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Response of greenhouse gases emissions and yields to irrigation and straw practices in wheat-maize cropping system

Haowen Zhang [a,b], Qing Liang [a], Zhengping Peng [a,b], Yi Zhao [c], Yuechen Tan [d], Xin Zhang [a,b,*], Roland Bol [e,f]

[a] State Key Laboratory of North China Crop Improvement and Regulation, Hebei Agricultural University, Baoding 071000, China
[b] College of Resources and Environmental Sciences, Hebei Agricultural University, Baoding 071000, China
[c] School of Chemistry and Environmental Engineering, Liaoning University of Technology, Jinzhou, Liaoning 121001, China
[d] Beijing Key Laboratory of Wetland Services and Restoration, Institute of Ecological Conservation and Restoration, Chinese Academy of Forestry, Beijing 100091, China
[e] Institute of Bio, and Geosciences, Agrosphere (IBG-3), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[f] School of Natural Sciences, Environment Centre Wales, Bangor University, Bangor LL57 2UW, UK

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ABSTRACT

Global water shortages and appropriate crop residues management are the major issues threatening the sustainable development of agriculture, food security, and the environment. In this study, we conducted a one-year field experiment (in 2020–2021) to investigate annual yield, greenhouse gas (GHG) emissions, global warming potential (GWP) and greenhouse gas intensity (GHGI) in a wheat-maize cropping system. Straw practices were kept in the main plot, including straw incorporation (SI) and straw removal (SR). Irrigation practices were allocated into sub-plots, including surface drip irrigation (DI), sub-surface drip irrigation (SDI), partial rootzone irrigation (PRI), and flood irrigation (FP). All treatments were fertilized at the level of 210 kg N ha^{-1} for each season. The soil acted as a net sink for CH_4 but as a source of N_2O emissions during the annual crop growth period under all irrigation treatments. The highest direct GHGs, net GWP, and GHGI were found in FP compared with all other irrigation practices under SI or SR. SI significantly increased annual yield (5.0%), CH_4 emission (17.1%) and ΔSOC (119.9%), but decreased N_2O emissions (19.4%) and GWP_d (19.6%), thus resulting in a net GWP reduction of 23.6% as compared to SR under SDI. Additionally, the best treatment for minimizing the negative environmental impacts was found in SDI, which reduced net GWP by 39.7% ($P < 0.05$), and decreased GHGI by 43.0% ($P < 0.05$) as compared to FP under SI. We conclude that sub-surface drip irrigation combined with straw incorporation simultaneously mitigates GHG emissions, improves yield, and enhances soil C sequestration, making it a suitable environment-friendly agricultural management practice for sustainable farming in northern China.

1. Introduction

Croplands treated with fertilizer account for 39% and 76% of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions, respectively. It is estimated that CH_4 and N_2O contribute up to 12% of the total global greenhouse gas (GHG) emissions (Cui et al., 2014; IPCC, 2014; Fan et al., 2018). N_2O and CH_4 are both ozone-depleting gases and have a significant effect on global warming in agroecosystems. A variety of farm management practices and agrochemical inputs, such as machine operation, manufacturing, and transportation of agricultural resources greatly contribute to global GHG–driven climate change (Cui et al., 2019; Zhang et al., 2020).

Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) cropping system is widely practiced in northern China, which is the most important and intensive cereal crop production region in China (Yan et al., 2015). The need for irrigation to meet crop water demand and straw management are the main challenges that the region is facing. Therefore, optimized irrigation management strategies are needed to promote measures for conserving water, ensuring food security, and environmental sustainability (Wang et al., 2021a). The crop yields in semi-arid regions like northern China, particularly winter wheat are heavily dependent on groundwater irrigation (Zhang et al., 2017b).

* Corresponding author at: State Key Laboratory of North China Crop Improvement and Regulation, Hebei Agricultural University, Baoding 071000, China.
E-mail address: zhangxin_vic@hotmail.com (X. Zhang).

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Flood irrigation continues to be one of the widely used irrigation strategy worldwide (Akbari et al., 2018). Heavy irrigation causes nitrate (NO_3^-) to infiltrate deeper soil layers, promotes N_2O production through the denitrification process, and stimulates CH_4 emissions (Currell et al., 2012; Wu et al., 2019; Liu et al., 2021).

Combining drip irrigation with fertilizer (fertigation) has been used in smaller and precise applications. Frequent supplements of water and fertilizer are applied to the rooting zone through the surface (DI) or subsurface (SDI) drip irrigation system (Farneselli et al., 2015). DI and SDI have been developed to sustain wetted soil area (water-filled pore space: 60–70%) to reduce early-season evaporation (Zhao et al., 2021), inhibit soil denitrification process, and thereby reduce the release of N_2O emissions (Hou et al., 2016). Previous studies have demonstrated that fertigation can reduce N_2O emissions by 32–46% in comparison with other irrigation systems due to reduced irrigation and different soil-wetting patterns (Kennedy et al., 2013; Kuang et al., 2021). SDI application can reduce the amount of irrigation by supplying water and nitrogen fertilizer to sub-surface soil with maximum crop root density (Schmidt et al., 2018). Partial rootzone irrigation (PRI) irrigates half of the root zone and allows the other side to dry before irrigating on an alternate basis (Wang et al., 2010). PRI application exposes part of the rhizosphere environment to dry soil (Tang et al., 2010), which can substantially reduce irrigation water consumption and lead to improve soil organic matters decomposition, and GHG production (Wang et al., 2016, 2018b). Appropriate supplemental irrigation can simultaneously accelerate the aerobic decomposition of soil organic matter and reduce CH_4 emissions by limiting organic substrates for methanogens (Kögel-Knabner et al., 2010; Haque et al., 2016).

Straw production in China, exceeded more than 10^9 Mg per year, accounting for 25% of global production (Ji, 2015). Crop straw incorporated in the field improves soil fertility and reduces the severe air pollution caused by burning of straw (Wu et al., 2019). Straw incorporation significantly reduced soil N losses in the form of N_2O emissions and nitrate leaching by 17.3% and 8.7%, respectively, which was mainly due to induction of net N immobilization (Xia et al., 2018). SOC responded more sensitively to straw incorporation (Liu et al., 2014). Although straw incorporation contributed to CO_2 and CH_4 emissions, the soil organic carbon (SOC) stock in surface soil has significantly increased by 14% in 11 years in northern China (Chen et al., 2009). It has also been reported that straw incorporation also plays an essential role in soil C sequestration, demonstrating over 90% of reduction potential for GHG mitigation in agroecosystems (Smith et al., 2007; Liao et al., 2014), and minimize negative environmental impacts (Rizhiya et al., 2011; Zheng et al., 2019; Li et al., 2021a). The results of previous research that assessed the effect of straw incorporation on N_2O emissions and net GHG were found to be inconsistent. Some studies have reported positive effects of crop incorporation because of a mineralizable-N substrate for N_2O generation through nitrification process (Li et al., 2021b) and reduced oxygen availability in the soil profile which favor N_2O production through denitrification (Mutegi et al., 2010), or neutral effects (Zhang et al., 2017a).

Since the early 1990 s, various farming measures, including water-saving and straw management strategies have been put in place to maintain high crop yields in northern China (Zhang et al., 2019). However, fewer studies have been carried out to measure the combined effect of irrigation water management and straw incorporation on greenhouse gas emissions and crop yield in this region. Therefore, it is of great theoretical and practical value to evaluate crop yield, GHG emissions, net global warming potential (GWP) and GHG intensity (GHGI) under different irrigation scenarios and straw practices. It is also important to accurately guide for water-saving irrigation by determining the suitable irrigation system and further explaining the water-saving mechanism that improves grain production and reduces GHG emissions. The objectives of this study were to: 1) evaluate the effects of irrigation and straw practices on crop yields and GHG emissions; and 2) quantify the individual and interaction effects of irrigation and straw practices on net GWP and GHGI, in order to optimize agricultural management practices and mitigate the impacts of greenhouse gases released from wheat-maize cropping system.

