



Maize residue input rather than cover cropping influenced N₂O emissions and soil–crop N dynamics during the intercrop and cash crop periods

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ABSTRACT

The well-known benefits of cover cropping for mitigating climate change and improving soil quality could be threatened by increased greenhouse gas emissions. Therefore, such practices could have negative consequences in the context of global climate change. The present year-long field experiment, carried out under irrigated semiarid conditions, evaluated the effect of returning maize crop residues at two topsoil input levels in combination with bare fallow, a cereal (barley, *Hordeum vulgare* L.) and a legume (vetch, *Vicia sativa* L.) as cover crops as part of an annual cover crop–cash crop (maize, *Zea mays* L.) rotation. In addition, control plots, without the addition of nitrogen fertilizer (either in the previous cropping season or during the experiment), were established following the same experimental design in order to assess the carry-over impact of residual nitrogen from prior crops. Nitrous oxide (N₂O), methane (CH₄) and carbon dioxide (CO₂) fluxes were measured together with soil mineral nitrogen and crop yields and nitrogen use efficiency. The significant effect of maize residue input on N₂O emissions during the cover crop phase (this was 43% greater for the lower maize residue input than for the higher) was offset after subsequent maize fertilization (there was a 170% increase following the higher maize residue input compared to the lower). Although no differences in soil mineral nitrogen content were reported between treatments before maize fertilization, N₂O emissions were 72% higher on the fertilized plots than on the control plots. Before maize fertilization, N₂O emissions were increased by the incorporation of cover crop residues and soil rewetting after irrigation, with the highest N₂O fluxes being reported for the cereal crop. Cumulative CO₂ fluxes were higher in the plots with cover crops (cereal and legume) than in bare fallow plots, while CH₄ sink was not affected by cover cropping or maize residue input. The grain yield penalty for maize production (a 7% decrease) with the legume cover crop on the nitrogen fertilized plots (the opposite of what was observed in the control area) highlights the need for an accurate estimation of the nitrogen supply from the mineralization of legume residues. Overall, cover crop and maize residue input did not have any significant effect on annual cumulative N₂O emissions, so the positive effects of these practices should be considered to recommend them under semiarid conditions for climate change mitigation and adaptation.

1. Introduction

The agricultural practice of leaving crop residues on the surface or incorporating them into the soil has numerous benefits compared to their complete removal after harvesting, such as improving soil quality or reducing soil erosion (Blanco-Canqui and Lal, 2009; Malhi et al., 2006; Turmel et al., 2015). Despite potential increases in soil

greenhouse gas fluxes (Abalos et al., 2022b; De Notaris et al., 2022), the recent meta-analysis of P. Li et al. (2023) reported significant increments in nitrogen use efficiency (NUE) and yields (with average increases of 23% and 9%, respectively) associated with straw inputs. Cover cropping is another agricultural practice that has been described to improve soil structure (Blanco-Canqui et al., 2011), enhance wildlife and soil microbial diversity (Muhammad et al., 2021), regulate weed and pathogen

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control and pollination, improve soil fertility and hydrology, regulate the influence of extreme meteorological events (Quintarelli et al., 2022; Van Eerd et al., 2023) and reduce soil erosion (Poelau and Don, 2015). However, the effects of cover crops on cash crop yields have been more variable and controversial (Garba et al., 2022), depending on the crop (maize, soybean or rice) and cover crop species (legume, non-legume or mixtures), and also on the soil properties, fertilizer management for the cash crop, and duration of cover cropping (Van Eerd et al., 2023). Both cover cropping and residue retention have been proposed as potential strategies for increasing soil organic carbon stocks in agricultural soils. Increases of 2.7–18.2% in soil organic carbon contents when crop residues are incorporated into the soil (in comparison with complete removal) or of 7.3% on average with cover cropping instead of bare fallow have been previously described (Bolinder et al., 2020; Joshi et al., 2023).

Despite the abovementioned positive effects of crop residue retention and cover cropping, their consequences on nitrous oxide (N_2O) emissions need to be studied. The atmospheric concentration of N_2O has been rising since the industrial revolution from 270 ppb to over 332 ppb in 2019 (IPCC, 2021), which is directly related to the increased use of N-based fertilizers to achieve higher crop yields. Agriculture accounts for 66% of the total anthropogenic N_2O emissions (IPCC, 2022), and this gas is involved in global warming and stratospheric ozone depletion (Xie et al., 2023). According to the meta-analysis by Abalos et al. (2022b), on average, the N provided to soil microorganisms by crop residues when they are incorporated into the soil leads to a 40–50% increase in N_2O emissions compared to crop residues being removed. These results were in agreement with De Notaris et al. (2022), who observed that residue removal could offer significant N_2O mitigation potential, despite social barriers to its widespread adoption. However, Abalos et al. (2022a) reported that several factors, such as the maturity of residues, their management, the timing of their incorporation or the interaction with N fertilization, affect the N_2O emissions from residues. For example, the incorporation of mature residues such as straw from cereals, maize or grain legumes, with a generally high C:N ratio (> 30), favours the immobilization of soil N, reducing N_2O emissions compared to the incorporation of immature crop residues (Abalos et al., 2022b; Li et al., 2016). However, immobilization of N from this type of residue generally occurs in the following months after application, producing net mineralization after this period (i.e., 4–6 months after their incorporation) and therefore releasing labile C and N for nitrifying and/or denitrifying microorganisms (Abalos et al., 2013).

According to the meta-analysis by Muhammad et al. (2019), cover crops reduced N_2O emissions compared to bare fallow. However, this effect was obtained only for nonlegume cover crops, probably because of their higher effectiveness in increasing crop N uptake and thus reducing the pool of soil residual NO_3^- content (Abdalla et al., 2019; Gabriel et al., 2012; Thapa et al., 2018). Furthermore, the ability to fix atmospheric N_2 by legume species can increase the soil available N (from rhizodeposition and plant decomposition), thus potentially increasing N_2O losses (Ussiri and Lal, 2013). The effects of cover crops on N_2O emissions depend not only on cover crop species and associated traits and biochemical properties such as the C:N ratio (Fernandez Pulido et al., 2023; Muhammad et al., 2019) but also on the cropping period, e.g., during the cover cropping phase (with crucial influence of N acquisition potential), after termination or during the early cash crop development stages (with crucial influence of plant material decomposition) (Guardia et al., 2016; Sanz-Cobena et al., 2014). According to Basche et al. (2014), during the cover crop decomposition period, most N_2O is emitted from cover cropping, and the easily decomposable C from the low C:N residues, especially those from legumes, provides an energy source for denitrifying microorganisms (Li et al., 2016). Y. Li et al. (2023) recently reported that soil pH and concentrations of total N and organic C in soils were the main drivers behind the response of N_2O emissions to cover cropping. If so, this would offer further opportunities for mitigation at intermediate values.

The combinations of cover crops with different tillage intensities or fertilizer sources applied during the cash crop phase have been broadly studied (Ekwunife et al., 2022; Muhammad et al., 2019; Taghizadeh-Toosi et al., 2022), but little is known about the influence of previous cash crop management (N fertilization and residue input). Cover crops are recommended for recycling the residual N from the previous cash crop (which is often intensively fertilized). The pivotal influence of this legacy effect of synthetic fertilizer and surplus N on the abovementioned cover cropping stages has not been studied thus far, particularly in combination with the input of cash crop residue left on the topsoil, which is the critical layer for driving N_2O release from the soil (Butterbach-Bahl et al., 2013; Kuang et al., 2023). In addition, addressing whether the likely simultaneous N input from mineralization of the recalcitrant maize residue several months after its incorporation in autumn (Abalos et al., 2022b), the more labile cover crop residue (incorporated in spring) and the easily available synthetic N applied to the subsequent cash crop typically in early summer (Guardia et al., 2016) may result in an increase in N_2O emissions that needs to be clarified to promote the best strategy for sustainable management of crop residues, both environmentally and agronomically. Moreover, the effect of residue input and temporal mineralization pattern is expected to influence both ecosystem respiration and methane (CH_4) uptake in cover cropping systems, also depending on cover crop species and synthetic N application (Sanz-Cobena et al., 2014; Wang et al., 2022). In this sense, Ho et al. (2015) observed an enhancement of methanotrophic activity in soil after amendment with different biobased residues in an incubation experiment, probably because of a higher nutrient availability in these soils. Under field conditions, scarce information exists about the effect of different crop residues on CH_4 oxidation capacity, especially when both green manure and maize stover are coapplied.

In this context, the objectives of this field experiment (performed during one experimental year) were to evaluate the effect of two contrasting inputs of cash crop residues and residual N in the topsoil combined with different cover cropping strategies on N_2O emissions and crop yield in an irrigated agroecosystem, distinguishing between three critical periods (i.e., cover crop development, cover crop incorporation and maize cropping phase), and addressing the side effects on crop yields, NUE, soil mineral N content and C gaseous emissions (i.e., CO_2 and CH_4). The hypotheses formulated were that: i) greater inputs of maize residue may reduce N_2O emissions before maize fertilization in a subsequent campaign, due to immobilization (high C:N ratio), while also increasing N_2O emissions after synthetic N application, due to the release of N and particularly labile C for denitrifiers; ii) the legume cover crop would increase N_2O emissions due to its reduced effectiveness in terms of offsetting residual N and due to the mineral N input increase from the decomposition of their N-rich residues, which would increase yield-scaled N_2O losses in comparison to the cereal cover crop and bare fallow; and iii) the residual N from the previous cropping season would increase N_2O emissions and drive the performance of cover crops compared to bare fallow, especially during the cover cropping phase.

