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Maize-soybean intercropping reduces greenhouse gas emissions from the fertilized soil in the North China Plain

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Abstract

Background and Aim Continuous monocropping with high nitrogen (N) fertilizer input substantially increases greenhouse gas (GHG) emissions in maize-based agroecosystems in the North China Plain (NCP). Introducing soybeans as an intercrop with maize and partially substituting urea with manure might effectively decrease GHG emissions. The aim of this study was to quantify the synergistic effect of maize-soybean intercropping and manure on soil GHG emissions.

Methods A two-year field experiment with three cropping systems (maize monocrop, soybean monocrop, and maize-soybean intercrop) and four N treatments (control, urea, manure, and manure + urea) was carried out at Luancheng Agro-Ecosystem Experimental Station in the NCP. All N treatments, except the control, received 150 kg N $ha^{-1}season^{-1}$, either full dose as a basal application or two equal split applications.

Results Results showed that all treatments contributed as a net source of N_2O and CO_2 fluxes but acted as a net sink of CH_4 fluxes. In both cropping seasons, intercrops had significantly lower N_2O emissions compared to monocropping systems, with 38% and 14% less emissions than maize monocrops in 2018 and 2019, respectively. Additionally, maize monocrops had significantly higher soil CO_2 emissions than other systems, while maize-soybean intercropping had 12% and 13% less CO_2 emissions than maize monocrops in 2018 and 2019, respectively. Among fertilized treatments, manure-treated soils emit notably lower N_2O fluxes compared to sole urea treatments. In this study, N_2O and CO_2 fluxes had a strong positive correlation with soil mineral N concentrations, soil temperature, and moisture content. Possibly due to more efficient N utilization, intercrop soils exhibited significantly lower NH_4^+ and NO_3^- concentrations, leading to reduced nitrification and denitrification in the system, resulting in lower N_2O emissions from maize-soybean intercrops.

Conclusion Our findings indicate that intercropping maize and soybean reduces soil NH_4^+ and NO_3^- concentrations, as well as significantly decreasing soil N_2O and CO_2 emissions when compared to traditional maize monoculture. Therefore, due to its potential for reducing soil GHG emissions, maize-soybean intercropping can be regarded as an effective alternative cropping system to the prevailing maize-dominant monoculture to develop a sustainable agroecosystem in the NCP region.

Keywords Cereal-legume intercropping · Monocropping · GHG emissions · Nitrous oxide (N_2O) · Carbon dioxide (CO_2) · Global warming potential

1 Introduction

The Earth's climate is changing rapidly, owing primarily to rising anthropogenic greenhouse gas (GHG) emissions (IPCC 2023). In China, agriculture is a significant contributor to GHG emissions (mainly N_2O, CO_2, and CH_4), responsible for 17% of the nation's total GHG emissions (Huang et al. 2018), whereas agricultural CH_4 and N_2O emissions account for 50% and 92% of total national CH_4 and N_2O emissions, respectively (Bai et al. 2023). The North China Plain (NCP) is a major agricultural production area in China and contributes to 23% of the country's total grain production (Yang et al. 2022). The winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) double cropping system is the predominant farming system in the NCP region, which heavily relies on substantial agricultural inputs, such as water and nitrogen fertilizer (Yang et al. 2023). N fertilizer application rate in this region is as high as 600 kg

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N ha^{-1} y^{-1}, which is far above the recommended doses (200–400 kg N ha^{-1} y^{-1}) for this region (Hu et al. 2023; Zhang et al. 2023a). This over-fertilization followed by irrigation, substantially escalates GHG emissions (Ning et al. 2023). Therefore, reducing GHG emissions from agricultural practices plays a pivotal role in fostering low-carbon, climate-resilient agriculture and will support China's commitment to achieving carbon neutrality by 2060 (Liang et al. 2021). Recently, the Chinese government has introduced an action plan to boost soybean production by expanding the planting area and listing it as one of the top rural and agricultural development tasks (Zhang and Lu 2020). Thus, in the North China Plain, a cereal-legume intercropping system, *i.e.*, a maize-soybean intercropping system, might be deemed an effective agricultural practice for achieving the national goal of soybean rejuvenation and mitigating GHG emissions from a high-fertilized monocropping system.

Cereal-legume intercropping systems have several major advantages over monoculture in increasing yield and yield stability (Te et al. 2023; Wang et al. 2022a; Raseduzzaman and Jensen 2017), increasing resource use efficiency (Raza et al. 2023; Te et al. 2023), reducing disease and pest incidence (Chadfield et al. 2022), improving soil properties (Ma et al. 2022a), controlling weeds (Law et al. 2022), and so on. In the cereal-legume intercropping system, belowground interactions have an essential role in changing the soil microbial composition and dominant microbial species, which is strongly related to the improvement of soil available nutrients (N and P) and enzymatic activities (Ma et al. 2022a; Li et al. 2016).

Changes in soil parameters such as pH, dissolved organic carbon (DOC), soil mineral N concentration, C/N ratio, soil moisture, and temperature may alter the microbial-mediated processes that cause soil GHG emissions. N_2O is a by-product of nitrification and an intermediate product of denitrification processes. Soil mineral N (NH_4^+ and NO_3^-) is a substrate for nitrification and denitrification processes. Therefore, high soil mineral N is responsible for high N_2O emissions. Soil moisture affects nitrification and denitrification activity by regulating soil oxygen availability and redox potential (Bizimana et al. 2024; Ning et al. 2023). In comparison to monoculture, cereal-legume intercropping systems have a greater capacity to assimilate mineral N and moisture from the soil due to differences in root depth and features, improved root proliferation, and inter-specific root interactions (Te et al. 2023). As a result, there is less residual nitrogen and drier soil conditions in the intercropping system. One maize-soybean intercrop study has reported 35–45% less soil mineral N during the harvesting period (Tang et al. 2017). Similarly, at different growth stages, the maize-peanut and maize-soybean intercropping systems reduce soil NH_4^+ content by 11–60% and 10–47% and NO_3^- content by 30–60% and 19–56%, respectively, compared to the maize monoculture (Wang et al. 2022a). Additionally, the distinct vertical and horizontal canopy distribution in maize-soybean intercropping allows efficient use of incoming solar energy, with maize occupying the upper layer and soybeans the lower layer (Liu et al. 2018). Consequently, soil temperature tends to be lower in maize-soybean intercropping systems than in monoculture.

Grain legumes lower soil pH by releasing organic acids and hydrogen ions (H^+) into the rhizosphere. Furthermore, lower soil pH conditions enhance N_2O emissions due to incomplete denitrification caused by the inhibition of the N_2O reductase enzyme under acidic conditions (Žurovec et al. 2021). Despite the fact that legume crops lower soil pH and hence increase N_2O emissions, we can hypothesize lower N_2O emission in the maize-soybean intercropping system due to lower soil mineral N concentration, lower temperature and drier soil conditions, and interspecific root interactions. Similarly, lower soil CH_4 emissions or higher soil CH_4 uptake could be expected in the maize-soybean intercropping system due to lower soil temperature and drier soil conditions in the intercropping systems, as both soil temperature and moisture content are positively correlated with the soil CH_4 emissions (Raseduzzaman et al. 2024; Fan et al. 2022).

Soil CO_2 fluxes are the result of root and soil microbial respiration, rhizodeposits, and decomposition of organic matter and crop litter, all of which are regulated by soil moisture and soil temperature (Ning et al. 2023). Furthermore, soil DOC concentration has a significant impact on soil CO_2 emissions (Shaaban et al. 2022). As a microbially driven process, DOC, on the other hand, is controlled by the factors including soil temperature, moisture, soil mineral N concentration, and volume of root biomass (Wang et al. 2021). However, application of manure enhanced the fraction of aromatic and phenolic compounds in dissolved organic matter and slowed down the mineralization of DOC (Tian et al. 2010). In the manure-treated maize-soybean intercropping system, thus CO_2 emissions are expected to be low due to intercrop impacts on parameters regulating DOC concentration and CO_2 emissions.

Aside from cropping systems, the type of N fertilizer used may significantly impact GHG emissions (Charles et al. 2017). Urea, known for its rapid denitrification in soil, possesses the highest potential for field-scale GHG emissions among synthetic N fertilizers (Wu et al. 2021). Furthermore, manure application generally increases soil dissolved carbon, which could enhance the activity of methane-oxidizing bacteria and, consequently, CH_4 oxidation, leading to reduced CH_4 emissions from upland soils (Sullivan et al. 2013; Liu et al. 2013). Mairura et al. (2023) found that, combined applications of manure and synthetic fertilizers considerably reduce global warming potential and yield-scale emissions without reducing maize yield.

Given this evidence, it is possible to hypothesize that substituting a part of urea with manure could effectively reduce GHG emissions from agricultural fields.