2. Material and methods

2.1. Study site and treatments

The study was conducted in Ningjin County, Hebei Province (115°5′28"E, 37°37′21"N). The soil type of the study site was calcareous fluvo-aquic soil (0–20 cm) with the physio-chemical properties as follows: soil textural class was silt loam; calcium carbonate content was 3%; bulk density was 1.34 g cm^{-3}; pH (1:2.5, soil/water) was 8.04; soil organic matter was 19.9 g kg^{-1}; and total N concentration was 1.60 g kg^{-1}. Field study was carried out in the winter wheat (*T. aestivum* L.) and summer maize (*Z. mays* L.) cropping system from October 16, 2020 to October 10, 2021. In this study, straw treatment was kept in the main plot, including straw incorporation (SI) and straw removal (SR). The maize and wheat straw of the previous cropping seasons were mechanically chopped into the length of 5–8 cm and then incorporated in the soil (SI) or all removed (SR). Irrigation treatment was allocated into sub-plots under split-plot design, including surface drip irrigation (DI), sub-surface drip irrigation (SDI), partial root zone irrigation (PRI), and flood irrigation (FP), with the N fertilizer application rate of 420 kg N ha^{-1} yr^{-1}. Therefore, eight treatments with three replicates, resulting in a total of 24 plots (each with an area of 10 m length × 4 m width). As shown in Fig. S1, split applications of N fertilizer were adopted with two splits (each split was 105 kg N ha^{-1}) for each crop as follows: basal fertilization and top dressing at wheat jointing or at the 10-leaf stage of maize. In addition, phosphorous (superphosphate) and potassium (potassium sulfate) fertilizers were applied together at the rate of 135 kg P_2O_5 ha^{-1}, 105 kg K_2O ha^{-1} for wheat and 70 kg P_2O_5 ha^{-1}, 100 kg K_2O ha^{-1} for maize, respectively.

For drip irrigation, drip lines were installed with a space of 30 cm in row on surface (DI) or in subsurface soil (10 cm-depth, SDI and PRI). The pressure emitters had a water flow of 0.15 L h^{-1} and were spaced 30 cm apart. The measurements were treated from the turn-green (middle March) stage to the harvest stage in wheat season and through whole maize growth stage. The irrigation amount used in each key stage of DI and SDI was calculated by the following equation (Wang et al., 2018a):

$$I = s\rho p h \theta_f (q_1 - q_2)/\eta \quad (1)$$

where *I* is the irrigation water amount, m^3; *S* is the irrigated area, m^2; ρ is the soil bulk density (1.34 g m^{-3}); *p* is the soil wetness ratio, 0.8; *h* is the depth of the wetting soil layer, 0.4 m; θ_f is the maximum value of the field water holding capacity, 34.26%; q_1 and q_2 represent the upper irrigation limit (85%) and the measured soil moisture content, respectively, %; and η is irrigation efficiency, 0.95.

The irrigation amount used in PRI was half of DI or SDI from the turn-green stage to the harvest stage in wheat season and in whole maize season in each irrigation events. Details of the timing and amount of each irrigation and rainfall and fertilizer application at different crop growth stages for all treatments are presented in Fig. 1. Therefore, the annual irrigation amount of DI/SDI, PRI and FP were 227 mm, 137 mm and 405 mm, in which 158.1 mm, 97.7 mm and 315 mm were received during wheat (Oct. 16 2020–June 18 2021) and 68.8 mm, 39.4 mm and 90 mm were received during maize season (June 19 2021–Oct. 10 2021), respectively. The cumulative precipitation was 752.4 mm, in which 139.2 mm and 613.2 mm were received in wheat and maize season, respectively. The mean air temperature was 21.2 ℃ (−3.0 to 36.8 ℃), the mean soil temperature under SI and SR was18.6 ℃ (−0.8 to 30.4 ℃) and 19.0 ℃ (−0.1 to 30.6 ℃), respectively (Fig. 1).

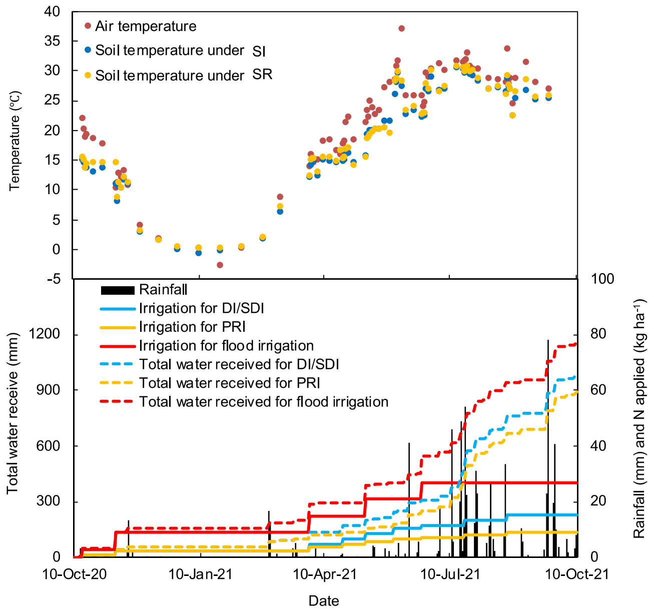

Fig. 1. Fertilization, irrigation, rainfall events, and total water received over the experimental period. Definitions of different treatments (i.e., DI, SDI, PRI, and FP) are given in caption of Table 1. SI: Straw incorporation; SR: Straw removal.

2.2. N_2O and CH_4 flux measurements

Direct greenhouse gas emissions released from the soil are CO_2, CH_4, and N_2O. However, in cropland systems, CO_2 has not yet been considered as one greenhouse gas because crops are mainly harvested and consumed within one year (Gao et al., 2018).

The gas samples of the other two GHGs (CH_4, and N_2O) were collected from June 2020 to June 2021 using a closed chamber method. In each replicated field plot, a stainless-steel base frame (30 × 30 × 10 cm) was permanently installed during the experimental period by inserting into the soil, while it would be inserted on the row laying a drip line (Fig. S1). Each chamber was made of a cube, with stainless steel walls and frames, a bottom area of 30 × 30 cm and a height of 50 cm that was adapted to the plant size. The chambers were coated with heat-insulating foam to prevent a significant change in the inner air temperature during sampling. Before we collected air samples, we filled the channel with a certain amount of water. Then, a chamber was mounted on the top of the base frame by inserting it into the channel filled with water to ensure a gas-tight enclosure. Immediately after enclosure, we took the first air sample using a 30-ml plastic syringe with a three-way valve. Later, we took another two air samples from the same chamber enclosure, at an interval of 20 min. Then, the chamber was immediately removed to allow for the least disturbance of the experimental area. The above sampling procedures were conducted at each experimental plot on two-week basis during the winter but were performed weekly during the other seasons. Sampling was carried out daily in the following three days and per three-day from 4th to 14th day following the events like fertilizer application, irrigation, rainfall, and tillage. The sampling was completed between 08:00 a.m. and 11:00 a.m. at the local standard time to obtain a single flux of a gas at each plot for the day. The gas samples were stored in glass vials (30 ml) and analyzed with an Agilent 7820 A gas chromatograph equipped with an auto-sampler and an electron capture detector within 24 h using the DN−CO_2 method for N_2O (Yan et al., 2015) and with a flame ionization detector for CH_4 (Wu et al., 2019). For the three gas samples analyzed, N_2O and CH_4 fluxes were determined by a linear method. And then the fluxes were calculated using the Eq. 2 as follows:

$$F = \frac{M}{V_0} \times \frac{P}{P_0} \times \frac{273}{273 + T} \times H \times \frac{dC_t}{dt} \tag{2}$$

where F is N_2O/CH_4 flux, μg m^{-2} h^{-1}; M is gas molar mass, g mol^{-1}; V_0 is gas volume under standard condition, 22.41 × 10^{-3} m^3; T (°C) and P (hPa) are the air temperature and pressure in each sample day; P_0 is the standard air pressure, 1013 hPa; H is height, cm; and dC_t/d_t is the rate of change of gas concentration (μg m^{-3} h^{-1}).

