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Emissions of Greenhouse Gases and NO from Rice Fields and a Peach Orchard as Affected by N Input and Land-Use Conversion

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Abstract: Nitrogen (N) inputs and land-use conversion are management practices that affect soil greenhouse gas (GHG) and nitric oxide (NO) emissions. Here, we measured soil methane (CH_4), nitrous oxide (N_2O), and NO fluxes from rice fields and a peach orchard that converted from paddies to assess the impacts of nitrogen (N) inputs and land-use conversion on their emissions. Treatments included four paddy field treatments (PN0, PN160, PN220, and PN280) and one peach orchard treatment (ON280) with number indicating the N-input rate of kg N ha^{-1}. The results showed that cumulative emissions of CH_4, N_2O and NO ranged from 28.6 to 85.3 kg C ha^{-1}, 0.5 to 4.0 kg N ha^{-1} and 0.2 to 0.3 kg N ha^{-1} during the rice-growing season, respectively. In terms of greenhouse gas intensity, the PN280 treatment is the recommended N application rate. Land-use conversion significantly reduced the global warming potential from croplands. The conversion shifted soils from an essential source of CH_4 to a small net sink. In addition, N_2O emissions from the rice–wheat rotation system were 1.8 times higher than from the orchard, mainly due to the difference in the N application rate. In summary, to reduce agriculture-induced GHG emissions, future research needs to focus on the effects of N inputs on rice-upland crop rotation systems.

Keywords: N fertilizer; GHG emissions; nitric oxide; fruit; climate change

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1. Introduction

Anthropogenic emissions of greenhouse gases (GHGs) are significant drivers of global climate change. Methane (CH_4) and nitrous oxide (N_2O) are two of the essential greenhouse gases; in a 100-year time horizon, their sustained global warming potential (GWP) is 34 and 298 times higher than carbon dioxide (CO_2), respectively [1]. Moreover, anthropogenic nitric oxide (NO) is considered the primary precursor of tropospheric ozone (O_3) and the key factor that leads to the formation of acid rain [2]. It is reported that fertilized agricultural soil is the primary source of these emissions [3,4]. Agricultural activities generate 50% and 92% of the total GHG fluxes of CH_4 and N_2O in China, respectively [5].

Rice fields are a significant source of global CH_4 emissions [6,7]. China is the second-largest rice producer, accounting for about 35% of global rice production [8]. Annual CH_4 emissions from rice fields in China are about 7.4 Tg yr^{-1}, accounting for 10% of anthropogenic CH_4 emissions [9]. Rice has relied on excessive nitrogen (N) fertilizer application to enhance crop yields in China [10]. Excessive N fertilizer input would decrease N use efficiency and increase denitrification from rice soils [11]. In addition, alternating wet and dry water-saving irrigation practices in rice fields further exacerbate the sources of N_2O and NO [12,13].

Subtropical orchards are potential hotspots for nitrous oxide emissions [14]. Increasing the market demand and the high economic value of fruits, higher returns have become the crucial drive for farmers to convert traditional rice fields to orchards [15,16]. Currently, the orchard has become the third-largest agricultural cultivation in China, and its area has ranked first in the world for many years [17]. The area of orchards increased from 0.17 to 10.7 Mha from 1980 to 2010, while the area under rice decreased from 33.3 to 26.5 Mha during the same period [18]. According to a survey, the annual mean N fertilizer input of 550 kg N ha^{-1} in orchards was much higher than that of rice, wheat, maize, and other food crops (<250 kg N ha^{-1}) [19,20]. In these drained upland systems, high N fertilizer inputs lead to significant emissions of N_2O and NO [21]. Field measurements have shown that N_2O emissions from orchards in the same area are much greater than those from farmland [22,23].

Land-use conversion is considered the second largest anthropogenic source of GHG emissions [1]. This land-use conversion process includes changes in crop types, management, soil aeration, and physicochemical and microbial properties, which would change the CH_4 and N_2O emissions [24]. For example, tillage management can increase soil N_2O emission and CH_4 absorption compared with no-tillage [25,26]. GHG emissions may differ between the two cropping systems due to different growing conditions (anaerobic submerged conditions in rice versus aerobic conditions in orchards), and studies have reported that land use type switching from rice to upland crops increases cumulative N_2O emissions by a factor of 4.0 to 5.3 [27–29].

In this study, we conducted in situ field measurements on rice fields and peach orchards throughout the rice-growing season. Specifically, the objectives of our study were to (1) measure the effect of N fertilizer application gradient on rice field production and GHG and NO emissions; (2) determine the response of soil GHG and NO emissions and GWP balance to changes in land-use. We hypothesized that (i) N fertilizer level management of rice fields has a significant impact on CH_4 and N_2O emissions and crop production, and (ii) conversion of rice fields to peach orchards would result in a significant shift from a CH_4-dominated GHG balance to an N_2O- and NO-dominated balance but would have little effect on the total GWP. The results of this study are intended to support the national GHG inventory change scenario in China due to land-use conversion.

2. Materials and Methods

2.1. Site Description and Experimental Design

Field experiments were conducted from June 2019 to June 2020 in Jiangsu Province, China (31°57′ E, 120°00′ N). The two most common land-use types in the plain of the middle and lower reaches of the Yangtze River soil regions were selected for the present study, namely, a rice field and peach orchard ("Yingchun"). According to the local field management system, conventional rice fields have been planted continuously for about 20 years, and part of the farmland was converted to peach orchards in 2014, with a tree age of 5 years. The density of this peach orchard was around 495 plants ha^{-1}, and the distance between two rows or trees was approximately 4 or 5 m. Soil properties at the initiation of the experiment are shown in Table 1. The region is characterized by a subtropical monsoon climate with an average annual temperature of 15.3 °C, and annual rainfall of 1055 mm (Figure 1). The clay soil at the study site is classified as Fluvisols, with 32.7% sand, 35.6% silt, and 31.7% clay [30].