However, while most studies have focused on yield advantage, nutrient acquisition, water use efficiency, and agronomic traits in intercropping systems (Raza et al. 2023; Te et al. 2023; Wang et al. 2022b), only a few studies have focused on GHG emissions from intercropping, particularly there is a lack of data and insights on cereal-legume intercropping systems. Especially, the synergistic effects of maize-soybean intercropping and N fertilizer types on GHG emissions are unknown and need further research. The main objectives of the present study were 1) to investigate the effects of maize-soybean intercropping on N_2O, CO_2, and CH_4 emissions compared to maize and soybean monoculture; 2) to investigate the effects of manure on GHG emissions compared to urea fertilizer; and 3) to analyze the effect of cropping systems and N fertilizer type on different soil properties and their relationship with N_2O, CO_2, and CH_4 emissions from the soil.

2 Materials and methods

2.1 Site description

The field experiment was carried out from mid-June to early October in 2018 and 2019 at the Luancheng Agro-Ecosystem Experimental Station (37°89′ N, 114°68′ E; elevation 50 m above sea level) of the Chinese Academy of Sciences in the North China Plain region in Hebei province. This region has a temperate, semi-arid monsoon climate, with cold winters and scorching summers. The annual average temperature in 2018 and 2019 was 14 °C, while the annual average precipitation was 368 mm, with the majority falling in July, August, and September. The average, highest, and lowest temperatures during June to September were 26.5 °C, 42 °C, and 6.5 °C in 2018 and 26.5 °C, 39 °C, and 11 °C in 2019, respectively. Figure 1 depicts the daily mean, maximum and minimum temperature, and precipitation at the experimental site during the growing season. The soil is classified as a silt loam Haplic Cambisol, with 25% sand, 63% silt, and 12% clay. Prior to the experiment, the soil

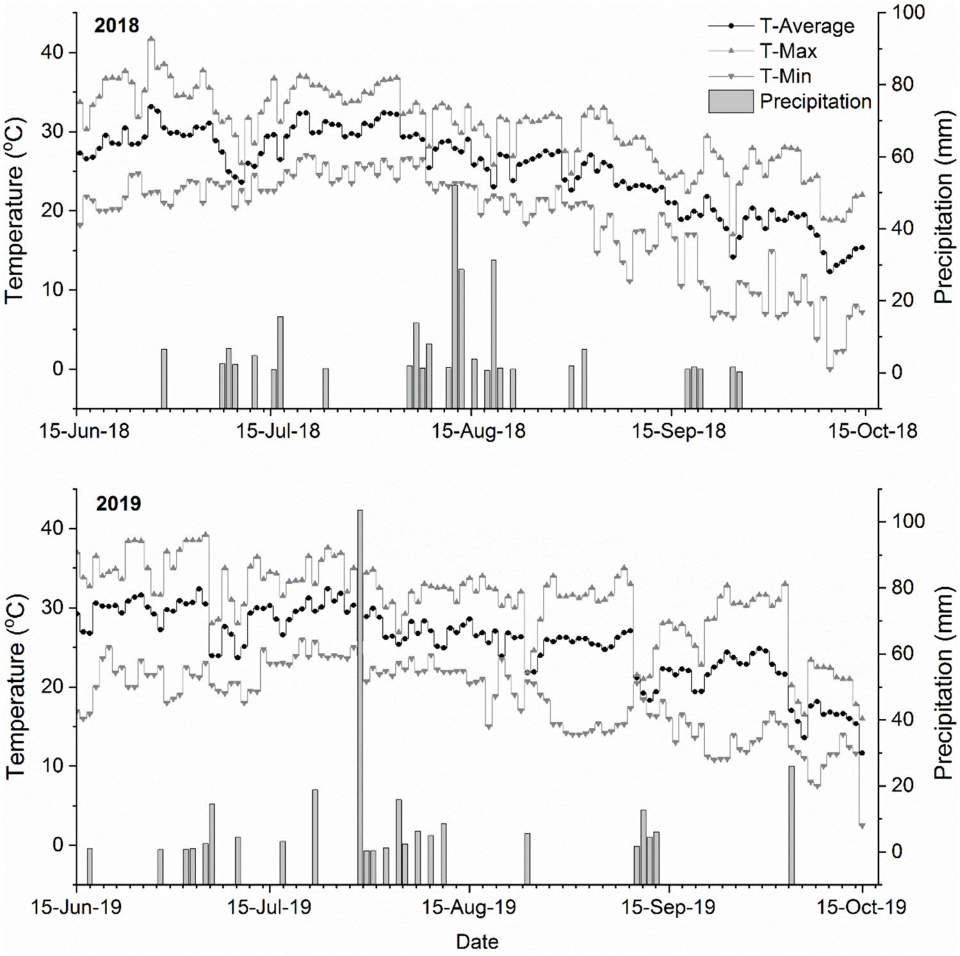


Fig. 1 Daily precipitation (mm), daily maximum, minimum, and average air temperature (°C) during two growing seasons (2018–2019) at the Luancheng Agro-ecosystem Experimental Station

organic matter content was 15 g kg^{-1}, pH was 8.16, total nitrogen was 1.1 g kg^{-1}, available phosphorus (P-Olsen) was 15 mg kg^{-1}, and exchangeable potassium was 95 mg kg^{-1} in the top 0–20 cm soil layer.

The NCP is a crucial grain-producing region in China. The production of wheat and maize in the NCP accounts for 75% and 35% of the country's total production, respectively (Wang et al. 2023a). The dominant cropping system in this region is a winter wheat-summer maize (or soybean) double-cropping system without a fallow period. Both wheat and maize are irrigated via flooding irrigation using groundwater. Winter wheat is planted in the middle of October and harvested in early June. After wheat harvesting, residues were cut into small pieces (< 10 cm fragments) with a mechanical shredder. Fertilizer or manure was then uniformly applied in the field and incorporated with the soil to a depth of 15 cm with a rototiller. Maize (or soybean) is planted in the middle of June and harvested in early October.

2.2 Experimental design

The field experiment was established in June 2018 with four nitrogen (N) treatments and three cropping system treatments. The N treatments were i) control (no nitrogen), ii) urea, iii) manure, and iv) manure + urea, whereas the cropping systems were i) maize monocrop (*Zea mays cv.* Zhengdan 958), ii) soybean monocrop (*Glycine max* cv. Zhonghuang 37), and iii) maize-soybean intercrop. Without control, all N treatments received 150 kg N ha^{-1}season^{-1}, either full dose as a basal application or two equal split applications. To maintain the uniform effect of N fertilizer on GHG emissions and to ensure impartial comparisons across various fluxes, all cropping systems received an equal amount of N fertilizer input. The details of the N, P, and K applications are presented in Table S1. The composted poultry manure (Shijiazhuang Ikos Agricultural Technology Co., Ltd., Hebei) had an organic matter content of 40%, organic carbon content of 23.7%, a C/N ratio of 11.29, pH of 7.95, a mineral N content of 0.7%, a total N content of 2.1%, P_2O_5 content of 1.9%, and K_2O content of 1.1%. Manure treatment received full doses of N as basal application, while urea and manure + urea treatments received half of N (75 kg N ha^{-1}) as basal application and the rest half of N as top dressing. All treatments received 75 kg P_2O_5 ha^{-1} as calcium superphosphate and 100 kg K_2O ha^{-1} as potassium chloride before planting. Manure and fertilizer are incorporated with the soil to a depth of 15 cm with a rototiller within 3 h of application.

The experiment was organized as a randomized split-plot design with nitrogen treatment as the main plot factor and cropping system treatment as a subplot factor with three replicates. Each sub-plot was 160 m^2 (16 m × 10 m) in size, with a 1 m buffer between them. The crops were planted in a north–south orientation. In maize monocrop, the row-to-row distance was 60 cm and the planting density was 58,000 plants ha^{-1}, whereas in soybean monocrop, the row-to-row distance was 40 cm and the planting density was 250,000 plants ha^{-1}. In the intercropping system, two rows of maize (60 cm spacing) alternate with two rows of soybean (40 cm spacing), and the distance between adjacent maize and soybean rows was 40 cm. Each year, two irrigations were applied when soil moisture was low. Herbicide and insecticide application, weeding, and other management operations were carried out in accordance with local farming practices. The details of management activities are presented in Table S2. All crops were harvested with mechanical harvesters on 3 October in 2018 and 5 October in 2019. All crop residues were returned to the plot and fertilized with the same N doses (same N treatments) and incorporated into the soil with a rototiller to grow winter wheat for another study.

2.3 Gas flux measurements

The gas samples were collected using non-steady-state static chambers. Immediately after sowing, one open-ended base collar (polymethyl methacrylate, 60 cm length, 20 cm width, and 7 cm tall) was placed into the soil to a depth of roughly 5 cm in each plot. The collars were installed 3–4 m inside the plot from the boarder to avoid the boarder effects. In maize and soybean monocrop plots, the collars were placed between two rows, and in intercrop plots, they were placed between maize and soybean rows and remained in the field from planting to harvesting. The chambers were also made of temperature-isolated polymethyl methacrylate (PMMA) with a size (length × width × height) of 60 cm × 20 cm × 40 cm. A fan was installed inside the top of the chamber and powered by a battery to homogenize the gas concentration and air temperature within the chamber. The chambers were also fitted with a thermometer to monitor the chamber temperature and a sampling tube with a three-way stopcock. To prevent leakage, the sampling tube and thermometer were both glued to the chamber.