Cumulative GHG emissions were calculated using Eq. (3) as follows:

$$F = \sum_{i=1}^{n-1} \frac{f_{i+1} + f_i}{2} \times (t_{i+1} - t_i) \times \frac{24}{100000} \tag{3}$$

where F is the cumulative emissions (kg ha^{-1}), i (1…n) is the ith observation, and 24/100000 is the transformation coefficient unit from μg m^{-2} h^{-1} to kg ha^{-1}.

2.3. Auxiliary measurements and carbon storage

The daily data for precipitation were obtained from the meteorological station located at the experimental site. The amount of irrigation water used in each growth stage was recorded. On each sampling day, chamber, air, and topsoil (0–10 cm) temperatures were recorded using a digital thermometer.

Surface soil samples (0–20 cm) were collected at each growth stage of wheat and maize. The samples collected from the position under the drip line and between near lines were mixed into one sample, which was sieved through a 2 mm mesh. The gravimetric water content was measured using the oven-drying method at 105 ℃ for 24 h. Soil NH_4^+–N and NO_3^-–N concentrations were determined with a continuous flow analyzer (TRAACS2000, Bran and Luebbe, Norderstedt, Germany) after extraction with 1 M KCl (soil: solution = 1:5).

Another soil sample was collected from each plot using a steel cylinder (5 cm diameter) at a depth of 0–20 cm before wheat seeding (October 2020) and at maize harvest (October 2021), air-dried, sieved through 0.5 mm mesh, and divided into two subsamples to measure the pH, TN and SOC concentration. pH was determined with a pH meter (PHS-25, REX, Shanghai, China). One part of the sample was treated by immersing the soil in 0.3 mol L^{-1} HCl solution for 24 h to remove carbonates and oven-dried at 65 °C to measure SOC concentration. TN and SOC concentration were measured using a C/N analyser (Vario Max CN, Elementar, Hanau, Germany). The difference between the initial and final SOC concentration in 0–20 cm soil layer was recorded during the rotation year to determine the change rate of SOC (dSOC/dt; g C kg^{-1} yr^{-1}) (Gao et al., 2018). The soil C sequestration (ΔSOC, kg CO_2–eq ha^{-1} yr^{-1}) was calculated using Eq. (4) (Zhang et al., 2020)

$$\Delta SOC = dSOC/dt \times \rho \times 20/10 \times 44/12 \tag{4}$$

where ρ is the bulk density of the topsoil at 0–20 cm depth (g m^{-3}), and 12 and 44 are the molecular weights of C and CO_2, respectively.

2.4. Net GWP and GHGI

The direct GWP (GWP_d; kg CO_2-eq ha^{-1}) was the sum of CO_2, which is equivalent to CH_4 and N_2O. In this study, indirect GWP (GWP_i; kg CO_2-eq ha^{-1}) has been related to the use of power for irrigation, diesel fuel, herbicide, insecticide, polyethylene pipelines, labor, and seed inputs. The straw was not included in the calculation of GWP_i, since these straws were harvested and consumed within a year. The SOC change is the net balance between CO_2-eq inputs and outputs of the returned crop straws (Gao et al., 2018). The emission factors converted into CO_2-eq are described in Table S1.

The net GWP and greenhouse gas intensity (GHGI) were calculated following Eqs. (5) and(6):

$$\text{Net GWP}\left(\text{kgCO}_2 - \text{eq ha}^{-1}\right) = \text{GWP}_d + \text{GWP}_i - \Delta\text{SOC} \quad (5)$$

$$\text{GHGI (kg CO}_2\text{–eq Mg}^{-1}\text{)=Net GWP/Yield} \quad (6)$$

2.5. Statistical analysis

The results in table have been expressed as mean ± standard error of the three replicates of each treatment. Straw practices (i.e., SI and SR) and irrigation practices (i.e., DI, SDI, PRI and FP) were applied in the main and sub-plot, respectively. Sources of variation included straw, irrigation, and their interaction. The effect of different straw and irrigation practices and interaction on soil parameters, cumulative N_2O and CH_4 emissions, GWP_d, ΔSOC, net GWP, GHGI and crop yield were analyzed by SPSS 22.0 software (SPSS Inc., Chicago, IL, USA) using a two-way ANOVA at a significance level of 0.05. Significant differences among different irrigation practices under SI or SR were tested using a least significant differences (LSD) at a significance level of 0.05. Significant differences between SI and SR under DI, SDI, PRI and FP were tested using an independent t-test at a significance level of 0.05. Simple correlation analysis was performed to determine whether seasonal cumulative GHG emissions, net GWP, yield, and GHGI were related to soil conditions using Origin pro, 2021 (Origin lab, Northampton, MA, USA).

3. Results

3.1. Crop yield and soil conditions

Our results showed that straw practices significantly affect SOC concentration, NO_3^-–N and NH_4^+–N concentration, and moisture (Fig. 2), while irrigation practices significantly affected the soil pH, NH_4^+–N concentration, and moisture. In the study, a significant interaction effect of straw and irrigation was observed on C/N ratio and pH.

However, the concentration of SOC, TN, NO_3^-–N and NH_4^+–N, and C/N ratio, moisture at 0–20 cm depth of soil layer showed no significant differences under SI treatment in these four treatments. The highest pH value was observed in FP under SI (Fig. 2). However, NH_4^+–N concentration and moisture were significantly increased under SI as compared to SR in all irrigation practices.

Among all treatments, there were no significant influences of straw practices and irrigation practices and interaction effect on wheat and

