Comparison of N$_2$O Emissions From Cold Waterlogged and Normal Paddy Fields

Xiangyu Xu$^{1,2,3†}$, Minmin Zhang$^{1,2,3†}$, Yousheng Xiong$^{1,2,3}$, Muhammad Shaaban$^{4,5}$, Jiafu Yuan$^{1,2,3*}$ and Ronggui Hu$^{6}$

$^1$Institute of Plant Protection and Soil Fertilizer, Hubei Academy of Agricultural Sciences, Wuhan, China, $^2$Key Laboratory of Fertilization from Agricultural Wastes, Ministry of Agriculture, Wuhan, China, $^3$Qianjiang Scientific Observing and Experimental Station of Agro-Environment and Arable Land Conservation, Ministry of Agriculture, Qianjiang, China, $^4$Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China, $^5$Department of Soil Science, Faculty of Agricultural Sciences and Technology, Bahauddin Zakariya University, Multan, Pakistan, $^6$College of Resources and Environment, Huazhong Agricultural University, Wuhan, China

Paddy fields are major sources of atmospheric N$_2$O. Soil temperature and moisture strongly affect N$_2$O emissions from rice fields. However, N$_2$O emissions from cold-waterlogged paddy fields (CW), an important kind of paddy soil in China, are not well studied so far. It is unclear whether the N$_2$O emissions from cold-waterlogged paddy fields are the same as normal paddy fields (NW). We investigated the N$_2$O emission characteristics from the CW and NW paddy fields under with (R$_1$) and without (R$_0$) rice in Tuku Village, Baisha Town, Yangxin County (YX site, monitoring in 2013) and Huandiqiao Town, Daye City (DY site, monitoring in 2014); compared the difference and influencing factors between the CW and NW paddy fields at two sites in South China. The results showed that the N$_2$O emissions from NWR$_0$ were 13.4 times higher than from CWR$_0$, and from NWR$_1$ were 10.3 times higher than from CWR$_1$ in the YX site. The N$_2$O emissions from NWR$_0$ were 2.4 times higher than from CWR$_0$, and from NWR$_1$ were 17.3 times higher than from CWR$_1$ in the DY site. The structural equation models (SEMs) showed that the N$_2$O emissions are mainly driven by rice planting and soil moisture in the NW fields at the annual scale, while soil temperature in the CW fields. Overall, N$_2$O emissions from cold waterlogged paddy fields are significantly lower than those of normal paddy fields due to the low temperature and higher water content; however, there are dinitrogen emissions from cold waterlogged paddy fields denitrification should be further examined.

Keywords: cold-waterlogged paddy field, N$_2$O, soil temperature, nitrate, ammonium

INTRODUCTION

Nitrous oxide (N$_2$O) is the third-largest long-lived greenhouse gas following CO$_2$ and CH$_4$. The lifetime of N$_2$O in the atmosphere is about 121 years, and its greenhouse effect is 265 times that of CO$_2$ on a hundred-year scale (IPCC, 2014). Farmland ecosystems are the primary anthropogenic source of N$_2$O emissions.

The nitrification and denitrification of the soil’s nitrogen cycle can lead to N$_2$O emissions (Spott et al., 2011; Butterbach-Bahl et al., 2013; Hu et al., 2015a). Soil water change, soil aggregate...
fragmentation, organic matter degradation, and organic nitrogen mineralization regulate N₂O emissions (Cuhel et al., 2016; Sheng et al., 2013; Wissing et al., 2013; Zhu et al., 2013; Wang et al., 2014; Weller et al., 2016).

Rice is a staple food and feeds nearly 50% of the global population (Alexandratos and Bruinsma, 2012). Paddy fields are an important source of N₂O emissions, and 8–11% of China's agricultural N₂O emissions were estimated from rice fields (Zou et al., 2009). A cold-waterlogged paddy field is a major type of low-yield paddy soil in China, accounting for 15.2% of the total paddy fields in this country (Xie et al., 2015). Its main characteristics are higher groundwater levels and lower soil temperature than normal paddy fields (Qiu et al., 2013; Liu et al., 2016). Those environments make strong anaerobic conditions, poor soil structure, high organic matter contents, and low rates of N mineralization (Xie et al., 2015). Those properties of CW fields result in significantly lower rice biomass yields and higher methane emissions than normal paddy fields (NW fields) (Xu et al., 2020).

