

Greenhouse Gas Flux and Crop Productivity after 10 Years of Reduced and No Tillage in a Wheat-Maize Cropping System

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Abstract

Appropriate tillage plays an important role in mitigating the emissions of greenhouse gases (GHG) in regions with higher crop yields, but the emission situations of some reduced tillage systems such as subsoiling, harrow tillage and rotary tillage are not comprehensively studied. The objective of this study was to evaluate the emission characteristics of GHG (CH_4 and N_2O) under four reduced tillage systems from October 2007 to August 2009 based on a 10-yr tillage experiment in the North China Plain, which included no-tillage (NT) and three reduced tillage systems of subsoil tillage (ST), harrow tillage (HT) and rotary tillage (RT), with the conventional tillage (CT) as the control. The soil under the five tillage systems was an absorption sink for CH_4 and an emission source for N_2O . The soil temperature positively impacted on the CH_4 absorption by the soils of different tillage systems, while a significant negative correlation was observed between the absorption and soil moisture. The main driving factor for increased N_2O emission was not the soil temperature but the soil moisture and the content of nitrate. In the two rotation cycle of wheat-maize system (10/2007–10/2008 and 10/2008–10/2009), averaged cumulative uptake fluxes of CH_4 under CT, ST, HT, RT and NT systems were approximately 1.67, 1.72, 1.63, 1.77 and 1.17 $\text{t ha}^{-1} \text{ year}^{-1}$, respectively, and meanwhile, approximately 4.43, 4.38, 4.47, 4.30 and 4.61 $\text{t ha}^{-1} \text{ year}^{-1}$ of N_2O were emitted from soil of these systems, respectively. Moreover, they also gained 33.73, 34.63, 32.62, 34.56 and 27.54 t ha^{-1} yields during two crop-rotation periods, respectively. Based on these comparisons, the rotary tillage and subsoiling mitigated the emissions of CH_4 and N_2O as well as improving crop productivity of a wheat-maize cropping system.

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Introduction

Methane (CH_4) and nitrous oxide (N_2O) play a key role in global climate change [1]. The global warming potential of these gases are respectively 25 and 298 times that of carbon dioxide (CO_2) [2]; thus, the release of these gases is a crucial contributory factor to increasing loads of greenhouse gases (GHG). According to estimations of the IPCC [3], the fluxes of CH_4 and N_2O from agricultural sources account for 50% and 80% of the total emission of these gases, respectively. There have been many studies on CO_2 emission in different ecosystems [4–6]; however, emissions of CH_4 and N_2O emission have been researched incompletely, especially in agricultural ecosystems [7,8].

In general, appropriate soil tilling may reduce GHG emissions because the emissions from soil are strongly affected by tilling, results that have been found by many studies [8–10], most of which, have reported the emissions of CH_4 and N_2O under conventional tillage (CT) and no-tillage (NT) systems in different sites [5,9]. However, the both generally revealed two extremes in maintenance the soil organic carbon stock and crop productivity,

agricultural environment protection, the results in these aspects showed the regional character and sometimes they did not suit for agricultural sustainable development [8,9,11]. In which case, some reduced tillage systems such as subsoiling (ST), harrow tillage (HT) and rotary tillage (RT) have been introduced [11], and sometimes they as more important tillage practices combination with no tillage were used to in rotation-tillage systems, which changed some soil environment factors and crop yield [12]. Although these reduced systems were frequently used and developed rapidly due to they are not only advantageous to improve crop yield but also increase the utilization efficiency of soil, water and fertilizer [13,14], the emissions of CH_4 and N_2O under these systems were remain unclear.

The production, consumption and transport of CH_4 and N_2O in soil are strongly influenced by some soil factors. Many studies demonstrated that CH_4 uptake by soil is correlated with soil temperature [15,16] and the N_2O emission. The conditions of soil moisture and N concentration were also shown as two major driving factors of the emission of N_2O : the emission generally

peaked during N fertilizer application and irrigation [17,18]. However, the effects of those factors on the emissions of CH₄ and N₂O under different tillage systems in the North China Plain are still not fully understood among available results.

Therefore, the aim of the present study was to quantify the emissions of CH₄ and N₂O under no tillage and three reduced tillage systems in the wheat-maize cropping system and to analyze the correlations between the two gas emissions and the soil temperature, moisture and nitrate content. The crop productivity of the wheat-maize cropping system during two crop-rotation periods was also analyzed.

Materials and Methods

Ethics Statement

This experiment was established in a long-term tillage and residue-management experiment site of Shandong Agricultural University. The farming operations of this experiment were similar to the rural farmers' operations and did not involve endangered or protected species; the operations were approved by the State Key Laboratory of Crop Biology, Shandong Key Laboratory of Crop Biology and National Engineering Laboratory for Efficient Utilization of Soil and Fertilizer Resources, Shandong Agricultural University.

Experimental Site

The study site was located at Tai'an (Northern China, 36°09'N, 117°09'E), which has the typical characteristics of the North China Plain. The average annual precipitation is 697 mm, and the average annual temperature is 13.0°C, with the minimum (−2.6°C) and maximum (26.4°C) monthly temperatures in January and July, respectively. The annual frost-free period is approximately 170–196 d in duration, and the annual sunlight time is 2627.1 hours. The soil is a loam with 40% sand, 44% silt, 16% clay. The characteristics of the surface soil (0–20 cm) were measured as follows: pH 6.8; soil bulk density 1.43 g cm^{−3}; soil organic matter 1.36%; soil total nitrogen 0.13%; and soil total phosphorous 0.13%. The meteorological data during the experiment is shown in Figure 1.

