future studies could benefit from implementing respiration partitioning techniques to more precisely quantify the contribution of each component. This would allow for a more nuanced understanding of the biological drivers of soil CO_2 fluxes and improve the robustness of carbon budgeting in agroecosystems. Indeed, emissions during the fallow period were not negligible, as they reached about 0.6 t CO_2 per year in the fertilized NT system. It is important to note that soil CO_2 emissions likely originated primarily from the mineralization of organic matter and should be accounted for in calculations and models used to assess carbon farming credits. Weed root systems, particularly in NT management, can help increase carbon stocks. Future studies should investigate their contribution not only with regard to CO_2 emissions, but also as part of a potential integrated strategy for carbon farming.

5. Conclusions

This article measured and quantified soil respiration and its main abiotic and biotic drivers during the fallow period between the harvest of a winter crop and the sowing of a summer crop. Monitoring was conducted over two seasons in a long-term experiment comparing two soil tillage management practices (conventional tillage vs. no-tillage) and two nitrogen fertilization levels (0 and 180 kg N ha^{-1} yr^{-1}).

Results revealed that no-tillage resulted in generally higher soil temperatures, while fertilization led to lower soil temperatures. No-tillage also increased soil water content compared to conventional tillage, mainly during the winter. Cumulative soil CO_2 emissions were influenced not only by annual temperature and rainfall patterns but also by the presence of fast-growing weeds, which were in turn linked to soil management. Positive correlations were observed between soil CO_2 emissions and soil temperature, while negative correlations were found with soil water content. However, these negative relationships were statistically significant only under the no-tillage management system.

These findings highlight the importance of including soil respiration during fallow periods in carbon accounting for Mediterranean agricultural systems, as limiting CO_2 monitoring to the crop-growing season may result in incomplete evaluations. In systems with extended fallow periods—such as those involving rotations between microthermal and macrothermal crops—the influence of weeds should also be considered, as their contribution to soil CO_2 emissions remains largely overlooked. Consequently, further research on weed management is recommended, not only for its impact on crop performance but also for its potential role in integrated carbon farming strategies.

CRediT authorship contribution statement

Matteo Francioni: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Paride D'Ottavio:** Writing – review & editing, Resources. **Marco Bianchini:** Writing – review & editing, Methodology, Investigation, Data curation. **Paola Antonia Deligios:** Writing – review & editing. **Luigi Ledda:** Writing – review & editing. **Chiara Rivosecchi:** Writing – review & editing. **Federico Mammarella:** Writing – review & editing, Investigation. **Alessio Giampieri:** Writing – review & editing, Investigation. **Gianluca Brunetti:** Writing – review & editing. **Stefano Zenobi:** Writing – review & editing. **Marco Fiorentini:** Writing – review & editing. **Biagio Di Tella:** Writing – review & editing. **Roberto Orsini:** Writing – review & editing, Resources, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT for linguistic revision in English. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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.agee.2025.109805.

Data availability

Data will be made available on request.

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