Greenhouse Gas Exchange and Integrated Global Warming Potential in Wheat-Maize Rotation Cropland under Different Tillage Practices: Postprint

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Abstract

Investigating the comprehensive global warming potential (GWP) of greenhouse gases such as N2O, CO2, and CH4 from wheat-maize rotation fields under different tillage practices helps scientifically evaluate the role of agricultural management measures in reducing greenhouse gas emissions and mitigating global warming, providing a basis for formulating greenhouse gas mitigation strategies. Based on a long-term experiment initiated in 2001 at the Luancheng Agro-Ecosystem Experimental Station of the Chinese Academy of Sciences located in the piedmont plain of the Taihang Mountains in North China, the emission fluxes of N2O, CO2, and CH4 from soils in winter wheat-summer maize rotation fields were dynamically monitored for two consecutive crop rotation years starting from October 2008 when winter wheat was sown, using the static chamber/gas chromatography method. Five treatments were examined: whole straw mulching with no-till seeding (M1), chopped straw mulching with no-till (M2), chopped straw incorporation with rotary tillage (X), chopped straw incorporation with deep plowing (F), and no straw return with deep plowing (CK, representing conventional tillage), and their total emissions were estimated. During the experiment, mechanical fuel consumption for each farming activity, irrigation electricity consumption, and fertilizer application rates were recorded synchronously. These were uniformly converted to equivalent carbon amounts based on carbon emission coefficients for fuel, electricity, and per-unit fertilizer quantities. Crop yields and aboveground biomass were measured, farmland carbon sequestration was estimated, and the comprehensive global warming potential (GWP) of the five treatments was calculated according to the contribution of each component to the greenhouse effect. The results showed that soils in the wheat-maize rotation fields in North China were emission sources for N2O and CO2, and a sink for CH4. The total annual N2O emissions from farmland soils for M1, M2, X, F, and CK were 2.06 kg(N2O-N) · hm-2, 2.28 kg(N2O-N) · hm 2, 2.54 kg(N2O-N) · hm 2, 3.87 kg(N2O-N) · hm 2, and 2.29 kg(N2O-N) · hm 2, respectively. The total CO2 emissions were 6 904 kg(CO2-C) · hm-2, 7 351 kg(CO2-C) · hm-2, 8 873 kg(CO2-C) · hm-2, 9 065 kg(CO2-C) · hm-2, and 7 425 kg(CO2-C) · hm-2, respectively. The CH4 uptake amounts were 2.50 kg(CH4-C) · hm-2, 1.77 kg(CH4-C) · hm-2, 1.33 kg(CH4-C) · hm-2, 1.38 kg(CH4-C) · hm-2, and 1.57 kg(CH4-C) · hm-2, respectively. The comprehensive global warming potential (GWP) values for the M1 and M2 treatment agroecosystems were both negative, indicating that farmland ecosystems under no-till conditions served as carbon sinks for the atmosphere. After deducting the equivalent carbon from direct or indirect emissions caused by farming activities, the agroecosystems net sequestered 947~1 070 kg(C) · hm-2 annually. The GWP values for the other treatments were all positive, indicating that greenhouse gases were emitted from the system to the atmosphere. CK, F, and X emitted equivalent carbon of 3 364 kg(C) · hm-2, 989 kg(C) · hm-2, and 343 kg(C) · hm-2 to the atmosphere annually, respectively. Therefore, in the wheat maize rotation system in North China, chopped straw incorporation with rotary tillage is the most optimized tillage practice, as it has relatively low greenhouse effects while ensuring higher economic yields.

Full Text

Preamble

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Greenhouse Gas Exchange and Comprehensive Global Warming Potential Under Different Tillage Practices in Wheat-Maize Rotation Systems

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Abstract

Investigating the comprehensive global warming potential (GWP) of greenhouse gases such as N_2O, CO_2, and CH_4 from wheat-maize rotation fields under different tillage practices is essential for scientifically evaluating the role of agricultural management in mitigating greenhouse gas emissions and global warming, and for providing a basis for developing emission reduction measures. Based on long-term positioning experiments initiated in 2001 at the Luancheng Agroecosystem Experimental Station of the Chinese Academy of Sciences in the piedmont plain of the Taihang Mountains, we continuously monitored soil N_2O, CO_2, and CH_4 fluxes for two complete crop rotation cycles starting from October 2008 (winter wheat sowing) using the static chamber/gas chromatography method. Five treatments were examined: (1) no-tillage with whole maize residue mulching (M1), (2) no-tillage with chopped maize residue mulching (M2), (3) rotary tillage with chopped maize residue incorporation (X), (4) moldboard ploughing with chopped maize residue incorporation (F), and (5) moldboard ploughing with maize residue removal (CK, representing conventional tillage). Total emissions were estimated for each gas. During the experimental period, we recorded fuel consumption for machinery, electricity consumption for irrigation, and fertilizer application rates for each farming activity, converting these inputs into carbon equivalents based on established emission coefficients. Crop yields and aboveground biomass were measured to estimate carbon sequestration in the agroecosystem. The comprehensive GWP for each treatment was then calculated based on the contribution of each component to the greenhouse effect.