Experimental Design

The study based on a 10-year tillage experiment, began in 2002, included no tillage (NT) and three reduced tillage systems involving subsoiling (ST), harrow tillage (HT), rotary tillage (RT), with the conventional tillage (CT) as the control. The treatments were arranged in a randomized block design with three replications. Each plot was 35 m long and 4 m wide.

The experimental site was cropped with a rotation of winter wheat (*Triticum aestivum* Linn.) and maize (*Zea mays* L.). Winter wheat (Jimai-22) was sown at a rate of 90 kg ha^{−1}, on 12 October 2007 and 15 October 2008, and was harvested 6 June 2008 and 10 June 2009. The basal fertilizer was added before sowing and contained with 225 kg N ha^{−1}, 150 kg P₂O₅ ha^{−1} and 105 kg K₂O ha^{−1}, and 100 kg N ha^{−1} was used as topdressing at the jointing stage with 160 mm of irrigation water. The maize was sown on 20 June 2008 and 22 June 2009, which included 66600 plants ha^{−1} and was harvested 8 October 2008 and 10 October 2009. For the maize, 120 kg N ha^{−1}, 120 kg P₂O₅ ha^{−1} and 100 kg K₂O ha^{−1} were used as a basal fertilizer, and 120 kg N ha^{−1} was used as topdressing at the jointing stage.

When the wheat and maize were harvested, the amount of residue returned to each plot at an equal level according to the crop biomass and water content of residue, in order to ensure their amount and C content of the residue among treatment had no significant difference. The residue equal quality returned to the field, then pulverized using a residue chopper and mixed with the soil in the tillage operations. The operations of tillage and residue-management are shown in Table 1.

Gas Sampling and Analysis

The emission measurements of CH₄ and N₂O for each treatment were conducted using the static-chamber method [19]. According to some studies, there is optimal gas-sample collection duration in a day during which the sample can show the mean gas flux of the day [20–22]. Our previous study have showed that the ratios of the CH₄ flux between 9 a.m. and 10 a.m. and N₂O flux between 9 a.m. and 12 p.m. to the daily mean flux, respectively, verged 1 by the correction coefficient and regression analysis [23]. So, the CH₄ and N₂O were collected between 9 a.m. and 10 a.m. and between 9 a.m. and 12 p.m. respectively from October 2007 to August 2009 at approximately 1-month intervals [12,23]. Both

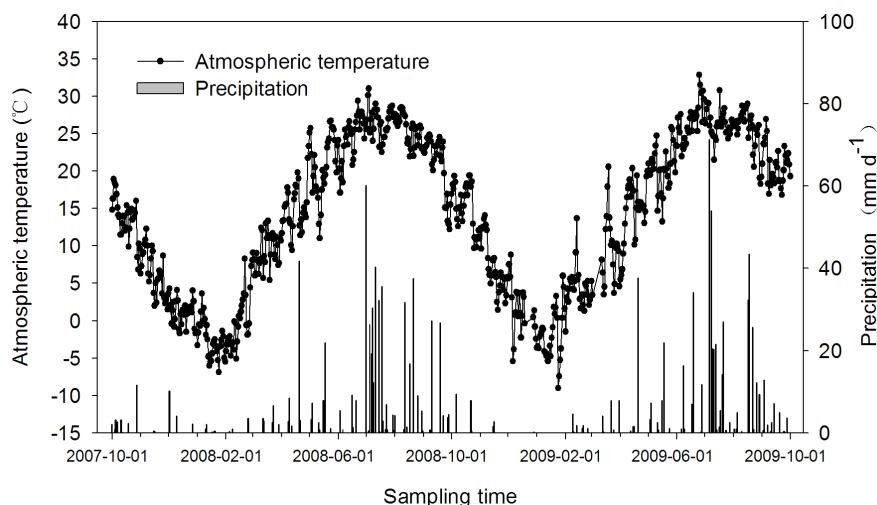


Figure 1. The atmospheric temperature and precipitation at the experimental site. The data were collected by the agricultural meteorological station approximately 500 m from the experiment field.
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Table 1. The residue-management and tillage systems in the experimental plots.

Item	Tillage systems				
	CT	ST	HT	RT	NT
Wheat-residue					
Retention rate (t ha ⁻¹)	11.02	11.02	11.02	11.02	11.02
Residue-C (g kg ⁻¹)	51.27	51.27	51.27	51.27	51.27
Maize-residue					
Retention rate (t ha ⁻¹)	10.05	10.05	10.05	10.05	10.05
Residue-C (g kg ⁻¹)	52.15	52.15	52.15	52.15	52.15
Tillage					
Depth (cm)	25~35	40~45	12~15	10~15	–
Machine	moldboard	vibrating subsoil shovel	disc harrow	rototiller	–

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CH₄ and N₂O were sampled at 5 minutes, 20 minutes and 35 minutes using a needle tube. The diurnal variations of CH₄ and N₂O in this study were collected from 2nd to 4th of May at 2-hour interval in 2009. All gases samples were collected at same time in order to avoid the order difference of sampling time. The atmospheric temperature, the temperature in the static chamber, the soil surface temperature and the soil temperature at a depth of 5 cm were determined simultaneously.