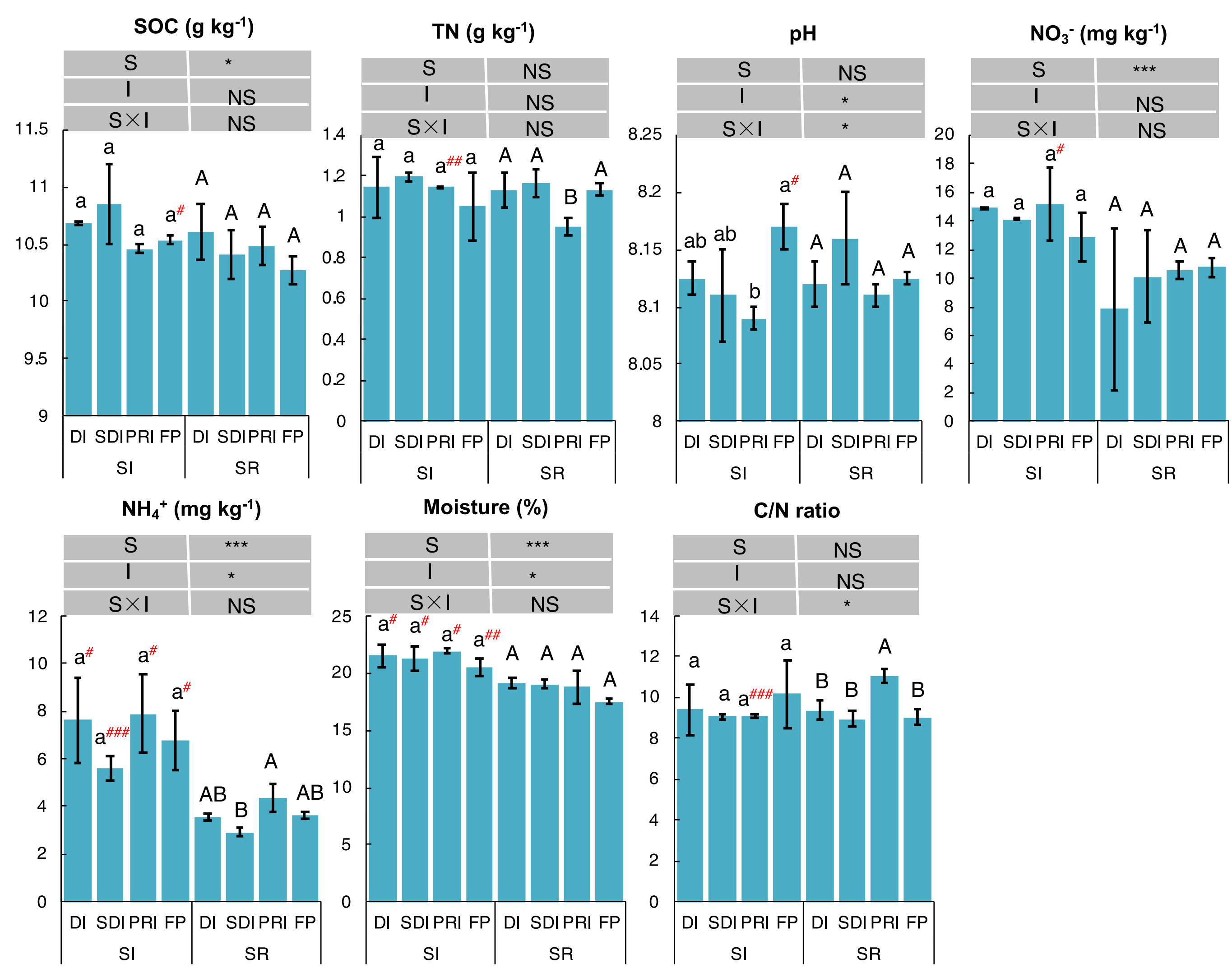

Fig. 2. Different parameters of 0–20 cm soil layer at maize harvest period. Error bars represent standard error (n = 3). Definitions of different treatments (i.e., DI, SDI, PRI, and FP) are given in caption of Table 1. S: straw practices; I: irrigation practices. * and * ** indicate the significant influence at the level of 0.05 and 0.001, respectively. NS means no significance. Different lowercase and uppercase letters indicate that the irrigation practices are significantly different at the $P < 0.05$ level under SI and SR, respectively. #, ##, and ### indicate the significant difference between SI and SR under the same irrigation practice at the level of 0.05, 0.01, and 0.001, respectively.

maize yield, but significant influences of straw practices and irrigation practices were found on annual yield (Fig. 3). SDI combined with SI was observed to produce the highest annual yield, which was 17.4 ± 0.2 Mg ha^{-1}. Additionally, NH_4^+–N concentration was significantly and negatively correlated to crop yield under SI (Fig. 4).

3.2. N_2O fluxes and cumulative emissions

Four N_2O emission pulses occurred in association with fertilizer N application events (Fig. 5). The highest peak fluxes of N_2O were found after topdressing in maize season, were 761.2 ± 46.1 μg m^{-2} h^{-1} (DI), 333.7 ± 22.7 μg m^{-2} h^{-1} (SDI), 416.4 ± 68.6 μg m^{-2} h^{-1} (PRI), 763.0 ± 96.4 μg m^{-2} h^{-1} under SI, and 765.8 ± 254.3 μg m^{-2} h^{-1} (DI), 528.1 ± 144.6 μg m^{-2} h^{-1} (SDI), 580.2 ± 98.0 μg m^{-2} h^{-1} (PRI), 1137.6 ± 63.0 μg m^{-2} h^{-1} (FP) under SR. The N_2O fluxes under SR treatment were higher than those under SI after each event of fertilizer application (with annual average increments of 16.3% and 25.8% under fertigation and flood irrigation, respectively). All of the highest average N_2O fluxes were found in FP under SI and SR treatments (Fig. S2).

The effects of straw practices ($P < 0.001$) and irrigation practices ($P < 0.001$) and an interaction effect ($P < 0.001$) were observed on N_2O emissions (Table 1). The FP had the highest cumulative N_2O emissions, which were 1.28 ± 0.08 kg N ha^{-1} for wheat and 1.79 ± 0.14 kg N ha^{-1} for maize under SI treatment, and 1.45 ± 0.01 kg N ha^{-1} for wheat and 2.27 ± 0.07 kg N ha^{-1} for maize under SR (Fig. 6). As compared to FP, the N_2O production was significantly deceased in fertigation under SI or SR (Fig. 6). For example, the annual N_2O emission of SDI was significantly decreased by 40.3% under SI and 52.8% under SR, as compared to FP. Additionally, the C/N ratio and pH significantly correlated with N_2O emissions under SR and SI treatment, respectively (Fig. 4).

3.3. CH_4 fluxes and cumulative emissions

The cropland area was observed to be a weak sink of CH_4 during the experimental period. The CH_4 emissions were significantly affected by straw practices ($P < 0.001$) and irrigation practices ($P < 0.001$, Table 1), and the emission pulses occurred in association with irrigation events (Fig. 5). The highest average of CH_4 fluxes was observed in FP under SI (Fig. S2), which caused the highest cumulative CH_4 emissions at − 0.94 kg ha^{-1} under SI (Fig. 7). The CH_4 emissions were significantly decreased by 17.1% (SDI) and 14.0% (PRI) under SI as compared to SR, respectively (Fig. 7). Additionally, soil moisture and pH significantly correlated with CH_4 emissions under SR and SI treatments, respectively (Fig. 4).

3.4. Indirect GHG emissions, global warming potential and intensity

For annual GWP_i, the smallest value (4239.5 kg CO_2–eq ha^{-1}) was observed in PRI, which was 29.8% lower than FP. For all treatments, fertilizer and electricity were the major contributors, accounting for 23.4–33.3% and 29.8–61.7% of GWP_i release, respectively (Fig. S3).

As shown in Table 1, straw and irrigation practices both significantly affected net GWP and GHGI. SI was beneficial to reduce net GWP and GHGI, in which, the net GWP (3785.7 kg CO_2–eq ha^{-1}) and GHGI (217.4 kg CO_2–eq Mg^{-1}) of SDI under SI were decreased by 23.6% ($P < 0.05$) and 27.3% ($P < 0.05$) as compared to SR.

