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Comparison of N_2O Emissions From Cold Waterlogged and Normal Paddy Fields

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Paddy fields are major sources of atmospheric N_2O. Soil temperature and moisture strongly affect N_2O emissions from rice fields. However, N_2O 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_2O emissions from cold-waterlogged paddy fields are the same as normal paddy fields (NW). We investigated the N_2O 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_2O 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_2O 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_2O 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_2O 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_2O, soil temperature, nitrate, ammonium

INTRODUCTION

Nitrous oxide (N_2O) is the third-largest long-lived greenhouse gas following CO_2 and CH_4. The lifetime of N_2O 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_2O emissions.

The nitrification and denitrification of the soil's nitrogen cycle can lead to N_2O 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 N_2O emissions (Čuhel et al., 2010; 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 N_2O emissions, and 8–11% of China's agricultural N_2O 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 N_2O 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 N_2O 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, N_2O fluxes characteristics, total N_2O emissions, and influencing factors of cold-waterlogged paddy fields have not been explored. We hypothesized that the cold-waterlogged paddy fields have lower N_2O 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 N_2O emissions characteristics on an annual scale in two representative regions and analyze the main controlling factors that affect N_2O emissions. It's significant to understand rice fields' total greenhouse effect, accurately assessing the N_2O 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 (NWR_1) or without (NWR_0) rice and CW planted with (CWR_1) or without (CWR_0) rice in both sites. The area of each plot with rice was 100 m^2 (10 m × 10 m), and the subplot without rice was 3 m^2 (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: P_2O_5: K_2O = 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

N_2O 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 are 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 N_2O in gas samples were analyzed by gas chromatography (Agilent 7890A, United States) equipped with an electron capture (ECD) for N_2O concentration analyses at 350°C, and the carrier gas was purified N_2. We calculate the N_2O fluxes by making a linear regression of the gas concentration.

The N_2O fluxes was calculated using the following formula:

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

Where F is the N_2O flux (ug $m^{-2}h^{-1}$); ρ is the N_2O density in the standard state (kg m^{-3}); V is the effective volume of the closed chamber (m^3), S is the base area (m^2); dC/dt is the change of N_2O concentration in the sealed chamber per unit time, and T is the average temperature in the closed section.

TABLE 1 | Soil physical and chemical properties (mean ± SD, $n = 3$) in paddy fields at the two experimental sites in Hubei Province, China.

Site	Type	OM (g kg^{-1})	TN (g kg^{-1})	AN (mg kg^{-1})	TP (g kg^{-1})	AP (mg kg^{-1})	TK (g kg^{-1})	AK (mg kg^{-1})	pH	MST (°C)
YX	CW	25.58 ± 0.58b	2.01 ± 0.12a	185.5 ± 22.2a	0.65 ± 0.05b	3.72 ± 0.11b	17.12 ± 0.31b	32.20 ± 2.36b	6.19 ± 0.01a	26.99 ± 2.31a
	NW	21.74 ± 0.37c	1.62 ± 0.11b	189.7 ± 19.5a	0.81 ± 0.07a	7.86 ± 0.56a	19.50 ± 0.89b	36.14 ± 3.56b	6.16 ± 0.01a	27.36 ± 2.58a
DY	CW	33.05 ± 0.66a	1.55 ± 0.06b	157.2 ± 16.3b	0.24 ± 0.02c	4.26 ± 0.32b	25.6 ± 1.58a	58.14 ± 6.56a	5.19 ± 0.01b	23.76 ± 2.12b
	NW	32.51 ± 0.41a	1.48 ± 0.09b	162.2 ± 11.0b	0.24 ± 0.01c	6.74 ± 0.15 ab	24.3 ± 1.25a	61.16 ± 5.89a	5.06 ± 0.02b	23.83 ± 2.68b

Note: OM, TN, AN, TP, AP, TK, AK, and MST indicate organic matter, total nitrogen, available nitrogen, total phosphorus, available phosphorus, total potassium, available potassium, and mean soil temperature. YX and DY mean Yangxin site and Daye site. CW and NW mean cold-waterlogged paddy fields and normal paddy fields. Different lowercase letters within a single column indicate statistically significant differences at p *< 0.05 between treatments. MST is mean temperature of 5 cm soil layer during rice planting.*

The N_2O cumulative gas emissions was calculated by interpolation using the following formula (Iqbal et al., 2008):

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

where Ec is the cumulative emissions (mg m^{-2}), n is the number of observations, F_i (ug $m^{-2}h^{-1}$), and F_{i+1} (ug m^{-2} h^{-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_2SO_4 solution (soil: water = 1:5) for 1 h shaking and then filtrated to determine soil mineral N (NH_4^+-N and NO_3^--N) and dissolved organic carbon (DOC). The NH_4^+-N and NO_3^--N were analyzed using a flow-injection auto-analyzer. The DOC was measured with a TOC analyzer (Wu et al., 2017).