The samples were measured using a Shimadzu GC-2010 gas chromatograph. CH₄ was measured using a flame ionization detector with a stainless-steel chromatography column packed with a 5A molecular sieve (2 m long); the carrier gas was N₂. The temperatures of the column, injector and detector were 80°C, 100°C and 200°C, respectively. The total flow of the carrier gas was 30 ml min⁻¹, the H₂ flow was 40 ml min⁻¹, and the airflow was 400 ml min⁻¹. N₂O was measured using an electron-capture detector with a Porapak-Q chromatography column (4 m long); the carrier gas was also N₂. The temperatures of the column, injector and detector were 45°C, 100°C and 300°C, respectively. The total flow of the carrier gas was 40 ml min⁻¹, and the tail-blowing flow was 40 ml min⁻¹. The gas fluctuations were calculated based on the gas-concentration change over time per unit area.

The emission fluxes of CH₄ and N₂O were calculated using the following formula [19]:

$$F = \frac{60HMP}{8.314(273 + T)} \frac{dc}{dt}$$

where F is the gas emission flux or uptake flux (μg m⁻² hour⁻¹), 60 is the conversion coefficient of minutes and hours, H is the height of the static chamber (m), M is the molar mass of gas (g mol⁻¹), P is the atmospheric pressure (Pa), 8.314 is the ideal gas constant (J mol⁻¹ K⁻¹), T is the average temperature in the static chamber (°C), and dc/dt is the slope of the line of the gas-concentration change over time.

The cumulative fluxes of CH₄ and N₂O were calculated by summing the products of the daily mean flux of two neighboring observations multiplying the days [6,24], the calculation formula as follows:

$$F_{\text{cumulative}} = \sum \left[\frac{(F_i + F_{i+1})}{2} \times d \right]$$

$$F_i = F_{\text{avg}} \times 24$$

where, $F_{\text{cumulative}}$ is the cumulative flux of CH₄ or N₂O (t ha⁻¹ year⁻¹); F_i is the daily flux of observation i (t ha⁻¹ d⁻¹); F_{i+1} is the daily flux of observation $i+1$ (t ha⁻¹ d⁻¹); d is the days; F_{avg} is the mean flux of CH₄ or N₂O, which able to represent daily mean flux of CH₄ or N₂O according to the correction coefficient and regression analysis between the gas flux in observation duration and the daily total fluxes in diurnal variation.

Soil Sampling and Analysis

The meteorological data during the experiment (10/2007–10/2009) were by the agricultural meteorological station approximately 500 m from the experiment field. We measured soil temperature at a depth of 5 cm and the soil moisture in the 0–20 cm soil layers using a WET Sensor (WET brand, made in the UK). Soil samples (0–10 cm, 10–20 cm and 20–30 cm) were collected at five random positions of each plot and air dried to a constant weight, triturated and passed through a 2 mm sieve after thorough incorporation; they were then used to determine NO₃-N using the UV colorimetric method [25].

Crop Yield

Winter wheat and maize were harvested at maturity, and the both harvest area was 9 m² in the central area of each plot to exclude edge effects. After air-drying, the grains were separated from the plants and oven-dried at 65°C for 48 h, and the dry weight was determined.

Statistical Analyses

The data were mapped using Sigma Plot 10.0, and all of the statistical analyses were performed using SPSS statistical software (SPSS Inc., Chicago, IL). The standard deviation (S.D.) and least significant difference (LSD) were calculated to compare the treatment means.

Results

Seasonal Variation of CH₄ Uptake

The soil acted an absorption sink for CH₄ in all tillage systems, which significantly varied by different soil tillage (Figure 2). The CH₄ flux during the sampling period (10/2007–10/2009) ranged from 6.31 to 41.36 μg m⁻² h⁻¹ under CT, from 4.03 to 33.45 μg

$\text{m}^{-2} \text{h}^{-1}$ under ST, from 5.30 to $35.21 \mu\text{g m}^{-2} \text{h}^{-1}$ under HT, from 6.78 to $32.54 \mu\text{g m}^{-2} \text{h}^{-1}$ under RT, and from 1.10 to $26.21 \mu\text{g m}^{-2} \text{h}^{-1}$ under NT. Moreover, the fluxes tended to respond to the change of atmospheric temperature during the sampling time (Figure 2), with higher uptake fluxes in the summer and lower in the winter in the different tillage systems.

Seasonal Variation of N_2O Emission

The emitting of N_2O from the soil was observed under the different treatments (Figure 3), but the differences were small among the treatments in the same sampling time. However, the peak N_2O emission coincided with the irrigation and fertilization periods, which had the highest emission fluxes of all of the periods ($P < 0.01$), and the flux did not accord with the trend of atmospheric temperature. Meanwhile, the flux in all of the samples of N_2O ranged from 14.07 to $130.39 \mu\text{g m}^{-2} \text{h}^{-1}$ under CT, from 14.20 to $126.43 \mu\text{g m}^{-2} \text{h}^{-1}$ under ST, from 12.68 to $134.93 \mu\text{g m}^{-2} \text{h}^{-1}$ under HT, from 10.81 to $126.42 \mu\text{g m}^{-2} \text{h}^{-1}$ under RT, and from 13.04 to $128.29 \mu\text{g m}^{-2} \text{h}^{-1}$ under NT.

Diurnal Variations of CH_4 and N_2O Under CT and NT

The diurnal flux variations of CH_4 uptake and N_2O emission significantly differed between the CT and NT treatments (Figure 4). In both of the treatments, the CH_4 uptake exhibited the lowest and highest fluxes at 6 a.m. and 2 p.m., respectively, but the lowest and highest values of CH_4 absorption were 12.99 and $23.77 \mu\text{g m}^{-2} \text{h}^{-1}$, respectively, under CT and 12.23 and $23.03 \mu\text{g m}^{-2} \text{h}^{-1}$, respectively, under NT (Figure 4a). The emission troughs and peaks of N_2O under CT and NT were observed at 4 a.m. and 4 p.m., respectively, with flux values of

16.90 and $41.89 \mu\text{g m}^{-2} \text{h}^{-1}$ under CT and 13.57 and $34.38 \mu\text{g m}^{-2} \text{h}^{-1}$ under NT, respectively (Figure 4b).