2. Materials and methods

2.1. Experimental location

The field experiment was conducted from November 2020 to November 2021 in the “Centro Nacional de Tecnología de Regadíos” (CENTER) located in the experimental field “El Palomar” southeast of Comunidad de Madrid, Spain (40° 25' 1'' N, 3° 29' 45'' W). The soil type according to the USDA was classified as a calcareous *Typic Xerofluvent* with a silt loam texture, 8.16 ± 0.02 (1:2.5 w-v) pH_{H_2O} , 1.46 ± 0.07 $g\ cm^{-3}$ bulk density, 1.64 ± 0.12 $g\ total\ N\ kg^{-1}$ and 2.07% total organic matter on the upper horizon (0–20 cm). The climatological data (rainfall, air and soil temperature) were collected from the information of a meteorological station located at the CENTER and provided by the “Sistema de Información Agroclimática para el Regadío” webpage (<https://www.cenregad.es/>)

[://portal.mapa.gob.es/websiar/SeleccionParametrosMap.aspx?dst=1](http://portal.mapa.gob.es/websiar/SeleccionParametrosMap.aspx?dst=1)). The mean air temperature and accumulated rainfall during the last 15 years were 14.2 °C and 401 mm, respectively. The area is characterized by a semiarid Mediterranean climate with high interannual variability.

2.2. Experimental design

The experiment consisted of a three-replicated split-plot design with maize residue input as the main factor and cover cropping as the split factor. Within the main factor, two different types of plots were established: i) Maize residue maintained and incorporated by a shallow disk harrow pass at 10–15 cm depth, thus leading to a higher input of residue in the topsoil (+R), and ii) removal of maize residue from the topsoil followed by deep incorporation of the remaining residue up to 40 cm depth, thus leading to a lower input of maize residue in the topsoil (–R) (Fig. S1). In the previous cropping season (summer 2020), maize was fertilized with urea at a rate of 200 kg N ha^{−1}. The different cover cropping treatments were bare fallow (F), a legume (L) cover crop (vetch, *Vicia sativa* L. var “Rada”) and a cereal (C) cover crop (barley, *Hordeum vulgare* L. var “RGT PLANET”). Bare fallow was maintained with sporadic weeds and no labour or herbicides were applied. After cover crops termination, the bare fallow subplots were managed in a similar way to the cover crop subplots, applying the farming procedures described below prior to sowing the maize crop. The main factor was arranged in a completely randomized design, while the split factor was set out with a completely randomized set-up. Control plots (which did not receive any synthetic N fertilization in either the 2020 maize cropping season or the 2021 cash crop maize phase) received the same maize residue and cover cropping treatments. The experimental design of the control plots was similar to that of the fertilized plots (a split-plot design with residue input and cover cropping as the main and split factors, and with three replicates). Control plots were located in the same experimental area as the fertilized plots. The dimensions of all the subplots (both fertilized and unfertilized) were 5 m x 30 m. The experiment started in mid-November with the management of maize straw from the previous cropping season (*Zea mays* L., FAO500). The average C:N of the maize residue was 89.5. Vetch and barley were sown at a rate of 200 kg ha^{−1} on November 17, chemically terminated on April 13 using herbicide (Roundup®, glyphosate 36%, 5 L ha^{−1}) and incorporated into the soil with a disc harrow on May 6. Maize (*Zea mays* var. “Pioneer 0725” 500) was sown as the cash crop on June 10 at a rate of 9.5 plants m^{−2} and was irrigated by sprinkler during its cropping cycle (ca. 50 mm per week split into two irrigation events per week). Maize was hand-fertilized on July 19 with calcium ammonium nitrate, which was homogeneously distributed over the soil surface of each plot. Moreover, the stainless steel rings -where the chambers for gas sampling were subsequently placed- were fertilized prior to the entire plot with the proportional share of the total N rate (Charteris et al., 2020). Maize was fertilized following integrated soil fertility management practices. Briefly, the gross N rate was calculated considering the expected yield and grain N extraction, while the net N rate was adjusted considering the soil mineral N concentration before dressing fertilization as well as the availability of N from the mineralization of cover crop residues. The N from cover crop residues available for maize was estimated by multiplying the total N content in cover crop dry biomass by the predicted % of plant available N at 10 weeks after cover crop residue application following the approach described in Sullivan et al. (2019). As a result, N fertilization rates of 170, 220 or 210 kg N ha^{−1} were applied in the L, C or F subplots, respectively. Maize was harvested at physiological maturity on November 19.

2.3. Greenhouse gas flux measurements

The greenhouse gas (GHG) (i.e., N₂O, CH₄ and CO₂) fluxes from the soil were measured over the whole experimental period using manual

static chambers. One opaque polyvinyl chloride chamber (24 cm height, 35 cm diameter) was placed in each subplot over stainless steel rings that were inserted 4 cm into the soil surface to avoid the lateral diffusion of the gases. The rings were removed only during management events. Gas samples from the headspace of the chambers were taken at 0, 30 and 60 min after chamber closure as described in Harvey et al. (2020). During cover crop development, the GHGs were sampled at least once every two weeks, increasing the sampling frequency after rainfall events, and the plants were located inside the chambers during gas sampling. During the maize cropping phase, the chambers were located between two maize lines. When maize irrigation started, especially during the first month after maize fertilization, the sampling frequency was increased (2–3 samples per week). Afterward, the frequency of sampling was decreased progressively. The GHG concentration in the samples was determined with an HP-6890 gas chromatograph with an HTC-3 Headspace autosampler (Agilent Technologies). The samples were carried through HP Plot-Q capillary columns connected to a ⁶³Ni micro electro capture detector to analyse N₂O and to a flame ionization detector to measure CH₄ and CO₂. Daily GHG fluxes were estimated as the slope of the linear regression between concentration and time.

2.4. Soil analyses

Three subsamples were taken from the topsoil (0–10 cm) of each subplot using a stainless steel cylinder (3.5 cm diameter x 10 cm length). The topsoil layer is the one that mainly contributes to N₂O emissions, with the 0–5 cm layer accounting for more than 85% of total fluxes (Kuang et al., 2023). This was done at least once a month, throughout the experiment, with the sampling frequency being increased to once a week in the first three weeks after maize fertilization on 19 July. The subsamples were mixed, thoroughly homogenized in the laboratory and stored at −20 °C until determination. Mineral N (ammonium, NH₄⁺, and nitrate, NO₃[−]) was extracted for 1 h (8 g fresh soil:50 mL KCl 1 M). Soil extracts were then centrifuged, filtered using 0.45 µm cellulose syringe filters (Agilent) and analysed using a flow injection analyser provided with a UV–vis spectrophotometer detector (FIAS 400, Perkin Elmer and SFA FUTURA, AMS Alliance for NH₄⁺ and NO₃[−] analyses, respectively). Ammonium determination in the soil extracts was performed by gaseous diffusion of NH₄⁺ previously transformed into NH₃(g) in an alkaline medium. The NH₃(g) was defused through a permeable membrane and reacted with some acid–base indicators, being detected by the spectrophotometer at λ = 590 nm (PerkinElmer, 2001). The nitrate in soil extracts was previously reduced to NO₂ with VCl₃, then reacted with sulphanilamide and an aromatic amine and was transformed into a chromophore aromatic species that is detected at λ = 540 nm (Miranda et al., 2001). The dissolved organic C (DOC) was water extracted (8 g soil: 50 mL Milli-Q water) for 1 hour and then centrifuged and filtered (Filterlab 1300/800). Quantification of DOC was performed by a total organic carbon analyser (Analytik Jena multi N/C 3100) equipped with an infrared detector. Furthermore, the water-filled pore space (WFPS) on every gas sampling day was estimated by using the bulk density of the topsoil (1.46 ± 0.07 g cm^{−3}) and measuring the moisture content by oven-drying 5 g soil at 105 °C to a constant weight.

2.5. Plant analyses and maize yield

Before the cover crops were chemically terminated, the aboveground biomass was sampled and fresh-weighed in the field. The samples taken from each subplot consisted of a representative mixture of three subsamples which were obtained using a 0.25 m² frame. In the laboratory, the dry biomass production was determined after drying the samples until constant weight at 70 °C and was ground (IKA® MF 10 Basic Microfine Grinder Drive) to analyse the N and C contents, using an elemental analyser (TruMac CN Leco®) and applying the Dumas method (AOAC, 2005). At physiological maturity, aboveground maize biomass was harvested by collecting fifteen maize plants randomly in every

subplot. The aboveground biomass was weighed at harvest. To determine dry matter grain and stover (aboveground biomass without grain) yields, the stover and grain moisture were determined after drying plant samples at 70 °C. Maize grain and stover were ground (IKA® M 20 universal mill and IKA® MF 10 Basic Microfine Grinder Drive, respectively), and the total N concentration was analysed by Kjeldahl digestion. The NUE was calculated as the apparent recovery efficiency of applied N, using the following formula (Congreves et al., 2021):

$$NUE = \frac{(U_N - U_0)}{F_N}$$

where U_N represents the total N uptake in the aboveground biomass at maturity with applications of N fertilizer; U_0 is the total N uptake in the aboveground biomass at maturity without applications of N fertilizer; and F_N is the amount of N fertilizer applied (170, 220 and 210 kg N ha⁻¹, respectively applied to the legume, cereal and bare fallow plots).