Soil water content has a decisive influence on the process of nitrification and denitrification (Davidson and Verchot, 2000). Soil water-saturated areas or flooding conditions hinder gas diffusion and form an anaerobic soil environment (Zhu et al., 2013). Alternating wet and dry, the most common water management measures in normal rice fields, causes repeated nitrification and denitrification and results in a large amount of N₂O production and emission (Hofstra and Bouwman, 2005, Hu et al. (2015b), Patrick and Wyatt (1964), Fierer and Schimel (2002), Gaihre et al. (2017), Islam et al. (2018)), and N₂O emissions from lowland rice fields showed significant spatial and seasonal variations from lowland rice fields (Gaihre et al., 2017). However, due to the high groundwater level, the effects of alternating dry and wet measures in cold-waterlogged paddy fields are far inferior to normal rice fields.

As mentioned above, there are considerable differences in soil water content, soil temperature, soil organic matter content, rice yield, and methane emissions between CW fields and NW field. However, N₂O fluxes characteristics, total N₂O emissions, and influencing factors of cold-waterlogged paddy fields have not been explored. We hypothesized that the cold-waterlogged paddy fields have lower N₂O emissions than normal rice fields. The impact of rice planting on nitrous oxide emissions and the significant effect of nitrous oxide emissions should differ from normal rice fields. Therefore, this study intends to systematically monitor the cold-waterlogged paddy field's N₂O emissions characteristics on an annual scale in two representative regions and analyze the main controlling factors that affect N₂O emissions. It’s significant to understand rice fields’ total greenhouse effect, accurately assessing the N₂O emissions of China’s rice field system, and reasonably formulate the emission reduction measures of this type of rice field.

**MATERIALS AND METHODS**

**Study Site and Experimental Design**

The study was conducted at two sites with different climate zones in Huangshi, Hubei Province, China. One belongs to a subtropical climate zone in Tuku Village, Baisha Town, Yangxin County (YX site, 2013), and soil-derived from acid aplite. Another is Huandiqiao Town, Daye City (DY site, 2014), a northern subtropical monsoon climate zone and soil derived from carbonatite. Soil physical and chemical properties of the surface layer soil (0–20 cm) are listed in Table 1. We conducted eight treatments, including NW planted with (NWR₁) or without (NWR₀) rice and CW planted with (CWR₁) or without (CWR₀) rice in both sites. The area of each plot with rice was 100 m² (10 m × 10 m), and the subplot without rice was 3 m² (1.5 m × 2 m). Each treatment had three replicates. Urea, calcium superphosphate, and potassium chloride were applied as nitrogen, phosphorous, and potassium fertilizers, respectively (N: P₂O₅: K₂O = 180: 90: 120 kg hm⁻²) at both sites. Specifically, 50% nitrogen, 100% potassium, and 100% phosphorus were applied as basal fertilizer. The remaining 30% nitrogen applied at the jointing stage, and another 20% nitrogen applied ~15 days after full heading.

**Gas Collection and Analysis**

N₂O fluxes were measured using a static chamber technique, as reported previously (Xu et al., 2020). Each static chamber consisted of three parts: a bottom base, a middle chamber, and a top chamber. The chambers were wrapped with a layer of thermal insulation material. The base’s four walls were drilled at 10 cm from the top with two rows of 2-cm-diameter holes to facilitate water and fertilizer flow. The base (42 cm long × 42 cm wide × 20 cm high), with a groove around the top edge, was inserted 20 cm into the soil and remained *in situ* except for tillage. The middle chambers with a groove around the top edge and top chambers (42 cm long × 42 cm wide × 50 cm high) covered the base (with a volume equal to the sum of middle and top chambers).

At transplanting, we transplanted four rice plants (at the same density as outside of the chamber) in the base. The gas samples were sampled every 7–10 days in the non-rice season. During the rice planting period, gases were collected for five consecutive days; thereafter, the gases were periodically collected at 7-days intervals. For each sampling, the gas within the chamber was collected four times from 8:00–10:00 a.m., using a 30-ml gas-tight syringe at 0, 5, 10, 15, and 20 min. The samples were transported to the laboratory and analyzed within 24 h. Meanwhile, soil temperature at a depth of 5 cm was recorded using an electronic digital thermometer.

The concentrations of N₂O in gas samples were analyzed by gas chromatography (Agilent 7890A, United States) equipped with an electron capture (ECD) for N₂O concentration analyses at 350°C, and the carrier gas was purified N₂. We calculate the N₂O fluxes by making a linear regression of the gas concentration.