Table 1. The main soil properties in the rice field and transformed peach orchard at a depth of 0–15 cm. Data are means ± standard error (*n* = 3).

Cropland	pH (H_2O)	Bulk Density ($g\ cm^{-3}$)	Total C ($g\ C\ kg^{-1}$)	Total N ($g\ N\ kg^{-1}$)	NH_4^+ ($mg\ N\ kg^{-1}$)	NO_3^{-1} ($mg\ N\ kg^{-1}$)	DOC ($mg\ C\ kg^{-1}$)
Rice field	6.9 ± 0.13	1.10 ± 0.02	10.85 ± 0.42	2.14 ± 0.18	0.86 ± 0.08	181.21 ± 84.26	25.73 ± 1.23
Peach orchard	7.2 ± 0.04	1.37 ± 0.01	12.71 ± 0.29	2.01 ± 0.04	2.92 ± 0.28	10.31 ± 0.27	58.68 ± 2.03

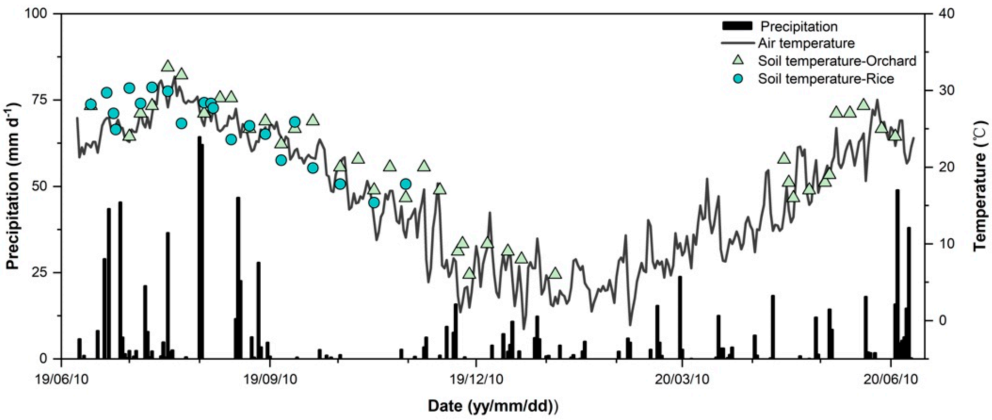

Figure 1. Mean daily air temperature, cumulative precipitation, and soil temperature (for the rice field and peach orchard) during the experimental period of June 2019–June 2020. The soil temperature break of the orchard (15 January to 23 April 2020) in the figure indicates no sampling due to the COVID-19 pandemic.

The rice field experiments consisted of four plots with four N application levels, four different levels were non-fertilized (PN0), 160 kg N ha^{-1} (PN160), 220 kg N ha^{-1} (PN220), and 280 kg N ha^{-1} treatments (PN280). The N input for the ON280 treatment in the orchard was the same as that for the PN280 treatment. Four rice treatments and a peach orchard were arranged in a completely randomized block design with three replicates (10 $\times$ 12 m). The rice was planted by sowing on 25 June and harvested on 22 October. Compound fertilizers were applied on 3 July and 15 August, respectively, with a split of 50% as the basal dose and another split of 50% at the tillering stage as the topdressing dose. The fertilizer dosage for the PN280 treatment was the local conventional management, and 160 and 220 kg N ha^{-1} were mainly referred to as the N fertilizer application rates in the N reduction experiment. The phosphorus and potassium fertilizers in the other treatments of the rice field were made up of P_2O_5 and K_2O. The flooding period of the rice field was from 20 July to 15 August and 25 August to 21 September, and the other times were intermittent irrigation. The three fertilization dates for the peach orchard are 2 December 2019, 24 April 2020, and 12 May 2020. In addition to the amount of N applied in the rice field, all field managements (e.g., weed and pest control) were consistent with the local conventional production. Peach orchards were fertilized and managed according to local practices, all plots were free of pests and weeds (including foliar insecticides and local herbicides), and there was no artificial irrigation. Local farmers converted their rice fields to crab pond culture after the rice-growing season. Therefore, the average CH_4 and nitrogen oxide emissions of conventional fertilizer treatments from previous rice–wheat rotation studies in the same region were used to replace the missing wheat season data (Table S1). The impact of land use conversion was scientifically assessed by supplementing missing data from the wheat growing season in the rice–wheat rotation with an average wheat season N application of approximately 260 kg N ha^{-1}.

2.2. Gas Sampling and Flux Measurements

In situ CH_4, N_2O, and NO fluxes were collected once a week throughout the experiment. When N fertilizer was applied, gas samples were taken three times a week to capture GHGs emissions peaks. The fluxes were collected using a static chamber-based method [31,32]. A permanent PVC chamber base (area 0.25 m^2, height 0.20 m) was installed into the soil at a depth of 10 cm on each plot. The 0.50 m-long square sampling chamber was placed onto the base by inserting the flange of the chamber into a water trough at the upper end of the chamber base. It covers a layer of insulation to minimize changes in air temperature. We used a 50 cm high extension chamber to follow the growth of the plant. Four gas samples (1.5 L) were collected from each plot at an interval of 5 min and then taken to the laboratory for determination concentration within 24 h. The concentrations of CH_4 and N_2O in the samples were analyzed by a modified gas chromatograph (Agilent 7890A, Santa Clara, CA, USA) as described previously [31,32]. NO concentrations were analyzed with a model 42i chemiluminescence NO-NO_2-NO_x analyzer (Thermo Environmental Instruments, Inc., Franklin, MA, USA) [33]. The details of the gas chromatography configuration information have been documented in previous reports [32]. The fluxes of CH_4, N_2O, and NO were calculated by a linear approach based on the slope of the mixing ratio change in four samples. The average fluxes and standard errors of N_2O were calculated from triplicate plots. Seasonal cumulative emissions of CH_4, N_2O, and NO were sequentially accumulated from the fluxes between every two adjacent intervals of measurements [32].