2.6. Calculations and statistical analyses

The experiment was split into three periods: 1) from mid-November 2020 to mid-April 2021, thus considering the development of cover crops until their termination during the intercrop period (P1); 2) from the end of P1 to maize dressing fertilization on 19 July 2021, thus considering the incorporation of cover crops and the beginning of the development of maize under irrigated conditions (P2); and 3) from maize fertilization to maize harvest on 11 November 2021 (P3).

Cumulative GHG emissions at the end of each period and total cumulative emissions at the end of the experiment were calculated by trapezoidal integration by linear interpolations of daily fluxes (Venterea et al., 2020). Yield-scaled N₂O emissions (YSNE) expressed as g N₂O-N kg grain⁻¹ were calculated as the ratio between the total cumulative N₂O-N emissions and maize grain yield. The N₂O emission factor (EF) was estimated as the ratio of total cumulative N₂O-N emissions, subtracting those of the corresponding control, to the synthetic 170, 220 or 210 kg N ha⁻¹ applied in the legume, cereal or fallow plots, respectively.

Analyses of variance (two-way ANOVAs) were performed to analyse the effect of maize residue management and cover cropping systems on GHG emissions and plant and soil parameters. Previously, the Shapiro–Wilk and Levene tests were used to verify the normal distribution and homogeneity of variance of the data acquired for each variable, respectively, and log-transformed if necessary. The least significant difference (LSD) test at $P < 0.05$ was used for multiple comparisons between means. Pearson's correlation was used to study the relationship between i) daily GHG fluxes and soil properties (NH₄⁺, NO₃⁻, DOC concentrations, WFPS and temperature), ii) cumulative GHG emissions, average NH₄⁺, NO₃⁻ and DOC concentrations during the three experimental periods and iii) total cumulative GHG emissions, YSNE, maize N content, NUE and N₂O EF. All statistical analyses were performed using Statgraphics® Centurion 19 software.

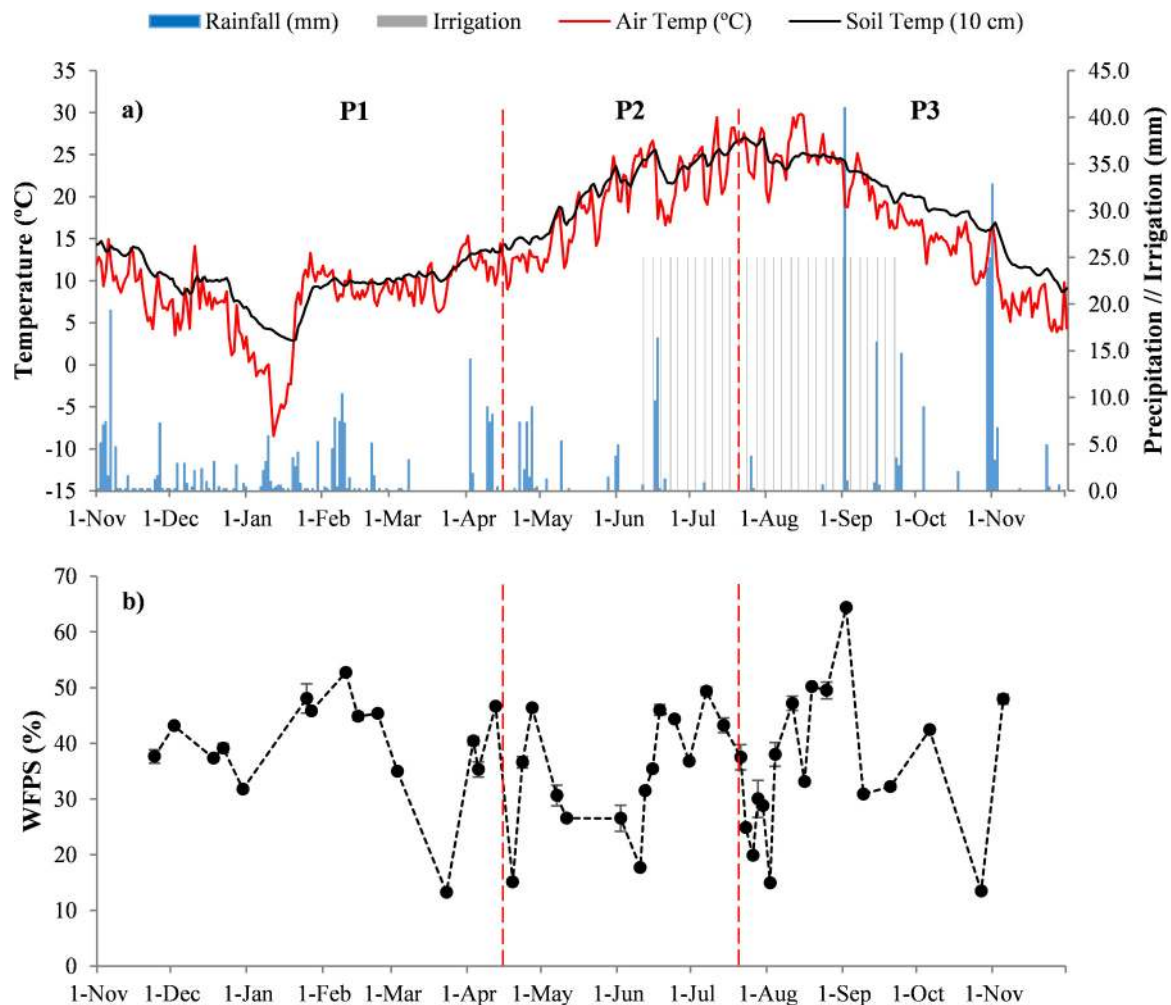


Fig. 1. Mean air and soil temperature (°C), rainfall and irrigation (mm) (a) and mean WFPS (%) in the upper soil layer (10 cm) (b) during the three experimental periods (P1, P2 and P3).

3. Results

3.1. Environmental conditions

The mean air and soil (10 cm) temperatures during the whole experimental period were 14.3 °C and 16.1 °C (Fig. 1a), with minimum air temperature in mid-January (−16.3 °C, Table S1) and maximum air temperature reached during the summer season in P3. The cumulated precipitation during P1 and P2 (156 and 74 mm, respectively) was 12% and 30% lower than that of the 15-year average in the area (Table S1).

The WFPS values ranged from 13.2% to 64.4% during the whole experiment (Table S1), with 72% reported values ranging between 30% and 50% (Fig. 1b). The average WFPS during the whole experiment was 36.7%, with no difference between the three experimental periods (Table S1).

3.2. Greenhouse gas emissions

3.2.1. N₂O emissions

The N₂O emissions were lower in the control area than in the N-fertilized area even before maize N fertilization (Fig. 2a). In the N-fertilized area, the mean N₂O cumulative emissions during P1 and P2 (25.7 ± 2.9 and 47.2 ± 6.1 mg N m^{−2}, respectively) were lower than those reported in P3 (107.4 ± 23.8 mg N m^{−2}) (Fig. 3a–c). The highest N₂O emission peak during P1 (Fig. 4a) was reported after a freeze–thaw period at the end of January (Fig. 1a). Another emission peak was reported in both areas after the beginning of maize irrigation and after several days of rainfall during P2, with values up to 8.82 mg N m^{−2} d^{−1} in −RC (Figs. 4a) and 1.33 mg N m^{−2} d^{−1} in control−RF (Fig. S2a). The highest correlation reported during P1 was between N₂O emissions and soil NO₃ concentration ($r = 0.708$), but this was not statistically significant (Fig. 5a). A positive correlation was reported between N₂O emissions and WFPS values during P2 ($P < 0.05$; $r = 0.558$, Fig. 5b). The cover crops only affected the N₂O emissions after their incorporation during P2, being 92.4% higher in C than in F (Fig. 3b). The higher input of maize residues in +R significantly mitigated N₂O emissions during P1 and P2, being 39.2% and 46.8% lower in +R than in −R, respectively (Fig. 3a,b). Furthermore, N₂O emissions were mitigated in control+R compared to control−R during P1 by 37.6% (Table S2). However, the opposite occurred after N fertilization in maize, with cumulative N₂O emissions 2.7 times higher in the +R plots than in the −R plots during P3 (Fig. 3c). Three emissions peaks were reported during the first month after fertilization coinciding with samplings made the day after irrigation events, with the highest values reported in the +RL and +RC treatments, reaching up to 20.2 and 29.7 mg N m^{−2} d^{−1}, respectively (Fig. 4a). These values decreased three or four days after irrigation events. The average EF and YSNE were 0.63% and 0.11 g N₂O-N kg^{−1}

grain without differences reported between maize residue incorporation or cover cropping treatments (Fig. 3e,f). When considering the whole experimental trial, daily N₂O emissions were strongly correlated ($P < 0.05$) positively with soil NO₃ ($r = 0.601$) and negatively with DOC concentration ($r = -0.535$) (Fig. 5d), although the relationships were significant only for the L and +R treatments (data not shown). Furthermore, a moderate correlation was reported with CO₂ emissions ($P < 0.01$; $r = 0.359$) and with air and soil temperature at 10 cm depth ($P < 0.01$; $r = 0.471$ and $r = 0.403$) (Fig. 5d).