Cumulative Emissions of CH_4 and N_2O

The cumulative fluxes of CH_4 and N_2O under the different tillage systems in the two rotation cycle of wheat-maize systems were shown in Table 2. The highest cumulative uptake flux of CH_4 presented in the RT treatment with $1.85 \text{ t ha}^{-1} \text{ year}^{-1}$ in the first rotation cycle of wheat-maize system (10/2007–10/2008), which was higher 8.3%, 13.7%, 22.5% and 60.9% than CT, ST, HT and NT treatments, respectively. But in the second rotation cycle (10/2008–10/2009), the highest one was the ST treatment. The order of total cumulative uptake fluxes of CH_4 under five tillage systems in two years was $\text{RT} > \text{ST} > \text{CT} > \text{HT} > \text{NT}$. The cumulative emission flux of N_2O ranged from 4.18 to $4.63 \text{ t ha}^{-1} \text{ year}^{-1}$ in the first year and from 4.15 to $4.67 \text{ t ha}^{-1} \text{ year}^{-1}$ in the second year, the total cumulative emission flux of N_2O ordered of $\text{NT} > \text{HT} > \text{CT} > \text{ST} > \text{RT}$, the flux under NT was only higher 7.2% than that of under RT.

Seasonal Variations of the Soil Temperature, Moisture and $\text{NO}_3^- \text{N}$

A significant difference of the soil temperature at 5 cm depth was measured in the different periods. The changes under the different tillage systems were related to the atmospheric temperature (Figure 5a). The averaged soil temperature in all of the periods under RT was higher than under the other tillage methods. The soil moisture of the 0–20 cm layer varied among the different treatments and was related to precipitation or irrigation (Figure 5b). The averaged moisture level of the 0–20 cm layer was highest in the NT treatment. Similarly, higher nitrate contents

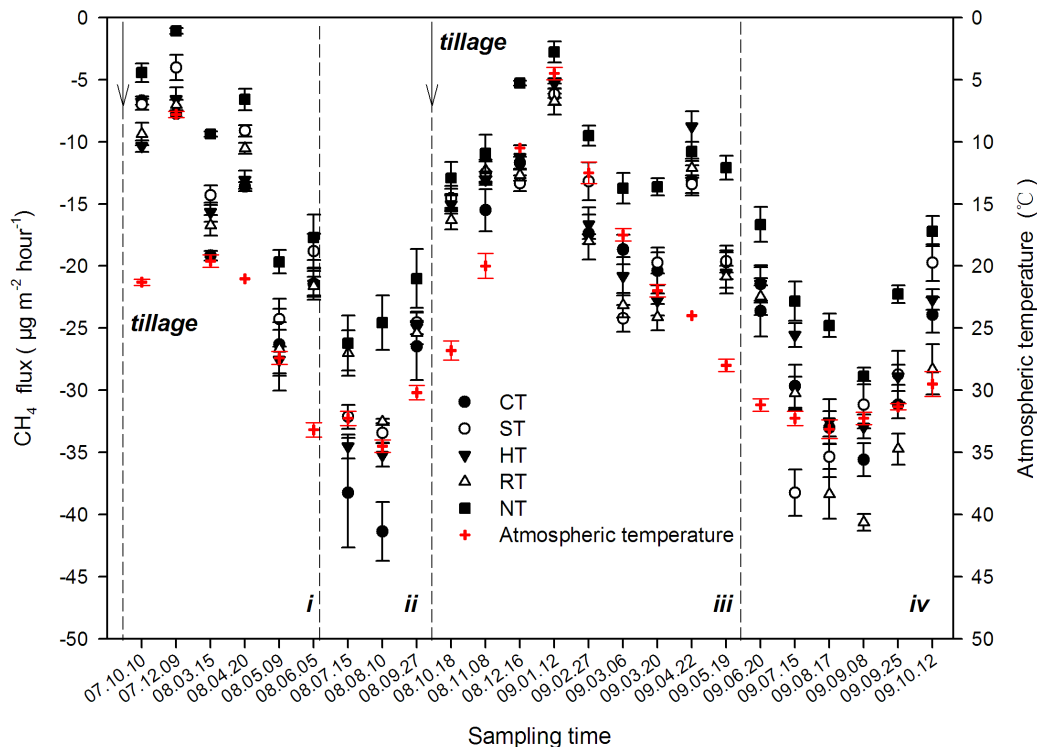


Figure 2. The seasonal characteristics of CH_4 flux under the different tillage systems. i and iii were the periods of wheat growth in 2007–2008 and 2008–2009, respectively; ii and iv were the periods of maize growth in 2008 and 2009, respectively. The arrows indicate the time of tilling, and the dotted lines distinguish the different periods of crop growth. The data are means \pm SD ($n = 3$). doi:10.1371/journal.pone.0073450.g002