Statistical Analysis

N_2O 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_2O 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_2O 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_2O 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_0 and CWR_1 was significantly higher than those of the NWR_0 and the NWR_1 at the DY site (**Figure 1**, $p < 0.01$), but no difference at the YX site. The average concentration of NO_3^--N for the CWR_0 was significantly higher than that for the NWR_0 at the DY site (**Figure 1**, $p < 0.01$), and the average concentration of NH_4^+-N of the CWR_1 was significantly higher than that of the NWR_1 at the DY site (**Figure 1**, $p < 0.01$). In the same site, the CW fields' mean soil temperature was lower than that of the NW fields' 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_2O Fluxes and Cumulative Emissions

The N_2O emissions characteristics of CW paddy fields and NW paddy fields are shown in **Figure 2**. The N_2O fluxes at the YX site are between −32.93 −778.98 μg m^{-2} h^{-1}, and the DY site is between −11.82 −93.42 μg m^{-2} h^{-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_2O fluxes of NWR_0 treatment are 35.29 ± 16.17 μg m^{-2} h^{-1}, and 8.91 ± 3.03 μg m^{-2} h^{-1} at YX and DY sites, respectively, and of CWR_0 treatment are 4.26 ± 1.72 and 2.10 ± 1.31 μg m^{-2} h^{-1} at YX and DY sites, respectively. The mean N_2O fluxes from CWR_0 treatment was12.1% of that of NWR_0 treatment at the YX site and was 23.6% at the DY site, respectively. The mean N_2O fluxes of NWR_1 treatment was 12.78 ± 2.91 μg m^{-2} h^{-1} at the YX site and was 36.00 ± 26.48 μg m^{-2} h^{-1} at the DY site,