3.2.2. CO₂ and CH₄ fluxes

Cumulative CO₂ emissions were only affected by cover crops before maize fertilization in the N-fertilized area (Table 1). At the end of the experiment, the total CO₂ emissions were respectively 77% and 105% higher for the cereal and legume cover crops than for bare fallow (Table 1). The cover crops influenced CO₂ emissions throughout the experiment in the unfertilized control area (Table S2). In the unfertilized area, the highest total cumulative CO₂ emissions were reported in control_L (119% higher than in control_F), followed by control_C (85% higher than in control_F) (Table S2). The highest input of maize residues only reduced CO₂ emissions during P1 in the control area (Table S2). The highest CO₂ fluxes were observed in early spring, when they reached 7.2 g C m^{−2} d^{−1} in −RL (Figs. 4b) and 10.6 g C m^{−2} d^{−1} in control−RL (Fig. S2b). Furthermore, CO₂ fluxes were increased after cover crop chemical termination and incorporation at the end of April and after intense rainfall and the beginning of irrigation in mid-June in both N-fertilized and control areas (Fig. 4b and Fig. S2b, respectively). In the N-fertilized area, the application of synthetic fertilizer also led to a CO₂ emissions peak. Cumulative CO₂ emissions at the end of the experiment were similar in the N-fertilized and control areas (average 301 ± 21 g C m^{−2}).

Daily CH₄ fluxes ranged from -1.46 to 1.67 mg C m^{−2} d^{−1} (Fig. 4c), with no differences between maize residue management or cover cropping systems in the N-fertilized and control areas (Table 1 and S2, respectively). During P1, net cumulative CH₄ emissions were reported in both areas, while during P2 and P3, the soil acted as a CH₄ sink, with higher CH₄ consumption in the control area during P2 compared to the N-fertilized area. Considering the whole experimental period, the cumulative CH₄ oxidation rates in the control area were 7.5 times higher ($P < 0.05$) than those reported in the N-fertilized area (-31 mg C m^{−2} and -3.7 mg C m^{−1}, respectively).

3.2.3. Mineral N and DOC

Maize stover management affected the NH₄⁺ concentration during P1 in both the fertilized and control areas, with an average increase of 16.3% in +R compared to −R (Table S3 and S4). The NH₄⁺ concentration during P2 was significantly greater in L than in F and C in both areas

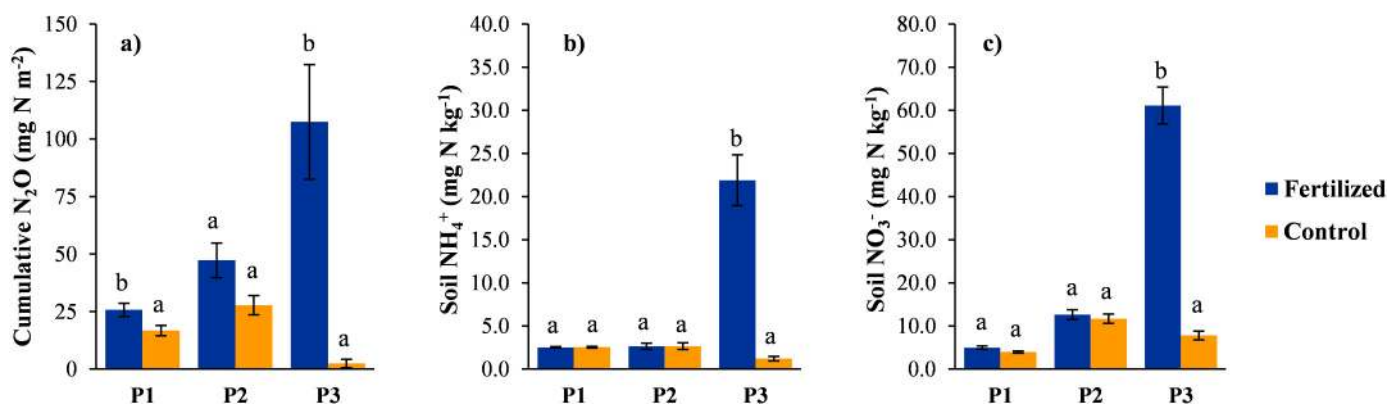


Fig. 2. Average (a) cumulative N₂O emissions, (b) soil NH₄⁺-N concentration and (c) soil NO₃[−]-N concentration for the three experimental periods (P1, P2 and P3) in the N-fertilized (blue bars) and unfertilized control areas (orange bars). Different letters in each period denote significant differences ($P < 0.05$) between areas according to the LSD test.

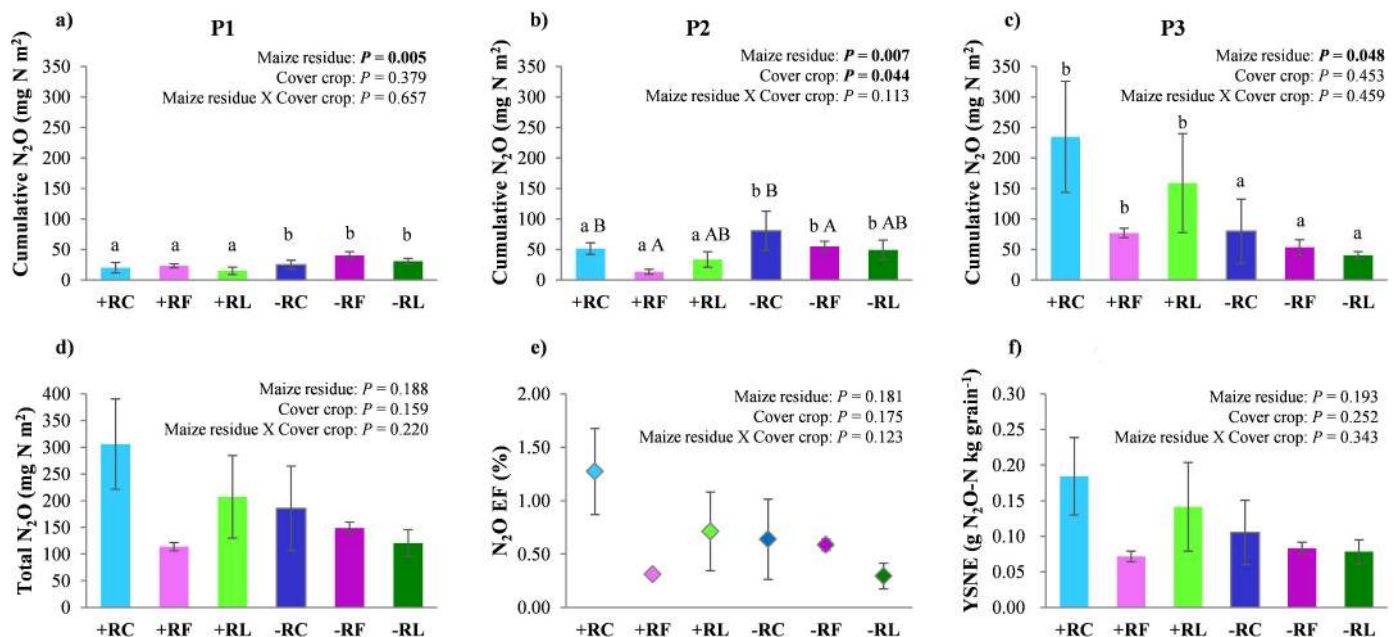


Fig. 3. (a, b, c) Cumulative N_2O -N emissions over the three experimental periods: P1, P2 and P3, respectively; (d) Total cumulative N_2O -N emissions at the end of the experiment; (e) the N_2O emission factor (EF) and (f) yield-scaled N_2O emissions (YSNE) in the different maize residue (higher input, +R, and lower input, -R) and cover crop (cereal, C; legume, L; and bare fallow, F) treatments in the N-fertilized area. Different lowercase letters denote significant differences in maize residue management for the same cover crop, while different uppercase letters denote significant differences between cover crops for the same maize residue management scheme, at the 95% confidence level and having applied the LSD test. Vertical lines represent the standard error of the mean ($n = 3$).

(Tables S3 and S4), with the highest values being reported 50 days after cover crop incorporation ($12.6 \pm 10.9 \text{ mg N kg}^{-1}$ in -RL) (Fig. 6a). Before maize N fertilization (P1 and P2), no differences were observed between the N-fertilized and control areas in terms of soil NH_4^+ (average 2.52 and $2.64 \text{ mg N kg}^{-1}$, respectively) and NO_3^- (average 4.55 and $12.2 \text{ mg N kg}^{-1}$, respectively) concentrations (Fig. 2b,c). In the N-fertilized area, the average NO_3^- soil concentration during P2 was 44.5% lower in C compared to F and 52.7% lower in C than in L (Table S3).