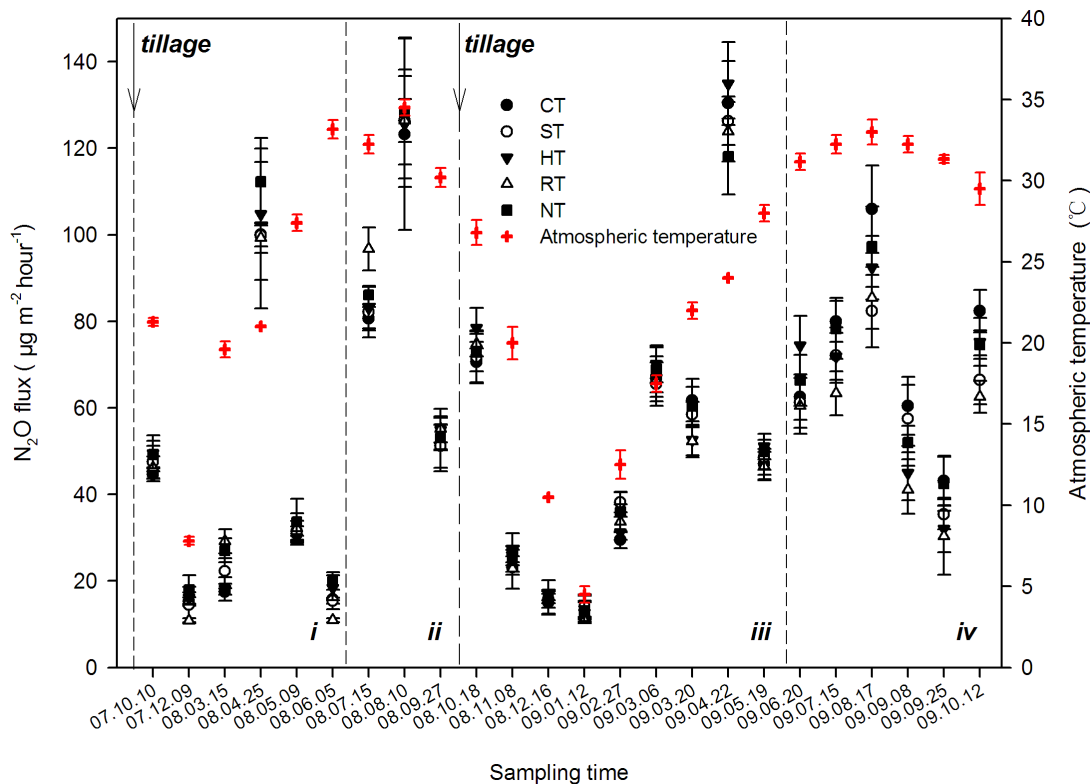


Figure 3. The seasonal characteristics of N₂O flux under the different tillage systems. i and iii were the periods of wheat growth in 2007–2008 and 2008–2009, respectively; ii and iv were the periods of maize growth in 2008 and 2009, respectively. The arrows indicate the time of tillage, and the dotted lines distinguish the different periods of crop growth. The data are means \pm SD ($n=3$). doi:10.1371/journal.pone.0073450.g003

were measured under the HT, NT, RT and ST treatments (Figure 5c); the levels in the NT, RT and ST treatments were higher than in the CT treatment by 4.21%, 2.42% and 1.40%, respectively.

Regression Analysis between CH₄, N₂O and Soil Factors

The absorption of CH₄ by the soil in different tillage systems was strongly affected by the soil temperature and soil moisture, and the uptake flux showed a positive correlation with the soil temperature ($R^2=0.44$, $P<0.01$; Figure 6a), and a negative correlation was observed with the soil moisture ($R^2=0.36$, $P<0.01$; Figure 6b).

The N₂O emission flux and soil temperature were not significantly correlated in this study. However, the N₂O emission flux was significantly related to the soil moisture ($R^2=0.63$, $P<0.01$; Figure 7a) and the content of nitrate ($R^2=0.50$, $P<0.01$; Figure 7b), which promoted the N₂O emission.

Crop Yields

The crop productivity of the wheat-maize rotation in the two years differed among the tillage systems (Table 3). The highest total productivity in two crop-rotation periods were measured in the ST treatment, with 34.63 t ha⁻¹, which was higher 2%, 6.2%, 0.2% and 25.7% than in the CT, HT, RT and NT treatment. The NT system showed the lowest productivity, only producing 27.54 t ha⁻¹ yield in two crop-rotation periods.

Discussion

Effects of Soil Factors on CH₄ Uptake and N₂O Emission

In general, the emissions of CH₄ and N₂O in different seasons are affected by the soil temperature [26,27]. In this study, the CH₄ uptake and N₂O emission were lower in winter and higher in summer (Figures 2 and 3) and significantly related with the change of the soil temperature (Figures 2 and 6a). Similar results have been indicated in previous studies [28,29]. However, the CH₄ uptake flux usually decreased with the irrigation (Figures 3 and 6b). Many studies reported that soil moisture was a limiting factor for CH₄ absorption by the soil [16,30], leading to reduced rates of gas and O₂ diffusion [17].

Sometimes, the seasonal characteristics of N₂O emission exhibit varied trends in different sites, generally affected by temperature, N fertilization or irrigation in a significant linear relationship [27,31], and higher NO₃-N concentrations in wet soils promote the activity of nitrification and denitrification [18]. The higher moisture of the soil in this study promoted N₂O emission (Figures 5b and 7a), and the emission also increased with N fertilizer application (Figures 5c and 7b). In addition, there was no significant correlation between the N₂O emission and soil temperature in the seasonal variation in this study, similar results also found by other studies [32].