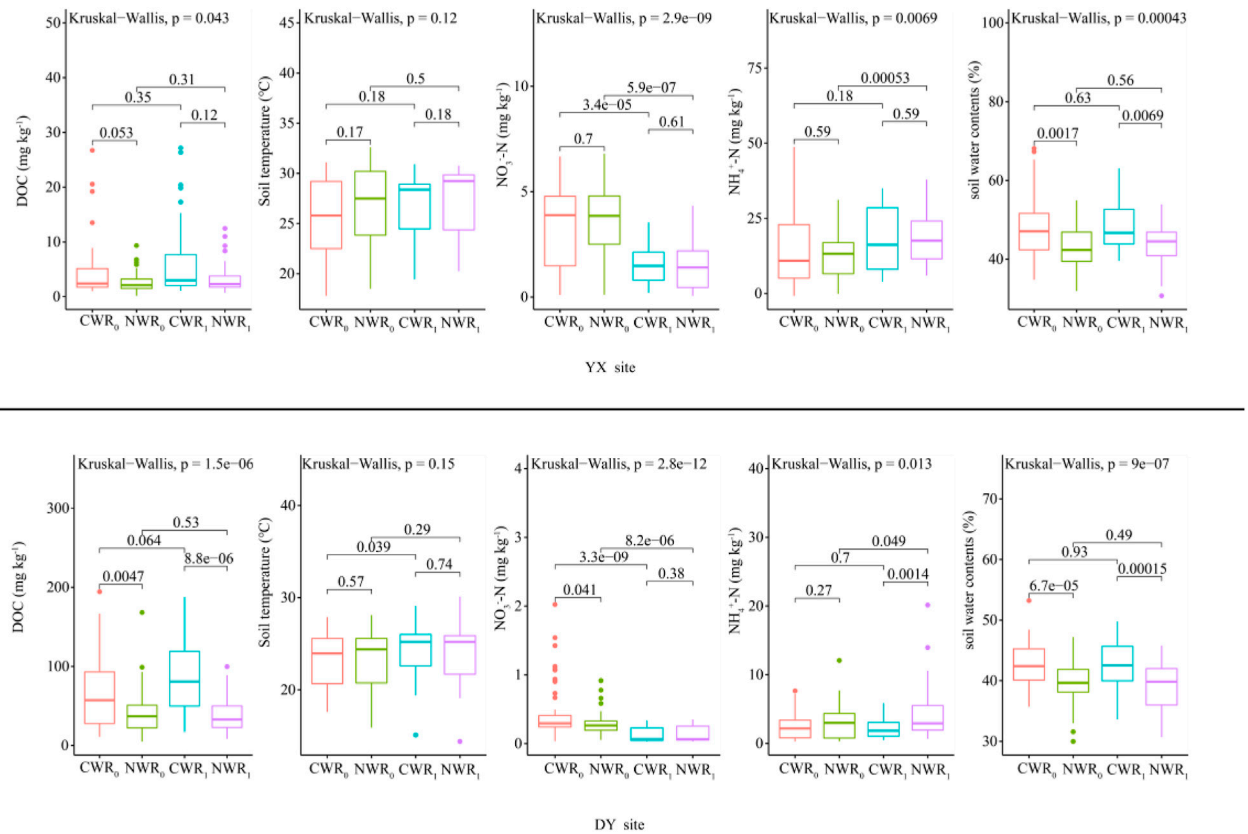

FIGURE 1 | The difference of environmental factors between YX site and DY site (adapted from Xu et al., 2020). Note: CWR_0 and CWR_1 are cold-waterlogged paddy field without and with rice planting, respectively; NWR_0 and NWR_1 are normal paddy field without and with rice planting, respectively. The number on the horizontal line indicates the significance of the difference. The points outside the box plot indicate outliers.

respectively. The mean N_2O 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_2O 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_2O emissions were calculated by interpolation (**Table 2**). The results showed that the N_2O cumulative emissions from the CWR_1 treatment were the lowest at both sites. The highest N_2O 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_2O cumulative emissions of the NW fields were significantly higher than that in the CW fields (**Table 2**, $p < 0.05$) at both sites. Rice planting significantly reduced the cumulative N_2O emissions from the NW field at the YX site but increased dramatically at the DY site. However, rice planting had no significant effect on the cumulative N_2O emissions from CW fields at both sites (**Table 2**).

Relationships between Environmental Factors and N_2O Emissions

For the YX site, the N_2O 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_2O fluxes decrease first and then rise with the rise of the soil water content ($p < 0.001$, **Figure 3** B_3), and the N_2O 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_2O 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_2O 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_2O 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_2O 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_2O fluxes (**Figure 3** and **Figure 4**).

The structural equation model showed that both fields' N_2O fluxes are significantly different between the experiment sites ($p < 0.05$, **Figure 5**). Soil temperature directly positively affects N_2O 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_2O fluxes. Rice planting directly affects ($p < 0.05$, **Figure 5** NW) on N_2O fluxes at the NW fields. Simultaneously, the soil water content and rice planting directly affected N_2O 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_2O fluxes in both sites. The DOC