4. Discussion

4.1. Crop grain yield

Under intensive agricultural practices, soil production ability and crop yield tend to decline with the continuous removal of straw (Yuan et al., 2021). The attainable yield of irrigated annual wheat -maize rotation ranged from 16.9 to 20.4 Mg ha^{-1} with an average of 18.8 Mg ha^{-1} (Gao et al., 2022; Lu and Fan, 2013; Wang et al., 2023). As shown in this study, the annual yield ranged from 16.1 to 17.4 Mg ha^{-1}, which was respected to previous studies. However, only a significant increase by 5.0% in SDI under SI as compared to SR was observed (Fig. 3). SDI can maintain a long duration with wet soil (Fig. S5), SI can supply organic C source (Liu et al., 2014), which both were beneficial for microbial decomposition of straw through mineralization and humification to produce simple organic compounds (e.g., SOC) and nitrogen compounds (e.g., NO_3^-–N, NH_4^+–N) (Fig. 2, Table 1; Wang et al., 2021b), that are

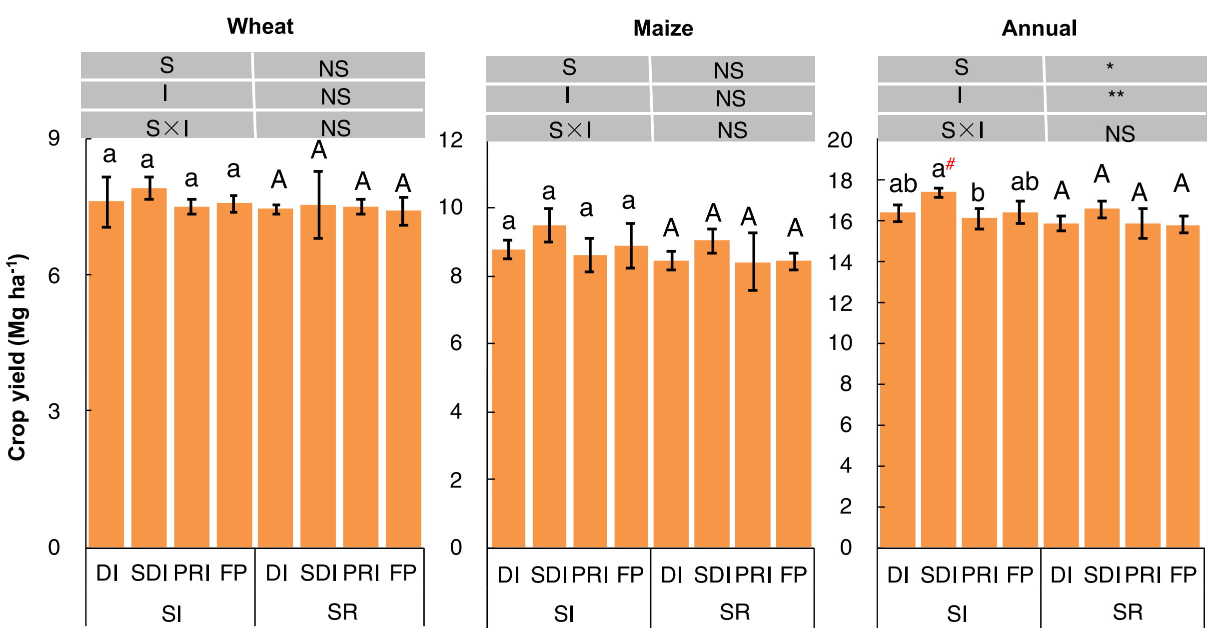

Fig. 3. Wheat, maize and annual yield (Mg ha^{-1}) in different treatments. Error bars represent standard error (n = 3). Definitions of different treatments (i.e., DI, SDI, PRI, and FP) are given in caption of Table 1. S: straw practices; I: irrigation practices. * and * * indicate the significant influence at the level of 0.05 and 0.01, respectively. NS means no significance. Different lowercase and uppercase letters indicate that the irrigation practices are significantly different at the $P < 0.05$ level under SI and SR, respectively. # indicates the significant difference between SI and SR under the same irrigation practice at the level of 0.05. Error bars mean standard error.

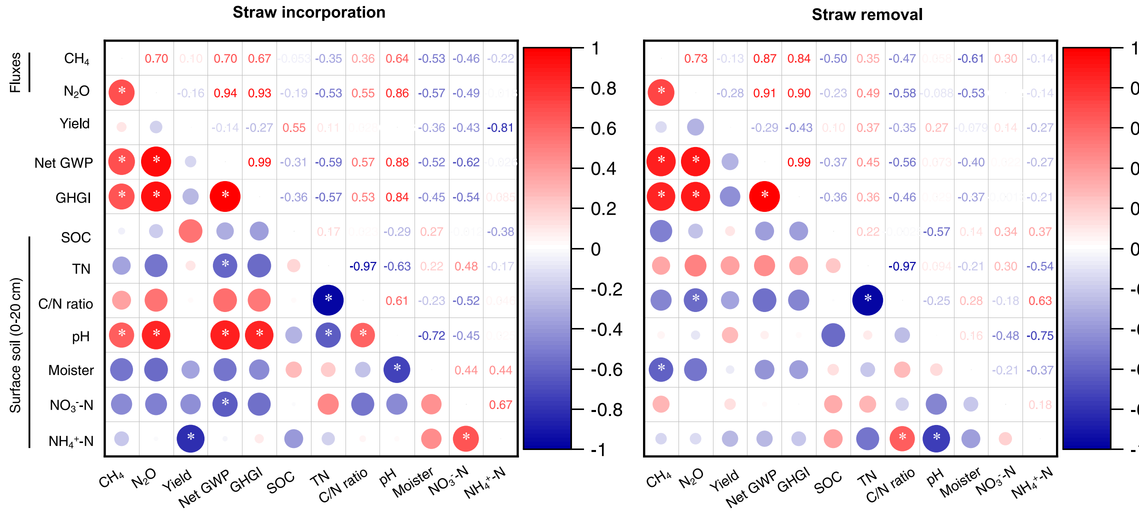

Fig. 4. Correlation analysis among direct GHG, yield, net GWP, GHGI, and surface soil parameters. Red bubbles mean positive correlation, blue bubbles mean negative correlation. Asterisk indicates a significant correlation at $P < 0.05$, the values mean the correlation coefficients.