2.3. Determination of GWP, GHGI, NAE, and Emission Factor

To further reveal the relationship between emissions of CH_4 and N_2O and climate change, we estimated the combined GWP of CH_4 and N_2O emissions from rice fields and the peach orchard. According to the improved weight index [34], the combined GWP of CH_4 and N_2O was calculated using the following equation:

$$\text{GWP}\left(\text{t CO}_2-\text{eq ha}^{-1}\right) = 34 \times \text{CH}_4 + 298 \times \text{N}_2\text{O}, \tag{1}$$

The greenhouse gas intensity (GHGI) associated with ecosystem production was further calculated by dividing the net GWP by rice yields. Rice yields were calculated by the weight of all aboveground rice grains collected on each plot.

$$\text{GHGI}\ (\text{t CO}_2-\text{eq t}^{-1}\text{yield}) = \text{GWP} \ / \ \text{grain yield}, \tag{2}$$

The N agronomic efficiency (NAE) is a basic indicator used by researchers, policymakers, and international organizations to assess the relative transformation of N inputs into agricultural products. Several metrics have been used to define N use efficiency (NUE) in agriculture, including recovery efficiency, agronomical efficiency, partial productivity, and physiological efficiency [35,36]. Here, N agronomic efficiency (NAE) is used to determine the NUE input of fertilizer N. The calculation equation for NAE is as follows:

$$\text{NAE}\left(\text{kg kg}^{-1}\right) = (\text{Y}_\text{N} - \text{Y}_\text{c}) \ / \ \text{N}_{-\text{fer}}, \tag{3}$$

where Y_N and Y_C indicate the yield with and without N applied, $N_{\text{-fer}}$ represents the N input of fertilization (kg N ha^{-1}).

The N fertilizer-induced direct emission factor (EF) of N_2O and NO was calculated as the difference between the total emissions of the fertilized and unfertilized treatments divided by the amount of N applied [1]. The equation is as follows:

$$\text{EF} = (\text{E}_\text{N}\text{–E}_0) \ / \ \text{N}_{-\text{fer}}, \tag{4}$$

where E_N and E_0 are the cumulative N_2O or NO emissions (kg N ha^{-1}) of the fertilized treatment and the non-fertilized treatment, respectively; $N_{\text{-fer}}$ is the total N amount of fertilization (kg N ha^{-1}).

2.4. Soil Physicochemical Properties

Parallel to gas sampling, soil temperature and volumetric water content were recorded to a 5 cm depth with a probe meter MPM 160 (ICT International Pty Ltd, Armidale, Australia) installed near the chamber. Temperature and precipitation data were collected from on-site automatic weather stations near the experiment field. Assuming a soil particle density of 2.65 (g cm^{-3}), the soil water-filled pore space (WFPS) is represented as the measured ratio of soil volume moisture content to total porosity. Fresh soil samples (0–20 cm) were collected every two weeks during the entire experiment, sieved with 2 mm, and stored for analysis of soil parameters. Soil pH and EC were analyzed in a soil-to-water ratio of 1:2.5 (*w/v*) using a pH electrode (PHS-3C mv/pH detector, Shanghai, China) and an EC meter (FE-30, Shanghai, China), respectively. The NH_4^+-N and NO_3^--N concentrations in 2 M KCl extractions were determined using a flow analyzer system (AutoAnalyzer 3, Bran+Luebbe GmbH, Hamburg, Germany). Soil dissolved organic carbon (DOC) was analyzed in a soil-to-water ratio of 1:5 (*w/v*) using a UV-Persulfate TOC analyzer (Teledyne-Tekmar Phoenix8000, Mason, OH, USA).

2.5. Statistical Analyses

The experimental results are given as the mean with the standard error (mean ± SE, $n = 3$). Differences in the rice growing season or annual total of CH_4, N_2O, NO, and N_2O plus NO emissions as affected by N input levels and land-use conversion were examined by a two-way analysis of variance (ANOVA). The cumulative seasonal and annual emissions of CH_4, N_2O, and NO were approximated by applying the trapezoidal rule to the time interval between the measured flux rates. The effects of soil physicochemical properties on CH_4, N_2O, and NO emissions were investigated by Pearson correlation coefficients. All data were analyzed using SPSS v. 21 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. CH_4 Fluxes

There was a positive correlation between the N application rate and the cumulative seasonal flux of CH_4. According to the measurement results of the current season, the CH_4 emissions in the rice-growing season ranged from 28.55 kg ha^{-1} in PN0 treatment to 85.28 kg ha^{-1} in PN280 (Table 2). Overall, compared with the PN0 treatment, the seasonal CH_4 emissions of the PN160, PN220, and PN280 treatments increased by 21–34% and 42–60%, respectively, although there was no significant difference between treatments. The seasonal patterns of CH_4 emissions from rice fields did not differ between treatments. After early sowing, CH_4 emissions were low in the absence of standing water in the field until peak fluxes were reached in September when the rice fields were waterlogged.

