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Oat green manure improves soil health indicators and lentil yield with GHG trade-offs under rainfed semiarid conditions

Morad Mirzaei^{1,2}  | William Burchill³  | Daniele Borgatti⁴  |
 Mortadha Ben Hassine⁴  | Yuan Li⁵  | Mohamed Allam⁶  | Sudip Sarkar⁷  |
 Jelena Baćanović-Šišić⁸  | Sara Azadi⁹  | Roberto Mancinelli¹⁰  |
 Emanuele Radicetti¹⁰ 

¹School of Natural Sciences, Botany Discipline, Trinity College Dublin, Dublin 2, Ireland²Teagasc, Environment, Soils and Land-Use Department, Johnstown Castle, Wexford, Ireland³School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland⁴Department of Chemical, Pharmaceutical and Agricultural Sciences, University of Ferrara, Ferrara, Italy⁵Grasslands and Sustainable Farming, Production Systems Unit, Natural Resources Institute Finland (Luke), Maaninka, Finland⁶Department of Agronomy, Faculty of Agriculture, Assuit University, Assuit, Egypt⁷ICAR Research Complex for Eastern Region, Patna, India⁸Section of Ecological Plant Protection, University of Kassel, Witzenhausen, Germany⁹Department of Physical Geography, Faculty of Geographical Sciences and Planning, University of Isfahan, Isfahan, Iran¹⁰Department of Agriculture and Forest Sciences, University of Tuscia, Viterbo, Italy

Correspondence

Morad Mirzaei, School of Natural Sciences,
 Botany Discipline, Trinity College Dublin,
 Dublin 2, Ireland.

Email: mirzaeim@tcd.ie

Emanuele Radicetti, Department of
 Agriculture and Forest Sciences, University
 of Tuscia, Viterbo, Italy.

Email: emanuele.radicetti@unitus.it

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Abstract

Green manuring may improve soil properties, but its effects on crop productivity and greenhouse gas (GHG) emissions remain poorly understood in rainfed semi-arid systems. This study evaluated oat (*Avena sativa* L.) as green manure on soil properties, GHG emissions, and lentil (*Lens culinaris* Medik.) yield in a rainfed semiarid cropping system in western Iran. A field experiment was conducted in 2021 and 2022 evaluating four oat biomass incorporation rates (0, 2, 4, and 8 Mg of dry weight ha⁻¹). A randomized complete block design with four replications was employed. Oat biomass was incorporated prior to lentil sowing to a depth of 30 cm. Soil CO₂ and N₂O fluxes were measured during lentil cultivation, while lentil yield, N uptake, and soil chemical properties were evaluated at harvesting. Regression analysis showed that soil organic carbon and total nitrogen increased linearly with oat biomass incorporation rate, while available water, aggregate stability, and grain yield showed quadratic responses, indicating improved soil functioning and

Abbreviations: DAS, days after sowing; DSA, dry stable aggregates; FC, field capacity; GHG, greenhouse gas; GM, green manure; OC, organic carbon; PWP, permanent wilting point; SOC, soil organic carbon; TN, total nitrogen; WSA, water stable aggregates.

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crop productivity but with marginal gains at higher biomass rates. Lentil N uptake increased linearly with increasing oat biomass incorporation, confirming improved nutrient acquisition. Soil CO₂ and N₂O emissions also increased with higher biomass inputs, although their responses varied between growing seasons. The principal component analysis indicated increasing oat biomass incorporation was associated with improvements in soil fertility and lentil performance, but also with greater GHG emissions. Overall, oat green manure improved soil fertility and lentil productivity under semiarid rainfed conditions, but residue management should be optimized to balance agronomic benefits with GHG trade-offs.

Plain Language Summary

Improving soil health while maintaining crop productivity is a major challenge in arid agroecosystems. This study assessed how incorporating different rates of oat (*Avena sativa* L.) biomass as green manure affects soil properties, greenhouse gas (GHG) emissions, and lentil (*Lens culinaris* Medik.) yield under rainfed conditions. Applying higher rates of oat biomass (8 t ha⁻¹) significantly increased soil organic carbon, nitrogen content, and aggregate stability, leading to a 26% rise in lentil grain yield compared with the control. However, greater residue inputs also enhanced soil CO₂ and N₂O emissions due to intensified microbial activity. When emissions were expressed per unit of yield, the agronomic benefits largely offset the temporary environmental costs. Overall, the results indicate that oat green manure can improve soil fertility and water retention in arid soils while contributing to sustainable lentil production if managed to balance productivity gains with GHG mitigation.

1 | INTRODUCTION

In the context of sustainable agriculture, grain legumes are especially valuable due to their combined nutritional and ecological benefits. Among grain legumes, lentil (*Lens culinaris* Medik.) stands out for its high content of protein, dietary fiber, complex carbohydrates, and essential micronutrients such as iron and zinc, attributes that contribute to its growing global demand (Khazaei et al., 2019; Roy et al., 2010). However, lentil productivity, particularly in arid and semiarid regions, is highly sensitive to climatic variables including temperature, rainfall, and evapotranspiration (Amiri & Deihimfard, 2018). In recent years, this system has experienced notable declines in soil quality and crop productivity, largely driven by unsustainable management practices such as intensive tillage, lack of crop rotation, limited organic inputs, and the excessive application of chemical fertilizers (Marteau-Bazouni et al., 2024). One widely employed strategy, which has potential to address some of these challenges, is the use of green manure (GM), which involves the incorporation of plant biomass into the soil prior to sowing the subsequent cash crop (Mamiev et al., 2019). This practice not only enhances soil fertility but also improves soil structure, reduces water evaporation, mit-

igates soil erosion, and supports soil biological activity (Lei et al., 2022; Ren et al., 2024).

Green manuring can also enhance crop yield and economic viability, while lowering the environmental footprint of agricultural production (Cherr et al., 2006; Song et al., 2022; Zhou et al., 2020). Despite its benefits, GM can have the potential to increase greenhouse gas (GHG) emissions. Previous studies have reported inconsistent effects on soil emissions of CO₂ and N₂O. This variability is primarily attributed to differences in the timing of biomass incorporation and the plant species used as GM (Alluvione et al., 2010; Basche et al., 2014; Ferrara et al., 2021; Gomes et al., 2009; Kallenbach et al., 2010; Lee et al., 2021; Massimiliano et al., 2015; Qiu et al., 2022). These contrasting findings underscore the need for a comprehensive evaluation of green manuring practices to optimize both crop productivity and soil properties while minimizing GHG emissions. Although the positive effects of green manuring on soil fertility and crop yield are well recognized, most available evidence comes from humid, irrigated, or relatively high-input cropping systems. Much less is known about the performance of GM under rainfed semiarid conditions, where residue decomposition, nutrient release, soil water availability, and GHG emissions

are strongly constrained by limited and irregular rainfall and seasonal drought. This knowledge gap is particularly relevant for western Iran, where rainfed lentil production is commonly affected by low soil organic matter, limited organic residue return, prolonged dry periods between residue incorporation and crop establishment, and strong fluctuations in soil moisture and temperature (Amiri & Deihimfard, 2018; Marteau-Bazouni et al., 2024; Mirzaei et al., 2021; Sarkar & Northup, 2023). Under these conditions, the response to GM may differ substantially from that observed in wetter or irrigated environments, because microbial activity, N mineralization, and crop nutrient uptake depend strongly on the synchronization between residue decomposition and water availability. In addition, lentil crop is particularly sensitive to drought and high temperature during reproductive development, making soil management practices important for stabilizing productivity in semiarid environments (Amiri & Deihimfard, 2018; Preiti et al., 2024). However, few studies have evaluated oat residues as GM in lentil-based systems, and no comprehensive assessment has examined how increasing oat biomass incorporation rates simultaneously affect soil physical and chemical properties, nitrogen dynamics, lentil productivity, and CO₂/N₂O emissions under rainfed semiarid conditions. Addressing this gap is essential for identifying GM management strategies that improve soil health indicators and crop performance while limiting GHG trade-offs in water-limited agroecosystems. Based on this background, the current study hypothesized that increasing the rate of oat biomass incorporation would improve soil fertility and lentil yield but may also intensify CO₂ and N₂O emissions due to enhanced microbial activity. The present study aimed to (1) evaluate the effects of different incorporation rates of oat residues as GM on CO₂ and N₂O emissions in a rainfed lentil cropping system, and (2) assess the impact of oat GM applications on soil properties and lentil yield.