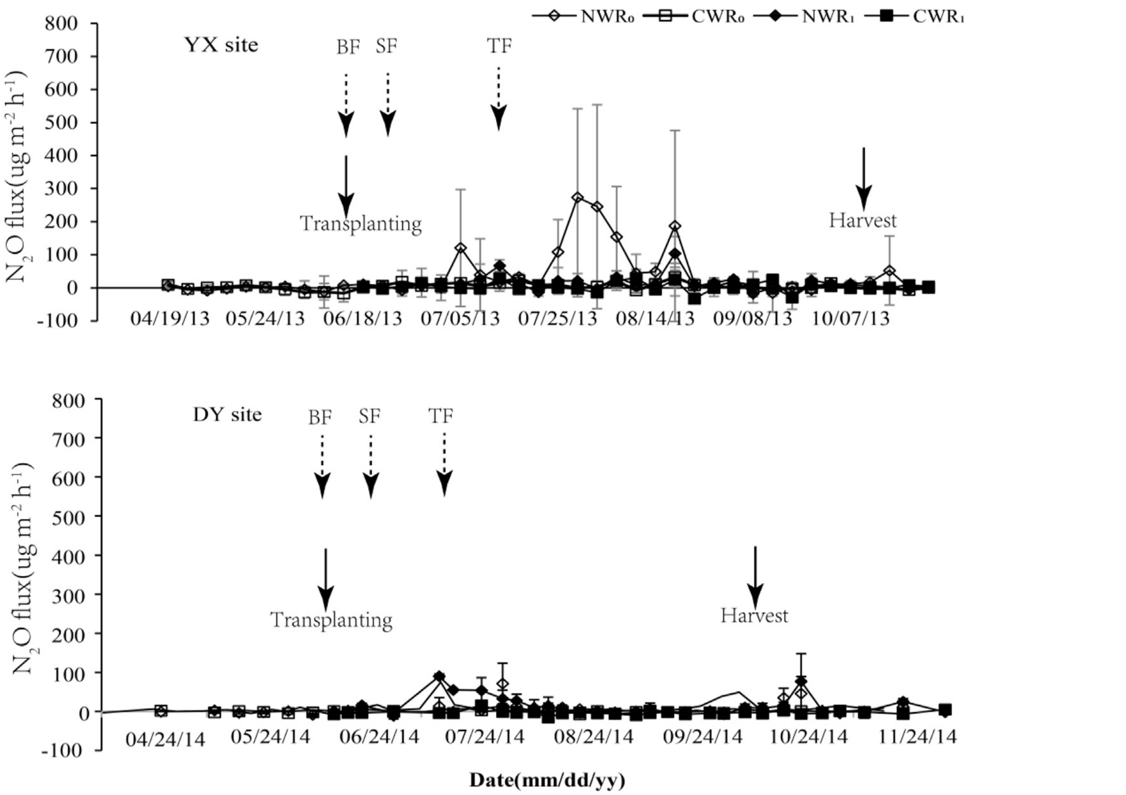

FIGURE 2 | Annual N_2O emissions from the CW and the NW paddy fields under different treatments. Note: CWR_0 and CWR_1 are cold-waterlogged paddy field without and with rice planting, respectively; NWR0 and NWR1 are normal paddy field without and with rice planting, respectively. The values are means ± SD (n = 3). BF, SF, and TF are base fertilization, seedling fertilization, and tillering fertilization.

TABLE 2 | N_2O cumulative emissions and ratio at different stages during the monitoring period.

Site	Month. Date	Cumulative emissions (mg N_2O m^{-2})			
		NWR_0	NWR_1	CWR_0	CWR_1
YX	4.19–6.17 (60 days, BT stage)	−2.7 ± 10.2 (−1.83%)	−2.7 ± 10.2 (−6.30%)	−2.8 ± 7.8 (−15.19%)	−2.8 ± 7.8 (−30.25%)
	6.18–7.25 (38 days, Fl stage)	40.1 ± 30.6 (27.49%)	15.0 ± 8.2 (35.33%)	10.8 ± 4.2 (58.33%)	4.6 ± 6.2 (49.67%)
	7.26–8.9 (15 days, Dr. stage)	56.4 ± 59.9 (38.69%)	4.4 ± 4.3 (10.46%)	2.0 ± 2.9 (11.02%)	1.6 ± 3.7 (17.34%)
	8.10–10.7 (52 days, Mo stage)	40.9 ± 34.9 (28.08)	24.0 ± 7.2 (56.63%)	10.0 ± 6.0 (54.11%)	3.6 ± 6.4 (38.92%)
	10.8–11.4 (27 days, AH stage)	11.1 ± 12.9 (7.58%)	1.6 ± 2.7 (3.88%)	−1.5 ± 3.6 (−8.26%)	2.3 ± 1.9 (24.30%)
	4.19–11.4 (192 days, full monitoring)	145.7 ± 53.7a (100%)	42.4 ± 19.5b (100%)	18.5 ± 8.8c (100%)	9.3 ± 8.8c (100%)
DY	4.24–6.10 (48 days, BT stage)	1.4 ± 4.8 (3.21%)	1.4 ± 4.8 (0.95%)	1.3 ± 1.2 (12.04%)	1.3 ± 1.2 (31.69%)
	6.11–7.23 (43 days, Fl stage)	9.4 ± 6.1 (21.45%)	57.8 ± 15.3 (36.43%)	3.3 ± 2.4 (29.97%)	3.2 ± 2.3 (77.87%)
	7.24–8.14 (22 days, Dr. stage)	8.4 ± 6.9 (19.25%)	10.1 ± 2.7 (6.37%)	1.0 ± 1.3 (9.15%)	−0.6 ± 1.5 (−13.70%)
	8.15–10.5 (51 days, Mo stage)	4.8 ± 1.1 (11.01%)	3.3 ± 3.1 (2.08%)	1.6 ± 2.4 (15.04%)	−1.7 ± 1.9 (−41.80%)
	10.6–12.2 (58 days, AH stage)	19.7 ± 13.1 (45.08%)	86.0 ± 93.8 (54.17%)	3.7 ± 4.1 (33.83%)	1.9 ± 0.6 (46.00%)
	4.24–12.2 (222 days, full monitoring)	43.7 ± 13.9b (100%)	158.7 ± 101.7a (100%)	10.9 ± 6.9c (100%)	4.1 ± 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 ($p < 0.05$*).*