Gas samples were collected in the morning between 8 a.m. and 11 a.m., since this period is typically considered to be representative of average daily flux emissions (Cosentino et al. 2012). The sampling interval was once per week, but after fertilizer application each time, gas samples were collected twice per week for two weeks, totaling 17 gas sampling events each year. During each gas sampling event, the chamber was placed on the base collar for 60 min, and gas samples were taken at 0, 20, 40, and 60-min intervals through the three-way stopcock. A water seal was used to prevent leakage between the base collar and chamber during gas sampling. Each time, 60 ml of gas was collected with a polypropylene syringe attached to stopcocks and transferred into a pre-evacuated 100 ml gas sampling bag (Delin, Dalian, China) with a

25-gauge needle. During gas sampling, two extra thermometers were also placed inside the chamber. One on the ground and the other at 5 cm of soil depth to check the ground temperature and the 5 cm depth soil temperature at the end of gas sampling. Weeds inside the chamber bases were clipped and removed prior each sampling event to avoid GHG contributions from plant respiration.

The concentration of N_2O, CO_2, and CH_4 was measured using gas chromatography (Agilent GC-6820, Agilent Technologies Inc., Santa Clara, CA, USA) equipped with a ^{63}Ni Electron Capture Detector (ECD), a Flame Ionization Detector (FID), and a Thermal Conductivity Detector (TCD) to detect N_2O, CO_2, and CH_4, respectively. Standard gases were used for calibration. Soil GHG fluxes were calculated as the rate of change in gas concentration inside the chamber headspace over the 60 min collection period. Gas flux rate F (μg m^{-2} h^{-1}) was calculated using the following equation, as described by (Raseduzzaman et al. 2024):

$$F = \frac{dc}{dt} \times \frac{M}{V_0} \times \frac{V}{A} \times \frac{273}{273 + T} \times \frac{P}{P_0} \times 60$$

where *dc/dt* is the slope of the changes of gas concentration over time in the chamber (ppbv min^{-1}); *M* is the relative molecular mass of N_2O (44 g mol^{-1}), CO_2 (44 g mol^{-1}), and CH_4 (16 g mol^{-1}); *Vo* is the volume of an ideal gas (22.41 g mol^{-1}); *V* is the volume of the chamber (m^3); *A* is the soil surface area occupied by the chamber base (m^2); *T* is the temperature (°C) inside the chamber; *P* is the atmospheric pressure (hPa) during gas sampling; *Po* is the standard atmospheric pressure (hPa); and 60 is the conversion factor for minutes to hour.

Seasonal cumulative emissions of N_2O, CO_2, and CH_4 (kg ha^{-1} $season^{-1}$) from planting to harvesting were estimated by linear interpolation between successive sampling days, as described by (Zhai et al. 2011):

$$Seasonal\ emissions = \sum \left\{ \frac{\left(F_{i+1} + F_i\right)}{2} \times \left(t_{i+1} - t_i\right) \right\} \times 24 \times \frac{1}{100000}$$

where F_i and F_{i+1} are the fluxes of N_2O, CO_2 and CH_4 (μg m^{-2} h^{-1}) at the previous and current gas sampling dates; t_i and t_{i+1} are the previous and the current gas sampling dates; 24 is used to convert fluxes from h^{-1} to d^{-1}; and 1/100000 is used to convert fluxes from μg m^{-2} to kg ha^{-1}.

The Net global warming potential (Kg CO_2 -eq ha^{-1} $season^{-1}$) was calculated by using the warming potential coefficient (CO_2 equivalent) of 298 for N_2O, 34 for CH_4 and 1 for soil CO_2 emissions, based on 100-year time scale of IPCC AR6 (IPCC 2023).

2.4 Soil sampling and analysis

Soil samples were collected at every two-week intervals from the furrow slice depth of 0–15 cm, concomitant with the gas sampling date. The top 0–15 cm depth of soil was chosen as the focus of our study, as it encompasses near-surface soil processes that significantly influence nutrient dynamics and GHG emissions. Previous studies have indicated that crucial soil processes often occur within the 0–10 or 0–15 cm soil depths, which play a substantial role in soil nutrient dynamics and GHG emissions (Ghimire et al. 2017; Hurisso et al. 2016). The samples were collected with a 4 cm diameter augur from 4–5 random locations per plot. After sample collection, soils from each plot were mixed uniformly and stored in the fridge at 4 °C until further analysis. Gravimetric soil moisture content was determined by oven drying of 60–70 g of field moist soil at 105 °C temperature for 48 h. To determine soil NO_3^- and exchangeable NH_4^+ content, 10 g of fresh soil was extracted with 50 ml of 1 M KCl solution (extraction ratio 1:5 w/v), shaken for 60 min, and filtered through Q5 filter paper (Gaudel et al. 2024a). Soil NO_3^- content was measured using a UV-2450 spectrophotometer (Shimadzu Corporation, Kyoto, Japan). Soil exchangeable NH_4^+ content was measured by Smartchem 140 discrete chemistry analyzer (AMS Alliance, Frepillon, France). According to Raseduzzaman et al. (2024), for soil dissolved organic carbon (DOC), 10 g of soil was extracted with 50 ml of distilled water (1:5 w/v), shaken for 60 min, filtered with Q5 filter paper, and subsequently centrifuged at 8000 rpm for 5 min. The supernatant was further passed through a 0.45 μm filter membrane and analyzed using a vario TOC cube auto-analyzer (Elementar, Hanau, Germany). Soil pH was measured in a suspension of 10 g of dry soil with 25 ml of distilled water (1:2.5 w/v) following 30 min of shaking (Gaudel et al. 2024b). To analyze soil C/N ratio, air dry soil was grounded, passing through a 0.2 mm sieve, then 150 mg of soil was used to prepare a capsule with tin foil and determined by dry combustion using a macro elemental analyzer (vario MACRO cube, Elementar, Hanau, Germany).

2.5 Statistical analysis

Data for all parameters were subjected to a normality assessment using the Shapiro–Wilk test, indicating non-normal distributions (P < 0.05), even following data transformation attempts. The effect of cropping systems and N treatments on the cumulative seasonal N_2O, CO_2 and CH_4 emissions and the net global warming potential in each year (2018 and 2019) was evaluated with analysis of variance (ANOVA). ANOVA was calculated by using a general linear model, and when the main effects were significant ($P \leq 0.05$), pairwise comparisons were analyzed using a post hoc least significant difference (LSD) test.

To analyze the effect of cropping systems and N treatments on soil properties and environmental factors, data were pooled among two growing seasons and evaluated by non-parametric Kruskal–Wallis test. If the main effects were significant ($P \leq 0.05$), then pairwise comparisons were performed with a post hoc Mann–Whitney test.

Relationships between GHG fluxes (N_2O, CO_2 and CH4), soil properties (NH_4^+, NO_3^-, soil C/N ratio, pH, and DOC concentrations), and environmental factors (soil moisture content and ground temperature, soil temperature at 5 cm depth) were performed with Spearman's rho rank correlation coefficient analysis (two-tailed test). ANOVA and non-parametric tests were performed by Minitab® 17 Statistical software (Minitab Inc., State College, PA, USA) and correlation analysis was performed by OriginPro 2021 software (OriginLab, Northampton, MA, USA).

Finally, we employed a structural equation modeling (SEM) framework to analyze the direct and indirect effects of measured variables on soil N_2O, CO_2, and CH_4 emissions. To evaluate the overall goodness of the model fit, we utilized several indices including the chi-squared degree of freedom ratio (χ^2/d.f.), probability level (P), normed fit index (NFI), incremental fit index (IFI), comparative fit index (CFI), and root mean squared error of approximation (RMSEA). Smaller RMSEA values indicate better fit, with values less than 0.1 indicating good fit and values less than 0.05 indicating very good fit. Additionally, a good fit is indicated by a χ^2/d.f. value less than 3, a P value greater than 0.05, and NFI, IFI, and CFI values greater than 0.9 (Gama-Rodrigues et al. 2014). The SEM analysis was conducted using the graphics module of Amos 24.0 software package (Smallwaters Corporation, Chicago, IL, USA).

3 Results

3.1 Weather conditions

Cumulative precipitation from June to September was 200 mm in 2018 and 248 mm in 2019, with the second cropping season receiving 24% more precipitation than the first cropping season. The daily maximum precipitation was recorded at 52 mm on August 13, 2018, and it was 104 mm on July 29, 2019 (Fig. 1). However, during the cropping season, high day temperatures and low relative humidity caused excessive soil evaporation. In the first season, 458 mm of evaporation was recorded, while in the second season it was 434 mm (data obtained from the Luancheng meteorological station). Due to excessive evaporation relative to rainfall, two irrigations were provided to maintain soil moisture. In both years, the first half of the growing season was warmer than the second half. The daily average air temperature was between 24–33 °C from mid-June to mid-August and 14–26 °C from mid-August to the end of September.