2 | MATERIALS AND METHODS

2.1 | Study area and experimental design

The study was carried out in 2021 and 2022 lentil growing seasons in the Shabab district, Chardavol County, Ilam Province, Iran (33°44'09.1" N, 46°38'47.2" E, 982 m a.s.l.). The climate is characterized by a mean annual air temperature of 11.8°C, with maximum values in July of 31.2°C and minimum temperatures of 0.5°C recorded in January. Average annual precipitation is 422 mm based on historical climate data from 2006 to 2022 (Figure S1). The soil is classified as Calcic Aridisol with the physicochemical properties presented in Table S1.

The field experiment was performed in two adjacent fields previously kept fallow. A randomized complete block design with four replications was applied in both growing seasons.

The treatment design was a single-factor arrangement, with oat GM incorporation rate as the only treatment factor. The experimental treatments consisted of the incorporation of oat GM at four application rates: 0, 2, 4, and 8 Mg DM ha⁻¹ (hereafter called GM0, GM2, GM4, and GM8, respectively) of oat dry matter. The oat biomass incorporation rates were chosen to represent a realistic range of residue inputs commonly reported for cereal cover crops and GMs in semiarid agroecosystems (Blanco-Canqui et al., 2015; Cherr et al., 2006; Poeplau & Don, 2015). The inclusion of GM0 enabled the assessment of baseline soil and crop responses in the absence of residue incorporation, while GM2, GM4, and GM8 provided a progressive gradient for evaluating dose-dependent effects on soil physical properties, N dynamics, GHG emissions, and lentil productivity. This experimental approach is consistent with previous studies investigating the influence of increasing residue incorporation rates on soil functioning and crop performance, where biomass gradients have been used to quantify threshold responses and identify optimal residue management strategies (Blanco-Canqui et al., 2015; Cherr et al., 2006; Poeplau & Don, 2015). Furthermore, incorporation rates correspond to substantial differences in C and N inputs to the soil, which are key drivers of microbial activity, nutrient cycling, soil water retention, and GHG production (Lal, 2004; Poeplau & Don, 2015). Each year, a total of 16 plots were established. Each plot measured 247 m² (19 m × 13 m).

2.2 | Treatment implementation and lentil cropping

In each growing season, at oat milk stage, oat biomass was collected using a 0.25 m² quadrant (0.5 m × 0.5 m) placed randomly at four places of oat field. Samples were cut and harvested from a field specifically cultivated to produce oat biomass to be used in this experiment. Oat samples were dried and analyzed to determine chemical characteristics. The average chemical composition of the oat residues was 16.6 g kg⁻¹ N, 1.6 g kg⁻¹ P, 13.5 g kg⁻¹ K, and 478.5 g kg⁻¹ organic carbon (OC). After dry matter determination, oat biomass was mechanically harvested, and residues were spread manually in the soil surface at the specific rate. Then, residues were incorporated into the soil using a moldboard plow to a depth of 30 cm on June 23, 2020, and June 17, 2021, respectively. Then the field was left bare until December. Disk harrowing at 10 cm of soil depth was carried out 2 weeks before lentil sowing to prepare lentil seedbed. Lentil (*L. culinaris* Medik.) seeds were sown manually on December 15, 2020, and December 18, 2021, respectively. The sowing rate was 80 kg ha⁻¹ placed in rows of 25 cm apart. Weed management was performed manually before the flowering stage in March 2021 and March 2022. Lentil was cultivated under rainfed conditions without supplemental irrigation.

2.3 | Determination of GHG fluxes

In both years, soil GHG fluxes were measured throughout the lentil growing season from January to May at 15-day intervals. A static closed polyvinyl chloride chamber system was used for GHG flux measurements following the methodology described by de Klein and Harvey (2015). The chamber consisted of two parts: a base and a lid. The base had a height of 12.5 cm and a diameter of 15 cm, while the lid contained a sampling port fitted with a rubber septum for gas collection. To minimize soil disturbance, chamber bases were installed in the soil after lentil sowing to a depth of 5 cm and left in the same place for the whole lentil growing season. Two static chambers were installed in the central area of each experimental plot to better account for within-plot spatial variability. Fluxes measured from the two chambers were averaged to obtain one plot-level value for each sampling date before statistical analysis. Gas sampling was conducted between 11:00 a.m. and 12:00 p.m. on each measurement date. A 20 mL air sample was collected using a syringe at 0, 30, and 60 min after chamber closure and transferred into pre-evacuated gas vials (Labco Exetainer, Labco Ltd.) fitted with rubber septa. Gas concentrations of N_2O and CO_2 were analyzed using gas chromatography (Bruker SCION 456-GC Gas Chromatograph (GC), Bruker Daltonics) equipped with an electron capture detector for N_2O detection and a thermal conductivity detector for CO_2 analysis. The gas concentrations were converted from volumetric to mass-based values using the ideal gas law. GHG fluxes were calculated based on the linear change in gas concentration inside the chamber over time, considering the ratio between chamber volume and soil surface area (de Klein & Harvey, 2015). Cumulative N_2O emissions were estimated using linear interpolation between consecutive sampling events, integrating the underlying area (Montoya et al., 2021; Wegner et al., 2018). The C input/output ratio was determined by dividing the C added to the system by means of oat biomass and lentil straw biomass at harvesting (considered as C input to the system) and the total C content in the CO_2 emissions and lentil seeds (considered as C output to the system). As suggested by Radicetti et al. (2020), this index may be considered as an indicator of the C cycle dynamics, with values greater than, equal to, or less than 1 indicating an increase, stability, or decrease in soil C content, respectively. In addition, yield-scaled CO_2 emissions were determined by dividing cumulative CO_2 emissions by lentil grain yield.

2.4 | Soil sampling and analyses

At each GHG flux measurement date, soil samples at a depth of 0–20 cm were collected in the central area of each plot in proximity to the chambers used for GHG measurements. Four soil samples were collected from four locations within each

plot and mixed uniformly to create one sample. In the laboratory, collected soil samples were split into two subsamples: (1) one was stored at 4°C for determining NH_4^+ and NO_3^- , and (2) the other sample was used to determine soil moisture content. Soil NH_4^+ and NO_3^- concentrations were determined following extraction with 2 M KCl according to Page et al. (1982). After filtration, NH_4^+ and NO_3^- concentrations were quantified by spectrophotometric colorimetric analysis (Agilent Cary 60 UV–Vis, Agilent Technologies). Soil moisture content was measured by oven-drying 50 g of soil at 105°C using a forced-air drying oven (Mettler UN55, Mettler GmbH + Co. KG), with values multiplied by soil bulk density to determine volumetric moisture content. Soil bulk density was measured using the core-ring method (5 cm height, 8 cm inner diameter, 251.2 cm³) (Blake & Hartge, 1986). In each plot, soil temperature was recorded at a 0- to 10-cm depth using a digital thermometer (Brannan Ltd.).

At lentil harvesting, topsoil samples (0- to 20-cm depth) were collected from all plots to evaluate the effects of oat GM application on soil properties. Five random soil samples were taken per plot and combined into one. Wet and dry sieving methods were used for the determination of water stable aggregates (WSA) and dry stable aggregates (DSA) (Elliott, 1986; Kemper & Rosenau, 1986). Samples were air-dried and then divided into two parts. One part was used for measuring soil available water (Aw), WSA, and DSA. Aw was calculated as the difference between moisture content at field capacity (FC) and permanent wilting point (PWP) (Cassel & Nielsen, 1986). Moisture retained at FC and PWP was determined using a pressure plate apparatus (Soil moisture Equipment Corp., Model 1500F1 Pressure Plate Extractor) at 0.3 and 15.0 bar, respectively. In addition, soil samples were analyzed for chemical properties. Soil organic carbon (SOC) and total nitrogen (TN) were determined using wet oxidation methods (Walkley & Black, 1934) and Kjeldahl method (Bremner, 1996), respectively. Available potassium (K) was extracted using ammonium acetate and analyzed via flame photometry (Jenway PFP7, Cole-Parmer Ltd.) (Knudsen et al., 1982), while available phosphorus (P) was determined via NaHCO_3 extraction and colorimetric analysis (Page et al., 1982). Micronutrients such as iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn) were measured using atomic absorption spectrophotometry (PerkinElmer AAnalyst 400, PerkinElmer Inc.) after extraction with diethylenetriamine-pentaacetic acid (DTPA) (Lindsay & Norvell, 1978). All soil and organic amendment analyses were performed in triplicate to ensure data accuracy and reliability.