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

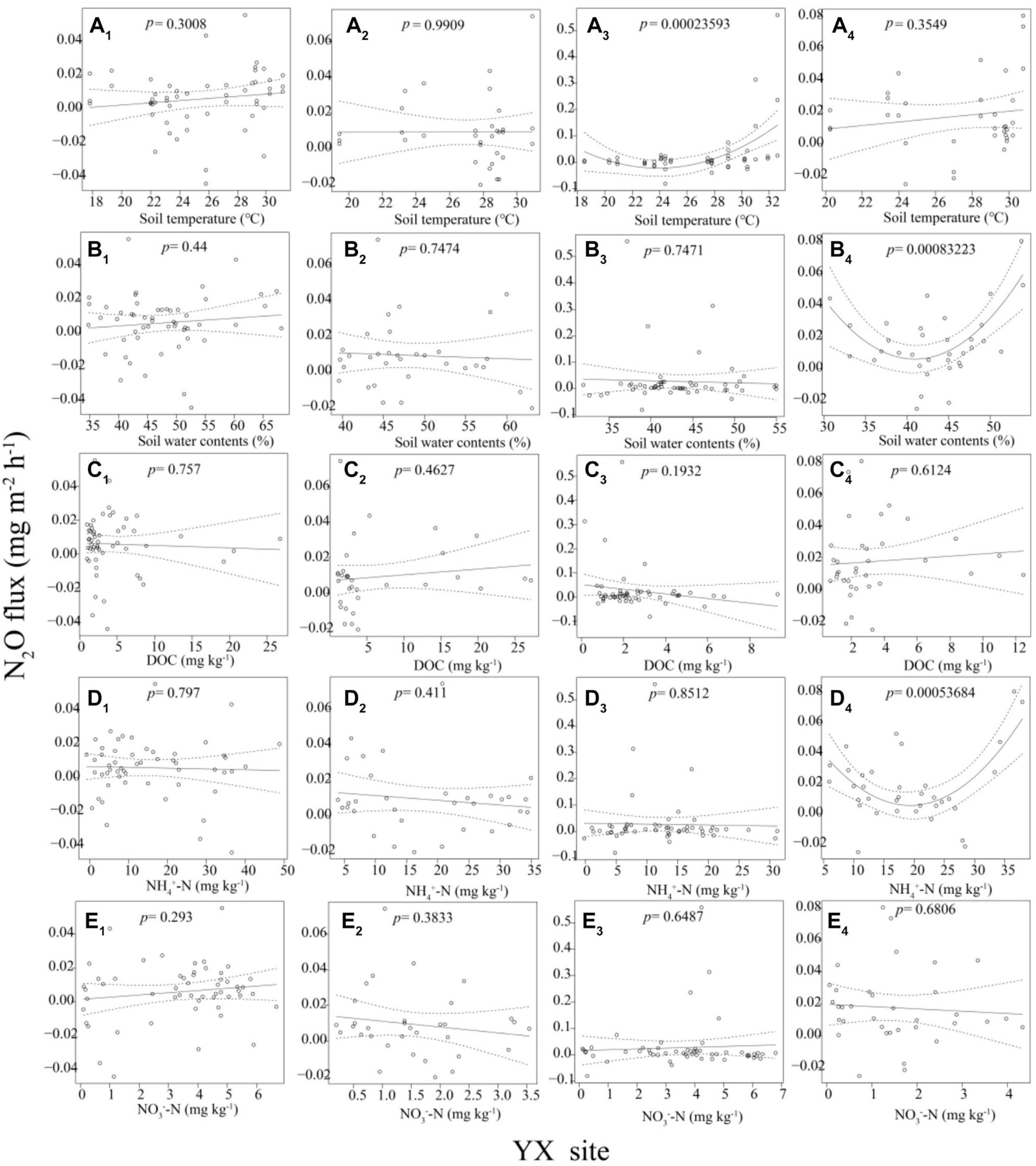

FIGURE 3 | A_1, B_1, C_1, D_1, and E_1 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the CWR_0, respectively. A_2, B_2, C_2, D_2, and E_1 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the CWR_1, respectively. A_3, B_3, C_3, D_3, and E_3 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the NWR_0, respectively. A_4, B_4, C_4, D_4, and E_4 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the NWR_1, respectively.