Table 2. Cumulative fluxes of CH_4, N_2O, NO, CH_4 plus N_2O, and N_2O plus NO for the rice-growing season and annual rice field and peach orchard, as well as direct emission factors (EF) of N_2O, NO, and N_2O plus NO for rice cropping systems. Data for the wheat growing season were obtained from the average emissions from conventional fertilizer treatments in previous rice–wheat rotation studies in the same region. Values are means ± SE ($n = 3$). Means that do not share a letter are statistically significantly different from each other ($p < 0.05$).

	Cropland	Treatment	CH_4	N_2O	NO	GWP	N_2O + NO	Direct Emission Factor (%)		
			(kg C ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(t CO_2-eq ha^{-1})	(kg N ha^{-1})	EF_{N_2O}	EF_{NO}	EF_{N_2O+NO}
Rice-growing season	Rice field	PN0	28.55 ± 7.34 ab	0.49 ± 0.41 c	0.15 ± 0.03 a	1.12 ± 0.18 bc	0.64 ± 0.44 c			
		PN160	36.53 ± 12.53 ab	2.44 ± 0.93 bc	0.19 ± 0.10 a	1.88 ± 0.70 abc	2.63 ± 1.03 bc	1.22	0.03	1.25
		PN220	61.00 ± 18.35 a	2.82 ± 0.08 ab	0.23 ± 0.05 a	2.77 ± 0.64 ab	3.05 ± 0.13 ab	1.06	0.04	1.1
		PN280	85.28 ± 31.43 a	4.00 ± 0.68 a	0.27 ± 0.02 a	4.09 ± 1.27 a	4.27 ± 0.70 a	1.25	0.04	1.29
	Peach orchard	ON280	−4.90 ± 2.01 b	1.57 ± 0.06 bc	0.25 ± 0.04 a	0.30 ± 0.06 c	1.82 ± 0.07 bc			
Annual	Rice-wheat estimation	PN0	28.61 ± 7.34 bc	2.12 ± 0.41 c	2.05 ± 0.03 b	1.61 ± 0.18 b	4.18 ± 0.39 d			
		PN160	40.72 ± 12.53 abc	8.07 ± 0.93 a	3.07 ± 0.10 a	3.79 ± 0.70 ab	11.15 ± 0.90 b	1.42	0.24	1.66
		PN220	65.19 ± 18.35 ab	8.28 ± 0.08 a	3.11 ± 0.05 a	4.68 ± 0.64 a	11.39 ± 0.11 ab	1.28	0.22	1.5
		PN280	89.47 ± 31.43 a	9.93 ± 0.68 a	3.15 ± 0.02 a	6.00 ± 1.27 a	13.08 ± 0.69 a	1.44	0.20	1.64
	Peach orchard	ON280	−0.65 ± 5.38 c	5.59 ± 0.47 b	1.16 ± 0.10 c	1.75 ± 0.32 b	7.11 ± 0.38 c			

Land-use patterns, temporal and spatial changes, and interactions significantly affected CH_4 fluxes. Due to the land-use conversion, there were significant differences in CH_4 flux patterns between orchards and rice fields. The rice-growing season and the annual results indicated the CH_4 emission of the peach orchard was lower than the rice field, and the peach orchard was a sink of atmospheric methane. The CH_4 flux had always been kept at a low level in the orchard, ranging from −1.74 to 1.18 mg C m^{-2} h^{-1} (Figure 2).