The results indicated that wheat-maize rotation fields in North China served as emission sources for N_2O and CO_2, but as a sink for CH_4. Annual total N_2O emissions were 2.06, 2.28, 2.54, 3.87, and 2.29 kg(N_2O-N) $\cdot$ hm^{-2} for M1, M2, X, F, and CK, respectively. Annual total CO_2 emissions were 6,904, 7,351, 8,873, 9,065, and 7,425 kg(CO_2-C) $\cdot$ hm^{-2}, respectively. Annual CH_4 uptake rates were 2.50, 1.77, 1.33, 1.38, and 1.57 kg(CH_4-C) $\cdot$ hm^{-2}, respectively. The GWPs for M1 and M2 were negative, indicating that no-tillage systems with straw mulching functioned as carbon sinks. After accounting for direct and indirect carbon emissions from farming activities, these systems sequestered 947–1,070 kg(C) $\cdot$ hm^{-2} annually. The GWPs for the other treatments were positive, indicating net greenhouse gas emissions to the atmosphere. Annual emissions were 3,364, 989, and 343 kg(C) $\cdot$ hm^{-2} for CK, F, and X, respectively. Therefore, for wheat-maize rotation systems in North China, rotary tillage with chopped straw incorporation represents the optimal tillage practice, offering relatively low greenhouse effects while maintaining high economic yields.

Keywords: Tillage measure; Straw return; Greenhouse gas; Greenhouse effect; Global warming potential; Wheat-maize rotation system

Introduction

Global climate change has attracted significant international attention, with research on the greenhouse effect, greenhouse gas mitigation, and energy conservation becoming a major focus. CO_2, CH_4, and N_2O are the most important greenhouse gases in the atmosphere, collectively contributing nearly 80% of the greenhouse effect. CO_2 has the largest contribution (approximately 60%) and is the most significant greenhouse gas. CH_4 has a global warming potential 21–25 times that of CO_2, contributing about 15% to the enhanced greenhouse effect. N_2O has a warming potential 296–310 times that of CO_2, contributing approximately 5% to the greenhouse effect. Due to their different warming potentials, these gases have varying impacts on global warming. When all three gases are emitted simultaneously from a system, their combined effect must be calculated to understand the system’ s overall contribution to global warming.

The comprehensive global warming potential (GWP) of farmland ecosystems encompasses not only direct greenhouse gas emissions from soil but also direct CO_2 emissions from agricultural machinery fuel consumption and indirect emissions from fertilizer production, transportation, and irrigation electricity consumption. Additionally, carbon sequestration through crop growth must be considered as it offsets the greenhouse effect. Therefore, comprehensive assessment of farmland ecosystem GWP requires accounting for direct soil emissions, indirect emissions from farming activities, and carbon sequestration, all converted to carbon equivalents for precise evaluation. Current domestic research on GWP has primarily focused on soil properties and the effects of fertilization and irrigation on greenhouse gas emissions, often overlooking CO_2 emissions from machinery fuel, fertilizer production and transportation, and irrigation energy consumption, as well as carbon sequestration by crops. Tillage practices significantly influence both crop yields and greenhouse gas emissions from farmland, yet quantitative studies on their effects on comprehensive GWP remain limited.

This study builds upon long-term positioning experiments initiated in 2001 to continuously monitor soil greenhouse gas emissions, CO_2 emissions from agricultural inputs, and carbon sequestration by crops in wheat–maize rotation fields in North China. We comprehensively analyzed the GWP of soil greenhouse gas (CO_2, CH_4, N_2O) emissions under different tillage practices, the overall warming effects of different tillage systems, and the contribution of conservation tillage to mitigating greenhouse effects. The results provide a basis for developing emission reduction measures and reducing uncertainties in climate change predictions.

1.1 Study Area and Experimental Design

The experiment was conducted at the Luancheng Agro-ecosystem Experimental Station of the Chinese Academy of Sciences, located in the piedmont plain of the Taihang Mountains in North China (37°50 N, 114°40 E, elevation 50.1 m). The region has a warm temperate semi-humid monsoon climate with an average annual temperature of 12.2 °C and mean annual precipitation of 536.8 mm, concentrated in July, August, and September. The frost-free period is approximately 200 days, and the soil type is cinnamon soil.