Immediately after maize fertilization (P3), the mineral N concentration increased to $221 \text{ mg NH}_4^+\text{-N kg}^{-1}$ in -RL and $212 \text{ mg NO}_3^-\text{-N kg}^{-1}$ in -RC and fell to levels similar to those reported before fertilization two weeks and two months after N fertilization for NH_4^+ and NO_3^- , respectively (Figs. 6a and 6b, respectively). During P3, the F plots reported the lowest NH_4^+ concentrations (52% and 37% lower than L and C, respectively), and NO_3^- was 22.6% higher in -R than in +R in the N-fertilized area (Table S3). The mineral N content in the control area during P3 was similar to that registered in previous periods, without any significant differences between treatments (Table S4).

In the case of DOC concentrations, no significant differences were reported between the N-fertilized and control areas throughout the experimental year. In the fertilized area (Fig. 6c), significant differences were only observed during P2, due to the interaction of the two factors (maize residue input and cover cropping), with lower DOC concentrations being registered on plots receiving lower inputs of maize residue (except for -RL) (Table S3). In the control area, higher values were reported for the +R control plots than for the -R control plots during P1 and P3 (Table S4). In addition, the development of cover crops during P1 reduced the DOC values in control_C and control_L compared to control_F (by 34.5% and 20.8%, respectively), with the opposite happening during P2 (47.7% increase in control_L compared to control_F). The average DOC concentrations registered during P3 (16.6 and $16.3 \text{ mg C kg}^{-1}$ in the fertilized and control areas, respectively) were both lower than those reported before maize fertilization (Tables S3, S4).

3.3. N uptake and yields in cover crops and maize

The average aboveground N uptake of cover crops was 53% higher ($P = 0.071$) in the legume than in the cereal cover crop, regardless of residue management (Table S5). The C:N ratio in the cereal cover crop was twice that in the legume cover crop, and the total aboveground biomass in barley was also higher than that in vetch ($0.1 < P < 0.05$). The differences between cover crop species in N content and in C:N ratio were intensified in the -R treatment (Table S5).

The average maize grain yield in the N-fertilized area was 16.6 Mg ha^{-1} (Table 2). Legumes significantly reduced the grain yield by 7.9% and 9.5% compared to F and C, respectively. The stover yield and the stover N content tended to be lower ($P < 0.1$) in the L-plots compared to C and F. The N yield in maize stover was also 16.3% and 19.3% lower in L compared to C and F, and the NUE was 149% and 151% higher in C and F compared to L, respectively. The grain N content and grain N uptake were strongly and negatively correlated with cumulative N_2O emissions after maize fertilization ($r = -0.651$, $P < 0.01$ and $r = -0.485$, $P < 0.05$, respectively) (Fig. S3).

All the abovementioned parameters (yield, % N and N uptake) were higher when maize was grown in the N-fertilized area compared to the control area ($P < 0.01$). In contrast to the fertilized area, grain yield and N uptake in control_L were 28% and 40% higher than those in control_C and 30% and 46% higher than those in control_F, respectively. Furthermore, in unfertilized plots, both grain yield and grain N uptake were 17% and 22% higher in +R than in -R, respectively (Table S6).

4. Discussion

4.1. Maize residue input as a key driver of N_2O fluxes

In line with the first hypothesis, during P1 and P2, the higher inputs of maize residue (+R) resulted in a significant reduction in soil N_2O emissions compared to the plots from which residues were removed (-R). This was consistent with the negative relationship that is frequently found between the return of crop residues with high C:N

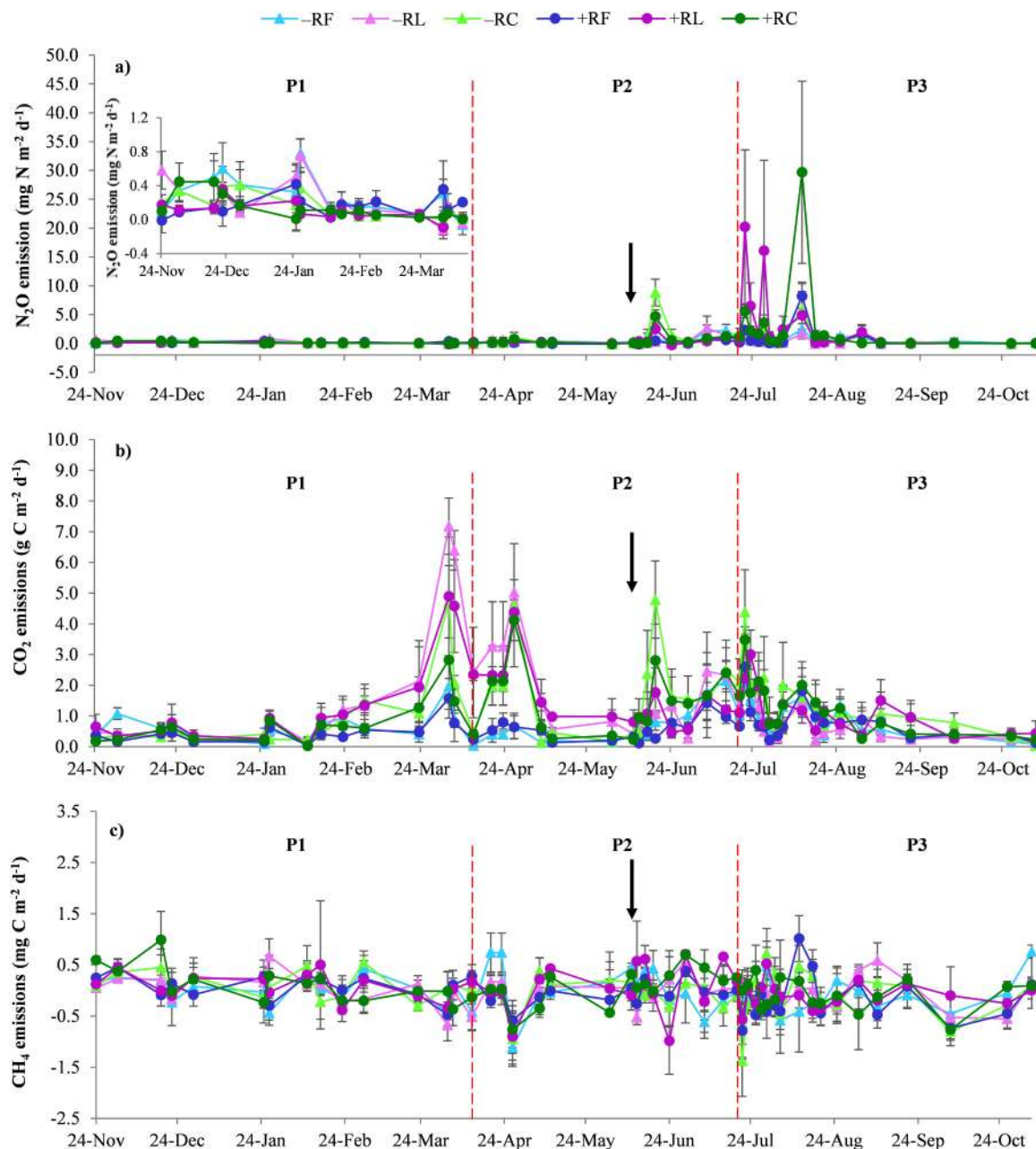


Fig. 4. Daily fluxes of (a) N₂O-N, (b) CO₂-C and (c) CH₄-C for the different maize residue (higher input, +R, and lower input, -R) and cover crop (cereal, C; legume, L; and bare fallow, F) treatments during the three experimental periods (P1, P2 and P3) in the N-fertilized area. Vertical lines denote standard errors of the means. The black arrow denotes maize sowing and the beginning of the irrigation.

ratios, such as maize residues, and N₂O emissions (Abalos et al., 2022b; Chen et al., 2013; Hu et al., 2019). The abatement of N₂O emissions when high C:N ratio residues (> 30) are incorporated has been associated with a decrease in soil mineral N levels as a result of their immobilization during residue degradation (Chen et al., 2013). This immobilization has a detrimental effect on the nitrification and denitrification processes, which are the main processes controlling soil N₂O production (Ussiri and Lal, 2013).

In contrast to the results obtained before fertilization, the cumulative N₂O emissions during P3 were 170% higher on the +R than on the -R plots (Fig. 3a-c). This was probably because coupled nitrification-denitrification was favoured when it was combined with: i) the incorporation of large amounts of C:N crop residue from maize (Sarkodie-Addo et al., 2003); ii) the addition of easily available NH₄⁺-N and NO₃⁻-N via synthetic fertilization; iii) the irrigation of the cash crop, with

the consequent increase in soil moisture, which favours mineralization (Elrys et al., 2021) and other biochemical processes involved in the release of N₂O (Butterbach-Bahl et al., 2013) (Fig. 1b); and iv) the warm soil and air temperatures registered in the summer season during the cash crop phase (Fig. 1a), which are positively related to microbial activity and N₂O emissions (Ussiri and Lal, 2013). This increase in microbial activity during the summer season was supported by the correlations reported in P3 between CO₂ and air and soil temperature ($P < 0.01$; $r = 0.612$ and $r = 0.633$, respectively) and between N₂O emissions and air temperature ($P < 0.05$; $r = 0.526$) (Fig. 5c). Purportedly greater microbial activity on the plots with the highest residue inputs was supported by lower soil mineral N concentrations (in comparison with those with low topsoil residue inputs) (Table S3) during P3.