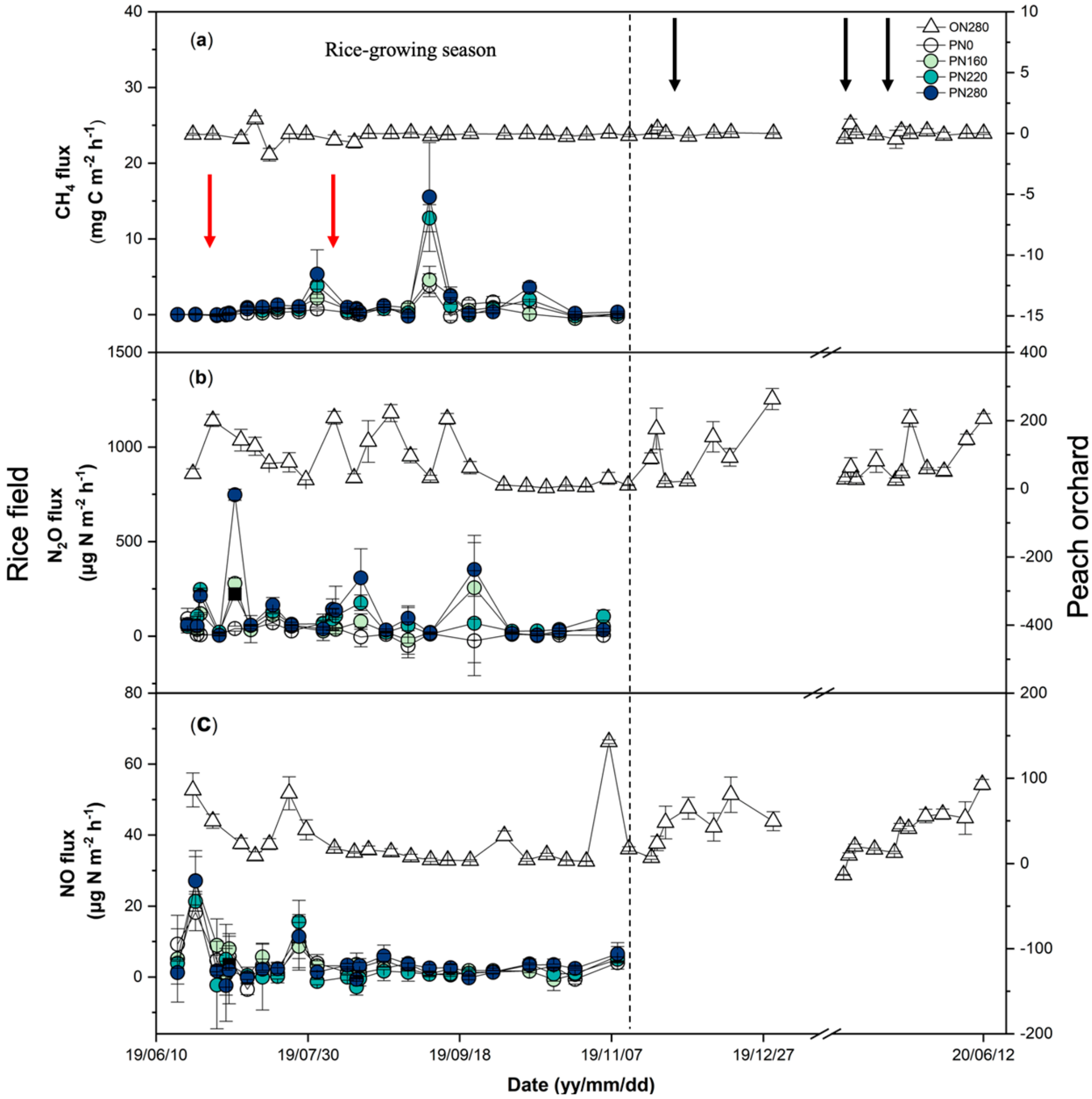

Figure 2. The seasonal fluxes of soil CH_4 (**a**), N_2O (**b**), and NO (**c**) in the rice and peach orchard fields under different fertilization treatments. The solid black line and gray shading indicate the fertilization time and irrigation period of the rice field, respectively. Values are mean ± SE (n = 3). The orchard break (15 January to 23 April 2020) in the figure indicates no sampling due to the COVID-19 pandemic. The left y-axis is for the rice field, and the right y-axis is for the peach orchard.

3.2. N_2O and NO Fluxes

The cumulative N_2O emissions during the rice-growing season were significantly affected by N fertilizer additions (Table 2). Seasonal N_2O fluxes showed significant positive correlations with WFPS, EC, and NO_3^--N (Figure 3). In the rice-growing season, the N_2O emissions ranged from 0.49 to 4.0 kg N ha^{-1} for PN0, PN160, PN220, and PN280 treatment. Compared with the PN0 treatment, the emission from fertilization treatments was approximately 4–8 times. Although the PN220 treatment with higher N application rates generated more N_2O emissions than the PN160 treatment, there was no significant difference between the two treatments. As the N input rate increased, EF_{N2O} showed a decreasing and then increasing trend, and on average, EF_{N2O} was 1.18% for N fertilizer application in rice fields (Table 2).