3.2 Soil N_2O emissions

Both cropping systems and N treatments were net sources of N_2O fluxes. In most gas sampling events, N_2O emissions were positive. In cropping systems, fluxes range from 0.67 to 316.3 μg m^{-2} h^{-1}, while in N treatments, they range from -4.33 to 741.9 μg m^{-2} h^{-1} across the growing seasons (Fig. S1). In both seasons, cropping systems, N treatments, and their interactions had a significant effect on soil N_2O emissions (Table 1). N_2O emissions were consistently lower in the maize-soybean intercrop than in maize and soybean monocrops under all N treatments across the growing seasons (Fig. 2). Consequently, the intercrop exhibited significantly lower ($P < 0.05$) cumulative N_2O emissions in both years (Table 2). Compared to maize monocrop, maize-soybean intercrop had 38% and 14% less N_2O emissions in 2018 and 2019, respectively.

Table 1 ANOVA (Pr > F) of N_2O, CO_2, CH_4 emissions, and Global warming potential as affected by cropping system and N fertilizer type

Year	Variable	d.f	N_2O emissions	CO_2 emissions	CH_4 emissions	Global warming potential
2018	Cropping system	2	0.000	0.010	0.075	0.007
	N treatments	3	0.000	0.021	0.034	0.005
	Cropping system × N treatments	6	0.000	0.007	0.373	0.007
2019	Cropping system	2	0.047	0.046	0.667	0.039
	N treatments	3	0.000	0.028	0.916	0.012
	Cropping system × N treatments	6	0.021	0.048	0.802	0.047

d.f. is degree of freedom

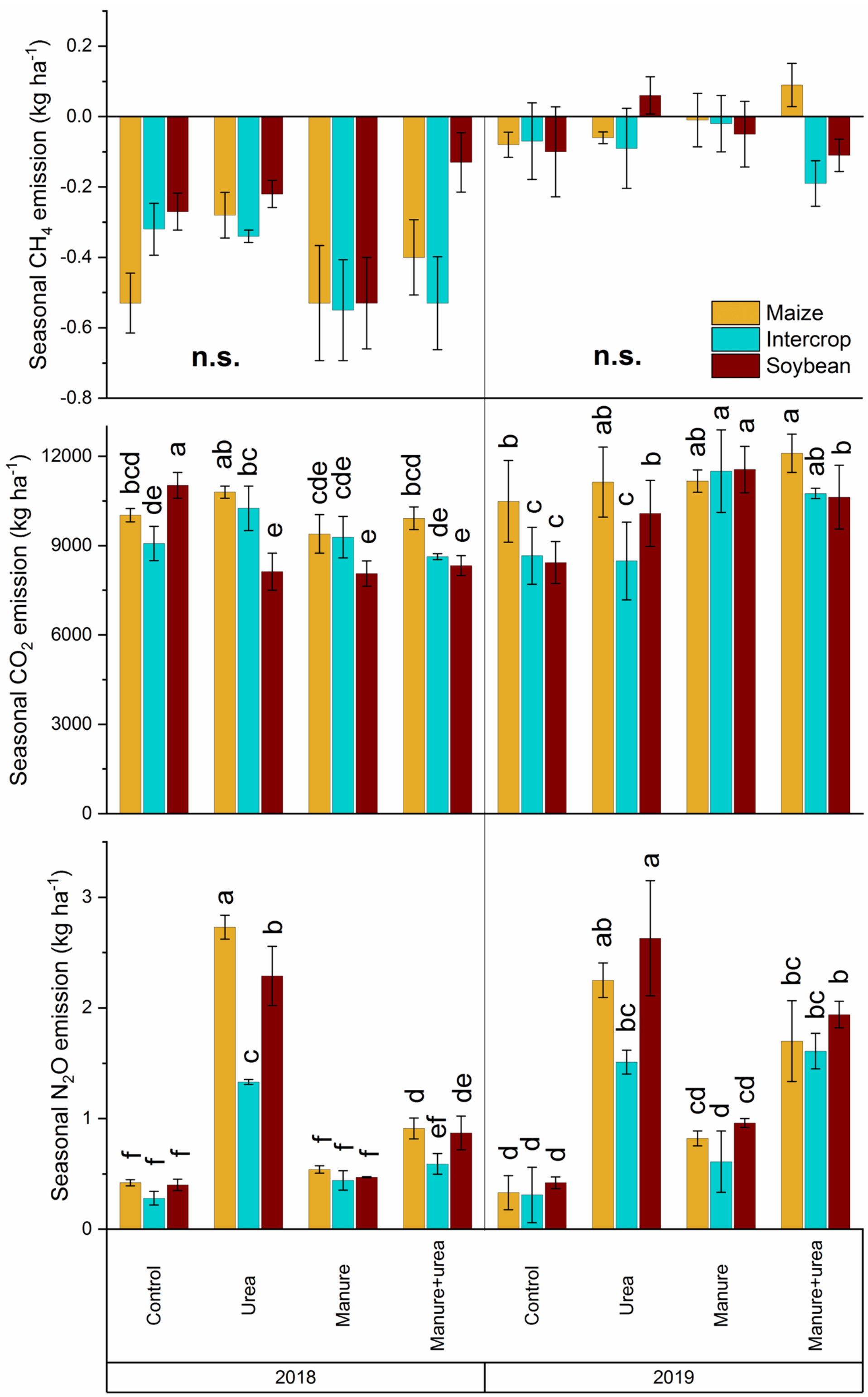


Fig. 2 Seasonal N_2O, CO_2, and CH_4 emissions (kg ha^{-1}) from different cropping systems under different N treatments during 2018 and 2019 study period. Different letters above the bar indicating significant difference ($P < 0.05$, LSD test). n.s. not significant

Peak N_2O fluxes occurred shortly after the application of N fertilizer, coinciding with rainfall or irrigation events, and lasted for 1–2 weeks before returning to background emissions (Fig. S1). The highest N_2O fluxes in fertilized treatments occurred after top dressing rather than after the basal application of fertilizer. Among fertilized treatments (without control), manure had consistently lower N_2O fluxes across growing seasons, resulting in significantly lower N_2O emissions than urea and manure + urea in both

Table 2 Seasonal N_2O, CO_2, and CH_4 emissions (expressed as Kg ha^{-1} season^{-1}) and global warming potential (expressed as Kg CO_2-eq ha^{-1} season^{-1}) from different cropping systems and N treatments during 2018 and 2019 study period at Luancheng Agro-Ecosystem Experimental Station

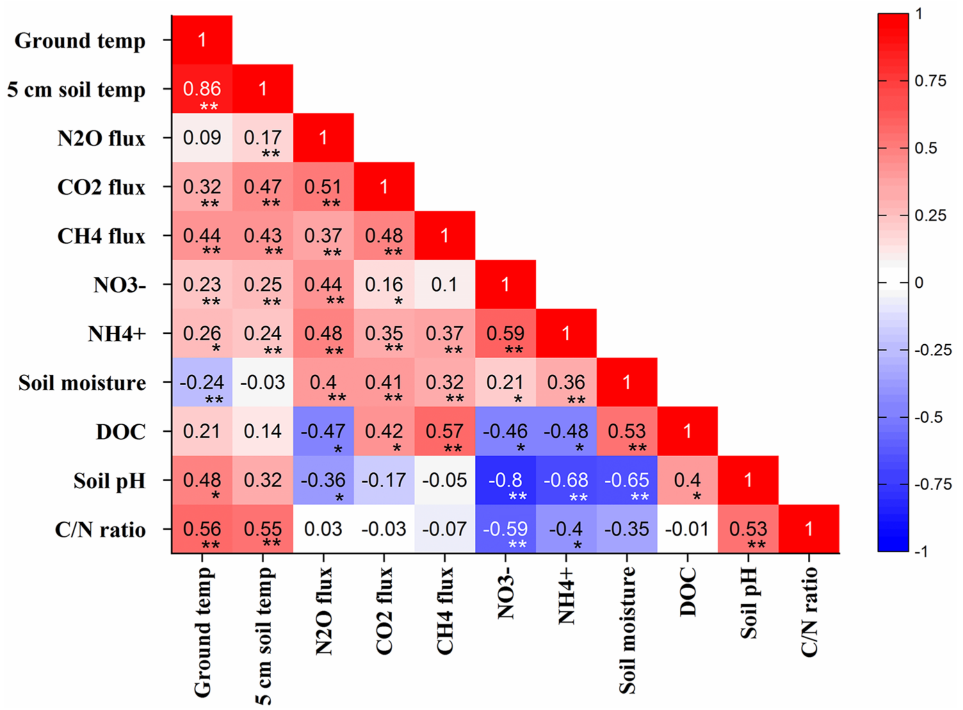
Year	Treatment	N_2O emissions	CO_2 emissions	CH_4 emissions	Global warming potential
			Kg ha^{-1} season^{-1}		Kg CO_2-eq ha^{-1} season^{-1}
2018	Maize	1.12 ± 0.29 a	10,332 ± 229 a	-0.44 ± 0.06 a	10,650 ± 328 a
	Intercrop	0.70 ± 0.11 b	9110 ± 308 b	-0.45 ± 0.05 a	9305 ± 289 b
	Soybean	1.00 ± 0.24 a	8785 ± 423 b	-0.29 ± 0.06 a	9073 ± 396 b
	Control	0.37 ± 0.03 c	10,041 ± 356 a	-0.38 ± 0.05 a	10,137 ± 355 ab
	Urea	2.12 ± 0.22 a	9726 ± 498 ab	-0.28 ± 0.03 a	10,347 ± 495 a
	Manure	0.48 ± 0.03 c	8911 ± 369 b	-0.54 ± 0.07 b	9037 ± 376 b
	Urea + Manure	0.79 ± 0.08 b	8959 ± 285 b	-0.36 ± 0.08 a	9183 ± 290 b
2019	Maize	1.30 ± 0.25 ab	11,386 ± 448 a	-0.01 ± 0.04 a	11,772 ± 476 a
	Intercrop	1.12 ± 0.18 b	9874 ± 648 b	-0.09 ± 0.04 a	10,205 ± 664 b
	Soybean	1.55 ± 0.33 a	10,029 ± 535 b	-0.05 ± 0.07 a	10,491 ± 568 b
	Control	0.35 ± 0.09 b	9192 ± 617 b	-0.08 ± 0.09 a	9295 ± 627 b
	Urea	2.13 ± 0.29 a	9899 ± 693 ab	-0.03 ± 0.04 a	10,534 ± 726 ab
	Manure	0.80 ± 0.09 b	11,308 ± 522 a	-0.02 ± 0.07 a	11,546 ± 544 a
	Urea + Manure	1.75 ± 0.13 a	10,995 ± 406 a	-0.07 ± 0.05 a	11,515 ± 417 a