The N₂O fluxes was calculated using the following formula:

$$F = \rho \times \frac{V}{S} \times \frac{dC}{dr} \times \frac{273}{273 + T}$$

Where $F$ is the N₂O flux (μg m⁻² h⁻¹); $\rho$ is the N₂O density in the standard state (kg m⁻³); $V$ is the effective volume of the closed chamber (m³); $S$ is the base area (m²); $dC/dr$ is the change of N₂O concentration in the sealed chamber per unit time, and $T$ is the average temperature in the closed section.
The N\textsubscript{2}O cumulative gas emissions was calculated by interpolation using the following formula (Iqbal et al., 2008):

\[ Ec = \frac{\sum_{i=1}^{n} (F_i + F_{i+1})}{2} \times t_{i+1} - t_i \times 24/1000 \]

where \( Ec \) is the cumulative emissions (mg m\textsuperscript{-2}), \( n \) is the number of observations, \( F_i \) (ug m\textsuperscript{-2} h\textsuperscript{-1}), and \( F_{i+1} \) (ug m\textsuperscript{-2} h\textsuperscript{-1}) are the fluxes of the \( i \) and \( i+1 \) sampling, and \( t_i \) and \( t_{i+1} \) are the \( i \) and \( i+1 \) sampling date.

### Soil Variable Measurements

Soil temperature near the base frames was measured at a depth of 5 cm in each plot and subplot using an E278 probe-type digital thermometer (Minggao Electronics Ltd., Shenzhen, China). Topsoil samples (0–20 cm) were collected randomly from five points per plot (including the plot and subplot) using a gauge auger (3-cm inner diameter) and transported immediately to the laboratory, and then homogenized and divided into two parts. One part was dried at 105°C for 24 h to determine soil water content by gravimetric. The other part was extracted with 0.5 M K\textsubscript{2}SO\textsubscript{4} solution (soil: water = 1:5) for 1 h shaking and then filtered to determine soil mineral N (NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N) and dissolved organic carbon (DOC). The NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N were analyzed using a flow-injection auto-analyzer. The DOC was measured with a TOC analyzer (Wu et al., 2017).

### Statistical Analysis

N\textsubscript{2}O accumulation emissions are expressed as the mean ± standard deviation (SD) from three replicates. Statistical analysis was conducted using SPSS 24 (IBM SPSS, Somers, United States). The relationship between N\textsubscript{2}O fluxes and environmental factors was performed in R (v3.6.1) using the "basicTrendline" packages with a single environmental factor as the independent variable and N\textsubscript{2}O flux as the dependent variable. The model parameter is used to select the fitting function, and the \( p \)-value and \( R^2 \) value are used to determine the final regression model. Finally, SEMs were used to analyse the direct and indirect relationships between environmental factors and the N\textsubscript{2}O fluxes. The first step in an SEM requires establishing an a priori model based on the known effects and the relationships among the driving variables. The piecewiseSEM package (version 2.1.0) was used to analyze SEMs. We used non-significant (\( p > 0.05 \)) Fisher’s C values to indicate a good fit (Ochoa-Hueso et al., 2020).

### RESULTS

#### Characteristic of Environmental Factors

Regardless of rice planting, the mean soil water content of CW fields was significantly higher than that of NW fields during the monitoring period (Figure 1, \( p < 0.01 \)), and rice planting has no difference at both types of fields at two sites. The average concentration of DOC for the CWR\textsubscript{0} and CWR\textsubscript{1} was significantly higher than those of the NWR\textsubscript{0} and the NWR\textsubscript{1} at the DY site (Figure 1, \( p < 0.01 \)), but no difference at the YX site. The average concentration of NO\textsubscript{3}\textsuperscript{-}-N for the CWR\textsubscript{0} was significantly higher than that for the CWR\textsubscript{1} at the YX site during the entire monitoring period, and the differences were not statistically significant (\( p > 0.05 \)). However, from July 1, 2013, to September 1, 2013, the average soil temperature of the CW fields (28.45 ± 1.98°C) was significantly lower (\( p < 0.001 \)) than the NW fields (29.87 ± 1.98°C) (Figure 1 A3), and from July 1, 2014, to September 1, 2014, the average soil temperature of the CW fields (29.97 ± 1.20°C) was significantly lower (\( p < 0.001 \)) than the NW fields (31.52 ± 1.74°C) (Figure 1 A3).