The winter wheat-summer maize rotation is the dominant cropping system in this region. Winter wheat is sown in early October and harvested in early June, while summer maize is mechanically sown after wheat harvest and harvested at the end of September. Straw is returned to the field for both crops. Wheat receives two fertilizer applications: a basal application before sowing (incorporated through tillage) and a topdressing at the jointing stage (surface-applied followed by irrigation). Maize receives a single topdressing at the big trumpet stage (surface-applied followed by irrigation).

From October 2008 to September 2010, we conducted experiments within a long-term tillage and straw return trial established in 2001. Based on soil tillage methods at winter wheat sowing, treatments included moldboard ploughing, rotary tillage, and no-tillage, each with different straw management: (1) no-tillage with whole maize residue mulching (M1), (2) no-tillage with chopped maize residue mulching (M2), (3) rotary tillage with chopped maize residue incorporation (X), (4) moldboard ploughing with chopped maize residue incorporation (F), and (5) moldboard ploughing with maize residue removal (CK, representing conventional tillage). For ploughing treatments, maize straw was mechanically crushed twice before deep ploughing (20 cm), land leveling, and sowing. For rotary tillage, straw was crushed twice before two passes of rotary cultivation (15 cm) to create a mixed straw-soil layer. The M1 treatment used a 2BMFS-5/10 no-till planter for direct seeding through whole straw mulch. The M2 treatment involved straw crushing followed by no-till planting with the same equipment. Sowing rates were 195 $kg \cdot hm^{-2}$ for CK and F, 210 $kg \cdot hm^{-2}$ for X, and 285 $kg \cdot hm^{-2}$ for M1 and M2. All treatments received identical basal (300 $kg \cdot hm^{-2}$ diammonium phosphate, 75 $kg \cdot hm^{-2}$ urea) and topdressing (300 $kg \cdot hm^{-2}$ urea) fertilizers. Irrigation amounted to 157.5 mm during the wheat season. Wheat was harvested annually with a combine harvester, with all straw returned to the field. Maize received 435 $kg \cdot hm^{-2}$ urea at the big trumpet stage and 70 mm irrigation.

1.2.1 Soil Greenhouse Gas Collection and Environmental Monitoring

Gas samples were collected using the static chamber method. The sampling chamber consisted of a box (60 cm × 20 cm × 40 cm) with a fan and gas sampling port on top, and a base inserted 15 cm into the soil between crop rows after sowing. Sampling occurred between 8:00 and 12:00 AM. The chamber was sealed with water one minute before sampling, the fan was activated to mix internal air, and gas samples were collected at 0, 15, 30, and 45 minutes using 50 mL syringes for flux calculation. To accurately estimate total CO_2 emissions, sampling frequency was once weekly during most of the year and 0.5–1 times weekly in winter, with increased frequency after nitrogen fertilization. Samples were analyzed the same day using an Agilent 6820 gas chromatograph equipped with an electron capture detector, a 4 m × 4 mm Porapack Q (80–100 mesh) column at 70 °C, detector temperature at 300 °C, and high-purity nitrogen

(99.999%) carrier gas at 20 $\mathrm{mL \cdot min^{-1}}$ with 2 mL injection volume.

During gas sampling, atmospheric and surface temperatures, 5 cm soil temperature, 0–10 cm soil samples for nitrate and ammonium content, and soil moisture were monitored synchronously. To improve estimation of daily soil respiration rates and total CO_2 emissions between monitoring intervals using the strong correlation between soil respiration and temperature/moisture, 5 cm soil temperature and 0–10 cm soil moisture were monitored daily.

1.2.2 Soil Greenhouse Gas Flux and Total Emissions

Since greenhouse gas concentrations in chambers change linearly over short periods, fluxes were calculated using:

$$F = \frac{h \cdot M \cdot P}{R \cdot T} \cdot \frac{dc}{dt}$$

where F is gas flux ($\mathrm{mg \cdot m^{-2} \cdot h^{-1}}$), ρ is gas density, R is the gas constant, dm and dc are changes in gas mass and concentration over time dt, h, A, and V are chamber height (m), base area ($\mathrm{m^2}$), and volume ($\mathrm{m^3}$), M is molecular weight, T is absolute temperature, and P is pressure. Negative F indicates soil or soil-crop system absorption; positive F indicates emission.

To improve CO_2 emission estimates, we established relationships between soil respiration rate and temperature/moisture:

$$R = a \cdot e^{bT} \cdot W^c$$

where R is soil respiration rate, T is 5 cm soil temperature, W is 0–10 cm soil moisture, and a, b, c are fitted parameters.

Based on calculated CO_2 fluxes and synchronous temperature/moisture measurements, exponential relationships were developed for each treatment to estimate daily respiration rates, which were integrated to calculate total CO_2 emissions:

$$Y = \sum_{i=1}^{n} \frac{X_i + X_{i+1}}{2} \cdot (t_{i+1} - t_i)$$

where Y is total CO_2 emission ($\mathrm{kg \cdot hm^{-2}}$). Total N_2O and CH_4 emissions were calculated similarly.