years. The urea-fertilized treatments had the maximum seasonal N_2O emissions in both cropping seasons.

Throughout the cropping seasons, N_2O fluxes were higher during irrigation and rainfall, thus there was a significant positive correlation between N_2O fluxes and soil moisture content ($r = 0.40$; $P < 0.01$) (Fig. 3). Comparatively higher N_2O emissions occurred during the first half of the growing seasons when the average air temperature was high (ranging between 24–33 °C). As a result, a significant positive correlation was found between N_2O emissions and soil temperature ($r = 0.17$; $P < 0.01$). Also, N_2O emissions had strong positive correlations with soil NH_4^+ ($r = 0.48$; $P < 0.01$) and NO_3^- contents ($r = 0.44$; $P < 0.01$), while soil pH had a negative correlation with soil N_2O emissions ($r = -0.37$; $P < 0.05$).

3.3 Soil CO_2 emissions

In our study, both cropping systems and N treatments had a significant effect on soil CO_2 emissions (Table 1).



	Ground temp	5 cm soil temp	N2O flux	CO2 flux	CH4 flux	NO3-	NH4+	Soil moisture	DOC	Soil pH	C/N ratio
Ground temp	1										
5 cm soil temp	0.86 **	1									
N2O flux	0.09	0.17 **	1								
CO2 flux	0.32 **	0.47 **	0.51 **	1							
CH4 flux	0.44 **	0.43 **	0.37 **	0.48 **	1						
NO3-	0.23 **	0.25 **	0.44 **	0.16 *	0.1	1					
NH4+	0.26 *	0.24 **	0.48 **	0.35 **	0.37 **	0.59 **	1				
Soil moisture	-0.24 **	-0.03	0.4 **	0.41 **	0.32 **	0.21 *	0.36 **	1			
DOC	0.21	0.14	-0.47 *	0.42 *	0.57 **	-0.46 *	-0.48 *	0.53 **	1		
Soil pH	0.48 *	0.32	-0.36 *	-0.17	-0.05	-0.8 **	-0.68 **	-0.65 **	0.4 *	1	
C/N ratio	0.56 **	0.55 **	0.03	-0.03	-0.07	-0.59 **	-0.4 *	-0.35	-0.01	0.53 **	1

Fig. 3 Spearman's rho rank correlation coefficient analysis between N_2O, CO_2, CH_4 fluxes, soil properties, and environmental factors in different treatments during two years (2018 & 2019) study period. The data level indicates the r values. The asterisk(s) (*) under r values denote significant correlation at the 0.05 level (*) or the 0.01 level (**) based on a 2-tailed test

Throughout the study period, soil CO_2 fluxes were positive in all treatments (Fig. S2). In all N treatments, soil CO_2 emissions from the maize monocrop were consistently higher compared to the soybean monocrop and the maize-soybean intercrop (Fig. 2), resulting in significantly higher seasonal soil CO_2 emissions from the maize monocrop in both cropping seasons (Table 2). In 2018, the intercrop and soybean soil emitted 12% and 15% less CO_2 than maize, while in 2019, the emissions were 13% and 12% lower, respectively. Peak CO_2 fluxes occurred after tillage, and N application coincided with irrigation. No significant difference was observed in seasonal soil CO_2 emissions among the three fertilized treatments. In our study, soil CO_2 fluxes had a significant positive correlation with both soil temperature ($r = 0.47$; $P < 0.01$) and moisture content ($r = 0.41$; $P < 0.01$) (Fig. 3). CO_2 fluxes were also strongly correlated with soil mineral N (NH_4^+ and NO_3^-) as well as DOC concentration ($r = 0.42$; $P < 0.05$).

3.4 Soil CH_4 emissions

Soils of both cropping systems and N treatments acted as a net sink of CH_4 fluxes. However, both positive and negative CH_4 fluxes were seen throughout the study period (Fig. S3). In cropping systems, CH_4 fluxes range from -45.6 to 26.4 μg m^{-2} h^{-1}, and in N treatment, it was -47.8 to 30.8 μg m^{-2} h^{-1} across the growing seasons. In 2018, there was a significant difference among the N treatments ($P < 0.05$), where sole manure-treated soil uptake significantly higher CH_4 fluxes than other treatments (Table 2).

In 2018, during fertilizer application periods, when irrigation was applied and soil moisture was high, CH_4 emissions were positive. No distinct pattern has been found in 2019. However, a positive peak of CH_4 fluxes was found after heavy rainfall (104 mm) on July 29, 2019. Therefore, there was a significant positive correlation between CH_4 fluxes and soil moisture content during the study period ($r = 0.32$; $P < 0.01$) (Fig. 3). Similar to N_2O and CO_2 fluxes, CH_4 fluxes also showed a strong correlation with soil temperature ($r = 0.43$; $P < 0.01$). Additionally, CH_4 fluxes were positively correlated with N_2O ($r = 0.37$; $P < 0.01$) and CO_2 fluxes ($r = 0.48$; $P < 0.01$), as well as with soil NH_4^+ ($r = 0.37$; $P < 0.01$) and soil DOC contents ($r = 0.57$; $P < 0.01$).

3.5 Global warming potentials

All cropping systems, N treatments, and their interactions significantly influenced the net global warming potential (Table 1). In both cropping seasons, maize monocrops had a significantly higher ($P < 0.05$) warming potential than maize-soybean intercrops and soybean monocrops (Table 2). In 2018, intercrop and soybean monocrop had a total of 13% and 15% less GHG emissions, respectively, and in 2019, the reductions were 13% and 11%, respectively, compared to maize monocrop. Among the fertilized treatments, urea exhibited a considerably higher ($P < 0.05$) warming potential than manure and manure + urea treatments in the first cropping season.

3.6 SEM analysis of soil greenhouse gas emissions

The SEM analysis revealed multivariate effects on GHG emissions, as depicted in Fig. 4. For soil N_2O emissions, soil NH_4^+ emerged as the largest contributor with a total effect of 0.99 ($P < 0.001$) (Fig. 4d), indicating its significant impact. Soil NO_3^- also played a role, with a total effect of 0.28 ($P < 0.01$), highlighting the influence of nitrification over denitrification. Soil moisture content exhibited a significant effect on N_2O emissions, both directly ($\beta = 0.21$, $P < 0.001$) and indirectly by affecting NH_4^+ with a total indirect effect of 0.24 (Fig. 4a). Soil temperature also showed both direct and indirect effects, with a total effect of 0.27, explaining only 27% of the variation in N_2O emissions.

Similarly, for soil CO_2 emissions, DOC stood out as the primary driver with a direct effect of 0.84 ($P < 0.001$) (Fig. 4b), explaining 84% of the emission variation. Soil moisture had both direct (0.43) and indirect effects, amplifying CO_2 emissions by increasing DOC content ($\beta = 0.42$; $P < 0.01$). Soil temperature, despite its high direct effect ($\beta = 0.77$, $P < 0.001$), had a low total effect ($\beta = 0.38$) due to its negative impact on DOC content ($\beta = -0.49$; $P < 0.001$).