The results obtained indicate that any potential benefits relating to N₂O mitigation deriving from the topsoil retaining residues during the

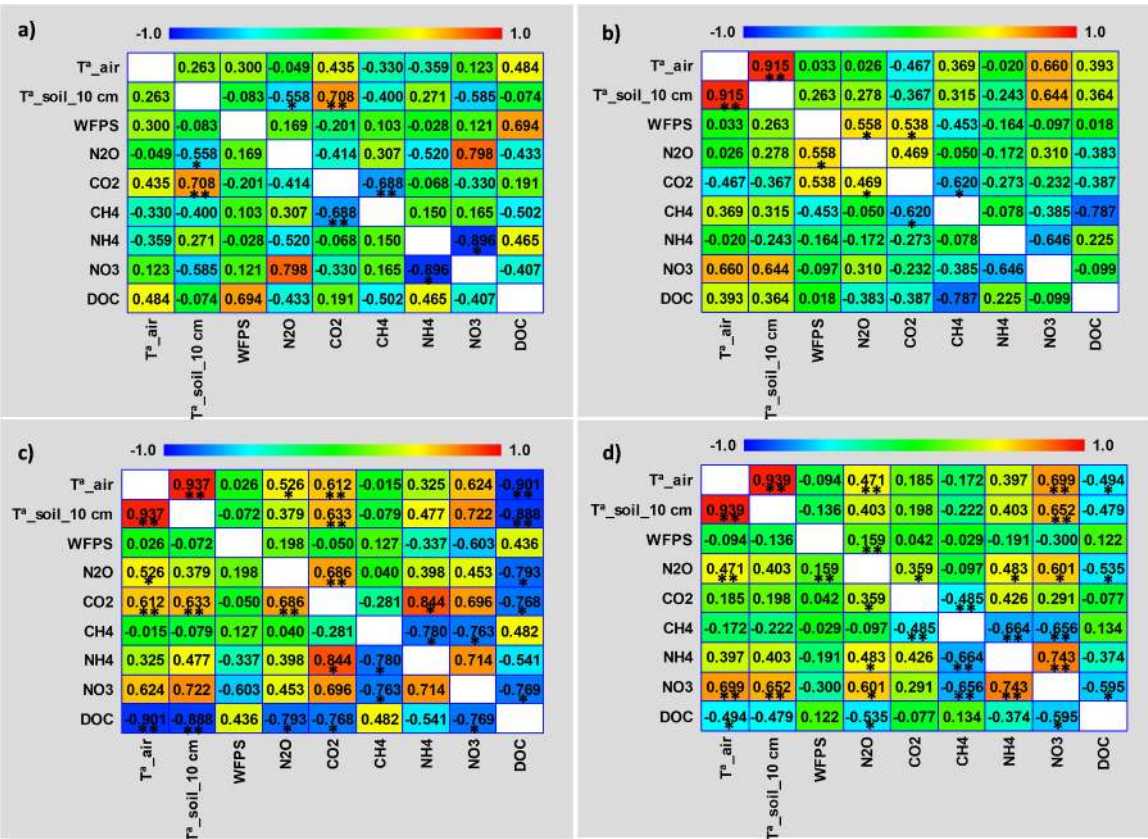


Fig. 5. Pearson correlation coefficients for the daily air and soil (at 10 cm depth) temperature, the daily N₂O, CO₂ and CH₄ fluxes, and daily soil properties (WFPS, NH₄⁺, NO₃⁻ and DOC) analysed over three experimental periods ((a) P1, (b) P2 and (c) P3, respectively) and over the whole experimental trial (d) in the N-fertilized area. The asterisks indicate the level of significance level (* P < 0.05, ** P < 0.01).

Table 1

Cumulative CO₂-C and CH₄-C emissions over the three experimental periods (P1, P2 and P3) and total cumulative emissions at the end of the experiment for the different maize residue (higher input, +R, and lower input, -R) and cover crop (cereal, C; legume, L; and bare fallow, F) treatments in the N-fertilized area.

	CO ₂ cumulative emissions (g C m ⁻²)			Total CO ₂ (g C m ⁻²)	CH ₄ cumulative emission (mg C m ⁻²)			Total CH ₄ (mg C m ⁻²)
	P1	P2	P3		P1	P2	P3	
Maize residue	<i>P</i> = 0.239	<i>P</i> = 0.499	<i>P</i> = 0.703	<i>P</i> = 0.635	<i>P</i> = 0.905	<i>P</i> = 0.720	<i>P</i> = 0.979	<i>P</i> = 0.855
+R	102	108	84.5	295	14.0	0.30	-16.3	-1.98
-R	125	122	79.6	327	11.7	-1.39	-15.8	-5.48
S.E.	20	10	20.8	40	12.0	2.90	11.6	12.0
Cover crop	<i>P</i> = 0.005	<i>P</i> = 0.003	<i>P</i> = 0.570	<i>P</i> = 0.016	<i>P</i> = 0.672	<i>P</i> = 0.746	<i>P</i> = 0.142	<i>P</i> = 0.480
C	103 a	138 b	101	342 b	16.8	-0.10	-16.1	0.59
F	68.3 a	56.0 a	69.3	194 a	9.3	-4.45	-20.8	-16.0
L	168 b	153 b	75.6	397 b	12.5	2.92	-11.2	4.20
S.E.	19.0	19.7	20.0	39	5.8	6.72	3.0	12.0
Maize residue x Cover crop	<i>P</i> = 0.962	<i>P</i> = 0.939	<i>P</i> = 0.869	<i>P</i> = 0.895	<i>P</i> = 0.912	<i>P</i> = 0.837	<i>P</i> = 0.648	<i>P</i> = 0.858

Different letters within columns denote significant differences (*P* < 0.05) between maize residue management or between cover crops by applying the LSD test. S.E.: standard error.

intercrop period (P1 and P2) (Fig. 3a,b) were no doubt offset by increased N₂O emissions during the cash crop phase (Fig. 3c). Thus, the N₂O emissions after cash crop fertilization had an important influence on total N₂O losses (i.e., cumulative emissions after fertilization represented up to 75% and 38% of total N₂O emissions in +R and -R, respectively).

4.2. Influence of cover cropping on N₂O fluxes

Contrary to the initial hypothesis, using different cover cropping systems during the growing period had no effect on N₂O emissions (P1, Fig. 3a). Greater fluxes would, however, have been expected from plots with legume cover crops, as reported by Sanz-Cobena et al. (2014), as a

consequence of the capacity of legumes to fix atmospheric N₂ and thus influence the balance between soil N uptake and release. The meta-analyses by Basche et al. (2014) also revealed that using legume species as cover crops had a positive relationship with N₂O emissions when no additional N was applied. However, no significant differences in soil mineral N values were observed between the cover crops during their growing phase (P1, Table S3). This could explain similar results for N₂O emissions during this same period. In line with the results found in this study, Basche et al. (2014) suggested that the growth periods of cover crops were responsible for reduced effects in terms of N₂O emissions compared to those following their incorporation and decomposition, or the cash crop phase. This could be related to the limiting low temperatures usually reported during the winter season, which coincide