#### Characteristic of N\textsubscript{2}O Fluxes and Cumulative Emissions

The N\textsubscript{2}O emissions characteristics of CW paddy fields and NW paddy fields are shown in Figure 2. The N\textsubscript{2}O fluxes at the YX site are between -32.93 to -77.98 μg m\textsuperscript{-2} h\textsuperscript{-1}, and the DY site is between -11.82 to -93.42 μg m\textsuperscript{-2} h\textsuperscript{-1}. The NW rice field of the YX site has three obvious emission peaks without rice. The other three treatments have no emission peaks. All the treatment emission peaks of the DY site are significantly lower than the YX site under the same treatment.

The annual mean N\textsubscript{2}O fluxes of NWR\textsubscript{0} treatment are 35.29 ± 16.17 μg m\textsuperscript{-2} h\textsuperscript{-1}, and 8.91 ± 3.03 μg m\textsuperscript{-2} h\textsuperscript{-1} at YX and DY sites, respectively, and of CWR\textsubscript{0} treatment are 4.26 ± 1.72 and 2.10 ± 1.31 μg m\textsuperscript{-2} h\textsuperscript{-1} at YX and DY sites, respectively. The mean N\textsubscript{2}O fluxes from CWR\textsubscript{0} treatment was12.1% of that of NWR\textsubscript{0} treatment at the YX site and was 23.6% at the DY site, respectively. The mean N\textsubscript{2}O fluxes of NWR\textsubscript{1} treatment was 12.78 ± 2.91 μg m\textsuperscript{-2} h\textsuperscript{-1} at the YX site and was 36.00 ± 26.48 μg m\textsuperscript{-2} h\textsuperscript{-1} at the DY site.
respectively. The mean N$_2$O fluxes of CWR$_1$ treatment was 3.82 ± 2.07 μg m$^{-2}$ h$^{-1}$ at the YX site and was 0.43 ± 1.43 μg m$^{-2}$ h$^{-1}$ at the DY site, respectively, and mean N$_2$O fluxes from CWR$_1$ treatment was 29.89% of that from NWR$_1$ treatment at the YX site and was 1.20% at DY site, respectively.

The cumulative N$_2$O emissions were calculated by interpolation (Table 2). The results showed that the N$_2$O cumulative emissions from the CWR$_1$ treatment were the lowest at both sites. The highest N$_2$O cumulative emissions were observed in NWR$_0$ treatment at the YX site and in NWR$_1$ treatment at the DY site. Regardless of rice planting, N$_2$O cumulative emissions of the NW$_fi$elds were significantly higher than that in the CW$_fi$elds (Table 2, p < 0.05) at both sites. Rice planting significantly reduced the cumulative N$_2$O emissions from the NW$_fi$eld at the YX site but increased dramatically at the DY site. However, rice planting had no significant effect on the cumulative N$_2$O emissions from CW$_fi$elds at both sites (Table 2).

## Relationships between Environmental Factors and N$_2$O Emissions

For the YX site, the N$_2$O fluxes decrease first and then rise with the increase of the soil temperature in the NWR$_0$ treatment (p < 0.001, Figure 3 A$_3$). The N$_2$O fluxes decrease first and then rise with the rise of the soil water content (p < 0.001, Figure 3 B$_3$), and the N$_2$O fluxes decrease first and then rise with the increase of the NH$_4^+$-N concentration (p < 0.001, Figure 3 D$_3$) in the NWR$_1$ treatment. For the DY site, the N$_2$O fluxes decrease first and then rise with the increase of the soil DOC concentration (p < 0.05, Figure 4 C$_1$) in the CWR$_0$ treatment. The N$_2$O fluxes decrease first and then rise with the increase of the soil temperature (p < 0.001, Figure 4 B$_1$) in the CWR$_1$ treatment. The N$_2$O fluxes present a trend of first decreasing and then increasing with the increase of the soil temperature (p < 0.05, Figure 4 A$_4$), and N$_2$O fluxed increases with the soil NO$_3^-$-N concentration (p < 0.05, Figure 4 E$_4$) in the NWR$_1$ treatment. Other indicators at both sites have no significant relationship with N$_2$O fluxes (Figure 3 and Figure 4).