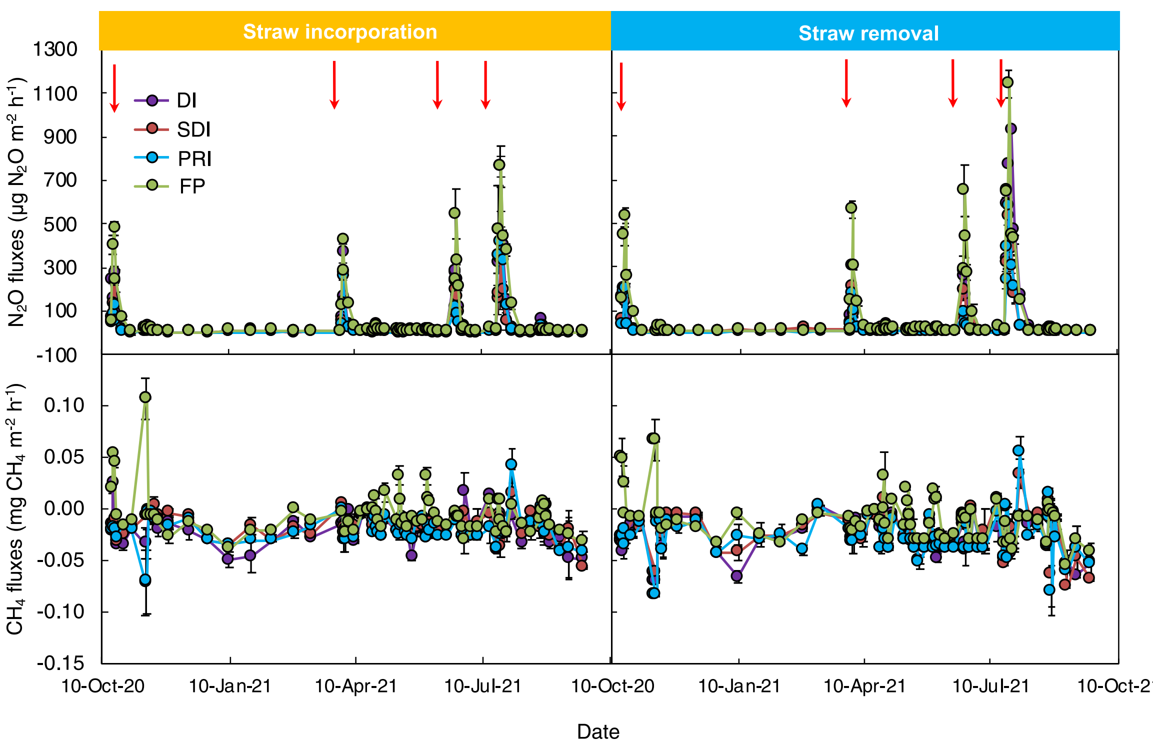

Fig. 5. N_2O and CH_4 fluxes under straw incorporation and removal. Error bars represent standard error (n = 3). The arrows indicate N fertilizer application events. Definitions of different treatments (i.e., DI, SDI, PRI, and FP) are given in caption of Table 1.

important for plant growth and therefore have a positive effect on crop yield (Islam et al., 2022; Fig. S4).

Northern China is a semi-arid region with dry winter and wet summer. Water is a limiting factor, especially for wheat (Li et al., 2019). Therefore, a better drip fertigation measurement could improve grain yield and fertilization efficiency (Bai et al., 2020). In addition, irrigation practice was the main contributor (accounted for 39.3%, $P < 0.01$) to crop yield while irrigation amount was only accounted for 11.9% through a redundancy analysis (Table S2), which emphasized that irrigation practices have a significant impact on crop yield (Fig. 3). Eventhough, SDI was found to be the best practice to achieve the maximum annual yield and 8.0% higher ($P < 0.05$) than PRI under SI, no significant difference was found among DI, SDI and FP. This is likely a consequence of: 1) higher water evaporation under surface irrigation (DI), which shortens the duration of suitable WFPS as compared to SDI (Fig. S5); 2) excessive water stress in PRI reduced the available C release from straw thus restricting the crop yield (Islam et al., 2022); 3) flood irrigation might cause an excessive build-up of water in the soil, and thus lead to anoxia over an extended period of time, which was not beneficial for soil nutrient transport and root respiration (Yu et al., 2020). Eventhough, the annual yield of SDI+SI has reached up to 17.4 Mg ha^{-1}, but there is still a yield gap to reach 18.8 Mg ha^{-1} in irrigated field (Lu and Fan, 2013; Wang et al., 2023).

Table 1
The annual yield, ΔSOC, GWP and GHGI over the experimental period.

Straw treatment	Irrigation treatment	Direct emission		GWP_d	GWP_i	ΔSOC	Net GWP	GHGI
		N_2O	CH_4	kg CO_2-eq ha^{-1} yr^{-1}				kg CO_2-eq Mg^{-1}
		kg CO_2-eq ha^{-1} yr^{-1}						
Straw incorporation	DI	965.7 ± 12.6b$^{\#\#}$	-48.0 ± 0.2c$^{\#}$	917.8 ± 12.8b$^{\#\#}$	5066.1	1344.6 ± 342.4a	4639.3 ± 355.2b$^{\#}$	283.3 ± 26.0b$^{\#}$
	SDI	639.4 ± 58.2c$^{\#}$	-37.7 ± 1.0b$^{\#}$	601.7 ± 57.9c$^{\#}$	5066.1	1882.0 ± 367.3a$^{\#}$	3785.7 ± 393.7b$^{\#}$	217.4 ± 23.1c$^{\#}$
	PRI	579.6 ± 21.2c	-44.0 ± 3.3c$^{\#}$	535.6 ± 23.9c	4239.5	992.7 ± 378.2a	3782.4 ± 354.3b	234.3 ± 19.2 BCE
	FP	1438.1 ± 83.9a$^{\#\#}$	-23.6 ± 0.2a$^{\#}$	1414.5 ± 83.7a$^{\#\#}$	6036.0	1168.0 ± 91.5a	6282.4 ± 175.2a	381.6 ± 0.9a
Straw removal	DI	1267.3 ± 58.0b	-52.5 ± 0.9c	1214.8 ± 58.8b	5066.1	691.1 ± 124.0a	5589.7 ± 65.2b	351.4 ± 9.3b
	SDI	793.7 ± 21.1c	-45.5 ± 1.9b	748.3 ± 19.5c	5066.1	856.0 ± 187.9a	4958.3 ± 168.3 BCE	298.9 ± 11.5 BCE
	PRI	595.7 ± 5.1d	-51.2 ± 1.0c	544.5 ± 4.2d	4239.5	549.4 ± 242.4a	4234.6 ± 238.1c	266.9 ± 23.1c
	FP	1741.5 ± 30.1a	-28.9 ± 1.9a	1712.6 ± 31.7a	6036.0	906.1 ± 440.6a	6842.5 ± 472.2a	433.0 ± 38.5a
Strawpractices (S)		* **	* **	* **	-	* *	* **	* **
Irrigation practices (I)		* **	* **	* **	-	NS	* **	* **
S×I		* **	NS	* **	-	NS	NS	NS

Note: Means ± standard error. DI: surface-drip irrigation with N application at 420 kg N ha^{-1} yr^{-1}; SDI: sub-surface drip irrigation with N application at 420 kg N ha^{-1} yr^{-1}; PRI: alternate partial rootzone irrigation under subsurface drip irrigation system with N application at 420 kg N ha^{-1} yr^{-1}; FP: flood irrigation with N application at 420 kg N ha^{-1} yr^{-1}. GWP: Global warming potential; GHGI: greenhouse gas intensity; Different letters within columns indicate significant differences among DI, SDI, PRI and FP under SI or SR by applying the Least Significant Difference (LSD) test at $P < 0.05$. $^{\#}$, $^{\#\#}$ indicate significant differences between SI and SR under DI, SDI, PRI or FP at 0.05 and 0.01 significance levels, respectively. * , * * and * ** represent the 0.05, 0.01 and 0.001 significance levels, respectively. NS, not significant. No statistical tests are applied for GWP_i because only a value for each treatment was observed.