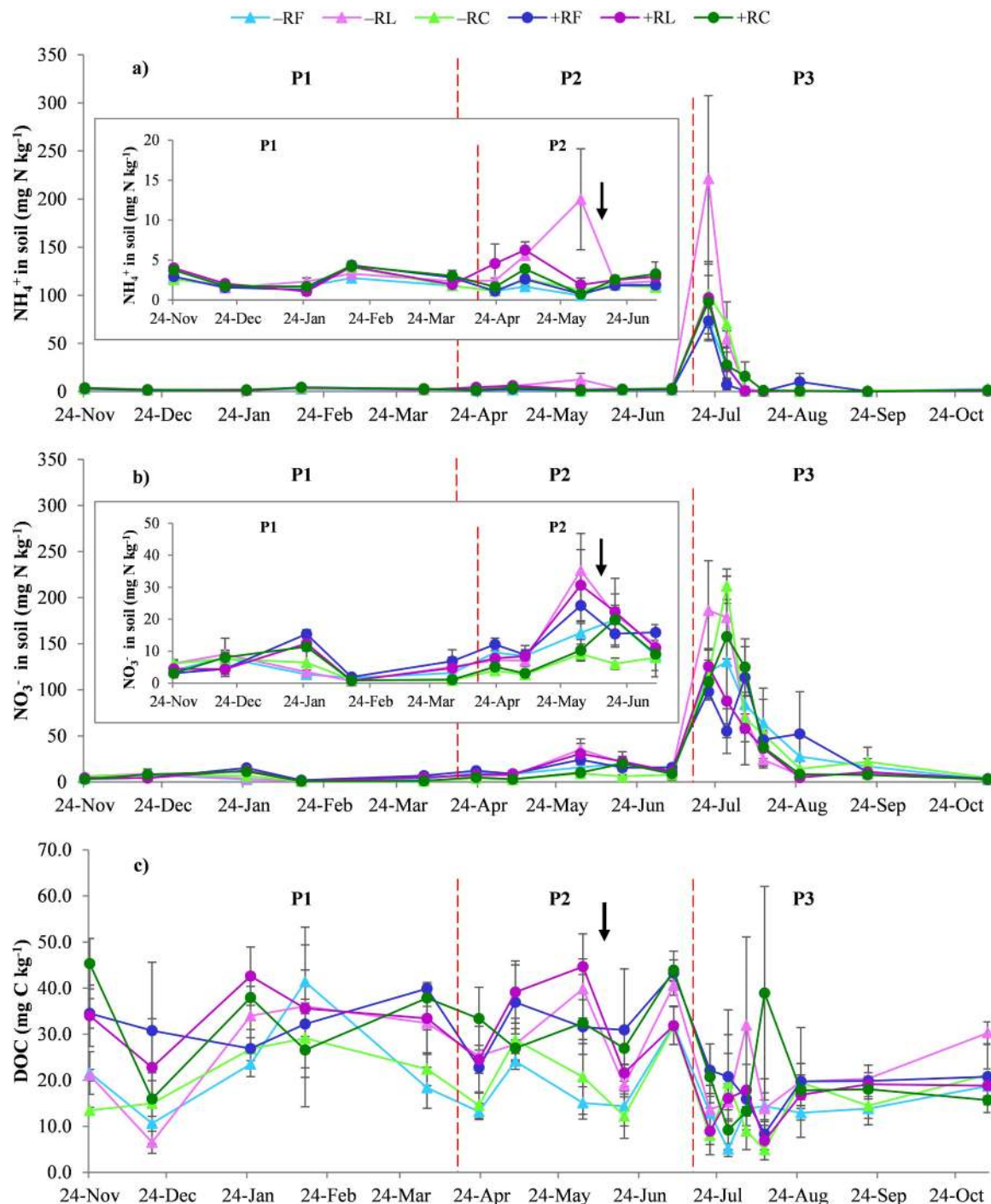


Fig. 6. (a) Soil $\text{NH}_4^+\text{-N}$, (b) soil $\text{NO}_3\text{-N}$ and (c) soil DOC concentrations for the different maize residue (higher input, +R, and lower input, -R) and cover crop (cereal, C; legume, L; and bare fallow, F) treatments during the three experimental periods (P1, P2 and P3) in the N-fertilized area. Vertical lines denote standard errors of the means. The black arrow denotes maize sowing and the beginning of irrigation.

with cover crop growth (Ussiri and Lal, 2013).

Although it is frequently observed that the incorporation of legume cover crop residue increases N_2O emissions compared to that from nonlegume species (Muhammad et al., 2019), the opposite was observed in the present study during P2. During that period, the cereal cover crop produced higher cumulative emissions than the legume after their incorporation (Fig. 3b); this contradicted the second hypothesis. The highest N_2O fluxes observed during this period occurred in mid-June (Fig. 4a), immediately after soil rewetting. They were a consequence of several days of rainfall and of the beginning of cash crop irrigation

resulting in a significant increase in WFPS, which coincided with warmer soil and air temperatures (Fig. 1). In fact, WFPS was the only variable that significantly correlated with N_2O emissions during this period ($r = 0.558$, Fig. 5b). Furthermore, the average WFPS values during P2 were 8% and 7% significantly higher in barley compared to the fallow and vetch subplots respectively (data not shown). This increase in WFPS, together with the greater amount of aboveground biomass and higher C:N ratio in barley crop compared to that of vetch (Table S5), could have stimulated N_2O production after rewetting (Barrat et al., 2021). Previous findings have reported higher N_2O

Table 2

Maize yield, N content and N uptake in maize stover (aboveground biomass without grain) and maize grain, weight of 100 maize grains and NUE for the different maize residue (higher input, +R, and lower input, -R) and cover crop (cereal, C; legume, L; and bare fallow, F) treatments in the N-fertilized area.

	Stover yield (Mg ha ⁻¹)	Grain yield (Mg ha ⁻¹)	100 grain weight (g)	N stover (%)	N Grain (%)	Stover N uptake (kg N ha ⁻¹)	Grain N uptake (kg N ha ⁻¹)	NUE (%)
Maize residue	<i>P</i> = 0.334	<i>P</i> = 0.426	<i>P</i> = 0.965	<i>P</i> = 0.927	<i>P</i> = 0.012	<i>P</i> = 0.246	<i>P</i> = 0.197	<i>P</i> = 0.107
+R	16.2	16.2	37.8	0.54	0.99 a	86.0	160	37.9
-R	17.7	17.0	37.9	0.54	1.03 b	95.8	176	57.3
S.E.	0.9	0.6	0.9	0.02	0.00	4.2	6	4.9
Cover crop	<i>P</i> = 0.066	<i>P</i> = 0.046	<i>P</i> = 0.449	<i>P</i> = 0.079	<i>P</i> = 0.835	<i>P</i> = 0.011	<i>P</i> = 0.340	<i>P</i> = 0.000
C	17.7 b	17.3 b	20.1	0.56 ab	1.00	98.4 b	173	63.2 b
F	16.7 ab	17.0 b	19.7	0.57 b	1.01	94.9 b	172	54.1 b
L	16.1 a	15.6 a	18.3	0.50 a	1.02	79.4 a	160	25.4 a
S.E.	0.4	0.4	0.4	0.02	0.02	3.5	7	3.7
Maize residue x Cover crop	<i>P</i> = 0.172	<i>P</i> = 0.221	<i>P</i> = 0.259	<i>P</i> = 0.401	<i>P</i> = 0.696	<i>P</i> = 0.112	<i>P</i> = 0.407	<i>P</i> = 0.271

Different letters within columns denote significant differences ($P < 0.05$) between maize residue management or between cover crops by applying the LSD test. S.E.: standard error.

emissions associated with less recalcitrant and lower C:N residues (Abalos et al., 2022a) due to the higher N availability from their mineralization. Indeed, during this decomposition period after cover crop termination, the rapid mineralization of the low C:N ratio vetch biomass (< 25) provided N in excess of the microbial N demand (Shan and Yan, 2013). This resulted in higher soil mineral N levels in the legume than in the nonlegume cover crop, in both the N-fertilized and control areas (Tables S3 and S4, respectively). These results suggest that this known and widely accepted pattern could be different in semiarid areas in which rewetting episodes are key drivers of annual N₂O emissions. These N₂O hot moments after rewetting could mainly be driven by denitrification (Butterbach-Bahl et al., 2013; Montoya et al., 2022). As a result, under the conditions of the present study, the greater aboveground biomass, C:N ratio and easily available C in the cereal residue along with the higher WFPS values, may have promoted levels of anaerobicity and denitrification during rewetting events (Z. Li et al., 2021). These conditions may have exceeded the effects of the greater N release from the decomposition of the legume residue.

As previously reported by Guardia et al. (2016), no significant differences between cover cropping systems regarding N₂O emissions were observed after integrated N fertilization. However, the higher C:N ratio for the aboveground barley biomass compared to that of vetch (Table S5) and the presence of readily decomposable carbon substrate for heterotrophic denitrifiers in immature residues (such as those from cover crops) could explain the numerically higher N₂O emissions from the barley plots than from the vetch and fallow plots (Abalos et al., 2022b; Butterbach-Bahl et al., 2013). It is important to highlight that incorporating vetch is a good strategy for mitigating the carbon footprint because it reduces the need for synthetic N fertilization and therefore upstream emissions associated with the industrial production of fertilizers (Guardia et al., 2019).

4.3. Legacy effect of synthetic N on N₂O emissions

In the present cover cropping field experiment, fertilized and unfertilized cash crop areas were established together with residue input and cover crop factors. This made it possible to shed light on the relevant residual N carry-over effect associated with intensively managed cash crops and the role of catch crops in surplus N recycling. The differences in cumulative N₂O emissions observed between the two areas during P2 were not as notable as those during P1 ($P < 0.05$ and $P < 0.1$ in P1 and P2, respectively) (Fig. 2a). Thus, although there was no significant difference between the two areas in terms of soil mineral N (Fig. 2b, c), the legacy effect of the N applied in the previous cropping season would have influenced the N₂O emissions, especially at the beginning of the experiment, which is in line with the initial hypothesis.

On average, 59% of the total cumulative N₂O emissions were produced during P3 (i.e., after maize N fertilization) in the N-fertilized area (Fig. 3c,d), while only 5% were emitted during P3 in the control area (Table S2). These results support those of Ferrari Machado et al. (2021), who identified N from fertilization as the dominant source of N₂O in studies involving crop residues.

Overall, no significant differences in N₂O EFs were reported in relation to maize residue management or cover cropping, despite barley cover crops and the incorporation of maize stover tending to increase them (Fig. 3 f). The average EF ($0.64 \pm 0.11\%$) observed in the present study was below the 0.91% average N₂O EF associated with cropping systems subjected to sprinkler irrigation under Mediterranean conditions (Cayuela et al., 2017), and was similar to the IPCC default value of 0.5% for dry climates (IPCC, 2019).