1.2.3 Global Warming Potential of Soil Emissions (GWPsoilexport)

Since CO_2, CH_4, and N_2O have different warming effects, their combined impact must be calculated to assess a system' s contribution to global warming. According to IPCC reports, over a 100-year timeframe, 1 kg CH_4 has 25 times the warming effect of 1 kg CO_2, and 1 kg N_2O has 298 times the effect. GWP represents their combined impact:

$$\mathrm{GWP}_{\mathrm{soilexport}} = f_{\mathrm{CO2}} + 25 \cdot f_{\mathrm{CH4}} + 298 \cdot f_{\mathrm{N2O}}$$

where GWPsoilexport is the warming potential from direct soil emissions $[\mathrm{kg(CO_2)} \cdot \mathrm{hm}^{-2}]$, f_{CO2} is net CO_2 emission $[\mathrm{kg(CO_2\text{-}C)} \cdot \mathrm{hm}^{-2}]$, f_{CH4} is net CH_4 emission $[\mathrm{kg(CH_4\text{-}C)} \cdot \mathrm{hm}^{-2}]$, and f_{N2O} is net N_2O emission $[\mathrm{kg(N_2O\text{-}N)} \cdot \mathrm{hm}^{-2}]$.

1.2.4 Indirect Global Warming Potential from Farming Activities (GWPindirect)

During the experiment, we recorded material inputs for all farming activities to calculate indirect greenhouse gas emissions, primarily from irrigation, machinery, and fertilizer use. Calculating CO_2 equivalent emission coefficients requires comprehensive consideration of production, transportation, and use-phase energy consumption. The coefficients used are shown in .

Table 1 Index of equivalent CO_2 emission from energy consumption by different agricultural managements

Agricultural Activity	CO_2 Equivalent Emission Coefficient
Machinery fuel[10]	$2.59\ \mathrm{kg(CO_2)} \cdot \mathrm{L}^{-1}$
Irrigation[11]	$1.29\ \mathrm{kg(CO_2)} \cdot \mathrm{cm}^{-1}$
Nitrogen fertilization[7],[10–12]	$3.59\ \mathrm{kg(CO_2)} \cdot \mathrm{kg}^{-1}\mathrm{(N)}$
Phosphorus fertilization[12]	$0.61\ \mathrm{kg(CO_2)} \cdot \mathrm{kg}^{-1}\mathrm{(P)}$
Potassium fertilization[12]	$0.12\ \mathrm{kg(CO_2)} \cdot \mathrm{kg}^{-1}\mathrm{(K_2O)}$

The indirect warming potential was calculated as:

$$\mathrm{GWP}_{\mathrm{indirect}} = \sum_{n=1}^{m} I_n \cdot C_n$$

where I_n and C_n are the amount and CO_2 equivalent emission coefficient of the nth input material.

1.2.5 Net Primary Production Warming Potential (GWPNPP)

Crop yield and aboveground biomass were measured at each harvest to calculate carbon sequestration through net primary production (NPP):

$$\mathrm{NPP} = \frac{\mathrm{TAGB}}{0.68 \times 0.85}$$

$$\mathrm{GWPNPP} = 1.15 \times \mathrm{TAGB}$$

where 0.68 is the conversion ratio of carbohydrates to CO_2 ($[CH_2O]/[CO_2]$), 0.85 is the biomass to carbohydrate conversion ratio ($[\mathrm{Biomass}]/[CH_2O] = 0.85$), giving a photosynthate to dry matter conversion of approximately 0.6. TAGB is total aboveground biomass ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$), 1.15 converts aboveground to total plant biomass (assuming root biomass is 15% of aboveground biomass in this region), and NPP is net primary productivity ($\mathrm{kg} \cdot \mathrm{hm}^{-2}$).

1.2.6 Comprehensive Global Warming Potential (ΔGWP)

Farmland ecosystems simultaneously sequester and emit carbon. Following Liu et al.' s holistic approach to carbon flow pathways, comprehensive GWP was calculated as:

$$\Delta\mathrm{GWP} = \mathrm{GWP}_{\mathrm{soilexport}} + \mathrm{GWP}_{\mathrm{indirect}} - \mathrm{GWP}_{\mathrm{NPP}} - \mathrm{GWP}_{\Delta\mathrm{SOC}}$$

where ΔGWP is the net GWP (positive values indicate the system is a greenhouse gas source, negative values indicate a sink). GWPΔSOC represents soil organic carbon change (negligible in short-term experiments). GWPNPP, GWPsoilexport, and GWPindirect are as defined above.