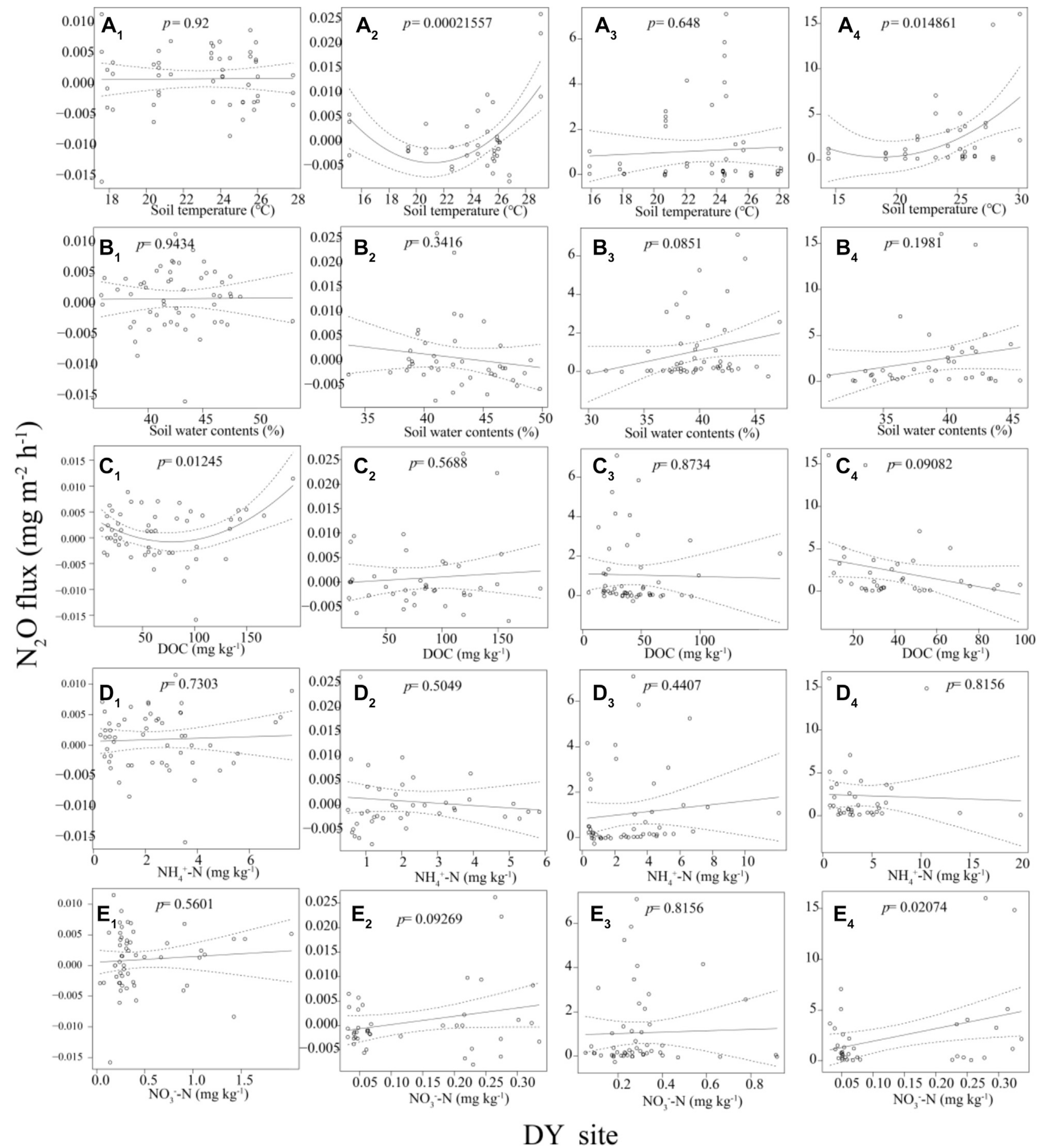

FIGURE 4 | A_1, B_1, C_1, D_1, and E_1 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the CWR_0, respectively. A_2, B_2, C_2, D_2, and E_1 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the CWR_1, respectively. A_3, B_3, C_3, D_3, and E_3 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the NWR_0, respectively. A_4, B_4, C_4, D_4, and E_4 means the relationships between N_2O fluxes and soil temperature, soil water content, DOC contents, NH_4^+-N contents, and NO_3^--N contents in the NWR_1, respectively.

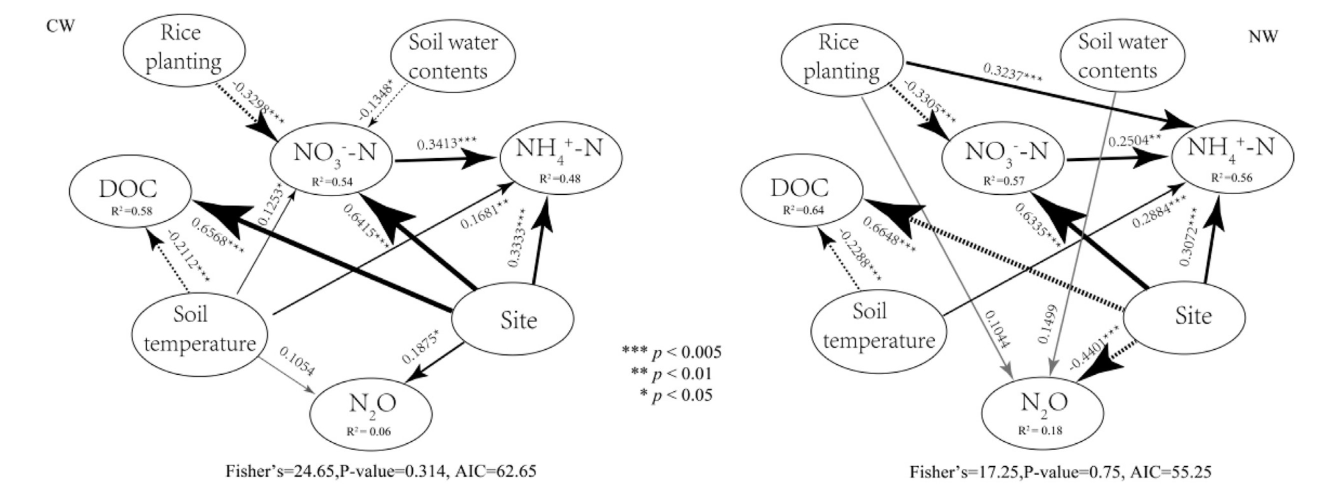

FIGURE 5 | Structural equation model. SEMs assessed direct and indirect associations between soil temperature (ST), soil water content (SWC), ammonium nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), and dissolved organic carbon (DOC) and N_2O fluxes. Numbers adjacent to the arrows are standardized path coefficients, analogous to relative regression weights, and indicate the relationship's effect size. Double-headed arrows indicate covariance between variables; single-headed arrows indicate a one way directed relationship. Solid lines indicate positive associations. Dashed lines indicate a negative association. The width of the arrow is proportional Line width is proportional to the strength of path coefficients. The proportion of variance explained (conditional R^2) appears below every response variable in the model.

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_2O 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_2O 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_2O 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_2O emissions. This may be why the relationship between a single factor and N_2O is not consistent in our study.

The N_2O 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_2O 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_2O 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_2O 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_2O 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_2O emissions (Xu et al., 2020). The above two points may lead to significantly lower N_2O emissions from CW fields.