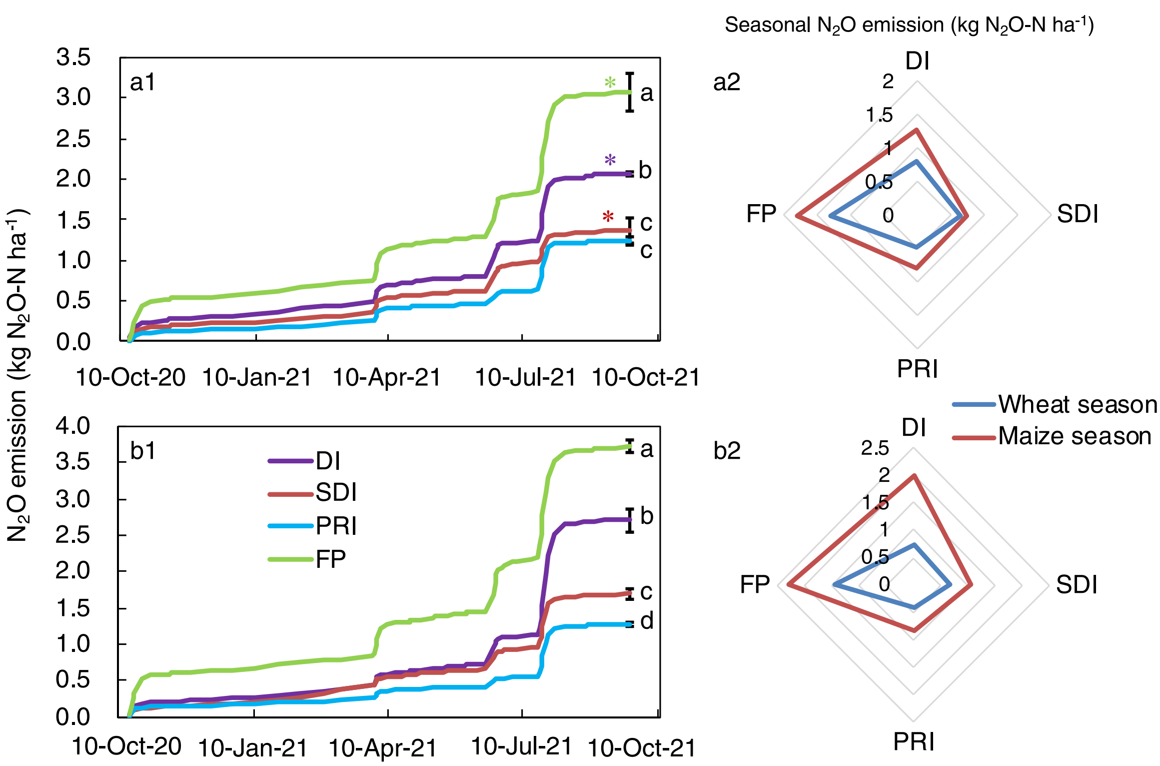

Fig. 6. Cumulative N_2O emissions under (a) straw incorporation and (b) straw removal. Error bars represent standard error (n = 3). a2: seasonal N_2O emissions under SI; b2: seasonal N_2O emissions under SR. Definitions of different treatments (i.e., DI, SDI, PRI, and FP) are given in caption of Table 1. Different lowercase letters indicate that the irrigation practices are significantly different at the $P < 0.05$ level under SI and SR. * indicates the significant difference between SI and SR under the same irrigation practice at the level of 0.05.

4.2. Soil organic carbon

The changes in SOC are a result of changes in the net balance between inputs (application of straw) and outputs (soil respiration) (Smith et al., 2010). Different farming managements (e.g., straw incorporation, fertilization, irrigation) can help with sequestration of carbon in soil by increasing SOC and reducing the available carbon for GHG emission, thereby, contributing to climate change mitigation (Tang et al., 2023; Yagioka et al., 2015; Zhang et al., 2020). This study observed 0.9–1.7% increase in the concentration of SOC with SI, as compared to a 0.5–0.9% increase with SR (Fig. S6, $P < 0.05$), which caused a 28.9–119.8% higher of ΔSOC under SI than SR (Table 1). Lal (2007) reported that, the

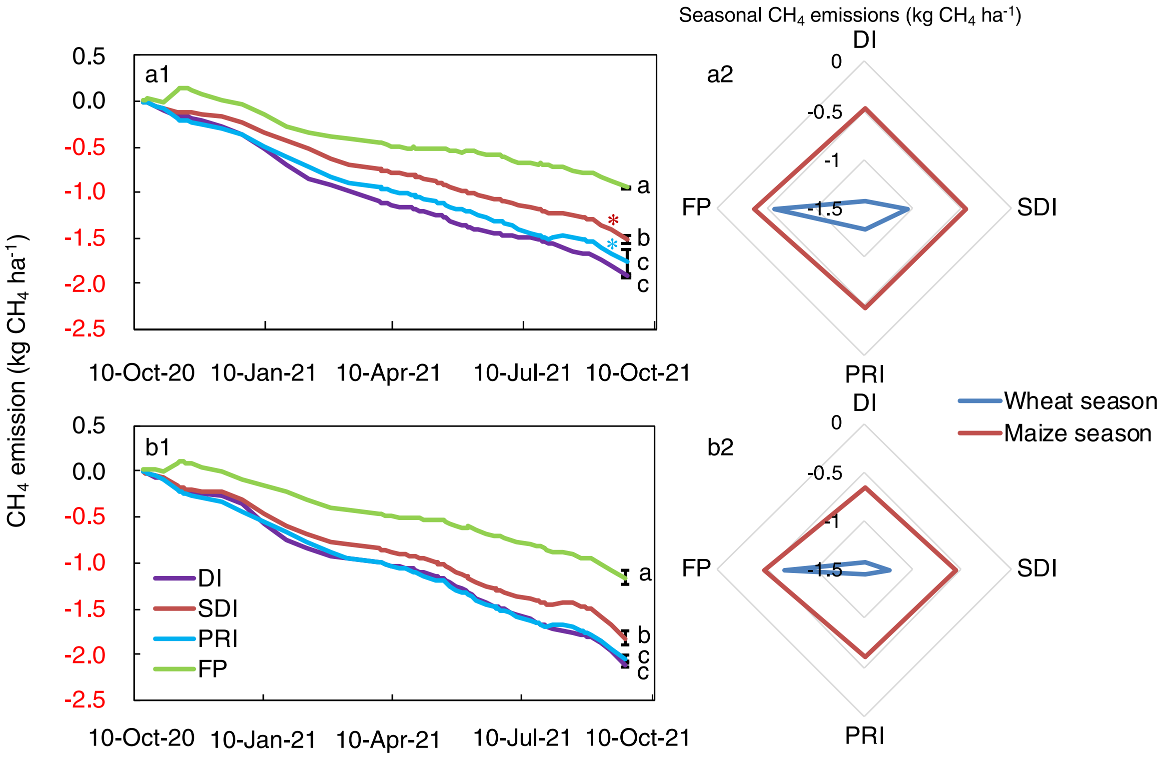

Fig. 7. Cumulative CH_4 emissions under (a) straw incorporation and (b) straw removal. Error bars represent standard error (n = 3). a2: seasonal N_2O emissions under SI; b2: seasonal N_2O emissions under SR. Definitions of different treatments (i.e., DI, SDI, PRI, and FP) are given in caption of Table 1. Different lowercase letters indicate that the irrigation practices are significantly different at the $P < 0.05$ level under SI and SR. * indicates the significant difference between SI and SR under the same irrigation practice at the level of 0.05.

rate of SOC accrual reached 0.3–0.5 Mg C ha^{-1} yr^{-1} (equivalate to 0.12–0.19 g kg^{-1} yr^{-1} increase of SOC concentration) under intensive agricultural practices with use of crop straw, corresponding to the observations in this study at the increase rate of 0.10–0.18 g kg^{-1} yr^{-1} (Table S3). As straw is incorporated, up to 65% of wheat straw and 77% of maize straw are decomposed annually, aiding significant soil C sequestration (Wang et al., 2012), which highlighted strong potential for soil C sequestration in this region, suggesting that use of straw can facilitate accumulation of SOC in agroecosystems and be considered for future agricultural management practices.