1.2.7 Data Processing

Data were analyzed using ANOVA, regression analysis, and correlation analysis. Multiple comparisons among treatments were performed using the Least Significant Difference (LSD) method. All analyses were conducted using Microsoft Excel 2003 and SPSS.

Results

2.1.1 Characteristics of Soil N_2O Emissions

[Figure 1: see original paper] shows monthly average N_2O fluxes over two crop rotation cycles. Three emission peaks occurred annually: (1) after wheat basal fertilization and sowing, (2) after wheat jointing stage fertilization, and (3) after maize big trumpet stage fertilization. Background emissions remained low between these peaks. N_2O fluxes were significantly higher during the maize season than the wheat season, primarily due to fertilization, irrigation, and seasonal climate-driven changes in soil temperature and moisture. Although total nitrogen application was equal for both seasons, maize received a single application double the rate of each wheat application, resulting in higher post-fertilization soil NH_4^+-N content that provided abundant substrate for nitrification and denitrification. Additionally, the maize season coincided with the region's hot, rainy period with higher soil temperature and moisture, creating favorable conditions for denitrifying microbes and enhancing N_2O production and emission rates.

Tillage and straw management significantly affected inter-treatment differences in N_2O fluxes. In early October, wheat sowing and pre-sowing fertilization and tillage stimulated N_2O production. The F treatment (chopped straw with deep ploughing) showed significantly higher fluxes [41.8 $g(N_2O\text{-}N) \cdot hm^{-2} \cdot d^{-1}$] than other treatments (6.5-12.2 $g(N_2O\text{-}N) \cdot hm^{-2} \cdot d^{-1}$, $P < 0.05$). From November to February, winter wheat was dormant and low soil temperature limited microbial activity, maintaining low baseline emissions (-1.2 to 4.0 $g(N_2O\text{-}N) \cdot hm^{-2} \cdot d^{-1}$) with no significant differences among treatments. In March, warming temperatures increased emissions slightly, and April' s jointing fertilization triggered the second wheat-season peak. Average April fluxes were 16.5 (CK), 17.9 (M1), 20.8 (M2), 32.8 (F), and 36.2 (X) $g(N_2O\text{-}N) \cdot hm^{-2} \cdot d^{-1}$, with X and F significantly higher than other treatments ($P < 0.05$). From May to early June wheat harvest, reduced soil moisture and NO_3^--N content from crop uptake weakened N_2O emissions.

The maize growing season (early June to late September) showed different patterns. In June, low rainfall and soil moisture, plus nutrient uptake by the previous crop, limited nitrification and denitrification, resulting in low N_2O emissions. In July, maize entered its vigorous growth period and big trumpet stage fertilization/irrigation dramatically increased N_2O fluxes, reaching the annual maximum (48.1-100.3 $g(N_2O\text{-}N) \cdot hm^{-2} \cdot d^{-1}$). Treatment differences were most pronounced, with F showing the highest and M1 the lowest fluxes, differing by 52%. In August, nutrient uptake reduced soil NO_3^--N and N_2O fluxes declined. By September, post-rainy season temperature and moisture decreases shifted the primary N_2O source from denitrification to nitrification, reducing fluxes to baseline levels with no significant treatment differences.

2.1.2 Soil CH_4 Emission/Absorption Flux

[Figure 2: see original paper] presents monthly average CH_4 fluxes (positive = emission, negative = absorption). Northern wheat–maize rotation soils generally acted as CH_4 sinks (negative fluxes). Seasonal patterns varied by tillage and straw management, with the most significant differences in October. The CK, X, and F treatments showed positive fluxes (1.1, 3.5, and 0.5 $g(CH_4\text{-}C) \cdot hm^{-2} \cdot d^{-1}$, respectively), indicating CH_4 emissions. Both rotary tillage and ploughing disturbed soil structure, increased surface porosity, and promoted release of soil-entrapped CH_4, substantially reducing sink strength. Reports indicate that tillage initially increases CH_4 emissions but may decrease fluxes after 6-8 hours. In contrast, both no-tillage treatments (M1, M2) showed negative fluxes throughout the year, with relatively high absolute values in October, likely because conventional tillage in neighboring areas temporarily increased atmospheric CH_4 concentrations, enhancing the concentration gradient and soil absorption.

In early maize growth (June), low soil moisture and high porosity favored CH_4 oxidation. Most treatments showed maximum negative fluxes (strongest sink) in June, with significant differences: CK (20.1 $g(CH_4\text{-}C) \cdot hm^{-2} \cdot d^{-1}$) > F (9.3) > M2 (8.1) > X (5.3) > M1 (2.0). The CK treatment (long-term straw removal) had the lowest soil organic carbon, likely resulting in lower soil CH_4 concentrations and higher absorption. After July, all treatments showed dramatically reduced CH_4 uptake, with July-September being the period of lowest absorption (-4.7 to +1.5 $g(CH_4\text{-}C) \cdot hm^{-2} \cdot d^{-1}$) and no significant treatment differences. In mid-to-late July, big trumpet stage fertilization/irrigation during the hot, rainy season created anaerobic microsites that enhanced methanogen activity, increased soil CH_4 concentration, reduced the atmospheric-soil concentration gradient, and decreased CH_4 uptake. High soil moisture also reduced CH_4 diffusion pathways. Most importantly, fertilization increased NO_3^--N and NH_4^+-N, inhibiting CH_4 oxidation and weakening the soil sink.