Tillage Effect on CH₄ Uptake and N₂O Emission

The fluxes of CH₄ uptake and N₂O emission were related to some soil factors (Figures 6 and 7), and these related soil factors general varied by the different tillage systems (Figure 5), because the changed soil structure and microflora by tillage would further

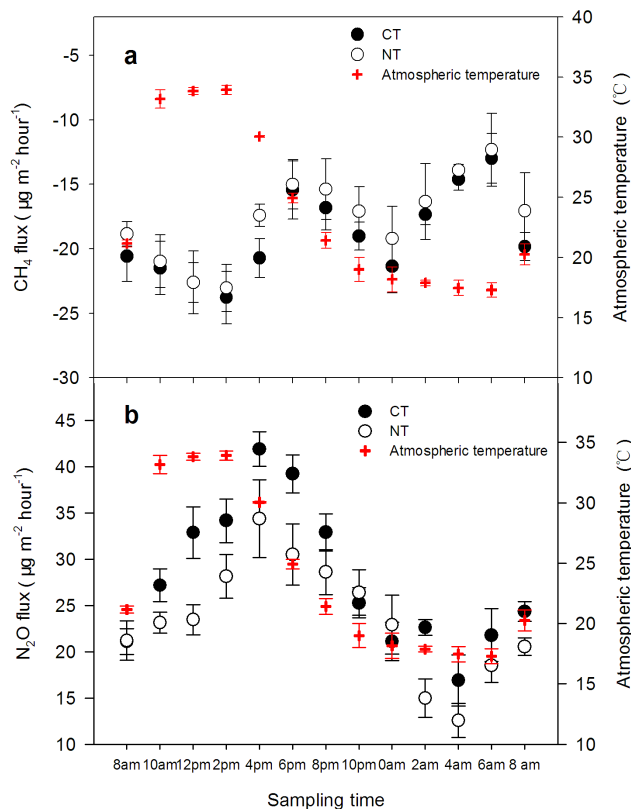


Figure 4. The diurnal flux variations of CH₄ uptake (a) and N₂O emission (b) in the CT and NT treatments. The data were collected from 2nd to 4th of May at 2-hour intervals in 2009. The data are means \pm SD (n = 3).
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drive emissions of the N₂O and CH₄ from soil [8,15]. For example, a soil with better permeability was a larger absorption sink of CH₄ [5]. In this study, the highest uptake flux of CH₄ was observed in the RT treatment (Table 2), which also contained the highest averaged soil temperature (Figure 5a). The regression analysis showed that there was a significant positive correlation between CH₄ uptake and soil temperature (Figure 6a). In contrast, under the five tillage systems used in this study, the lowest flux of

CH₄ uptake was observed under NT (Figure 2), which was consistent with many previous studies [13,14]. The highest moisture and the lowest temperature conditions were also found in the soil of the NT treatment (Figures 5a and 5b). Some previous studies have indicated that the excessive wet condition of soil generally led to compaction of the soil surface without tillage, which blocked CH₄ from entering into soil for oxidation in dry-land farming systems [32–35]. However, others opposite results also indicated that NT could increase CH₄ oxidation because the reduced disturbance of soil could increase the activity of methane-oxidizing bacteria [36,37], while disturbance may negatively affect CH₄ uptake by the soil [38], but sometimes this effect from disturbance is small and can largely be ignored [9,38]. Because the variations of these factors are important driving factors for soil microflora and also responded sensitive by the changed soil structure by tillage.

Similarly, the HT treatment, which had the highest emission of N₂O from the soil because the content of NO₃-N was the highest compared with the other treatments (Figures 5c and 7b). The emission flux of N₂O usually peaked after the stage of N-fertilizer application or irrigation [10], and the highest flux was observed in reduced systems (HT treatment). In some cases, there was a risk of increasing the emission of N₂O under NT or reduced tillage [9]. These methods mostly produced decreased N₂O emission relative to that reported by many previous studies [39,40] because little N₂O was generally produced with a better mixture of soil and residue, and the predominant form of nitrogen was NO₃-N or NH₄-N [14].

Tillage Effect on Crop Yield

Little information was reported on reduced tillage systems effect on crop yields. Sometimes, subsoiling was regarded an effective method to increase wheat production [41–43]. In this study, the highest crop productivity of two rotation periods was shown under the ST and RT systems (Table 3). However, the NT system in this study had the lowest crop total yield, and a similar trends were reported by other studies [5,10]. However, the yields under NT showed dissimilar results in different sites, in which generally reported with the NT increase crop yields compared to conventional tillage [44,45]. Furthermore, relative to other tillage systems, no-tillage grain yields and profits are often dramatically lower during the first few years of adoption. In fact, no tillage have not been widely applied in the world or at least China, because there are actual or perceived problems in crop grown using the

Table 2. The cumulative emissions of CH₄ and N₂O under the different tillage systems.

Item	Cumulative flux (t ha ⁻¹ year ⁻¹)				
	CT	ST	HT	RT	NT
The first rotation cycle of wheat-maize system (10/2007–10/2008)					
Cumulative uptake flux of CH ₄	1.71b	1.63c	1.51d	1.85a	1.15e
Cumulative emission flux of N ₂ O	4.18d	4.30c	4.37c	4.45b	4.64a
The second rotation cycle of wheat-maize system (10/2008–10/2009)					
Cumulative uptake flux of CH ₄	1.63d	1.81a	1.74b	1.67c	1.20e
Cumulative emission flux of N ₂ O	4.67a	4.46c	4.57b	4.15d	4.57b
The total cumulative flux in the two years					
CH ₄	3.34	3.43	3.25	3.53	2.34
N ₂ O	8.85	8.76	8.94	8.60	9.22

Different small letters in the same line indicate $P < 0.05$. n = 3.