The structural equation model showed that both fields’ N$_2$O fluxes are significantly different between the experiment sites (p < 0.05, Figure 5). Soil temperature directly positively affects N$_2$O fluxes in the CW field (Figure 5 CW). In contrast, other factors, such as soil water content, DOC, NO$_3^-$-N, NH$_4^+$-N, and rice planting, had no direct effect on N$_2$O fluxes. Rice planting directly affects (p < 0.05, Figure 5 NW) on N$_2$O fluxes at the NW fields. Simultaneously, the soil water content and rice planting directly affected N$_2$O fluxes in the NW fields. Other factors, such as DOC content, NO$_3^-$-N content, and NH$_4^+$-N, have no direct effects on N$_2$O fluxes in both sites. The DOC
concentrations, NO$_3^-$-N, and NH$_4^+$-N of both type fields were significantly different in both sites ($p < 0.005$, in Fig. 6CW and Figure 5 NW).

For NW paddy fields, rice planting has a significant direct positive effect on NO$_3^-$-N ($p < 0.005$, Figure 5 NW) and on NH$_4^+$-N ($p < 0.005$, Figure 5 NW), and a negative effect on DOC ($p < 0.005$, Figure 5 NW). Simultaneously, soil temperature has a significant direct negative effect on DOC ($p < 0.005$, Figure 5 NW) and a positive effect on NH$_4^+$-N ($p < 0.005$, Figure 6 NW).

For CW paddy fields, rice planting and soil water content have a

![Figure 2](image-url) Annual N$_2$O emissions from the CW and the NW paddy fields under different treatments. Note: CWR$_0$ and CWR$_1$ are cold-waterlogged paddy field without and with rice planting, respectively; NWR$_0$ and NWR$_1$ are normal paddy field without and with rice planting, respectively. The values are means ± SD ($n = 3$). BF, SF, and TF are base fertilization, seedling fertilization, and tillering fertilization.

**Table 2** | N$_2$O cumulative emissions and ratio at different stages during the monitoring period.

| Site | Month. Date | NWR$_0$ | NWR$_1$ | CWR$_0$ | CWR$_1$
|------|-------------|---------|---------|---------|---------|
| YX   | 4.19-6.17 (60 days, BT stage) | $-2.7 \pm 10.2$ (-1.83%) | $-2.7 \pm 10.2$ (-6.30%) | $-2.8 \pm 7.8$ (-15.19%) | $-2.8 \pm 7.8$ (-30.25%)
|      | 6.18-7.25 (28 days, Fl stage) | $40.1 \pm 30.6$ (27.49%) | $15.0 \pm 8.2$ (35.33%) | $10.8 \pm 4.2$ (58.33%) | $4.6 \pm 6.2$ (49.67%)
|      | 7.26-8.9 (15 days, Dr. stage) | $56.4 \pm 69.9$ (38.69%) | $4.4 \pm 4.3$ (10.46%) | $2.0 \pm 2.9$ (11.02%) | $1.6 \pm 3.7$ (17.34%)
|      | 8.10-10.7 (52 days, Mo stage) | $40.9 \pm 34.9$ (28.08) | $24.0 \pm 7.2$ (66.63%) | $10.0 \pm 6.0$ (54.11%) | $3.6 \pm 6.4$ (38.92%)
|      | 10.8-11.4 (27 days, AH stage) | $11.1 \pm 12.9$ (7.58) | $1.6 \pm 2.7$ (3.88%) | $-1.5 \pm 3.6$ (-8.26%) | $2.3 \pm 1.9$ (24.30%)
|      | 4.19-11.4 (192 days, full monitoring) | $145.7 \pm 53.7a$ (100%) | $42.4 \pm 19.5b$ (100%) | $18.5 \pm 8.8c$ (100%) | $9.3 \pm 8.8c$ (100%)
| DY   | 4.24-6.10 (48 days, BT stage) | $1.4 \pm 4.8$ (3.21%) | $1.4 \pm 4.8$ (0.96%) | $1.3 \pm 1.2$ (12.04%) | $1.3 \pm 1.2$ (31.69%)
|      | 6.11-7.23 (43 days, Fl stage) | $9.4 \pm 6.1$ (21.45%) | $57.8 \pm 15.3$ (36.43%) | $3.3 \pm 2.4$ (29.97%) | $3.2 \pm 2.3$ (77.87%)
|      | 7.24-8.14 (22 days, Dr. stage) | $8.4 \pm 6.9$ (19.25%) | $10.1 \pm 2.7$ (6.37%) | $1.0 \pm 1.3$ (9.15%) | $-0.6 \pm 1.5$ (13.70%)
|      | 8.15-10.5 (51 days, Mo stage) | $4.8 \pm 1.1$ (11.01%) | $3.3 \pm 3.1$ (2.08%) | $1.6 \pm 2.4$ (15.04%) | $-1.7 \pm 1.9$ (-41.80%)
|      | 10.6-12.2 (58 days, AH stage) | $19.7 \pm 13.1$ (45.08%) | $86.0 \pm 93.8$ (54.17%) | $3.7 \pm 4.1$ (33.83%) | $1.9 \pm 0.6$ (46.00%)
|      | 4.24-12.2 (222 days, full monitoring) | $43.7 \pm 13.9b$ (100%) | $158.7 \pm 101.7a$ (100%) | $10.9 \pm 6.9c$ (100%) | $4.1 \pm 6.0c$ (100%)