2.5 | Yield measurement

Lentil crops were harvested on May 8, 2021, and May 10, 2022, respectively. Total aboveground biomass of lentil plants was collected using a sampling area of 1 m² (1 m × 1 m)

placed in the middle of each experimental plot. Lentil was harvested by hand by cutting plants at ground levels and processed in laboratory. Then biomass samples were manually threshed carefully separated for seeds and straw and oven-dried at the temperature of 65°C until constant weight. The dried lentil biomass samples were then finely ground using a laboratory mill (IKA MF 10 Basic Microfine Grinder, IKA-Werke GmbH & Co. KG) and analyzed for C content (Walkley and Black method) and N content by means of the Kjeldahl method (Jones, 2001). The total C and N accumulation in lentil grain and straw was calculated by multiplying the biomass dry weight by the corresponding concentration value.

2.6 | Statistical analysis

All statistical analyses were performed using JMP Pro v.17. Oat biomass incorporation rate was treated as a quantitative explanatory variable corresponding to 0, 2, 4, and 8 Mg DM ha⁻¹. For variables measured once at harvest, including soil properties, crop yield, nitrogen uptake, carbon-related variables, and soil nutrient status, linear and quadratic regression models were fitted to evaluate dose–response relationships with increasing GM rate. Before fitting the final regression models, data were analyzed using analysis of variance (ANOVA) procedure considering growing season, GM rate, and their interaction were considered fixed effects, while block was included as a random effect. When this interaction was not significant, data from the two growing seasons were pooled and a single regression model was fitted across years, while accounting for growing season in the statistical model. When the Year × GM rate interaction was significant, separate regression models were fitted for each growing season. The quadratic model was retained only when the quadratic term was significant at $p < 0.05$; otherwise, the linear model was retained when significant. When neither the linear nor quadratic term was significant, the response was considered not significant. Regression equations, significance levels, and coefficients of determination (R^2) are reported in the tables.

For variables measured repeatedly during lentil cultivation, including soil moisture, carbon dioxide fluxes, nitrous oxide fluxes, nitrate concentration, and ammonium concentration, each sampling date was analyzed separately because these variables showed strong temporal dynamics during crop growth. At each sampling date, data were subjected to ANOVA, with growing season, oat GM rate, and their interaction included as fixed effects, and block included as a random effect. Treatment means and standard errors are presented in figures where appropriate to illustrate temporal patterns and interannual variability, while asterisks indicate significant level at the specific date. In addition, for each sampling date, the Year × GM rate interaction was tested before fitting dose–response regressions. When this interaction was

not significant, a pooled regression across years was fitted; when significant, year-specific regressions were fitted. Date-specific regression equations are reported in the Supporting Information. Principal component analysis (PCA) was performed to explore relationships among oat application rate and SOC, TN, available water, WSA, soil P, soil K, grain yield, straw biomass, CO₂-C emissions, and cumulative N₂O emissions.

3 | RESULTS

3.1 | Soil chemical and physical properties

SOC increased linearly with GM rate ($R^2 = 0.334$, $p < 0.001$; Table 1), indicating a progressive accumulation of soil C as oat biomass input increased. Similarly, TN showed a significant positive linear response to GM rate ($R^2 = 0.191$, $p = 0.0123$). Available water and DSA were better described by quadratic models ($R^2 = 0.743$, $p = 0.0064$ and $R^2 = 0.794$, $p < 0.001$, respectively), indicating that both variables increased with increasing GM rate but with a tendency toward reduced marginal gains at the highest biomass incorporation level. WSA also showed a significant quadratic response; however, the Year × GM rate interaction resulted significant for this variable ($p = 0.009$; Table 1). Therefore, separate regressions were fitted for each year. In both years, WSA increased with increasing GM rate, although the magnitude of response differed between years ($R^2 = 0.817$, $p = 0.0019$ in 2021 and $R^2 = 0.851$, $p = 0.0012$ in 2022, respectively; Table 1).

Soil moisture dynamics exhibited distinct seasonal variations (Figure S2). Early in the lentil growing seasons (15–45 days after sowing [DAS]), soil moisture levels in 2022 were significantly higher than in 2021 (Figure S2). However, during the later growth stages (75–120 DAS), the opposite trend was observed, with significantly lower soil moisture levels in 2022 compared to 2021. Across all growth stages and in both years, the GM8 treatment consistently maintained the highest soil moisture levels (Figure S2). In contrast, the control treatment (GM0) showed the lowest soil moisture levels throughout the experiment. Soil moisture showed clear dose–response patterns in relation to GM rate throughout the lentil growing season (Table S2). At 15 and 75 DAS, soil moisture increased linearly with GM rate when data were pooled across years. At 60 DAS, the response was quadratic ($R^2 = 0.822$, $p = 0.0096$; Table S2), indicating increased soil moisture with increasing GM rate but a tendency toward stabilization at higher biomass levels. Significant Year × GM rate interactions were detected at 30, 45, 90, 105, and 120 DAS (p value = 0.0097, 0.0197, 0.0372, and 0.0069, respectively), therefore, year-specific regressions were fitted for these sampling dates (Table S2). Soil temperature showed a continuous

TABLE 1 Analysis of variance and regression analysis of soil chemical and physical properties in response to increasing oat green manure (GM) incorporation rate. The growing season, oat GM rate, and their interaction were tested as fixed effects before fitting dose–response models.

Variable	<i>p</i> value Year	<i>p</i> value GM	<i>p</i> value Year × GM	Decision	Year	Model	Regression equation	Linear <i>p</i>	Quadratic <i>p</i>	<i>R</i> ²
SOC	0.061	0.002	0.242	Pooled	–	Linear	$Y = 4.353 + 0.172 \times \text{GM}$	<0.001	–	0.33
TN	0.923	0.072	0.287	Pooled	–	Linear	$Y = 0.425 + 0.013 \times \text{GM}$	0.012	–	0.19
Aw	0.028	<0.001	0.067	Pooled	–	Quadratic	$Y = 11.408 + 2.270 \times \text{GM} - 0.148 \times \text{GM}^2$	<0.001	0.006	0.74
WSA	<0.001	<0.001	0.009	Separate	2021	Quadratic	$Y = 15.168 + 2.971 \times \text{GM} - 0.241 \times \text{GM}^2$	<0.001	0.002	0.82
					2022	Quadratic	$Y = 14.382 + 5.329 \times \text{GM} - 0.421 \times \text{GM}^2$	<0.001	0.001	0.85
DSA	0.019	<0.001	0.071	Pooled	–	Quadratic	$Y = 15.676 + 7.291 \times \text{GM} - 0.494 \times \text{GM}^2$	<0.001	<0.001	0.79

Abbreviations: Aw, available water; DSA, dry-stable aggregates; SOC, soil organic carbon; TN, total nitrogen; WSA, water-stable aggregates. Linear and quadratic terms were considered significant at $p < 0.05$.

increase throughout the lentil growing seasons, from 15 to 120 DAS (Figure S3). Significant differences in soil temperature between the two growing seasons were recorded at 90 and 105 DAS, where 2022 exhibited significantly higher values compared to 2021. However, soil temperature did not significantly vary among residue treatments, regardless of the growing season (Figure S3).

3.2 | Lentil yield, straw biomass, and nitrogen uptake

The Year × GM rate interaction was not significant ($p > 0.05$) for grain yield, straw biomass, grain N uptake, or straw N uptake (Table 2). Grain yield showed a significant quadratic response to GM rate ($R^2 = 0.665$, $p = 0.0173$), indicating that yield increased with increasing oat biomass incorporation. Straw biomass showed a significant positive linear response to GM rate ($R^2 = 0.670$, $p < 0.001$; Table 2). Similarly, both grain N uptake and straw N uptake increased linearly with GM rate ($R^2 = 0.383$, $p < 0.001$ and $R^2 = 0.672$, $p < 0.001$, respectively), confirming that higher oat biomass incorporation enhanced crop nitrogen acquisition.

3.3 | Carbon dynamics and CO₂ emissions

Weather conditions during the GHG monitoring period differed substantially between growing seasons (Table S3). Cumulative precipitation from January to May was 210.8 mm in 2021 and 411.8 mm in 2022. The largest differences occurred during January and March, when precipitation in 2022 was approximately fourfold and threefold greater than in 2021, respectively. Mean air temperature was consistently higher in 2021 than in 2022 throughout most of the monitoring period, particularly during April (19.3°C vs. 16.9°C).