4.4. Effects on soil respiration and CH₄ fluxes

CO₂ emissions are highly dependent on soil microbial activity, which tends to increase with moderate soil temperature and is negatively affected by low water content (Nilahyane et al., 2020). The present study revealed an interannual variation in CO₂ fluxes (Fig. 4b and Fig. S2b). Furthermore, and as predicted by Barnard et al. (2020), a peak in CO₂ emissions was observed in both the N-fertilized and control areas for the cover crop plots (vetch and barley) in mid-June. This was a consequence of the soil rewetting after the first intense spring rainfall, the onset of irrigation preceded by mild temperatures registered in the spring season (Fig. 1a), and the incorporation of the cover crop in the topsoil. However, soil respiration decreased from mid-summer (at the beginning of P3), when the soil temperature increased ($>25^\circ\text{C}$), thus limiting the microbial activity. Opposite to the results reported by Wang et al. (2019), no differences between the control and the N-fertilized area were reported for any of the three periods relating to average cumulative CO₂ fluxes. This suggests that respiration was not affected by N addition, which is contrary to what has been previously reported (Wang et al., 2019). This may indicate that root biomass and respiration were similar in fertilized and non-fertilized plots, and that soil moisture and soil temperature were the key drivers of ecosystem respiration fluxes.

Net methanogenic activity was reported in both areas during P1 (Table 1 and Table S2), when the lowest soil and air temperatures were registered. These results were in line with the review by Shukla et al. (2013), who observed that CH₄ oxidation was reduced when soil temperatures in many temperate areas fell below 5°C, with this being a result of reduced gas diffusion and physiological stress. The total cumulative CH₄ fluxes at the end of the experiment were negative in both the N-fertilized (Table 1) and control (Table S2) areas. This suggests that there was an overall sink effect for CH₄, regardless of the maize residue

management or cover cropping system. Similar results have been reported by Guardia et al. (2016) and Sanz-Cobena et al. (2014) in field experiments conducted under similar climatic conditions. In accordance with the meta-analysis carried out by Wu et al. (2022) and with field studies involving irrigated maize (Huérffano et al., 2015), an 88% decrease in soil CH₄ consumption was observed in the N-fertilized area compared to the control area. This would suggest that the addition of N significantly reduced the rate of CH₄ uptake by the soil. The recent meta-analyses by P. Li et al. (2023) reported a significant decrease in cumulative CH₄ emissions associated with higher rates of straw input. However, similar to Wegner et al. (2018) in a corn–soybean rotation, no significant effect was reported for CH₄ fluxes between maize residue management systems or cover crops.

4.5. Maize yield, YSNE and NUE

As expected, the objective of enhancing maize yield when applying N via synthetic fertilization was evidently achieved (Table 6). However, the higher cumulative N₂O emissions in the N-fertilized area (Fig. 2a) drove the YSNE, resulting in them being significantly higher in fertilized plots (average 0.11 g N kg grain⁻¹, Fig. 3 f) compared to those in the control area (average 0.04 g N kg grain⁻¹, Table S6). Maize stover management did not affect the maize yield parameters in the fertilized area (Table 2). However, on the unfertilized plots, there was a 17% increase in grain yield and a 22% increase in grain N uptake on the +R compared to the -R plots (Table S6). This supports the findings of the global meta-analysis carried out by P. Li et al. (2023), who reported overall increases in both crop yield and NUE, by 9% and 23%, respectively. It also suggests that the incorporation of maize stover successfully provided mineral N to the subsequent crop, although its effects were masked when N was applied via fertilization. Long-term experiments have also reported increases in maize yields after several years of stover incorporation (Urrea et al., 2018).

The maize grown on vetch plots received the lowest mineral N via integrated soil fertility management (i.e., 170 kg N ha⁻¹) but produced the lowest grain ($P < 0.05$) and stover ($P < 0.10$) yields, as well as the lowest NUE values (Table 2). These differences were not related to grain weight but to the total number of grains on each cob (Table 2). These results were in line with those reported by Abdalla et al. (2019), who found that cover crops (both legumes and nonlegumes) reduced cash crop yields by around 4%, while the combination of legume and nonlegume cover crops increased cash crop yields by about 13%. The meta-analyses by Tonitto et al., (2006) also found that replacing fallow with a legume cover crop resulted in negative yield or had no effect on production. These yield penalties on vetch plots highlight the challenge inherent when trying to optimise integrated N management and to accurately predict the supply of N from the decomposition of legume residues. The incorporation of low C:N residues from cover crops, and particularly legume cover crops, can produce a very rapid release of mineral N when cash crop N uptake is still low (Drinkwater et al., 2000). The amount of plant available N obtained from cover crops would then not be efficiently taken up and maize yields could be reduced in comparison with treatments involving greater N inputs via N fertilization at top-dressing coinciding with the highest crop demand and N acquisition potential. However, in the unfertilized control area, the maize grown after the legume cover crop produced the highest yields and N uptake rates (Table S6). These results confirmed the potential benefits of including legumes in rotations (Gou et al., 2023) and the need to appropriately integrate the N supplied by synthetic fertilization and legume residues in order to reduce the C footprint of croplands and avoid yield penalties.

4.6. Uncertainties and future research

For the first time, this one-year study sheds light on the interaction between cover cropping and the amount of cash crop residue in the N

legacy. However, N₂O fluxes are often strongly driven by environmental conditions and this is the case with many rainfed Mediterranean croplands, which may exhibit large degrees of year-on-year variability (Lassaletta et al., 2021), as occurred at the experimental site highlighted in this study (Table S7). Under the conditions of this experiment, small influence of this variability could have been expected during the maize cropping phase (P3), since the meteorological and management conditions produced optimum conditions for the microbial communities commonly involved in nitrification, denitrification and mineralization (Z. Li et al., 2021; Ussiri and Lal, 2013). This occurred and was the result of warm temperatures in summer and the presence of sufficient soil moisture due to water being supplied through irrigation. During the cover cropping phase (P1), meteorological conditions are often more unpredictable, but high N₂O emissions are usually prevented by low soil temperatures (Aguilera et al., 2013). Relating to this point, a random-meta-forest analysis conducted by Y. Li et al. (2023) revealed that emissions from cover cropping systems were mainly driven by soil pH, N and SOC contents rather than by other variables, such as climate. However, after cover crop termination, temperature and soil moisture would seem to be the key drivers responsible for N release from labile residues, which is something that tends to occur to a significant degree in the first months after termination (Nyabami et al., 2023). They also influence the magnitude of N₂O peaks after rewetting, with these being intensified by intense periods of drought (Barrat et al., 2021). Even though the temperatures and amount of rainfall before the maize crop was sown were close to 15-year average values (Table S7), we hypothesize that extremely low and high quantities of rainfall during P2 could have resulted in lower than normal N₂O losses, respectively due to the reduced mineralization of crop residues and to the lower intensity of rewetting events. However, this will need to be confirmed in future multi-year field studies. Furthermore, it will be necessary to quantify the specific contributions made by nitrification, bacterial/fungal denitrification (which is relevant during N₂O rewetting pulses) and nitrifier denitrification through, e.g., site preference, is still needed (Wei et al., 2023; Wrage-Mönnig et al., 2018). It would also be relevant to study the dynamics of C and N mineralization (through ¹³C and ¹⁵N-labeled residues) in order to find ways of overcoming the limitations of integrated soil fertility management. It is therefore recommended to include the soil mineral N concentrations after cover cropping in calculations of N emission rates resulting from integrated fertilization. This is also strongly recommended in order to avoid potential yield penalties of the type reported in this study (Table 2).

5. Conclusions

This study integrates information about N₂O emissions during a cover crop-irrigated maize annual rotation and the interactions between crop residue compositions, meteorological conditions and forms of synthetic N fertilization. The results presented here show that the conservation agricultural practices herein studied (maize stover incorporation and cover crops development followed by their incorporation as green manure) had an important effect on the cumulative release of N₂O from cover crop–cash crop rotations. These agricultural practices could be considered important drivers of N₂O production, especially when conditions favour denitrification, as occurred in this study when the soil was irrigated during the maize cropping phase and also after N fertilization. However, both conservation agriculture practices had no effect on area-scaled and yield-scaled N₂O emissions when considering the entire cover crop–cash crop annual rotation. Despite the yield decrease of the integrated fertilized maize cash crop following the legume cover crop, the increased maize yields reported after vetch cover cropping without N fertilization underscore the need for an accurate integration of legume residues. This is essential to prevent penalties in cash crop yields.

Our findings may also help to adopt the best site-specific management option during the intercrop period in semi-arid arable agro-

ecosystems. Firstly, the influence of maize residue input was greater than that of cover cropping, even though this effect was offset at the end of the annual rotation. Secondly, greater N₂O emissions were observed from the cereal cover crop than the legume cover crop after cover crop termination. This suggests that under the conditions of this study, the enhancement of denitrifying activity after soil rewetting had a more significant effect than the higher availability of N from the decomposition of legume residues. The different periods of the cropping season should be considered when drawing conclusions and making recommendations about the effect of cover cropping on N₂O emissions.

CRediT authorship contribution statement

Jiménez-Horcadada Rafael: Formal analysis, Investigation, Methodology, Writing – review & editing. **García-Marco Sonia:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **García-Gutiérrez Sandra:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Guardia Guillerme:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Vallejo Antonio:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Montoya Mónica:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Writing – review & editing.

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.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2023.108873](https://doi.org/10.1016/j.agee.2023.108873).

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