**Note:** BT, Fl, Dr., Mo, AH indicate before transplanting, flooding, drainage, moisture, after harvest, respectively. Different letters in a row indicate significant differences in the same treatment between different sites ($p < 0.05$).
FIGURE 3 | $A_1$, $B_1$, $C_1$, $D_1$, and $E_1$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+-\text{N}$ contents, and $\text{NO}_3^-\text{N}$ contents in the CWR0, respectively. $A_2$, $B_2$, $C_2$, $D_2$, and $E_2$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+-\text{N}$ contents, and $\text{NO}_3^-\text{N}$ contents in the CWR1, respectively. $A_3$, $B_3$, $C_3$, $D_3$, and $E_3$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+-\text{N}$ contents, and $\text{NO}_3^-\text{N}$ contents in the NWR0, respectively. $A_4$, $B_4$, $C_4$, $D_4$, and $E_4$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+-\text{N}$ contents, and $\text{NO}_3^-\text{N}$ contents in the NWR1, respectively.
FIGURE 4 | $A_1, B_1, C_1, D_1,$ and $E_1$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+\text{-N}$ contents, and $\text{NO}_3^-\text{-N}$ contents in the CWR0, respectively. $A_2, B_2, C_2, D_2,$ and $E_1$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+\text{-N}$ contents, and $\text{NO}_3^-\text{-N}$ contents in the CWR1, respectively. $A_3, B_3, C_3, D_3,$ and $E_3$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+\text{-N}$ contents, and $\text{NO}_3^-\text{-N}$ contents in the NWR0, respectively. $A_4, B_4, C_4, D_4,$ and $E_4$ means the relationships between $\text{N}_2\text{O}$ fluxes and soil temperature, soil water content, DOC contents, $\text{NH}_4^+\text{-N}$ contents, and $\text{NO}_3^-\text{-N}$ contents in the NWR1, respectively.
significant direct negative effect on NO$_3^-$-N ($p < 0.005$, Figure 5 CW), and soil temperature have a significant direct positive effect on NO$_3^-$-N ($p < 0.05$, Figure 5 CW), NH$_4^+$-N ($p < 0.01$, Figure 5 CW), and a significant direct negative effect on DOC ($p < 0.005$, Figure 5 CW). NO$_3^-$-N directly affects NH$_4^+$-N ($p < 0.01$, Figure 5 NW and Figure 5 CW) at both type fields.

**DISCUSSION**

Our results demonstrated that the N$_2$O emissions from the CW fields are significantly lower than that of the NW fields, regardless of rice planting ($p < 0.05$, Table 2). In this study, the soil temperature of the CW fields is significantly lower than that of the NW rice fields during the high air temperature (Figure 6 A3 and B3). However, there is no significant difference on an annual scale. The relationship between soil temperature and N$_2$O emissions is not uniform (Zhou et al., 2018; Wang et al., 2019); this difference is mainly affected by soil moisture (Wu et al., 2013). N$_2$O emissions from soil are affected by the interaction of multiple environmental factors under natural conditions, and the relationship between temperature and water content determines whether to promote N$_2$O emissions. This may be why the relationship between a single factor and N$_2$O is not consistent in our study.