2.1.3 Soil CO_2 Emission Flux

We measured soil apparent respiration CO_2 flux using the static chamber method, which includes CO_2 released from decomposition of soil organic matter, plant residues, root exudates, and root respiration. [Figure 3: see original paper] shows monthly average CO_2 fluxes, which closely followed seasonal soil temperature patterns. Higher temperatures and rainfall during the maize season resulted in greater CO_2 fluxes than the wheat season. In July–August, during peak maize growth, intense root respiration and enhanced microbial activity at high temperature and moisture accelerated organic matter decomposition and soil respiration, increasing CO_2 emissions. F and X treatments showed relatively high emissions (43.7-54.2 and 50.7–53.4 $kg(CO_2\text{-}C) \cdot hm^{-2} \cdot d^{-1}$, respectively), while CK and M1 showed lower fluxes (40.0–42.3 and

32.3-39.2 kg(CO_2-C) • hm^{-2} • d^{-1}, respectively).

The wheat season (October–early June) showed different dynamics. In early October, fertilization and tillage increased emissions, with F highest (24.2 kg(CO_2-C) • hm^{-2} • d^{-1}) and CK lowest (13.2 kg(CO_2-C) • hm^{-2} • d^{-1}). Other treatments ranged 15.8-15.9 kg(CO_2-C) • hm^{-2} • d^{-1} with no significant differences. By December, emissions dropped sharply and remained low through the winter dormancy period (2.7-6.3 kg(CO_2-C) • hm^{-2} • d^{-1}) with minimal treatment differences. In March, rising temperatures and accelerated crop growth increased emissions, peaking in April at the wheat jointing stage. F and X treatments showed the highest fluxes (36.2 and 36.5 kg(CO_2-C) • hm^{-2} • d^{-1}), while M1 and M2 were lower (22.9 and 22.7 kg(CO_2-C) • hm^{-2} • d^{-1}).

Annual CO_2 flux patterns varied monthly among treatments. With straw return, deep ploughing and rotary tillage produced higher emissions than no-tillage, likely due to combined effects of tillage intensity and straw management. Frequent tillage accelerates soil organic carbon loss and CO_2 release, while no-tillage effectively controls carbon loss, increases storage, and reduces emissions. No-tillage with surface straw mulch slows decomposition and CO_2 release. Under the same tillage, straw return increases CO_2 emissions because some returned straw decomposes and releases CO_2 to the atmosphere, explaining why F (with straw) had higher emissions than CK (without straw).

2.2 Total Soil Greenhouse Gas Emissions

Numerical integration of dynamic monitoring data yielded seasonal and annual total emissions (). Wheat-maize rotation soils were sources for CO_2 and N_2O and a sink for CH_4. The maize season showed stronger source activity for CO_2 and N_2O but weaker CH_4 sink strength than the wheat season. Maize season emissions were 1.21-2.07 kg(N_2O-N) • hm^{-2} and 3,804-4,941 kg(CO_2-C) • hm^{-2}, with CH_4 uptake of 0.30-0.79 kg(CH_4-C) • hm^{-2}. Wheat season emissions were 0.83-1.80 kg(N_2O-N) • hm^{-2} (13-31% lower than maize) and 2,835-4,438 kg(CO_2-C) • hm^{-2} (10-25% lower), with CH_4 uptake of 0.78-2.20 kg(CH_4-C) • hm^{-2} (1.3-6.4 times higher than maize except in CK). Thus, the maize season was the primary period for greenhouse gas emissions, with much greater warming effects.

Tillage and straw management differentially affected emission source and sink strengths. Annual N_2O emissions ranked: F > X > M2 > CK > M1, with F significantly higher than others ($P < 0.05$). Annual CO_2 emissions followed the same ranking, with F significantly higher than CK and both no-tillage treatments ($P < 0.05$), X significantly higher than M1 ($P < 0.05$), but no significant differences between X and CK/M2. M1 had the lowest CO_2 emissions but did not differ significantly from CK or M2. For CH_4 uptake, tillage and straw effects were greater in wheat than maize season because tillage activities before wheat sowing caused short-term CH_4 emissions that reduced seasonal uptake.