Rice planting may provide channels for N_2O emissions, contributing more than 70% of soil N_2O 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_2O accumulative emissions in the NW field at the DY site. However, the N_2O emissions from NWR_1 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_2O production and emission. At the same time, it may also be the N_2O emissions from NWR_0 at the YX site were significantly

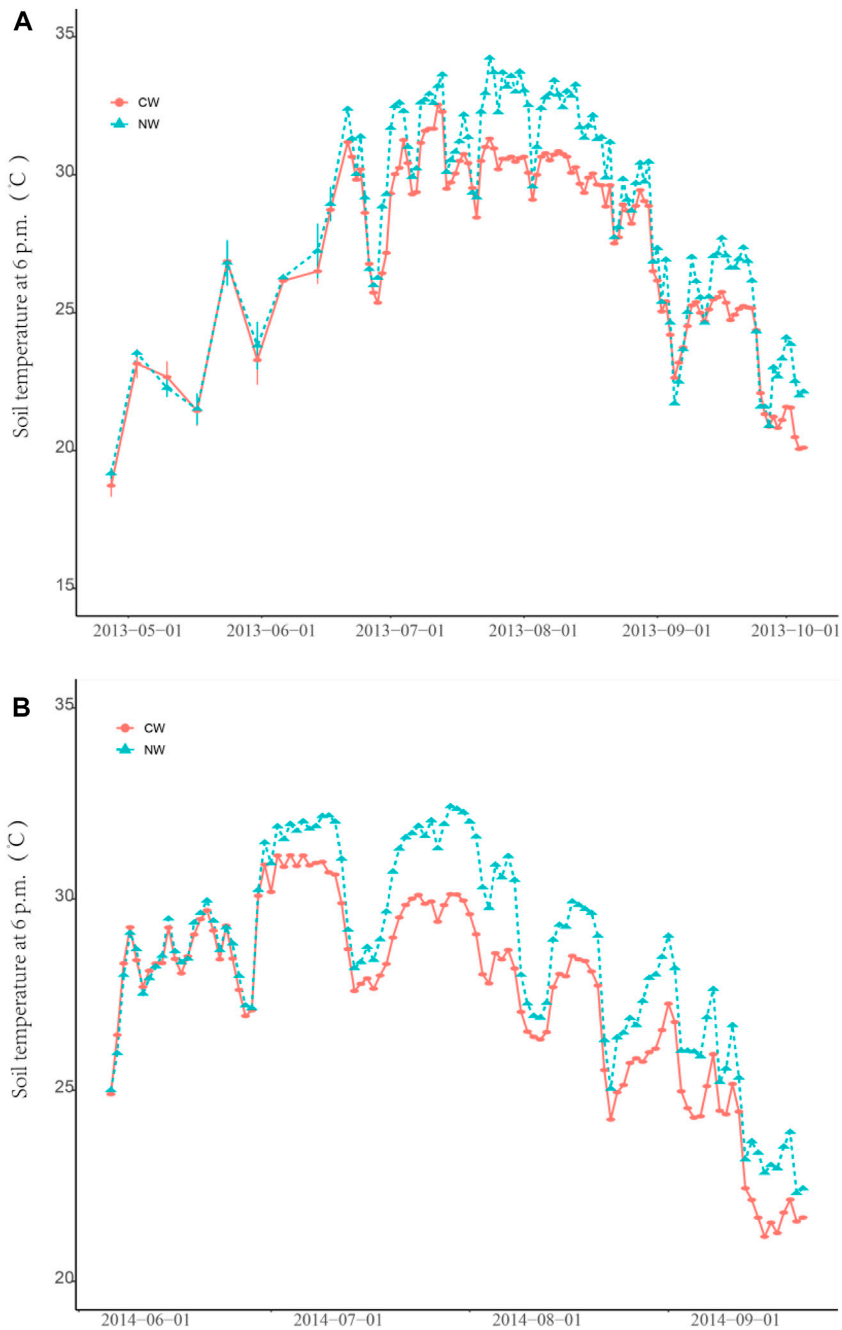

FIGURE 6 | Annual variation trend of soil temperature and temperature difference during high temperature period. Note: Buried three temperature recorders in each field. **(A)** and **(B)** are the annual variation trend of 5 cm soil temperature during the monitoring period in YX site and DY site, respectively.

higher than that of the DY site, which has no weeds. N_2O 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_2O emissions from low-pH soils are significantly higher than those with high-pH soils (Wang et al., 2017).

N_2O 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_2O emissions (n = 58, R^2 = 0.72, p < 0.001), and the relationship between soil temperature and N_2O emissions is affected by region (Pärn et al., 2018). In the present study, the structural equation model showed that the N_2O 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_2O 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_2O cumulative emissions were significantly lower than that of the NW fields under the same climatic conditions and planting systems. N_2O 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_2O 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_2O 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.

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.