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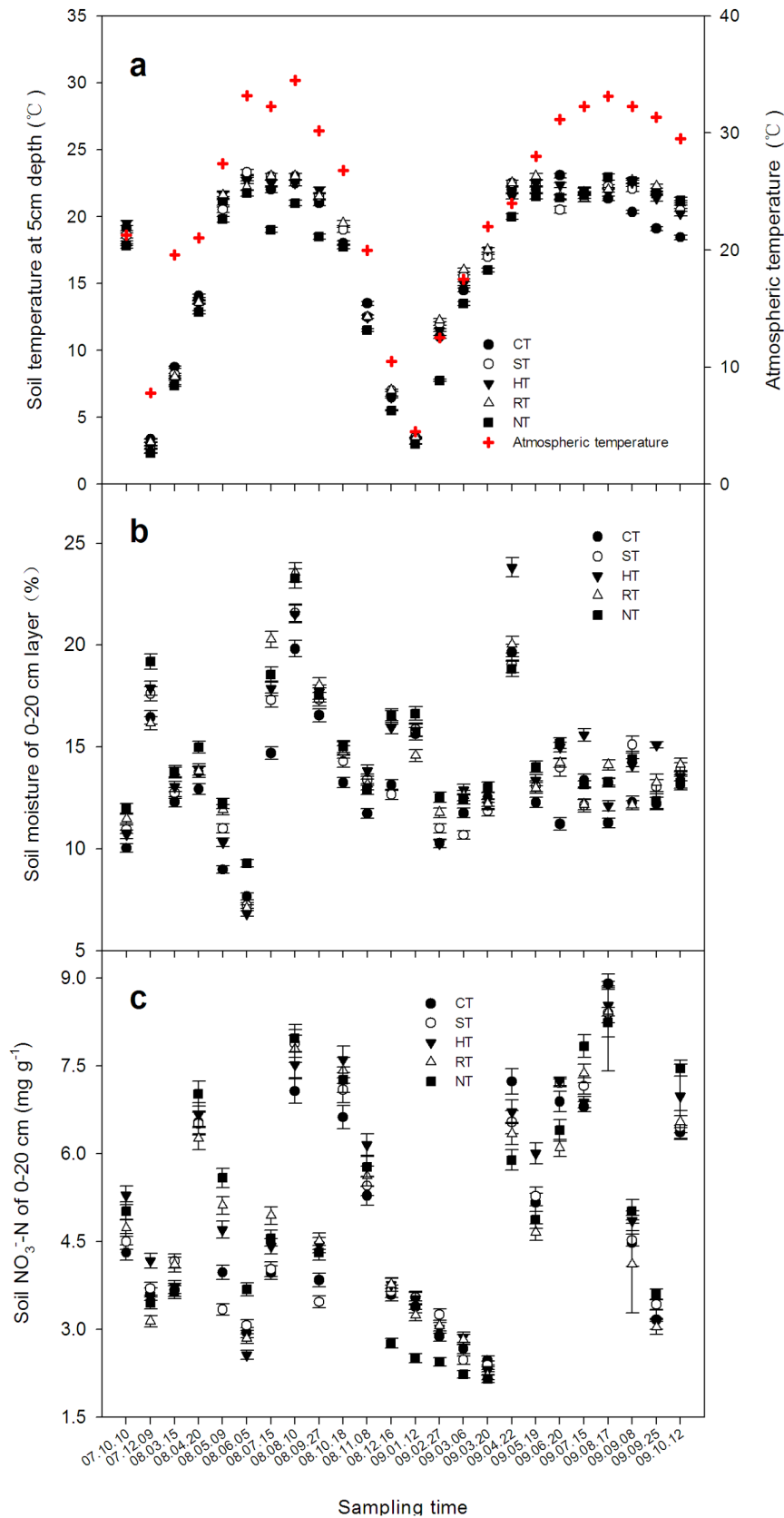


Figure 5. The seasonal variations of the soil temperature at a depth of 5 cm (a), soil moisture at 0–20 cm (b), and soil NO₃⁻-N content at 0–20 cm (c) under the different tillage systems. The data are means \pm SD (n=3).
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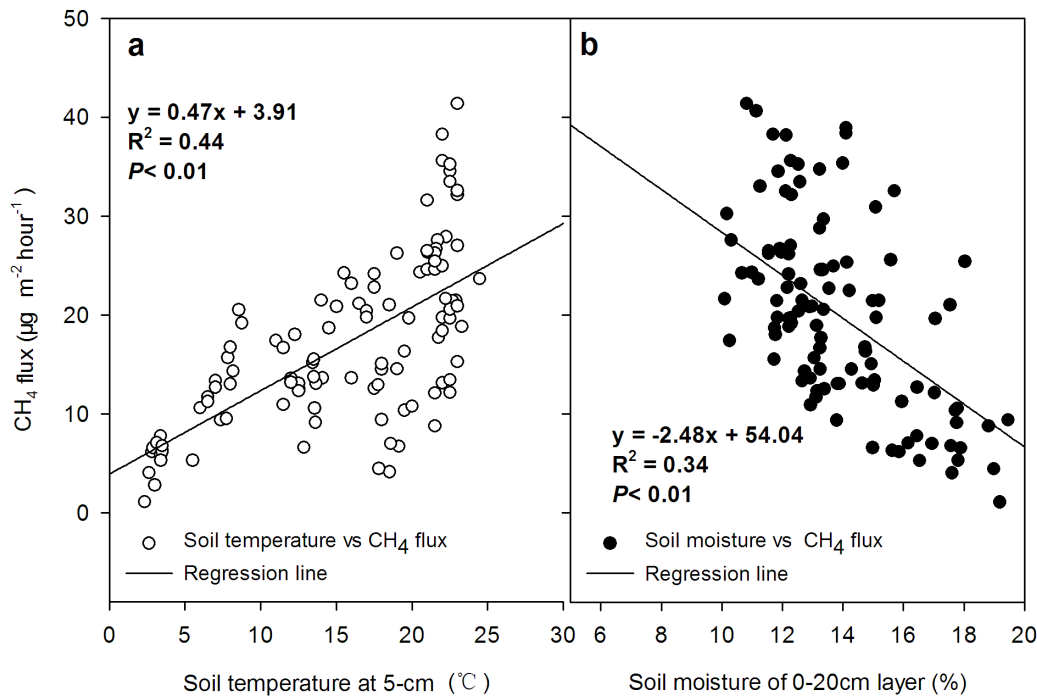