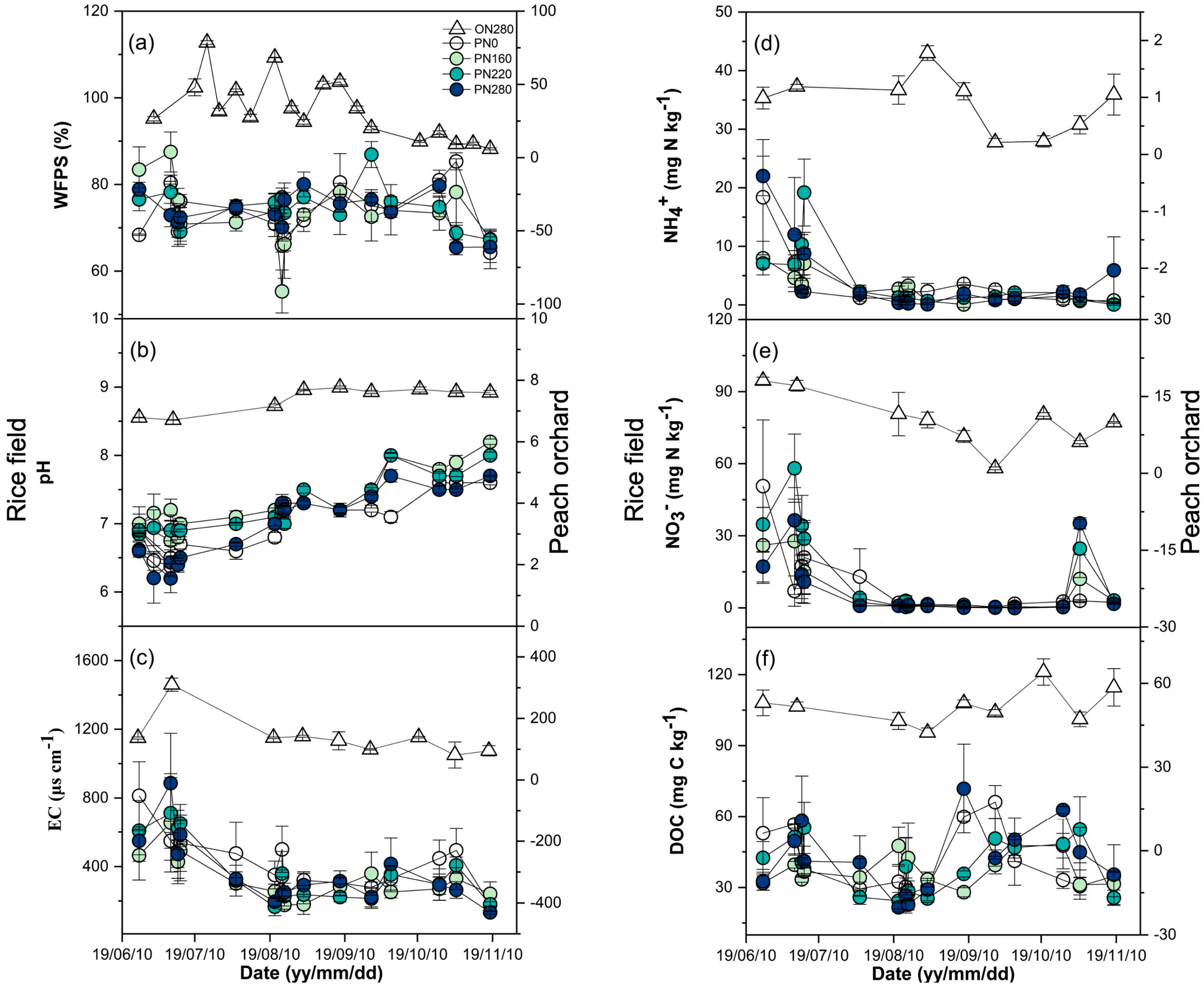

Figure 3. Seasonal dynamics of (**a**) water-filled pore space (WFPS), (**b**) pH, (**c**) electrical conductivity (EC), (**d**) ammonium (NH_4^+), (**e**) nitrate (NO_3^-), and (**f**) dissolved organic carbon (DOC) concentrations. Values are means ± SE (n = 3). The left y-axis is for the rice field, and the right y-axis is for the peach orchard.

There was a significant difference between the N_2O emission after land-use conversion. In the rice-growing season and the annual estimation scale, the N_2O emission of rice fields was significantly higher than the peach orchard under the same nitrogen application rate (Table 2). Seasonal variation of the rice field N_2O flux was characterized by pulsed emission events, which depend on the static water level and fertilization events. An imperceptible N_2O flux was observed during the flooding period of the rice field. After fertilization and drainage, N_2O pulsed emission occurs when the soil dries out/is re-wetted by rainfall. The orchard N_2O emission pulse usually occurred after N application, and the favorable climatic conditions in summer and the legacy effects of fertilization also contributed to the N_2O pulse emission (Figure 2).

In the rice-growing season, the seasonal pattern of soil NO flux was the same in the rice and orchard fields, with no significant differences between the different N input plots. The NO flux in the rice fields ranged from 11.7 to 216.0 μg N m^{-2} h^{-1} (Figure 2), and a significant pulse emission was captured after the fertilization event. There were no significant differences in seasonal NO cumulative fluxes for all treatments in the rice field, ranging from 0.15 to 0.27 kg N ha^{-1} (Table 2). In contrast, the cumulative seasonal emission of NO in the orchard was 0.25 kg N ha^{-1}, which was below the PN280 treatment.

3.3. Grain Yield, GWP, and GHGI of the Rice

Rice grain yield varied from 5.64 to 10.73 t ha^{-1} in all treatments (Table 2). The average yield of PN160, PN220, and PN280 were 7.90 ± 1.13, 8.14 ± 0.72, and 10.73 ± 0.50 t ha^{-1}, respectively. Compared to PN280, the grain yield of PN160 and PN220 treatments was significantly reduced by 24–26% ($p < 0.05$).

Radiative forcing effects of N_2O and CH_4 emissions from rice fields were assessed on a 100-year time scale using GWP. In addition, GHGI calculated by dividing GWP by rice yield shows a positive combined effect of warming on mitigating N_2O and CH_4 emissions and yield. Generally, in the rice-growing season, all treatments showed positive total GWP, and the GWP of fertilization treatment was higher than that of blank treatment. However, there was no significant difference between N reduction fertilization treatment and blank treatment, and the GWP of conventional fertilization (280 kg N ha^{-1}) was significantly higher than that of the blank treatment. Relative to the N_2O emission, CH_4 emission is the main contribution of GWP in the rice field. The results showed that the PN280 treatment significantly increased GWP (N_2O) in the rice field. When the GWP was linked to rice production, the GHGI of two N reduction treatments (PN160 and PN220) was reduced (Table 2), 35.9% and 15.4% lower on average than that of the conventional treatment, respectively. Combining the results of GHGI and the yield, the PN280 treatment could significantly increase the rice yield without considerably increasing the intensity of GHG emissions. In addition, the results of the rice-growing season and annual estimates indicated that land-use conversion significantly reduced GWP under the same N application rate (Table 2).

3.4. Soil Physicochemical Parameters

During the entire experiment period, the changes in soil inorganic N content under different treatments were regulated by the height of the static water layer during fertilization (Figure 3). High NH_4^+-N and NO_3^--N contents were mainly observed within 15 days of seedling emergence after basal fertilizer application. The dynamic change of DOC concentration in rice soil was mainly influenced by irrigation and fertilization activities. The results showed that seasonal CH_4 fluxes were significantly and positively correlated with soil temperature in the rice field (Figure 4). Seasonal N_2O fluxes were significantly related to WFPS, EC, and NO_3^--N. Seasonal NO fluxes were significantly correlated with DOC, WFPS, and NH_4^+-N. Notably, soil WFPS had a significant effect on both NO fluxes and N_2O fluxes.