Soil CO₂ emissions were significantly higher in 2021 compared to 2022 throughout the lentil growing seasons (Figure 1A). Oat residue incorporation led to increased CO₂ emissions, with the highest emissions recorded under the GM8 treatment (Figure 1A). In contrast, the control treatment (GM0) consistently exhibited the lowest CO₂ emissions across both years (Figure 1B). Regression analysis of CO₂ fluxes further confirmed that the response to GM rate varied across the growing season (Table S4). Significant Year × GM rate interactions were detected at most sampling dates (Table S4). In 2021, CO₂ flux generally increased linearly with GM rate across most sampling dates, with a quadratic response observed at 90 DAS. In 2022, CO₂ flux responses were weaker and less consistent, with significant responses detected only at selected sampling dates.

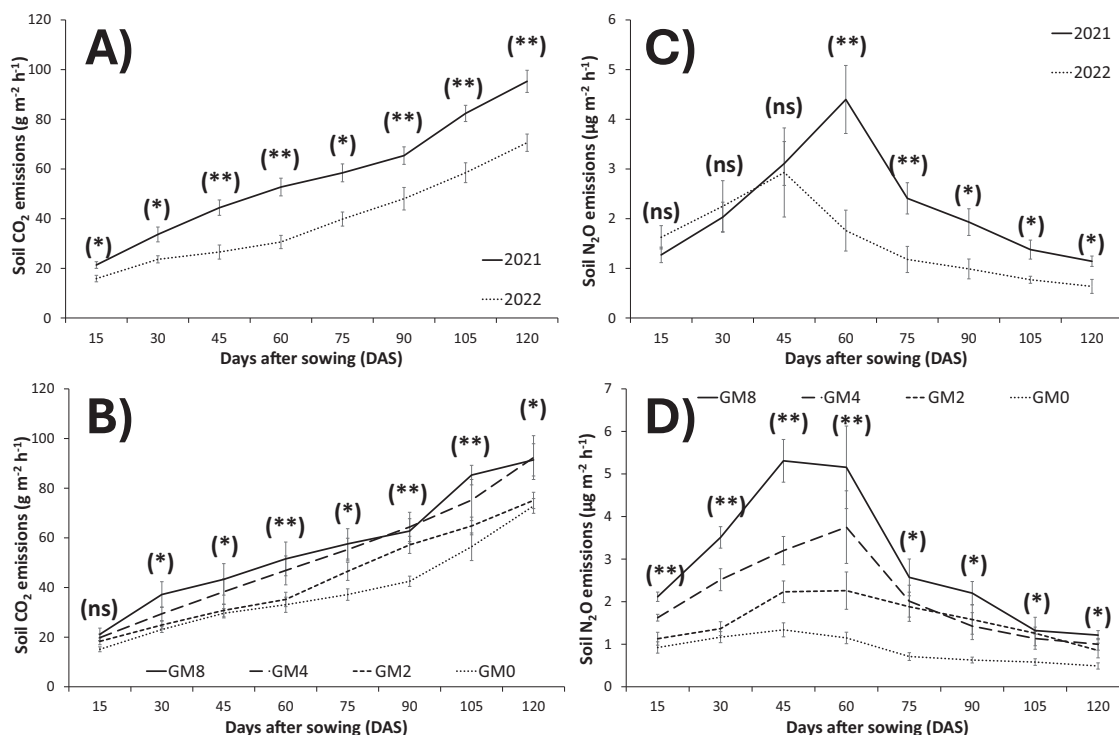


FIGURE 1 Soil carbon dioxide (CO₂) emissions (g m⁻² h⁻¹) and soil nitrous oxide (N₂O) emission (μg m⁻² h⁻¹) during the growing cycle of lentil in 2021 and 2022 (A and B) and at different rates of oat residue incorporation (C and D). Error bars represent $\pm$ standard error from the mean ($n = 18$ for the year and $n = 6$ for the oat residue rates, respectively). Asterisks indicate significant differences between growing seasons or among oat biomass incorporation rates according to analysis of variance (ANOVA). * and ** indicate significance at $p < 0.05$ and $p < 0.01$, respectively; ns indicates nonsignificant differences ($p > 0.05$). GM8, GM4, GM2, and GM0 are 8, 4, 2, and 0 Mg ha⁻¹ of dry matter of oat residues incorporated into the soil as green manure (GM), respectively.

The Year $\times$ GM rate interaction was significant for C output by CO₂ (p value < 0.001 ; Table 3). In 2021, C output by CO₂ showed a significant quadratic response to GM rate ($R^2 = 0.892$, $p = 0.0055$). In 2022, the response was linear, with C output by CO₂ increasing progressively as GM rate increased ($R^2 = 0.691$; $p < 0.001$; Table 3). Regression analysis of other carbon variables showed distinct responses to increasing GM rate (Table 3). Carbon input from biomass increased linearly with GM rate, reflecting the progressive addition of oat-derived OC to the soil ($R^2 = 0.997$, $p < 0.001$). Carbon output in grain yield also increased linearly with GM rate ($r^2 = 0.774$, $p < 0.001$; Table 3), indicating that increasing residue incorporation enhanced carbon allocation to harvested grain.

The C input/output ratio also showed a significant Year $\times$ GM rate interaction (p value < 0.001). In 2021, this ratio increased linearly with GM rate ($R^2 = 0.977$, $p < 0.001$), whereas in 2022 it followed a quadratic response ($R^2 = 0.992$, $p < 0.001$). Similarly, CO₂ emissions per unit of grain yield also showed a significant Year $\times$ GM rate interaction (p value < 0.001). In 2021, yield-scaled CO₂ emissions increased linearly with GM rate ($R^2 = 0.697$, $p < 0.001$), whereas in 2022 no significant dose–response relationship was detected ($p = 0.3369$; Table 3).

3.4 | N₂O emissions and soil inorganic nitrogen dynamics

During the early lentil growing period (15–45 DAS), soil N₂O emissions did not differ significantly between the two growing seasons (Figure 1C), while, in the mid-to-late growing stages (60–120 DAS), N₂O emissions were significantly higher in 2021 compared to 2022. Throughout the entire growing cycle, GM8 consistently exhibited the highest N₂O emissions, while GM0 had the lowest (Figure 1C). A sharp increase in N₂O emissions was observed in GM8 during 45 and 60 DAS, indicating a peak in nitrogen mineralization (Figure 1D). Soil N₂O fluxes showed clear dose–response patterns in relation to increasing GM rate, although the magnitude and shape of the response varied across sampling dates and growing seasons (Table S5). At 30, 45, and 90 DAS, the Year $\times$ GM rate interaction was not significant ($p > 0.05$), and pooled regressions showed a positive linear response of N₂O fluxes to GM rate. This indicates that increasing oat biomass incorporation progressively enhanced N₂O emissions during these stages of lentil growth. At 15, 60, 75, and 120 DAS, the Year $\times$ GM rate interaction was significant (Table S5). At these sampling dates, N₂O fluxes generally increased with GM rate, although the response was linear in some cases and quadratic in others.

TABLE 2 Analysis of variance and regression analysis of lentil yield, straw biomass, and nitrogen uptake in response to increasing oat green manure (GM) incorporation rate. The growing season, oat GM rate, and their interaction were tested as fixed effects before fitting dose–response models.

Variable	<i>p</i> value Year	<i>p</i> value Year × GM	<i>p</i> value GM	Decision	Year	Model	Regression equation	Linear <i>p</i>	Quadratic <i>p</i>	<i>R</i> ²
Grain yield	0.138	0.069	<0.001	Pooled	–	Quadratic	$Y = 0.546 + 0.038 \times \text{GM} - 0.003 \times \text{GM}^2$	<0.001	0.017	0.67
Straw biomass	0.917	0.468	<0.001	Pooled	–	Linear	$Y = 0.763 + 0.110 \times \text{GM}$	<0.001	–	0.67
Grain N uptake	0.174	0.410	0.002	Pooled	–	Linear	$Y = 17.252 + 0.954 \times \text{GM}$	<0.001	–	0.38
Straw N uptake	0.359	0.191	<0.001	Pooled	–	Linear	$Y = 21.703 + 3.827 \times \text{GM}$	<0.001	–	0.67

Linear and quadratic terms were considered significant at $p < 0.05$.