Regarding CH_4 emissions, soil NH_4^+ content exerted the highest total effect ($\beta = 1.37$; $P < 0.001$) (Fig. 4f). Although DOC had a significant direct effect ($\beta = 1.72$, $P < 0.001$), its total effect was mitigated by its negative influence on NH_4^+ ($\beta = -0.93$; $P < 0.001$) and NO_3^- content ($\beta = -0.80$; $P < 0.001$) (Fig. 4c). Soil moisture had both direct and indirect positive effects on CH_4 emissions, with a total effect of 0.84, driven by its significant impact on DOC ($\beta = 0.43$; $P < 0.001$) and NH_4^+ content ($\beta = 0.14$; $P < 0.01$).

4 Discussions

4.1 Effect of cropping systems and fertilizer on soil N_2O emissions

Our research uncovered that the intercropping of maize and soybeans led to significantly lower GHG emissions compared to their respective monoculture systems, which supports our hypothesis for lower N_2O emissions in intercropping systems. In the initial season, the intercropping system showed significantly reduced N_2O emissions ($P < 0.05$) with 38% less compared to maize monoculture. In the subsequent season, it exhibited 28% lower N_2O emissions ($P < 0.05$) than soybean monoculture and a 14% decrease

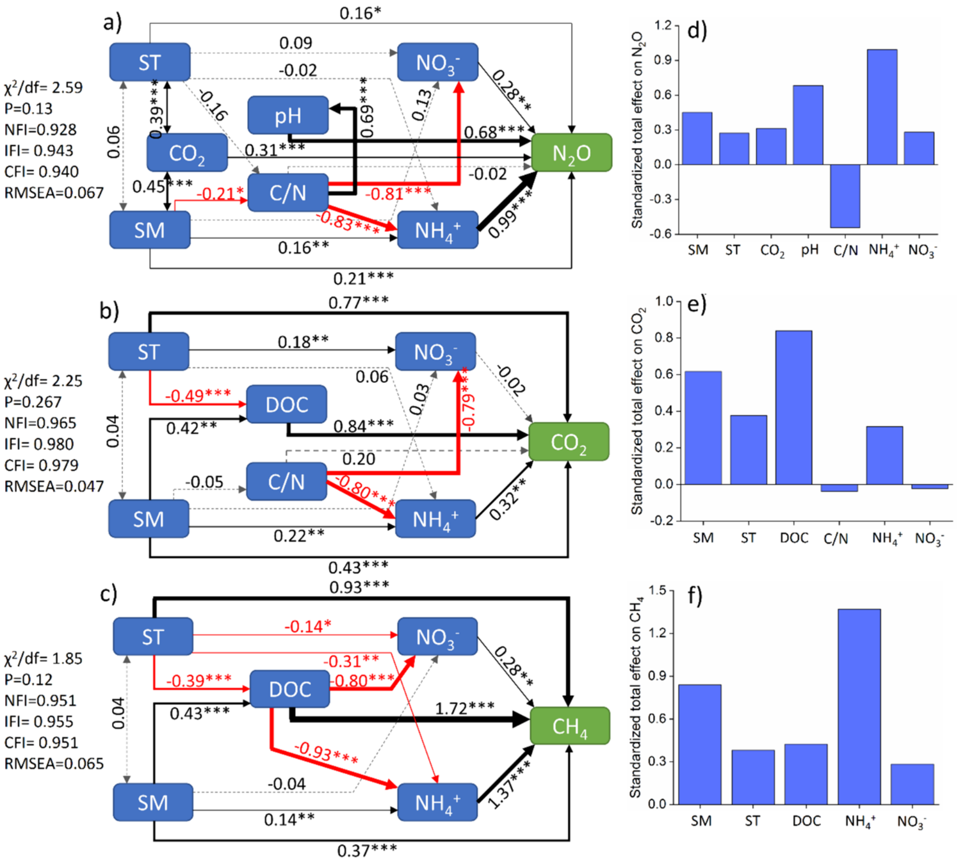


Fig. 4 Structural equation modeling (SEM) is used to assess multivariate effects on soil N_2O, CO_2, and CH_4 emissions (a–c) and the standardized total effect (direct plus indirect effects) of different variables (d–f). The solid black arrow indicates the significant positive path ($p < 0.05$), the solid red arrow indicates the significant negative path ($p < 0.05$), the dotted black arrow indicates the non-significant path ($p > 0.05$), the number next to each arrow is the standardized path coefficient, and the width of an arrow indicates the strength of the relationship. Asterisk(s) (*) with numbers indicates significance levels: *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$. ST = soil temperature at 5 cm depth; SM = soil moisture content; C/N = carbon to nitrogen ratio; DOC = dissolve organic carbon

(not statistically significant) compared to maize monoculture. This trend aligns with findings from earlier studies on intercropping, where N_2O emissions were notably lower in intercropping systems compared to their monoculture counterparts (Zhang et al. 2023b; Yin et al. 2022; Shen et al. 2018; Senbayram et al. 2015). The key explanation for lower N_2O emissions in intercropping systems might be related to reduced nitrification and denitrification in the system (Senbayram et al. 2015). In maize-soybean intercropping, the component crops likely exhibit a greater capacity for nutrient and moisture uptake due to their varied root depths and higher root biomass within the top 20 cm of soil (Yin et al. 2022; Zou et al. 2018). Moreover, maize plants have a preference for taking up more NH_4^+ than NO_3^- from the soil (Zhang et al. 2019), while legume plants preferentially uptake both NH_4^+ and NO_3^- (Gao et al. 2022). Consistent with these findings, our study indicated that the intercrop exhibited enhanced efficiency in nitrogen and moisture acquisition, resulting in lower residual mineral N (NH_4^+ and NO_3^-) and moisture content in the upper root zone (Fig. 5a, b, e). This created unfavorable conditions for both nitrification and denitrification processes in the maize-soybean intercropping system (Xu et al. 2017). Nevertheless, previous studies have reported that the cultivation of N-fixing legumes could stimulate soil N_2O emissions by providing N input in the soil (Senbayram et al. 2015; Rochette and Janzen 2005). However, these emissions are more pronounced when legume crops are grown in monoculture. It was reported that faba bean and pea could release 13–16% of their fixed N as rhizodeposition (Mayer et al. 2003). However, in cereal-legume intercropping systems, these N rhizodeposits could be effectively utilized by the neighboring cereal crops through N transfer (Hupe et al. 2021), leaving a lesser amount of residual N in the soil, subsequently lower N_2O emissions in the intercropping system.

In our study, higher N_2O fluxes were observed during the initial half of both growing seasons, coinciding with elevated soil temperatures and adequate moisture due to irrigation and relatively higher precipitation compared to the latter half of the growing season. Soil moisture primarily controls the reduction of NO_3^- in the soil, thereby affecting N_2O emissions (Liu et al. 2022). Maize monoculture had higher soil moisture content compared to soybean monoculture and maize-soybean intercrop, resulting in increased N_2O fluxes in maize monoculture. However, the influence of moisture on N_2O emissions appeared to be less pronounced in the maize-soybean intercropping system. Perhaps this was because intercrop root interactions and soybean nodule-associated N_2 fixing *Bradyrhizobium japonicum* enhance the abundance of the nosZ gene, which simultaneously uptakes