Irrigation changes the soil water environmental conditions, and indirectly affects soil aeration, microbial, and enzymatic activity (Šnajdr et al., 2008), thus affecting nutrient mineralization and its utilization by plants (Kamoni et al., 2015). SOC increased by 1.4–3.3% under drip irrigation as compared to FP (Fig. 2). It means irrigation benefited from the accumulation of SOC as demonstrated in a previous study (Zhang et al., 2020). Increasing soil moisture by heavy flood irrigation can inhibit the decomposition of soil organic matter under general anaerobic conditions (Moyano et al., 2013). During all treatments, the highest ΔSOC (1882.0 ± 367.3 kg CO_2–eq ha^{-1} yr^{-1}) was found under SDI treatment using SI (Table 1). The reason probably was the longer duration and higher WFPS (Fig. S5) due to the irrigation water was supplied into sub-surface soil layer (10 cm) to reduce the water evaporation, but increased the water moisture which inhibited the mineralization of SOC by microorganisms (Bozkurt and Mansuroglu, 2018; Cai et al., 2021), thus contributed to SOC increase (Fig. 4). However, compared to the high SOC concentration of 14.5–23.2 g kg^{-1} in Europe and US (Gao et al., 2018), there is still a large potential to increase SOC concentration in recent agroecosystems.

4.3. N_2O and CH_4 emissions

The N_2O emissions are produced from soil under both aerobic and anaerobic conditions (Mutegi et al., 2010), whereas, CH_4 emissions from irrigated soil are controlled by the production, oxidation, and transport processes, and produced under strictly anaerobic conditions as a terminal product of anaerobic mineralization of soil organic matter (SOM) (Lagomarsino et al., 2016).

In this study, a significant reduction in annual N_2O emissions was observed in DI, SDI and FP under SI by 23.8%, 19.4% and 17.4%, respectively (Fig. 6). Crop straw with a high C/N ratio (>25) usually interacted with N fertilization and forces the microbial N immobilization by reducing the available N pool for nitrifiers and denitrifying microbes. The C/N ratio of wheat and maize straw utilized in this study was greater than 25 as shown by Xu et al. (2019) and Li et al. (2021a), which might explain the significant reduction in N_2O production. The CH_4 emissions were shown to be significantly and positively related to SOC concentration (Wang et al., 2019; Huang et al., 2022), for example, the increment of SOC concentration (showed in Fig. 2) can provide abundant methanogenic substrates for methanogens, thus, stimulating CH_4 production and consequent emissions under SI as compared to SR. Overall, the SI benefited N_2O mitigation but inhibited the CH_4 uptake.

In the past several decades, many studies have looked at the effects of water conditions on N_2O and CH_4 emissions in wheat-maize cropping systems (Kennedy et al., 2013; Sainju et al., 2014; Li et al., 2019; Zhao et al., 2021). The most used water-saving irrigation regimes include sprinkler irrigation, drip irrigation, subsurface drip irrigation, and partial rooting irrigation. A global meta-analysis shows that drip irrigation significantly reduced N_2O emissions by 32% and 46% when compared to furrow and sprinkler irrigation systems, respectively (Kuang et al., 2021). Estimate from this study show the average emission factor of N_2O was 0.35% under drip irrigation as compared to 1% reduction of N_2O calculated by IPCC. Lower N_2O emissions are associated with several factors. First, soil water content under drip irrigation is lower than conventional irrigation, inhibiting the activity of N_2O-producing microbes and thereby, reducing N_2O production (Sánchez-Martín et al., 2008). Secondly, lower concentrations of N supplied through drip irrigation system (fertigation) are better utilized by crops and thus prevent its losses to the environment (Kennedy et al., 2013). Thirdly, using subsurface driplines under the 10 cm of soil layer (SDI), prevents accumulation of N fertilizer over the surface soil when water evaporates, thus resulting in higher WFPS (Fig. S5) than DI and limiting the gas diffusivity, i.e., the diffusion of soil N_2O into the atmosphere.

The soil in northern China is a sink for CH_4 emissions (Fig. 7; Li et al., 2019). Water-saving irrigation regimes are, therefore, beneficial in reducing CH_4 emissions in wheat-maize fields and ensure stable crop yield at the same time (Wu et al., 2019). In Fig. 5, only a peak flux of CH_4 can be observed after flood irrigation. This is likely due to the anaerobic soil conditions that stimulated methanogenic bacteria following heavy irrigation and therefore resulted in a substantial increase in CH_4 emissions during the wheat and maize seasons (Itoh et al., 2011). SDI can lead to aerobic conditions allowing oxidation of CH_4 due to lower soil moisture as compared to FP (Fig. S5). Evidently, SDI and PRI were the best methods for N_2O mitigation and CH_4 sink.

4.4. Net GWP and GHGI

Net GWP is often calculated by using CO_2 equivalents of soil, i.e. the CH_4 and N_2O emissions, along with different farm management and agrochemical inputs (Ruan and Philip Robertson, 2013; Huang et al., 2022). However, these measurements do not take into account CO_2 emissions from soil (Gao et al., 2018). Here, the fate of GHGs including direct (soil N_2O and CH_4 emissions), indirect (different farm management and agrochemical inputs), and SOC change needed to be considered when calculating the net GHG sink or source (Sainju et al., 2014; Gao et al., 2018). Drip irrigation is beneficial in directly reducing greenhouse gas emissions (i.e., N_2O and CH_4 mitigation) and also indirect GHG (i.e., power for irrigation) emissions, and SDI and PRI have been identified as the best choices for this objective (Fig. S3, Table 1). The reduction in N_2O emissions might offset the increase of CH_4 emissions when straw is incorporated and help to further decrease direct GHG emissions. In a cropping system, CH_4 fluxes generally did not contribute to net GWP (Sainju et al., 2014). However, indirect GHGs, released from fertilizer, pesticides, seeds, power use for irrigation, diesel fuel, polyethylene lines, and labour, may have strongly contributed to net GWP, and followed by ΔSOC (Zhang et al., 2020). Overall, SDI significantly improved ΔSOC and lowered N_2O production, and power for irrigation, thus reduced the net GWP under SI as compared to SR. The net GWP values of drip irrigation were significant lower than that of FP, which was comparable with previous studies (Yagioka et al., 2015).

GHGI provides a platform for comparing the effects of irrigation and straw practices on net GWP per unit of yield (Grassini and Cassman, 2012; Gao et al., 2018). In our study, GHGI was observed to be significant lower in DI (283.3 kg CO_2–eq Mg^{-1}) and SDI (217.4 kg CO_2–eq Mg^{-1}) under SI as compared to SR (Table 1), which is similar to 117.3–223.7 kg CO_2–eq Mg^{-1} reported in the United States (Cavigelli et al., 2009; Grassini and Cassman, 2012), and is also lower than that of 491.3–535.3 kg CO_2–eq Mg^{-1} reported in China (Gao et al., 2018) for irrigated wheat and maize systems. Additionally, the lowest GHGI was found in SDI under SI because of the highest annual yield. Therefore, SDI combined with SI is concluded to be the best combination for improved grain yield with lower GHG emissions. However, many previous studies have indicated that China still has a large potential to reduce net GWP and GHGI. It is therefore an essential target for future sustainable agriculture to close the gap between China and other developed countries with low net GWP and GHGI (Ju et al., 2009; Chen et al., 2014; Gao et al., 2018).

5. Conclusion

Limited irrigation water resources and high storage of crop residue are the main challenges faced by resource managers in intensive wheat-maize cropping system in northern China. Fertigation treatments (i.e., DI, SDI and PRI) are all significantly contributed to reduce GWP_i, net GWP and GHGI under SI or SR as compared to FP. SDI significantly decreased the N_2O production and increased soil C sequestration, reducing net GWP and GHGI under SI when compared with SR. Under SI, PRI resulted in the lowest annual yield, which was not beneficial to reduce GHGI. Therefore, SDI combined with SI simultaneously mitigated GHG emissions, reduced the global warming potential, improved yield and enhanced soil C sequestration, making it an alternative and effective method for the sustainable farming system with minimal environmental damage.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108281.

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