The strongest responses were observed during the early-to-mid growth stages, particularly around 45–60 DAS, indicating that the stimulation of N₂O emissions by oat residues was most pronounced when residue decomposition and microbial nitrogen turnover were active.

Soil nitrate content remained stable throughout most lentil growth stages, except for 30 and 105 DAS, where nitrate levels were significantly higher in 2022 than in 2021 (Figure 2A). Residue incorporation had a variable effect on soil nitrate content across growth stages (Figure 2B). GM8 exhibited the lowest nitrate levels in 15–45 DAS, likely due to initial microbial immobilization, while GM0 had the lowest values in 60–120 DAS, reflecting nitrogen depletion in the absence of organic inputs. The highest nitrate levels fluctuated among treatments depending on the growth stage (Figure 2B). Soil NO₃[–] concentrations also showed variable responses to GM rate over time (Table S6). At 15 and 30 DAS, pooled regressions showed a significant negative linear response, indicating that NO₃[–] concentration decreased as GM rate increased during the early growth stages. This pattern suggests greater microbial immobilization or plant/microbial N demand following the incorporation of larger amounts of oat biomass. Significant quadratic responses were observed at 75, 90, and 120 DAS when data were pooled across years, while significant ($p < 0.05$) Year × GM rate interactions at 45, 60, and 105 DAS required year-specific regressions.

Soil ammonium content was significantly higher in 30, 60, and 75 DAS during 2021 than in 2022, with no significant differences observed in later growth stages (90–120 DAS) (Figure 2C). Treatment effects varied across stages, with GM8 showing the lowest ammonium content between 30 and 75 DAS, likely due to rapid conversion to nitrate and increased N₂O emissions (Figure 2D). Soil NH₄⁺ concentrations exhibited less consistent dose–response patterns than NO₃[–], with several sampling dates showing nonsignificant responses to GM rate (Table S7). Significant Year × GM rate interactions were detected at 15, 45, 60, 75, and 105 DAS (p value = <0.001, <0.001, <0.001, 0.0191, and 0.0029, respectively; Table S7), indicating that the NH₄⁺ response to GM rate differed between growing seasons. At 90 DAS, pooled regression showed a significant quadratic response ($R^2 = 0.508$, $p < 0.001$), whereas no significant dose–response relationship was detected at 30 and 120 DAS ($p > 0.05$).

3.5 | Soil nutrients status

Regression analysis showed that soil nutrient status responded to increasing GM rate, although the response pattern differed among nutrients (Table 4). Soil P and K showed significant quadratic responses to GM rate when data were pooled across growing seasons ($R^2 = 0.880$, $p < 0.001$ and

TABLE 3 Analysis of variance and regression analysis of carbon dynamics in response to increasing oat green manure (GM) incorporation rate. The growing season, oat GM rate, and their interaction were tested as fixed effects before fitting dose–response models.

Variable	<i>p</i> value Year	<i>p</i> value GM	<i>p</i> value Year × GM	Decision	Year	Model	Regression equation	Linear <i>p</i>	Quadratic <i>p</i>	<i>R</i> ²
C input by biomass	0.489	<0.001	0.346	Pooled	–	Linear	$Y = 0.229 + 0.543 \times \text{GM}$	<0.001	–	0.99
C output by CO ₂	<0.001	<0.001	<0.001	Separate	2021	Quadratic	$Y = 3.070 + 0.522 \times \text{GM} - 0.034 \times \text{GM}^2$	<0.001	0.006	0.89
					2022	Linear	$Y = 2.590 + 0.084 \times \text{GM}$	<0.001	–	0.69
C output in grain yield	0.182	<0.001	0.405	Pooled	Pooled	Linear	$Y = 0.154 + 0.016 \times \text{GM}$	<0.001	–	0.77
C input/output	<0.001	<0.001	<0.001	Separate	2021	Linear	$Y = 0.103 + 0.095 \times \text{GM}$	<0.001	–	0.98
					2022	Quadratic	$Y = 0.069 + 0.200 \times \text{GM} - 0.006 \times \text{GM}^2$	<0.001	0.004	0.99
CO ₂ emission/yield	<0.001	<0.001	<0.001	Separate	2021	Linear	$Y = 21.383 + 0.973 \times \text{GM}$	<0.001	–	0.70
					2022	ns	$Y = 17.132 - 0.116 \times \text{GM}$	0.337	–	0.07

Linear and quadratic terms were considered significant at $p < 0.05$. ns, not significant.

TABLE 4 Analysis of variance and regression analysis of soil nutrient status in response to increasing oat green manure (GM) incorporation rate. The growing season, oat GM rate, and their interaction were tested as fixed effects before fitting dose–response models.

Variable	<i>p</i> value Year	<i>p</i> value GM	<i>p</i> value Year × GM	Decision	Year	Model	Regression equation	Linear <i>p</i>	Quadratic <i>p</i>	<i>R</i> ²
Soil P	0.310	<0.001	0.366	Pooled	–	Quadratic	$Y = 7.244 + 3.591 \times \text{GM} - 0.261 \times \text{GM}^2$	<0.001	<0.001	0.88
Soil K	0.014	<0.001	0.730	Pooled	–	Quadratic	$Y = 60.760 + 19.544 \times \text{GM} - 1.598 \times \text{GM}^2$	<0.001	<0.001	0.87
Soil Ca	0.002	<0.001	0.018	Separate	2021	Linear	$Y = 15.426 + 2.341 \times \text{GM}$	<0.001	–	0.70
					2022	Quadratic	$Y = 12.027 + 7.318 \times \text{GM} - 0.414 \times \text{GM}^2$	<0.001	0.014	0.91
Soil Mg	0.0046	<0.001	0.006	Separate	2021	Linear	$Y = 17.519 + 1.802 \times \text{GM}$	<0.001	–	0.67
					2022	Quadratic	$Y = 10.945 + 9.829 \times \text{GM} - 0.805 \times \text{GM}^2$	<0.001	0.001	0.82
Soil Fe	0.0019	<0.001	0.027	Separate	2021	Quadratic	$Y = 8.001 + 4.928 \times \text{GM} - 0.368 \times \text{GM}^2$	<0.001	0.005	0.83
					2022	Quadratic	$Y = 5.736 + 7.775 \times \text{GM} - 0.615 \times \text{GM}^2$	<0.001	<0.001	0.93
Soil Cu	0.781	<0.001	0.709	Pooled	–	Quadratic	$Y = 0.803 + 0.311 \times \text{GM} - 0.025 \times \text{GM}^2$	<0.001	0.006	0.55
Soil Mn	0.011	<0.001	0.062	Pooled	–	Quadratic	$Y = 5.776 + 1.769 \times \text{GM} - 0.117 \times \text{GM}^2$	<0.001	0.034	0.61
Soil Zn	0.057	<0.001	0.009	Separate	2021	Linear	$Y = 3.839 + 0.377 \times \text{GM}$	<0.001	–	0.61
					2022	Quadratic	$Y = 2.762 + 1.289 \times \text{GM} - 0.068 \times \text{GM}^2$	<0.001	0.043	0.89

Linear and quadratic terms were considered significant at *p* < 0.05.