The N$_2$O annual cumulative emissions from the NW fields are consistent with the results of Lan et al. (2020) but smaller than those reported by Huang et al. (2019), and the CW fields’ N$_2$O annual emissions are lower than previous studies (Huang et al., 2019; Lan et al., 2020). The possible reason is that the soil water content in Huang’s research is lower than that of the NW fields and the CW fields in this study. In this study, the soil water content of the CW fields is significantly higher than that of NW fields on the annual scale (Figure 1). Soil moisture determines the soil’s redox state (Mei et al., 2011; Blagodatskaya et al., 2014). Previous research had shown that it might reduce 30–80% of N$_2$O in the deep soil layer (anaerobic layer) to N$_2$ before being released into the atmosphere (Clough et al., 2005). The N$_2$ emissions from soil denitrification are considered to be a major gaseous N loss pathway, particularly in flooded paddy fields, where the strictly anaerobic environment promotes the complete reduction of nitrate or nitrite to N$_2$ through the intermediates of N$_2$O and NO (Davidson and Verchot, 2000; Butterbach-Bahl et al., 2013). In our study, the CW rice field has been saturated for a long time and under a strictly anaerobic state (Xu et al., 2020). The strong reduction state may lead to the complete reduction of N$_2$O to N$_2$ (Parton et al., 1996; Zhu et al., 2014). Simultaneously, the rice biomass accumulation is lower in the CW field than in the NW fields, and lower biomass accumulation means less N$_2$O emissions (Xu et al., 2020). The above two points may lead to significantly lower N$_2$O emissions from CW fields.

Rice planting may provide channels for N$_2$O emissions, contributing more than 70% of soil N$_2$O emissions during flooding but less than 20% after drainage (Yu et al., 1997; Yan et al., 2000). In this study, rice planting promoted the N$_2$O accumulative emissions in the NW field at the DY site. However, the N$_2$O emissions from NWR$_0$ were significantly lower than that of NWR$_0$ at the YX site, which may be related to more weeds in the treatment, and weeds (especially Monochoria vaginalis) could lead to a large amount of N$_2$O production and emission. At the same time, it may also be the N$_2$O emissions from NWR$_0$ at the YX site were significantly
higher than that of the DY site, which has no weeds. N$_2$O emissions from NWR$_1$ treatments at the DY site were significantly higher than that of the YX site, and this may be related to the lower rice biomass (15,957 kg hm$^{-2}$ at the DY site and 15,021 kg hm$^{-2}$ at the YX site) Xu et al. (2020) and the higher soil pH (Table 1), due to the N$_2$O emissions from low-pH soils are significantly higher than those with high-pH soils (Wang et al., 2017).

N$_2$O emissions from paddy fields are affected by various environmental factors (Schaufler et al., 2010; Hu et al., 2015a). Pärn et al. (2018) reported that soil NO$_3^-$-N and soil volumetric water content together determine the geographic differentiation of global organic soil N$_2$O emissions ($n = 58$, $R^2 = 0.72$, $p < 0.001$), and the relationship between soil temperature and N$_2$O emissions is affected by region (Pärn et al., 2018). In the present study, the structural equation model

![FIGURE 6](image_url) Annual variation trend of soil temperature and temperature difference during high temperature period. Note: Buried three temperature recorders in each field. (A) and (B) are the annual variation trend of 5 cm soil temperature during the monitoring period in YX site and DY site, respectively.
showed that the N$_2$O emissions of the same type of rice fields are significantly different between the different sites. At the same time, environmental factors have no significant direct effects on N$_2$O emissions. However, there are significant direct or indirect effects between soil environmental factors in each type of paddy field, confirming the cover-up effect of regional differences on environmental factors (Pärn et al., 2018).

**CONCLUSION**

The CW fields’ annual N$_2$O cumulative emissions were significantly lower than that of the NW fields under the same climatic conditions and planting systems. N$_2$O emissions from the CW fields are mainly in the flooding period after transplanting, while the NW fields are primarily in the drainage period after flooding. N$_2$O emissions from the CW fields are mainly affected by soil temperature; however, they are mainly affected by rice planting and soil moisture from the NW fields. The CW fields have very low N$_2$O emissions and may have gaseous nitrogen emissions by denitrification. We suggest that follow-up research should study and evaluate the gaseous nitrogen emissions, and this has certain enlightenment for the governance of environmental nitrogen pollution.

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**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author/s.

**AUTHOR CONTRIBUTIONS**

XX and JY conceived the idea, XX, MZ, and YX conducted experiment analyzed data, XX, MZ, and MS wrote the manuscript, RH, JY, and MS reviewed, revised and improved the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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