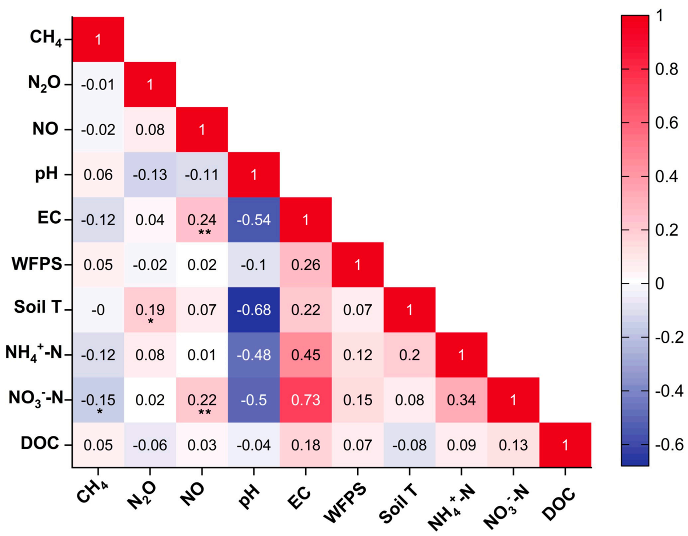

Figure 4. Dependency of CH_4, N_2O, and NO fluxes on soil physicochemical parameters in the rice field over a growing season; * and ** indicate statistical significance at $p < 0.05$ and 0.01.

Land-use conversion and field management have altered soil properties (Table 1 and Figure 3). Compared with rice fields, the contents of NH_4^+-N and DOC, soil bulk density, and pH value increased in the orchard after transformation, while the contents of NO_3^--N and TN decreased in the soil. Land-use conversion from rice fields to orchards also increased the soil temperature (Figure 1).

4. Discussion

4.1. Rice Crop Productivity and NAE Affected by N Input

Nitrogen inputs have long been considered key to ensuring crop productivity [37]. The grain yield of the PN280 treatment was significantly higher than the PN160 and PN220 treatments (Table 2). The positive effects on crop productivity were amplified with high N input. It was consistent with the previous results, within the range of reasonable N input, the increase in grain yield can be accompanied by acceptable N use efficiency [38]. The yield of PN280 was close to that of slow and controlled release fertilizer and partial replacement of organic fertilizer, but the N input was much higher than theirs [39]. Similar to the results, rice biomass and yield were positively correlated with N use efficiency in rice fields [40]. In the results, the high biomass and low yield of PN220 treatment may be due to the shortage of N supply at the filling stage, and the size or weight of rice spikelet was determined at the filling growth stage [41]. To improve rice yield and NAE, the dynamics of tillering and panicle rate under different N levels will be the focus of future research [42].

Nitrogen use efficiency (NUE) is an essential index to evaluate agricultural N management. As shown in the results of this study, increased crop productivity was associated with increased NAE at different N levels, and the PN280 plots were above the average value of 12.6 kg kg^{-1} in the Chinese rice field [38]. However, the NAE in all treatment plots was well below the 25–30 kg kg^{-1} recommended for good field management [43]. Previous studies have revealed that the key to improving NUE in crop production systems is to coordinate the synchronization between crop N requirements and N supplies from all sources throughout the growing season [44]. For this purpose, specific field management (micronutrients, water management) and precise fertilization are usually used. It would also reduce the environmental risk of gaseous N loss or runoff and leaching caused by N inputs [45].

4.2. CH_4 and N_2O Emissions Affected by N Input and Land-Use Conversion

The seasonal patterns and intensities of CH_4 and N_2O emissions from rice fields differed significantly from earlier measurements in the region. It was found that CH_4 cumulative emissions were lower than in previous studies, while N_2O cumulative emissions were much higher than other observations [46–48]. There are two explanations for the low CH_4 emissions. First, it was mainly affected by the planting method of broadcast seeding. Compared with the transplanted rice field, the sown rice field was drained in the early stage, and the methane was mainly produced in the flooded and anaerobic state. Second, irrigation management alternates short-term flooding and drainage, significantly reducing the possibility of CH_4 pulse discharge [41]. Previous results showed that the average CH_4 emission fluxes of single and multiple drainage fields were 71% and 55% of continuous drainage fields, respectively [49]. The results showed that the PN280 treatment significantly increased CH_4 emission compared with the non-fertilization treatment. Previous studies have reported that CH_4 emissions from rice fields are primarily determined by the balance between CH_4 production and oxidation [50]. Compared with the PN0 treatment, the PN280 increased rice biomass by 83.6% (Table 3). Better plant growth, such as greater biomass, may provide methanogens with more organic substrates through root exudates [51], leading to greater CH_4 yields [52,53].

Table 3. Yield, biomass, N agronomic efficiency (NAE), and greenhouse gas intensity (GHGI) for the rice-growing season. Values are means ± SE (*n* = 3). Different letters in a single column indicate a significant difference between treatments at the 0.05 probability level. NA, not available. Means that do not share a letter are statistically significantly different from each other ($p < 0.05$).