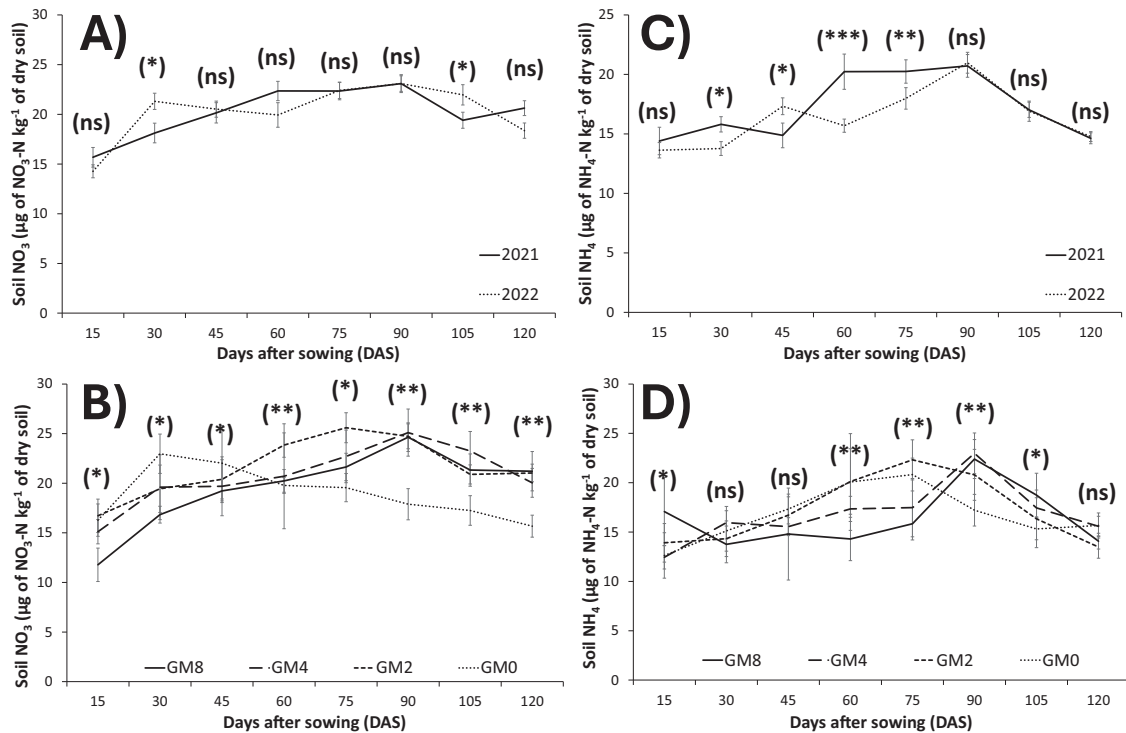


FIGURE 2 Soil nitrate (NO₃) content (μg kg⁻¹ of dry soil) and soil ammonium (NH₄) content (μg kg⁻¹ of dry soil) during the growing cycle of lentil in 2021 and 2022 (A and B) and at different rates of oat residue incorporation (C and D). Error bars represent $\pm$ standard error from the mean ($n = 18$ for the year and $n = 6$ for the oat residue rates, respectively). Asterisks indicate significant differences between growing seasons or among oat biomass incorporation rates according to analysis of variance (ANOVA). *, **, and *** indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively; ns indicates nonsignificant differences ($p > 0.05$). GM8, GM4, GM2, and GM0 are 8, 4, 2, and 0 Mg ha⁻¹ of dry matter of oat residues incorporated into the soil as green manure (GM), respectively.

$R^2 = 0.865$, $p < 0.001$; Table 4), indicating that both nutrients increased with oat biomass incorporation but tended to stabilize at higher application rates. Similarly, soil Cu and Mn also showed significant quadratic responses ($R^2 = 0.549$, $p = 0.0059$ and $R^2 = 0.609$, $p = 0.0340$, respectively), suggesting that increasing oat residue input enhanced the availability of these micronutrients, with reduced marginal gains at the highest GM rate.

The Year $\times$ GM rate interaction was significant for Ca, Mg, Fe, and Zn (p value = 0.0176, 0.0057, 0.0268, 0.0094, respectively); therefore, separate regressions were fitted for each growing season (Table 4). For Ca and Mg, the response was linear in 2021 ($R^2 = 0.703$, $p < 0.001$ and $R^2 = 0.671$, $p < 0.001$, respectively) and quadratic in 2022 ($R^2 = 0.910$, $p = 0.0140$ and $R^2 = 0.821$, $p = 0.0014$, respectively) indicating that the effect of GM rate on these nutrients varied according to growing season conditions. Soil Fe showed significant quadratic responses in both years ($R^2 = 0.830$, $p = 0.0048$ in 2021 and $R^2 = 0.933$, $p < 0.001$, respectively), while Zn increased linearly with GM rate in 2021 ($R^2 = 0.614$, $p < 0.001$) and followed a quadratic response in 2022 ($R^2 = 0.892$, $p = 0.0425$; Table 4). These year-specific responses indicate that the

influence of oat biomass incorporation on nutrient availability was partly modulated by interannual environmental conditions.

3.6 | Principal component analysis

The PCA performed using selected representative soil, crop, and GHG variables explained 77.3% of the total variance, with PC1 and PC2 accounting for 62.7% and 14.6%, respectively (Figure 3). PC1 clearly separated treatments according to increasing oat biomass incorporation rate. The control treatment (GM0) was positioned on the negative side of PC1, whereas treatments receiving higher oat biomass inputs, particularly GM4 and GM8, were located on the positive side of the axis. Most soil fertility, soil physical, crop productivity, and GHG emission variables were positively associated with PC1. SOC, TN, available water, WSA, soil P, soil K, grain yield, straw biomass, CO₂-C emissions, and cumulative N₂O emissions all shifted in the direction of increasing GM rate. PC2 mainly contributed to differentiating GHG-related responses from several soil and crop indicators. Cumulative CO₂-C and N₂O emissions showed stronger associations with

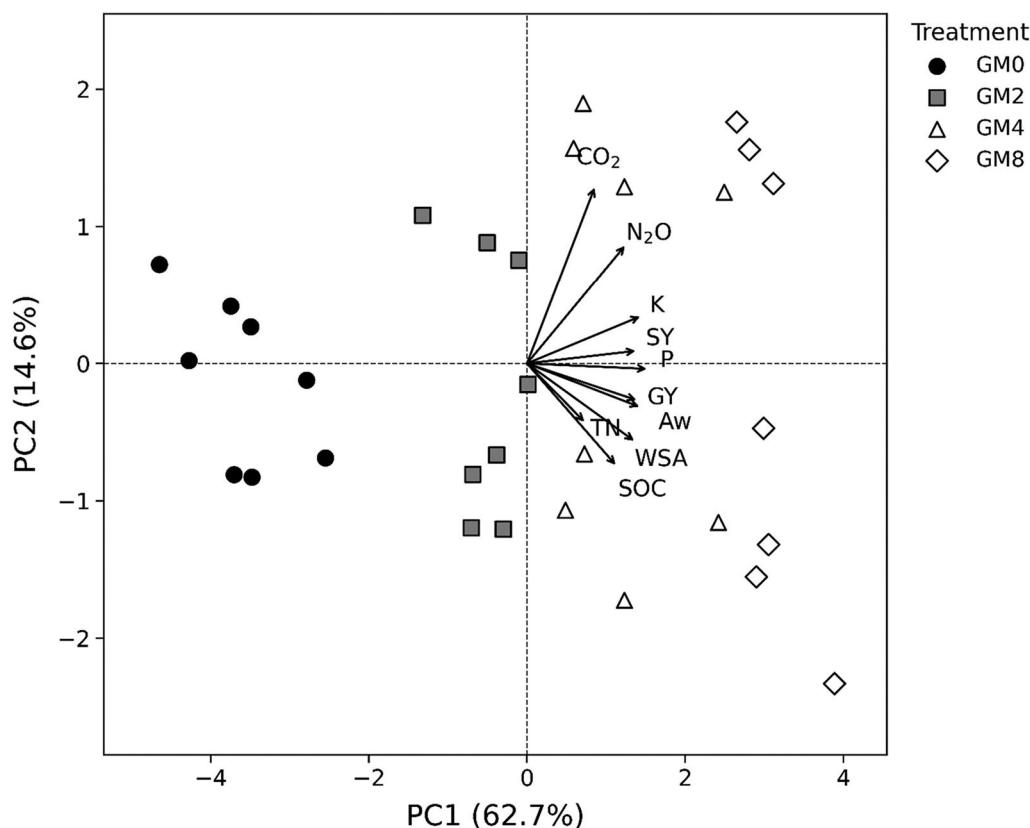


FIGURE 3 Principal component analysis (PCA) biplot showing the relationships among selected soil properties, crop performance, and greenhouse gas emission variables under different oat green manure (GM) incorporation rates. The PCA was performed using standardized representative variables: grain yield (GY), straw biomass (SY), cumulative carbon dioxide (CO₂) emissions, cumulative nitrous oxide (N₂O) emissions, soil organic carbon (SOC), total nitrogen (TN), available water (Aw), water-stable aggregates (WSA), soil phosphorus (P), and soil potassium (K). Symbols represent individual plot observations. Arrows indicate the direction and strength of association between variables and principal components. GM0, GM2, GM4, and GM8 correspond to 0, 2, 4, and 8 Mg of dry matter ha⁻¹ oat biomass incorporation, respectively.

the positive side of PC2, indicating that GHG responses were partly distinct from the soil fertility and crop productivity gradient represented by PC1.