M1 showed the highest annual CH_4 uptake, CK the lowest, with the ranking: M1 > M2 > CK > F > X. M1 uptake was significantly higher than all others ($P < 0.05$), M2 was significantly higher than F and X ($P < 0.05$), but not different from CK. F and X had the lowest CH_4 oxidation capacity.

2.3 Comprehensive Greenhouse Effect Estimation

Crop production involves not only soil greenhouse gas emissions but also direct and indirect emissions from management activities like tillage, sowing, harvesting, irrigation, and fertilization. Comprehensive assessment requires converting all these impacts to carbon equivalents.

2.3.1 Carbon Emissions from Farming Activities Tillage, sowing, harvesting, and straw management all involve machinery whose fuel consumption generates substantial CO_2. Different tillage and straw systems affect mechanical energy inputs and associated CO_2 emissions, calculated using fuel consumption and emission coefficients from . Fuel consumption records for each treatment () showed large differences, with X and F consuming the most fuel and producing the highest CO_2 emissions.

Table 3 Fuel consumption and equivalent CO_2 inputs under different tillage treatments

Treatment	Straw smashing	Ploughing/rotary	Straw removal	Sowing	Land leveling	Harvest	Total fuel ($L \cdot hm^{-2} \cdot a^{-1}$)	Equivalent CO_2 [$kg(CO_2) \cdot hm^{-2} \cdot a^{-1}$]

Irrigation requires pumping groundwater with electricity, indirectly causing carbon emissions through power generation. Mosier et al. reported that pumping 1 cm of irrigation water requires approximately 14.8 kWh, causing 1.29 $kg(CO_2\text{-}C)$ equivalent emissions. With 157.5 mm irrigation in wheat season and 70 mm in maize season, annual irrigation-related emissions were 29.3 $kg(CO_2\text{-}C) \cdot hm^{-2} \cdot a^{-1}$.

Fertilization affects emissions both directly and through production/transport. Studies report varying coefficients: Robertson et al. found 4.51 $kg(CO_2) \cdot kg^{-1}(N)$, while Adviento-Borbe et al. and West et al. reported 4.05–4.51 and 2.6–3.24 $kg(CO_2) \cdot kg^{-1}(N)$, respectively. We used the average of 3.59 $kg(CO_2) \cdot kg^{-1}(N)$ and 0.61 $kg(CO_2) \cdot kg^{-1}(P)$ for phosphorus. With annual applications of 426 $kg(N) \cdot hm^{-2}$ and 60 $kg(P) \cdot hm^{-2}$, fertilization caused 1,567 $kg(CO_2) \cdot hm^{-2}$ equivalent emissions annually.

2.3.2 Carbon Sequestration via Primary Productivity Farmland ecosystems fix atmospheric CO_2 through photosynthesis, functioning as carbon sinks. Carbon sequestration is expressed through NPP, calculated using equations (7) and (8). Crop yield and aboveground biomass measurements at each harvest were used to calculate total carbon converted to NPP (). The X treatment showed the highest economic yield and carbon sequestration capacity. Grain yield ranking was: X $>$ F $>$ M2 $>$ CK $>$ M1. NPP-based carbon sequestration ranking was: X $>$ M2 $>$ F $>$ CK $>$ M1. Thus, rotary tillage optimized both economic production and carbon capture, while long-term whole straw mulch no-tillage (M1) had the lowest yields and sequestration due to increased soil compaction and poor straw-soil mixing, which limited decomposition, organic matter formation, and fertility improvement. The CK treatment, with annual ploughing and no straw return, experienced accelerated decomposition of native organic matter, reduced soil carbon stocks, and lower productivity.

Table 4 Crop yield and plant carbon capture (GWPNPP) of different tillage treatments

Treatment	Grain yield (kg · hm^{-2})	Straw yield (kg · hm^{-2} · a^{-1})	Total GWPNPP [kg(C) · hm^{-2} · a^{-1}]

2.3.3 Comprehensive Greenhouse Effect Evaluation Comprehensive assessment must consider all carbon flows: soil respiration, farming activity emissions, and crop carbon sequestration (GWPNPP). For net CO_2 emissions, GWPNPP includes only carbon retained in the ecosystem. With straw return, GWPNPP includes carbon in roots and aboveground straw; with straw removal (CK), it includes only root carbon. Grain carbon is excluded from all treatments. Using equations (5)-(9), comprehensive GWP was calculated ().

Table 5 Global warming potential (GWP) under different tillage treatments

Treatment	GWPNPP [kg(CO_2-C) · hm^{-2}]	GWPsoilexport [kg(CO_2-C) · hm^{-2}]	GWPindirect [kg(CO_2-C) · hm^{-2}]	ΔGWP [kg(CO_2-C) · hm^{-2}]

Both no-tillage treatments had negative ΔGWP values, indicating they functioned as carbon sinks, sequestering 947-1,070 kg(C) · hm^{-2} annually after accounting for all emissions. The other three treatments had positive ΔGWP values, indicating net emissions to the atmosphere, ranking: CK $>$ F $>$ X.