Figure 6. The regression analysis of the CH_4 flux and soil temperature at 5-cm depth (a, $n = 105$) and soil moisture of the 0–20 cm layer (b, $n = 105$).

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NT, it may have limited adoption by growers. Some specific problems include lower early-season soil temperatures, reduced seed germination and emergence, below-optimal plant populations, poorer weed control, delayed plant development and maturity, increased grain moisture content, and lower grain yield potential [46–51]. Yet no tillage system effects on yield are highly

dependent upon soil type, drainage, climate/latitude, and crop rotation [52].

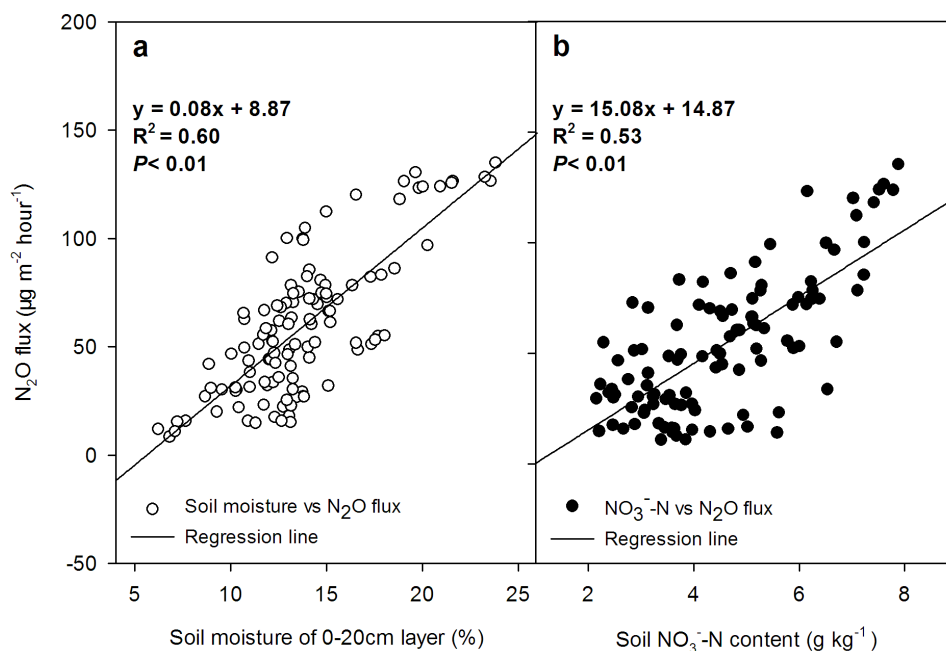


Figure 7. The regression analysis of the N_2O flux and soil moisture of the 0–20 cm layer (a, $n = 105$) and the soil NO_3^- -N of the 0–20 cm layer (b, $n = 105$).

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Table 3. The crop productivity in the different tillage systems.

Wheat-maize cropping-rotation system	Crop yield (t ha ⁻¹)				
	CT	ST	HT	RT	NT
The first rotation cycle					
Wheat (10/2007–06/2008)	5.90 d	6.18 c	6.58 a	6.35 b	4.65 e
Maize (06/2008–10/2008)	12.19 a	10.98 b	10.10 c	9.92 d	8.83 e
The second rotation cycle					
Wheat (10/2008–06/2009)	5.85 c	6.90 a	6.17 b	6.06 b	4.95 d
Maize yield (06/2009–10/2009)	10.03 c	10.58 b	9.76 d	12.23 a	9.11 e
Total productivity	33.95 b	34.63 a	32.62 c	34.56 a	27.54 d

Different small letters in the same line indicate $P < 0.05$. $n = 3$.
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Conclusions

The fluxes of CH₄ and N₂O were significantly affected by no tillage and reduced tillage systems, which also impacted soil factors, such as the soil temperature, moisture and nitrate content. These factors were related with the changes of CH₄ and N₂O fluxes. No-tillage did not reveal a better result for mitigating emissions of CH₄ and N₂O, as well as maintaining a high level of crop yield in this cropping rotation system. Comparison to the conventional tillage and no tillage, under the reduced tillage systems such as subsoiling and rotary tillage, may mitigate emissions of CH₄ and N₂O, and also gain a high level of crop

productivity in the wheat-maize cropping rotation system. Sometimes, the both also as an important rotation tillage systems was applied in this region, in particular the subsoiling. The results also provide information on optional tillage in rotation tillage systems for mitigating GHG emissions and improving crop yield.

Author Contributions

Conceived and designed the experiments: ST TN ZL SC. Performed the experiments: ST YW HZ BW NL. Analyzed the data: ST TN. Contributed reagents/materials/analysis tools: ST. Wrote the paper: ST TN.

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