4 | DISCUSSION

Increasing oat biomass incorporation produced coordinated changes in soil properties, lentil productivity, and GHG emissions under rainfed semiarid conditions. Overall, the findings indicate that increasing oat residue inputs improved soil functioning and crop performance, while also stimulating CO₂ and N₂O emissions. This confirms that GM can provide important agronomic benefits, but that these benefits need to be evaluated together with potential GHG trade-offs, as previously reported for residue-amended and GM systems (Alluvione et al., 2010; Basche et al., 2014; Cherr et al., 2006; Ferrara et al., 2021; Lee et al., 2021; Mancinelli et al., 2013).

4.1 | Soil improvement and crop response along the GM rate gradient

SOC and TN increased linearly with GM rate, indicating that greater oat residue inputs enhanced soil C and N accumulation. This response is consistent with the role of GM as direct organic matter inputs that contribute to soil fertility improvement, nutrient cycling, and soil carbon sequestration (Blanco-Canqui et al., 2015; Cherr et al., 2006; Lal, 2004; Poeplau & Don, 2015). Indeed, at the highest rate of 8 Mg ha⁻¹ (GM8), improved SOC, TN, and soil structural indicators (WSA and DSA). In rainfed systems, where soil organic matter is often limited, this progressive increase in SOC and TN is particularly relevant because organic inputs can improve nutrient retention, microbial activity, and overall soil functioning (Mirzaei et al., 2021; Sarkar & Northup, 2023). Soil physical properties were closely linked to these changes in soil organic matter. Available water and aggregate stability showed quadratic responses to GM rate, suggesting

that improvements increased with residue input but tended to level off at higher biomass rates. This pattern indicates that the largest improvements in soil physical functioning occurred from low to intermediate residue additions, whereas additional biomass produced smaller marginal gains. The improvement in aggregate stability and available water can be explained by the contribution of organic residues to aggregate formation, soil pore continuity, and water retention, as reported in studies on organic amendments and residue management (Mirzaei et al., 2021; Okolo et al., 2020; Yang et al., 2014). Higher OC levels promoted the formation of WSA, which play a crucial role in stabilizing soil carbon and nitrogen, ultimately enhancing soil fertility (Okolo et al., 2020; Yang et al., 2014). These improvements are particularly important in semiarid rainfed systems, where improved soil structure and water availability can reduce the impact of short dry periods during crop development (Amiri & Dehifard, 2018). This aligns with insights from Sarkar and Northup (2023), who highlighted that increased organic matter can buffer soil moisture fluctuations, thereby mitigating drought stress impacts on crop productivity. These changes may contribute to improved water retention and a more favorable environment for microbial activity, although nutrient leaching and microbial community structure were not directly measured (Khan et al., 2021). Furthermore, soil organic matter derived from oat residues contributes to greater drought resilience in dryland agricultural systems, thereby indirectly supporting the nutrient and water status required for robust plant growth (Sarkar & Northup, 2023). Wang et al. (2024) demonstrated that residues not only contribute to the overall nitrogen pool but can also modulate water retention, thereby indirectly affecting nitrogen availability by ensuring more consistent microbial activity. In this study, GM significantly increased levels of several macro- and micronutrients, likely due to improved cation exchange capacity and enhanced microbial activity. Oat residues can stimulate phosphatase activity, leading to greater phosphorus availability (Freund et al., 2021; Khan et al., 2021). However, a limitation of the present study is that oat biomass was produced in a separate field and subsequently incorporated into the experimental plots. This approach was adopted to ensure the application of precise biomass rates and to isolate the effects of oat biomass incorporation on soil properties, GHG emissions, and lentil productivity. However, under practical farming conditions, oat plants are commonly grown directly in the field as a cover crop before the subsequent cash crop. Consequently, root-derived carbon inputs, rhizosphere interactions, and potential effects on soil structure associated with living cover crops were not captured in the present experiment. Future studies should evaluate in situ oat cover crops to assess the combined contribution of aboveground and belowground biomass to soil functioning and GHG dynamics. The incorporation of oat residues altered the dynamics of both soil

inorganic N forms, soil nitrate content tended to be lower in the early stages following residue incorporation in the GM8 treatment due to rapid microbial immobilization, while later in the growing cycle, nitrate levels stabilized as mineralization advanced. This suggests a temporal decoupling between immobilization and subsequent mineralization phases, a process crucial for providing steady nitrogen supply throughout the crop growth cycle. The differential dynamics observed for ammonium versus nitrate highlight the importance of microbial mediation in nutrient transformations. Ammonium dynamics appeared less responsive to residue addition during early stages but converged later in the season, indicating that microbial nitrification and subsequent denitrification processes become more pronounced as biomass decomposition progresses (Chen et al., 2015; Phillips et al., 2015).

The crop response reflected these improvements in soil conditions. The GM8 treatment resulted in a 26% yield increase compared to GM0. This suggests that increasing oat residue input progressively improved vegetative growth and crop N acquisition, but grain yield gains tended to become smaller at the highest biomass rate. Taken together, these results show that the positive effect of GM rate on lentil productivity was not isolated from soil changes. Rather, the improvement in soil organic matter, nutrient status, aggregate stability, and soil water availability likely acted together to support greater N uptake and crop growth. This is particularly relevant for lentil, which is sensitive to drought and high temperature during reproductive development (Amiri & Dehifard, 2018). Indeed, Preiti et al. (2024) reported that, in a semiarid environment, drought, together with the high temperatures occurring in the late reproductive stage of lentil, negatively affected the crop's production behavior. However, in this study, we demonstrated that lentil grain yield increased as the oat residue incorporated into the soil as GM increased due to higher N grain uptake (Table 3). Therefore, the regression results suggest that oat GM improved lentil productivity mainly by enhancing the soil conditions that regulate nutrient availability and water retention. However, the quadratic response of grain yield also suggests that increasing residue input beyond a certain level may provide smaller additional agronomic benefits, emphasizing the importance of optimizing rather than simply maximizing biomass incorporation. The positive response of crop N uptake indicates that nutrients became available to lentil plants during the growing season, likely through microbial mineralization and improved nutrient cycling. Similar links between organic residue inputs, improved soil water retention, and crop nutrient acquisition have been reported in cover crop and residue incorporation systems (Khan et al., 2021; Sarkar & Northup, 2023; Wang et al., 2024). The enhanced nitrogen uptake observed in both grain and straw under the GM8 treatment suggests that microbial mineralization effectively synchronized nutrient release with crop demand, a critical factor in semiarid soils where

the timing of nutrient availability often misaligns with crop growth phases (Amiri et al., 2024).

4.2 | GHG emissions and agronomic–environmental trade-offs

Increasing GM rate increased carbon and nutrient inputs to the soil, thereby providing more substrate for microbial decomposition. In fact, the increase in CO₂ emissions with increasing GM rate should therefore be interpreted primarily as the result of microbial decomposition of the added oat residues rather than as evidence of accelerated decomposition of native soil organic matter (Mancinelli et al., 2013). This interpretation is supported by the simultaneous increase in SOC with GM rate, which does not indicate depletion of native soil carbon. Such effects are particularly pronounced with grasses like oat, which contain high levels of labile carbon compounds that stimulate microbial activity under dry environmental conditions (Wen et al., 2019). Oat residues, rich in labile carbon compounds and beta-glucans, stimulate microbial activity that drives nutrient cycling and organic matter decomposition. While responsible for increased CO₂ emissions, this enhanced microbial activity underpins the improved nutrient mineralization and aggregate formation that benefit crop growth. Similar increases in soil respiration after GM or residue incorporation have been reported in Mediterranean and semiarid systems, where residue quality, soil moisture, and temperature strongly regulate decomposition dynamics (Haney et al., 2018; Mancinelli et al., 2013; Wen et al., 2019). The enhanced carbon input provided by oat residues suggests that, despite elevated CO₂ emissions, the overall carbon balance within the agroecosystem may favor sequestration over time (Radicetti et al., 2020). Although the GM8 treatment resulted in higher emissions per unit area, the substantial improvements in yield and nutrient uptake suggest a more favorable emission-to-yield ratio compared to lower residue treatments. Soil CO₂ respiration serves as an indicator of microbial activity and is widely recognized as a key biological marker of soil quality (Haney et al., 2018). The response of CO₂ emissions differed between years, indicating that biomass input was not the only factor controlling carbon mineralization. Although 2022 received more rainfall during the monitoring period, CO₂ emissions were higher in 2021, likely because warmer conditions promoted microbial respiration when sufficient soil moisture was available. This confirms that CO₂ emissions from residue-amended soils are controlled by the interaction between substrate availability, temperature, and soil moisture rather than by residue input alone. Similar interactions between residue decomposition, climatic conditions, and soil biological activity have been reported following GM incorporation in Mediterranean and temperate cropping systems

(Alluvione et al., 2010; Ferrara et al., 2021; Mancinelli et al., 2013).