Cropland	Treatment	Annual N Rate (kg N ha^{-1})	Yield (t ha^{-1})	Biomass (t ha^{-1})	NAE (kg kg^{-1})	GHGI (t CO_2-eq t^{-1} Yield)
Rice field	PN0	0	5.64 ± 0.54 c	11.78 ± 3.81 b		0.20 ± 0.02 a
	PN160	160	7.90 ± 0.65 b	20.95 ± 1.11 a	14.14 ± 4.09 a	0.25 ± 0.10 a
	PN220	220	8.14 ± 0.42 b	24.60 ± 0.40 a	11.39 ± 1.88 a	0.33 ± 0.06 a
	PN280	280	10.73 ± 0.29 a	21.64 ± 2.37 a	18.18 ± 1.02 a	0.39 ± 0.13 a

Nitrogen application rate and irrigation management would affect N_2O emission [10,54]. Contrary to previous studies, multiple N_2O pulse emissions occurred in the rice-growing season (Figure 2). It was noted that a large amount of N_2O emissions occurred during the whole growth period after the basal fertilizer application and during mid-season drainage, which may be due to a variety of reasons. First of all, compared with conventional transplanting, the plots in this study were drained after fertilization in the early stage, which provided sufficient substrate and oxygen conditions for N_2O generation and was conducive to N_2O emission in the soil, which led to the peak of N_2O emission after rice sowing [55]. Second, the alternating wet and dry conditions due to irrigation and drainage during the rice growing season facilitated the production of N_2O [47,56]. At the same time, irrigation decreased soil organic N mineralization, but more mineral N in the soil could be used for N_2O production in the following drainage period [57]. This comparison strongly indicates that N_2O emission is significantly affected by fertilizer application rate.

In our study, CH_4 and N_2O fluxes were significantly affected by land-use patterns, which is consistent with our hypothesis. The transition from paddy fields to peach orchards transformed soils from an essential source of CH_4 to a small net sink (Table 2). The decrease in CH_4 emissions as the rice field changed to an upland system is consistent with previous studies [58,59]. First, changes in CH_4 fluxes after land-use conversion are due to highly variable soil moisture conditions (Figure 3a). Second, methanogenic archaea are suppressed due to improved soil aeration in upland systems, which drives increased availability of oxidants in the soil [60,61]. The N_2O emission was significantly higher in the PN280 than in the ON280 treatment (Table 2). This was determined by the N application rates for the rice–wheat rotation and the peach orchard, which were 540 and 280 kg N ha^{-1} yr^{-1}, respectively. The largest source of N_2O emissions from the soil is the application of synthetic N fertilizers and manure to croplands [62]. On average, the N_2O emissions from the rice–wheat rotation system were 1.8 times that of the peach orchard, close to the ratio of the nitrogen application rate. The irrigation management, which is different from conventional rice fields, leads to excellent nitrous oxide emissions, an essential factor for the high nitrous oxide emissions from rice–wheat crop rotation systems [54]. In addition, the unique hole application method of the peach orchard results in high N_2O emissions only at the point of application, which accounted for only 1/40 of the whole tree.

4.3. Soil GWP and GHGI Affected by N Input and Land-Use Conversion

The GWP and GHGI of CH_4 and N_2O were calculated to assess the climate impact of rice cropping systems affected by N levels and land-use conversion. The result showed that the GWP values of all treatments were positive, indicating that both rice fields and converted orchards were net sources of atmospheric GHGs. Consistent with previous studies, N inputs affect CH_4 emissions in wetland ecosystems by adjusting CH_4 production, oxidation, and transport [63]. Similarly, N_2O emissions from farmland are usually determined by field management, such as N application and water conditions [10,21]. The GWP is roughly comparable to earlier measurements in the region. Mid-season drainage reduces

CH_4 emissions but increases N_2O emissions [48]. Land-use conversion significantly reduces CH_4 and N_2O emissions, and thus, GWP is significantly reduced by 77.2% (Table 2). First, the EF_{N2O} of this study is much higher than 0.42–0.79% in previous rice fields quantization results because the special water regime of the rice field led to the sensitive change of direct N_2O emissions [47]. Compared with previous results, the increased GWP of N_2O emissions caused by mid-season drainage exceeded the reduced GWP of the CH_4 emissions [64]. Secondly, the observation period was limited to the rice-growing season. Fertilization in orchards occurred in December, March, and May of the following year, resulting in sizeable N_2O emissions. Therefore, no primary pulse emission of N_2O was observed in orchards during the rice-growing season [14].

Focusing only on GWP reduction is often a mistake, while GHGI also is evaluated to achieve high yield and low GHGs emissions [51]. Although the results showed a high yield and high emissions, the yield of the PN280 treatment increased by 31.81%, while GHGI only increased by 14.63% compared to the PN220 treatment (Table 2). The GHGIs of this study were within the range of the estimated value of rice fields with mid-season drainage (0.24–0.74 t CO_2-eq t^{-1} yield) [52]. The application of organic N fertilizer resulted in a small increase in CH_4 emissions and a large decrease in N_2O emissions, reducing the climatic impact of a double-cropping rice system [65]. To reduce GHGI and achieve higher NAE, it is better management practice to partially replace chemical N fertilizer inputs with organic fertilizers [66].

5. Conclusions

In summary, our results revealed the impact of land-use change on agricultural non-CO_2 GHG emissions and NO by comparing it with an adjacent orchard converted from a rice paddy. We found that N_2O and CH_4 emissions from paddy soils increased with increasing N inputs. During the rice-growing season, the CH_4 emission was 28.6–85.3 kg C ha^{-1}, and the N_2O emission was 0.5–4.0 kg N ha^{-1}. Chemical N fertilizer application and water status changes were the main factors affecting N_2O emissions from rice fields. Moreover, there was a strong positive correlation between the amount of N input and rice yield. The 280 kg N ha^{-1} is the recommended N application rate, which can significantly increase rice yield without greatly increasing GHGI. Both rice and transformed orchards are net sources of atmospheric GHGs. The rice-growing season and the annual data showed that land-use conversion significantly reduced soil CH_4 and N_2O emissions during the corresponding period, thus significantly reducing the soil GWP.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy12081850/s1, Table S1: CH_4 and NOx emissions from other rice-wheat rotation studies in the middle and lower reaches of the Yangtze River used in this study [67–72].

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