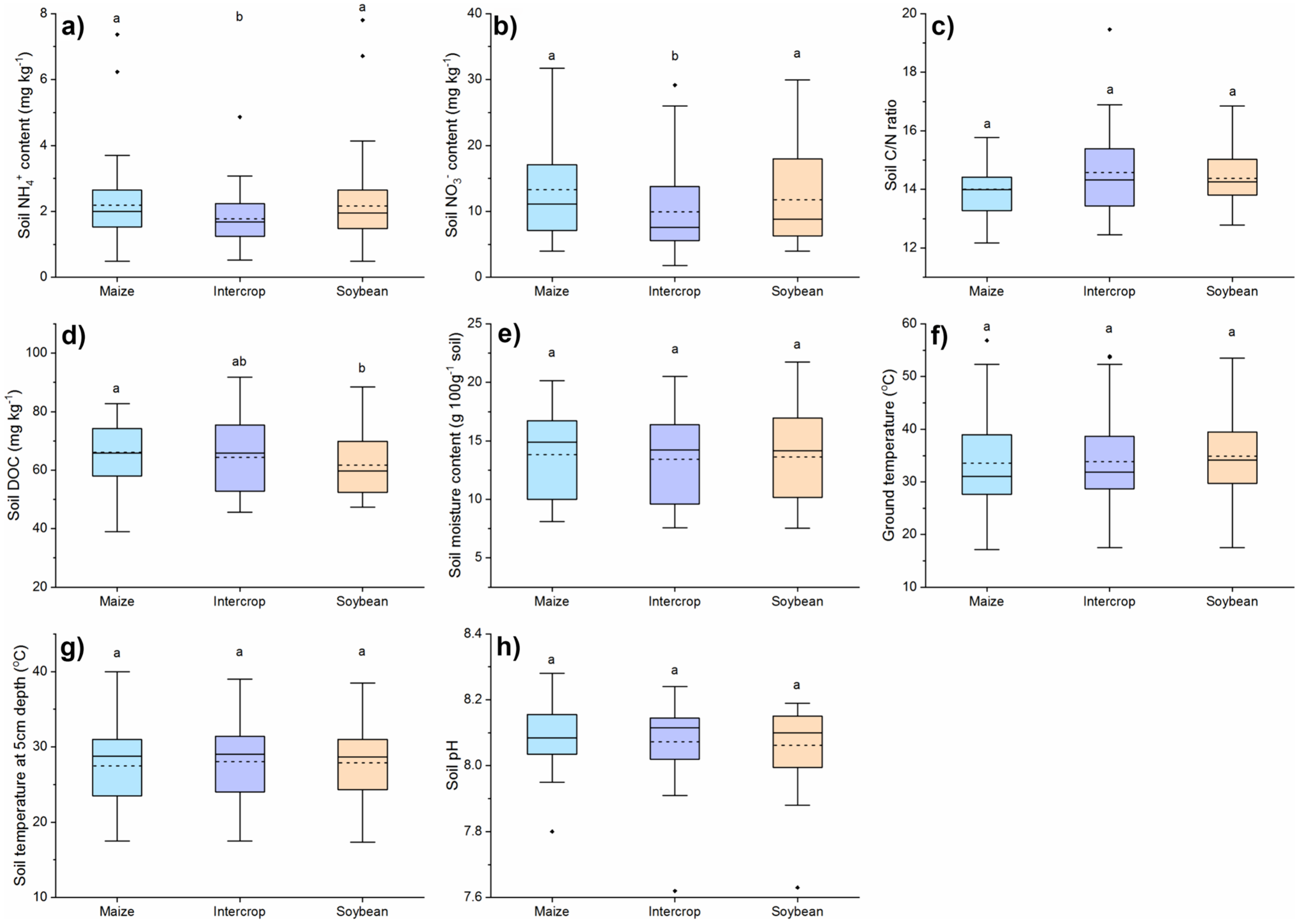


Fig. 5 Box plot analysis for different soil properties and environmental factors in maize, soybean, and intercrop plots across two cropping seasons (2018–2019). The boxes represent data between the 25th and 75th percentiles; solid lines and dotted lines inside the boxes represent the median and mean values, respectively, for each parameter. The error bars represent whiskers based on the 1.5 IQR value. The diamond-shaped black points outside the boundary of the whiskers are outliers

N_2O from the atmosphere and promotes soil N_2O reduction to N_2, hence reducing N_2O fluxes in the intercropping system (Liu et al. 2022; Qin et al. 2020; Itakura et al. 2013). Moreover, elevated soil temperature not only directly affects N_2O emissions by regulating enzymatic processes but also increases soil respiration, leads to a depletion of oxygen concentrations in the soil, and induces soil anaerobiosis, a significant precursor and driver of N_2O emissions (Butterbach-Bahl et al. 2013). Consequently, higher N_2O emissions were observed throughout the initial half of the growth season.

Although N fertilizer application in agricultural soils boosts grain yield, it is also known to cause a notable rise in soil N_2O emissions (Ma et al. 2022b). However, substituting urea with manure may reduce N_2O emissions (Mairura et al. 2023). In both cropping seasons, soils treated solely with manure exhibited significantly lower N_2O emissions compared to those treated only with urea, despite the same amount of N applied. Additionally, the combined manure and urea treatment showed either significantly lower N_2O emissions (in 2018) or a noticeable decrease (in 2019) compared to the urea treatment alone. The primary reason behind reduced N_2O emissions from manure-treated soil is attributed to the gradual release of plant-accessible N throughout the growing season from the manure (Lehrsch et al. 2016). Consequently, once the plants' N needs are met, there remains a lesser amount of mineral N accessible in the soil. Throughout our study period, both solely manure-treated and manure + urea-treated soils consistently exhibited notably lower NH_4^+ and NO_3^- concentrations in the soil compared to urea-treated soils (Fig. 6a, b), leading to reduced N_2O emissions in soils treated with manure.

4.2 Cropping systems and fertilizer effect on soil CO_2 emissions

Our initial hypothesis was that a maize-soybean intercropping system would reduce GHG emissions compared to a maize monocropping system. Our findings supported this

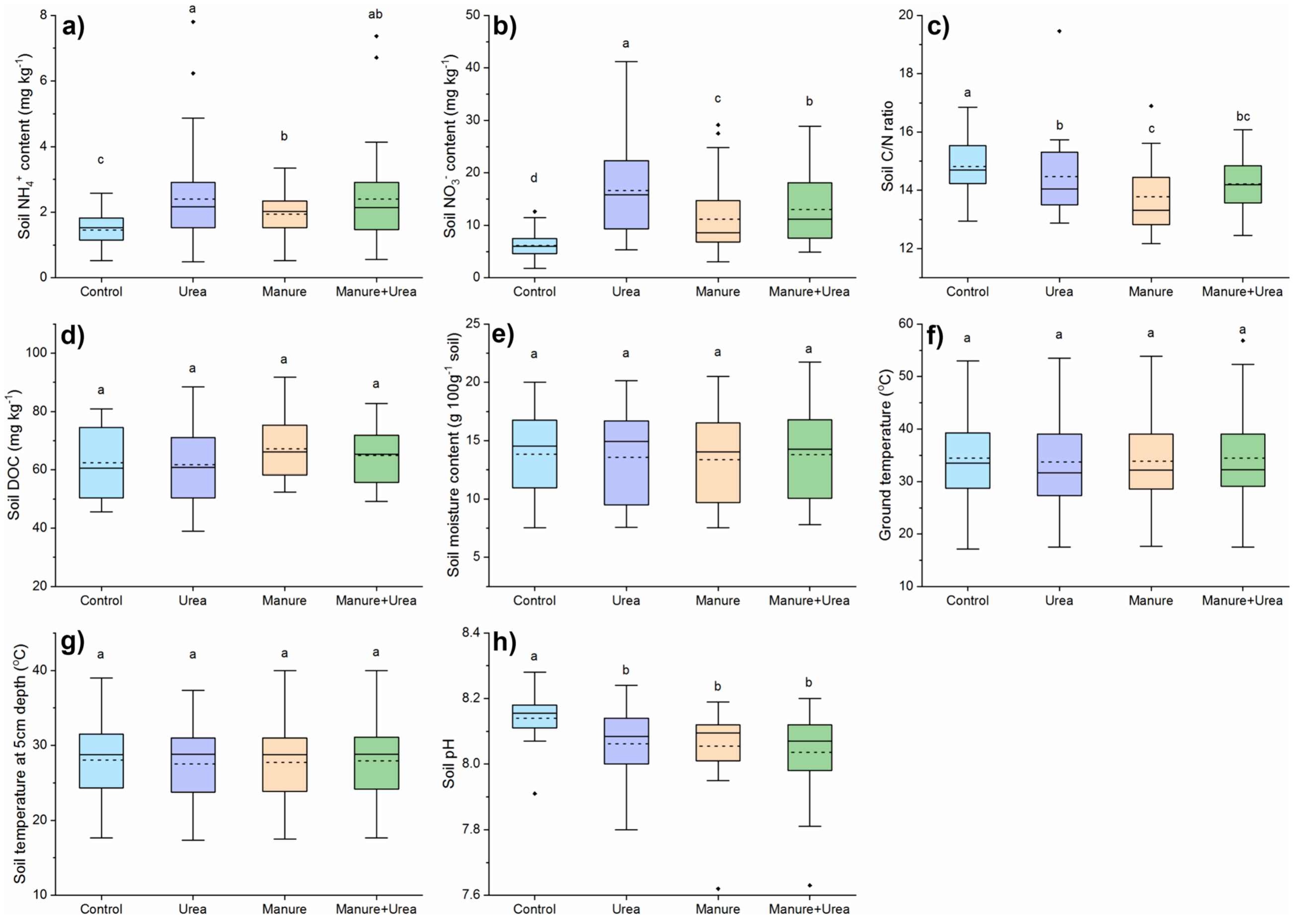


Fig. 6 Box plot analysis for different soil properties and environmental factors in different N treatment plots across two cropping seasons (2018–2019). The boxes represent data between the 25th and 75th percentiles; solid lines and dotted lines inside the boxes represent the median and mean values, respectively, for each parameter. The error bars represent whiskers based on the 1.5 IQR value. The diamond-shaped black points outside the boundary of the whiskers are outliers

hypothesis regarding CO_2 emissions (Table 2). In both seasons, CO_2 emissions from maize-soybean intercropping systems were significantly lower than those from maize monoculture, with 12% and 13% less emissions in 2018 and 2019, respectively. The reduction in CO_2 emissions from intercropping systems is consistent with findings from prior studies (Xu et al. 2022; Gou et al. 2021). Additionally, soybean monocrops also had significantly lower CO_2 emissions than maize monocrops in both cropping seasons, which suggests that part of the intercropping effect on lower GHG emissions is related to the partial replacement of maize crop by soybean crop in the maize-soybean intercropping system.