Nitrous oxide emissions also increased with GM rate at several sampling dates, especially during early-to-mid crop growth. This response likely reflected greater microbial nitrogen turnover following the incorporation of larger amounts of oat biomass. The regressions for NO₃[−] and NH₄⁺ showed that mineral N dynamics varied during the season, suggesting alternating phases of immobilization, mineralization, nitrification, and crop uptake. Therefore, N₂O emissions should not be attributed to a single pathway. Higher organic C availability, mineral N transformations, and soil moisture conditions can interact to regulate N₂O production after residue incorporation (Chen et al., 2015; Gomes et al., 2009; Kallenbach et al., 2010; Lee et al., 2021; Phillips et al., 2015). Indeed, GM8 consistently maintained higher soil moisture than the other treatments during most sampling dates, while soil temperature increased progressively throughout the growing season. Notably, the largest N₂O peaks occurred between 45 and 60 DAS, when soil moisture remained relatively high and soil temperature ranged between approximately 10°C and 15°C, conditions known to favor microbial nitrogen transformations and gaseous nitrogen losses (Chen et al., 2015; Phillips et al., 2015). The coincidence of elevated N₂O emissions with changes in inorganic nitrogen pools suggests that residue-derived carbon inputs stimulated microbial activity and nitrogen cycling during this period. However, as soil moisture generally remained below 25% and water-filled pore space was not measured, it is not possible to determine whether nitrification, denitrification, or localized/transient anaerobic microsites were the dominant source of N₂O. This limitation is important because denitrification is more directly related to water-filled pore space than to soil moisture alone. Previous studies have shown that N₂O responses to GM and cover crop residues depend strongly on residue quantity and quality, soil moisture, mineral N availability, and timing of incorporation (Basche et al., 2014; Gomes et al., 2009; Kallenbach et al., 2010; Lee et al., 2021). Therefore, the observed N₂O emissions are best interpreted as the result of multiple microbial N transformation processes rather than a single dominant pathway. Future studies should incorporate water-filled pore space measurements to better distinguish the relative importance of nitrification and denitrification under semiarid conditions. Similar complexity in the response of N₂O emissions to GM incorporation has been reported by Lee et al. (2021). Indeed, Lee et al. (2021) reported variable mitigation potential of agricultural practices on N₂O emissions, suggesting that the timing and method of GM incorporation can significantly influence nitrous oxide losses. The prominent peak in N₂O emissions observed in the GM8 treatment points to a short-term challenge that could potentially be managed through optimized residue incorporation techniques

or the combined use of nitrification inhibitors (Chen et al., 2019). However, it is important to note that an important limitation of this study is the 15-day interval used for GHG sampling. Indeed, although this frequency allowed consistent monitoring across treatments and growing seasons, it may not have captured short-lived CO₂ and especially N₂O emission peaks following rainfall events or rapid changes in soil moisture and temperature. As a result, cumulative emissions may be subject to uncertainty and could be underestimated. Therefore, the GHG data should be interpreted primarily as comparative seasonal estimates among treatments rather than complete annual emission budgets.

Although higher GM rates increased CO₂ and N₂O emissions, these emissions should be interpreted together with the positive crop response. Increasing GM rate also improved grain yield and N uptake, meaning that part of the residue-derived nutrient was captured by the crop rather than being lost from the system. This is important because the sustainability of GM practices depends not only on absolute emissions per unit area, but also on their relationship with crop productivity. Previous studies have similarly emphasized that GM can increase short-term gaseous losses while improving soil fertility and crop performance, creating a management trade-off rather than a purely negative environmental outcome (Alluvione et al., 2010; Cherr et al., 2006; Ferrara et al., 2021; Lee et al., 2021). The PCA analysis supports this interpretation by showing that soil fertility, soil physical properties, crop productivity, and GHG emissions were closely linked along the GM rate gradient. Higher oat biomass incorporation was associated with improved SOC, TN, available water, aggregate stability, grain yield, and straw biomass, but also with greater CO₂ and N₂O emissions. This confirms the main trade-off identified by the study: oat GM improves soil functioning and lentil productivity, but it also stimulates microbial processes responsible for gaseous carbon and nitrogen losses. Therefore, intermediate-to-high GM rates may represent a more balanced management option than simply maximizing biomass input, especially where the objective is to improve soil health indicators while limiting GHG emissions.

5 | CONCLUSION

This study demonstrated the significant potential of oat biomass as GM for enhancing soil properties and crop productivity in arid environments. GM incorporation improved lentil yield and quality by enhancing nitrogen uptake and soil nutrient availability. This likely occurred because biomass mineralization released organic N, reducing the need for mineral fertilizers and, consequently, reliance on synthetic inputs. GM plays a key role in increasing soil moisture retention, mitigating water loss due to drought, an essential benefit in arid regions where irrigation is limited or unavailable. The

application of oat residues supports soil structure by promoting the formation of stable soil aggregates, contributing to overall soil stability. The observed increase in GHG emissions can be attributed to higher microbial activity, which is particularly beneficial in arid soils that typically exhibit low microbial diversity. Overall, the results indicate that increasing oat biomass incorporation can improve soil fertility, soil water availability, aggregate stability, and lentil productivity under semiarid rainfed conditions. However, because higher biomass inputs also increase CO₂ and N₂O emissions, future studies should consider employing higher frequency gas sampling, particularly after rainfall events, to more precisely quantify the relative contributions of different microbial processes to GHG emissions, and to develop strategies for optimizing residue management to identify rates that maximize soil and crop benefits while limiting GHG costs. This balance is essential for developing GM strategies that enhance selected soil physical and chemical indicators and crop productivity while minimizing environmental trade-offs in water-limited agroecosystems.

AUTHOR CONTRIBUTIONS

Morad Mirzaei: Conceptualization; data curation; formal analysis; investigation; methodology; resources; supervision; validation; writing—original draft. **William Burchill:** Data curation; validation; visualization; writing—review and editing. **Daniele Borgatti:** Data curation; investigation; validation; visualization; writing—original draft. **Mortadha Ben Hassine:** Investigation; validation; visualization; writing—original draft; writing—review and editing. **Yuan Li:** Data curation; visualization; writing—original draft. **Mohamed Allam:** Data curation; validation; visualization; writing—review and editing. **Sudip Sarkar:** Investigation; methodology; validation; visualization; writing—review and editing. **Jelena Baćanović-Šišić:** Data curation; supervision; validation; visualization; writing—original draft; writing—review and editing. **Sara Azadi:** Data curation; formal analysis; investigation; methodology; validation; writing—review and editing. **Roberto Mancinelli:** Conceptualization; formal analysis; methodology; visualization; writing—review and editing. **Emanuele Radicetti:** Conceptualization; data curation; methodology; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be available on request.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the authors used OpenAI ChatGPT, GPT-5.5 Thinking, to assist with language editing. After using this tool, the authors carefully reviewed and edited the content as needed to ensure accuracy, scientific consistency, and compliance with journal requirements, and the authors take full responsibility for the content of the published article.

ORCID

Morad Mirzaei  <https://orcid.org/0000-0002-1309-7038>

William Burchill  <https://orcid.org/0009-0006-5970-7520>

Daniele Borgatti  <https://orcid.org/0009-0006-0400-0851>

Mortadha Ben Hassine  <https://orcid.org/0000-0002-8100-1819>

Yuan Li  <https://orcid.org/0000-0003-1047-0690>

Mohamed Allam  <https://orcid.org/0000-0001-6806-1860>

Sudip Sarkar  <https://orcid.org/0000-0002-4639-4303>

Jelena Baćanović-Šišić  <https://orcid.org/0009-0000-3323-3845>

Sara Azadi  <https://orcid.org/0000-0002-9763-9438>

Roberto Mancinelli  <https://orcid.org/0000-0002-8396-6307>

Emanuele Radicetti  <https://orcid.org/0000-0001-8654-3177>

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