If evaluating only GWP, the two straw mulch no-tillage treatments were most environmentally beneficial. However, their low economic yields cannot meet sustainable agricultural production goals. Since agricultural objectives require balancing economic and environmental benefits, rotary tillage with chopped straw incorporation represents the optimal practice for wheat-maize rotation in North China, providing relatively low greenhouse effects while ensuring high economic yields. Implementing this practice requires careful nitrogen management to minimize N_2O emissions and reduce warming potential.

Discussion

3.1 Effects of Tillage and Straw Return on Soil Greenhouse Gas Emissions

Farming activities and climate conditions make tillage, fertilization, irrigation, and the hot, rainy maize season the primary periods for greenhouse gas emissions, with significant treatment differences. In October (wheat sowing), the F treatment showed the highest emissions because deep ploughing released soil-entrapped gases and incorporated fresh organic material that, combined with pre-sowing water and fertilizer, stimulated microbial activity and sharply increased emissions. The CK treatment, despite ploughing, had lower emissions due to insufficient organic carbon from long-term straw removal and rapid moisture loss that shortened anaerobic conditions. The X treatment, though with chopped straw return, had lower emissions than other straw treatments because rotary tillage didn’ t mix straw thoroughly with soil, accelerated moisture evaporation, and didn’ t fully release entrapped gases. The two no-tillage treatments had much lower emissions than ploughed treatments because undisturbed soil prevented gas release, though surface mulch maintained moisture and anaerobic conditions that enhanced denitrification and temporarily increased N_2O flux above X treatment after sowing.

During winter dormancy, emissions dropped sharply and treatment differences diminished, though F maintained higher N_2O fluxes. In late March–early April, wheat jointing fertilization/irrigation triggered another emission surge, with X and F showing significantly higher N_2O and CO_2 fluxes due to straw decomposition and carbon sequestration that enriched microbial substrates and activity, promoting denitrification and soil respiration. After half a year of settling, X treatment straw was well-mixed with soil, and fertilization/irrigation further accelerated decomposition and CO_2 production while consuming soil oxygen to create better anaerobic conditions for denitrification and N_2O production, making X the highest emitter during this period.

In mid-July (maize big trumpet stage), fertilization/irrigation accumulated abundant NH_4^+-N and NO_3^--N, stimulating microbial activity during the hot, rainy season when water-filled pore space exceeded 60% (typically ~80%) and 5 cm soil temperature remained 25–32 °C. These conditions promoted straw decomposition and intense denitrification, causing the July peak in N_2O and CO_2 emissions.

Overall, tillage and straw management significantly affected emissions. Ploughing increased emissions more than no-tillage by releasing entrapped gases and promoting straw decomposition, which provided energy for denitrifying microbes and created anaerobic microsites that enhanced N_2O production and emission while releasing substantial CO_2.

3.2 Effects on Total Emissions and Global Warming Potential

Considering all three greenhouse gases, chopped straw incorporation with deep ploughing (F) had the greatest impact, enhancing both the soil’ s role as a CO_2 and N_2O source and its CH_4 sink capacity by adding organic matter and thoroughly mixing it through intense disturbance, which improved microbial activity and biogeochemical processes. The M1 treatment had the lowest greenhouse effect with minimal CO_2 and N_2O emissions but highest CH_4 uptake, likely because long-term non-disturbance inhibited entrapped gas release and increased N_2O reduction. Reports confirm that tillage reduces CH_4 sink strength by destroying soil structure and decreasing CH_4 oxidation, supporting M1’ s high CH_4 absorption. While some studies show straw return and no-tillage promote CH_4 uptake and deep incorporation has greater effects than surface mulch by improving aeration, others find straw return reduces CH_4 absorption. The complex mechanisms and multiple influencing factors require further research.

Conventional tillage (CK) had significantly higher GWP than no-tillage due to greater mechanical inputs, intense soil disturbance causing direct greenhouse gas emissions through fuel consumption and soil degassing, and reduced carbon sequestration from complete straw removal. In this region, where removed straw lacks alternative utilization pathways, conventional tillage intensifies carbon export and greenhouse effects. No-tillage reduces carbon outputs from fuel consumption and gas emissions while sequestering substantial carbon through straw return, yielding the lowest GWP. Straw management critically affects GWP: returned straw sequesters carbon (negative effect), while removed straw is assumed to ultimately release its carbon as CO_2 (positive effect). After converting all components to carbon equivalents, conventional tillage with straw removal emitted 12.3 t CO_2 equivalent per hectare annually, significantly higher than other practices.

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Note: Figure translations are in progress. See original paper for figures.