Throughout our study period, we observed an increase in soil CO_2 emissions when irrigation was applied or sudden rainfall occurred. In our study, CO_2 emissions showed a strong positive correlation with soil moisture and dissolved organic carbon (DOC) content. Moreover, soil DOC content increased with rising soil moisture content ($r = 0.53$, $P < 0.01$). There's a trend of increasing DOC content following rewetting after the dry spells (Dong et al. 2021). In our experiment, the soil experienced intermittent dry conditions, leading to the accumulation of microbial products due to reduced decomposition rates. When soil moisture increased, it contributed to elevated DOC levels (Fig. 4b), subsequently consumed by soil microbes as substrates, leading to enhanced CO_2 emissions (Marzaioli et al. 2022; Shaaban et al. 2022). DOC concentration in the soil is also influenced by factors such as plant litter, volume of root biomass, and root exudates (Kalbitz et al. 2000). Higher root biomass per unit area drives increased microbial activity (Eisenhauer et al. 2017). Compared to soybeans, maize generates relatively more above- and below-ground biomass, supporting increased heterotrophic (microbes, soil fauna) and autotrophic (root) respiration, consequently resulting in greater CO_2 emissions from maize monocrops (Luo et al. 2023). Consistently, throughout our study, maize soil exhibited significantly higher DOC concentrations than soybean soil

(Fig. 5d), leading to significantly higher CO_2 emissions than soybean in both cropping seasons.

4.3 Cropping systems and fertilizer effect on CH_4 emissions

In both cropping seasons, soils across all treatments acted as a net methane (CH_4) sink. However, no significant impact on CH_4 uptake was observed among cropping systems, although there was a tendency for maize-soybean intercropping to exhibit slightly higher CH_4 uptake than both maize and soybean monocrops (Table 2). However, the net CH_4 uptake observed in our study was lower than what previous intercropping studies in upland soils have reported (Yan et al. 2023; Raji & Dörsch 2020), potentially owing to variations in soil properties and environmental influences on CH_4 uptake.

During our study, several factors had significant effect on net CH_4 fluxes, including soil temperature, moisture content, NH_4^+, and DOC concentrations (Fig. 4c). Elevated soil moisture content during irrigation and rainfall restricts oxygen exchange between the soil and the atmosphere, creating an anaerobic environment in the soil that inhibits methanotrophic activities (the oxidation of CH_4) while promoting methanogenic activities responsible for CH_4 production (Meng et al. 2014). In our study, CH_4 emission exhibited a positive correlation with soil moisture content ($P < 0.01$). In the second growing season, which received 24% more rainfall than the first, the increased moisture levels may have hindered the ability of methanotrophs to oxidize atmospheric CH_4, leading to comparatively less CH_4 uptake across all cropping systems in 2019. Additionally, the application of N fertilizer may increase CH_4 emissions by providing substrates to methanogenic microbes (Shaaban et al. 2022). Our SEM analysis revealed a significant increase ($P < 0.001$) in CH_4 emissions associated with higher NH_4^+ content in soils, which emerged as the primary contributor to CH_4 emissions (Fig. 4f). Consistent with our findings, Shaaban et al. (2022) reported that N-fertilized soil produced three times more CH_4 emissions than non-fertilized treatments due to elevated NH_4^+ concentration in the soil.

4.4 Cropping system effect on global warming potential

The net exchange of N_2O, CH_4, and CO_2 between the soil and atmosphere in cropping systems is measured as the global warming potential (GWP) of crop production. Furthermore, according to the IPCC AR6, on the 100-year time scale, the GWP of N_2O and CH_4 is 298 and 34 times greater than that of CO_2, respectively (IPCC 2023). As a result, even small emissions of N_2O and CH_4 can result in significant CO_2 equivalents (CO_2-eq) and pose a substantial risk to the environment (Chen et al. 2020).

However, results from our study support the initial hypothesis that intercropping maize with soybean would reduce net GHG emissions (CO_2-eq) compared to the existing maize monoculture system. On average, in both cropping seasons, the intercrop exhibited a 13% lower GWP compared to maize monoculture. Similar reductions in GWP in intercropping have also been observed in previous studies (Ghani et al. 2022; Shen et al. 2018).

In our study, the GWP was dominated by CO_2 emissions, with smaller contributions from N_2O emissions. In upland agriculture, CH_4 fluxes generally contribute to mitigating the net GWP, as upland soils uptake CH_4 from the atmosphere (Ghani et al. 2022). Among the GHGs, CO_2 alone contributes more than 90% of the overall global warming potential in this study. Meier et al. (2017) also reported that soil CO_2 emissions were the key determinants of the net GWP and the GHG balance. Thus, reducing CO_2 and N_2O emissions from the agricultural soil is crucial to mitigate GWP. In the present study, equal amounts of N were used in all cropping systems to maintain uniformity. However, due to the nitrogen-fixing ability of soybean, intercropping with maize could reduce N input in the system, further reducing GWP. Therefore, assessment of GWP could serve as a helpful decision-making mechanism for researchers and policymakers aiming to select climate-smart cropping systems to develop sustainable agroecosystems.

4.5 Cropping systems and fertilizer effects on soil properties

Soil physical and chemical properties like soil temperature, soil mineral N content (NH_4^+ and NO_3^-), soil pH, moisture content, DOC, and C/N ratio are crucial factors influencing the soil microbial community structure, thus affecting processes like nitrification, denitrification, and respiration in the soil (Xu et al. 2017). At the same time, these soil properties are also affected by the crops grown in the soil and the types of N fertilizer used. Specifically, soil mineral N concentrations were likely influenced by both cropping systems and N fertilizers. In our study, soil NH_4^+ and NO_3^- concentrations were found to be lower in maize-soybean intercropping systems, with 19% and 18% less NH_4^+ concentration and 26% and 16% less NO_3^- concentration than in maize and soybean monoculture, respectively. These reduced concentrations correlated significantly with lower N_2O and CO_2 fluxes (Fig. 3), leading to decreased N_2O and CO_2 emissions and a significantly reduced global warming potential in intercropping.

The type of nitrogen fertilizer also exerted a substantial influence on mineral N content. Both NH_4^+ and NO_3^- content were significantly higher in sole urea treatment (Fig. 6a, b), which reflects higher N_2O emissions from this soil. All fertilized treatments exhibited higher soil NH_4^+ levels, releasing more H^+ during nitrification, consequently decreasing soil pH significantly compared to the unfertilized control (Fig. 6h). While all nitrogen fertilizers significantly decreased the soil C/N ratio (Fig. 6c), the fluxes of N_2O, CO_2, and CH_4 did not directly correlate with this ratio in our study. Several studies have reported contrasting relationships between the soil C/N ratio and N_2O emissions. Yao et al. (2022) reported a significant positive correlation, while Wang et al. (2023b) and Mu et al. (2014) reported a significant negative correlation between the soil C/N ratio and N_2O emissions. However, in our study, N_2O emissions did not directly correlate with the C/N ratio (Fig. 3). Instead, the soil C/N ratio had an indirect effect ($P < 0.001$) on N_2O emissions by regulating NH_4^+ and NO_3^- concentrations in the soil (Fig. 4a). A higher C/N ratio led to decreased inorganic N concentration in the soil, resulting in lower N_2O emissions. Among the three cropping systems, although there was no significant difference in the soil C/N ratio, on average, the intercropping system had a higher soil C/N ratio than maize and soybean monoculture. Consequently, the intercropping system had significantly lower NH_4^+ and NO_3^- concentrations and therefore lower N_2O emissions.

5 Conclusions

The existing summer maize – winter wheat double cropping system in the North China Plain is characterized by high nitrogen fertilizer inputs, resulting in surpluses and GHG emissions. In order to address this issue, one possible solution is to diversify the cropping system by introducing soybeans as an intercrop with maize. Our findings indicate that intercropping soybeans with maize notably decreased soil NH_4^+ and NO_3^- concentrations, and exhibited tendencies toward lower N_2O fluxes. Additionally, this intercropping effectively reduced CO_2 emissions from the soil. On average, maize-soybean intercropping reduces 1.46 tons of CO_2-eq ha^{-1} emissions in each season compared to maize monoculture. Furthermore, using manure instead of synthetic N fertilizer also reduced N_2O emissions. However, the application of N fertilizer, particularly urea as a top dressing, remains crucial for achieving higher maize yields. Therefore, partially substituting urea with manure as a basal application could effectively decrease GHG emissions while upholding productivity and long-term soil quality. Moreover, the incorporation of crop residues in the soil is a common practice in the NCP. The decomposition of these crop residues, particularly legume residues, may have a significant impact on GHG emissions from winter wheat. Thus, further studies and measurements are needed to quantify the effect of different crop residues on GHG emissions from the winter wheat.

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Data availability The data supporting this study's findings are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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