Effects of mild alternate wetting and drying irrigation and rice straw application on \( \text{N}_2\text{O} \) emissions in rice cultivation

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Abstract. The shortage of water resources and the decline in soil organic matter (SOM) are critical limiting factors affecting the improvement in rice productivity, while alternate wetting and drying (AWD) irrigation and recycling application of rice straw (S) are considered favorable mitigation measures. However, the impact of such measures on rice yield and greenhouse gas (GHG) emissions, especially nitrous oxide (\( \text{N}_2\text{O} \)) emissions, needs to be further clarified to ensure that agronomic practices save water, conserve soil, and reduce GHG emissions. Therefore, we explored the effects of mild AWD irrigation combined with on-site rice straw recycling on \( \text{N}_2\text{O} \) emissions and rice yield through rice pot experiments. This experiment included 2 irrigation methods (continuous flooding (CF) irrigation and mild AWD irrigation), 2 nitrogen (N) application levels (0 and 225 kg N ha\(^{-1}\)) and 2 rice straw return levels (0 and 9000 kg ha\(^{-1}\)), for a total of 10 treatments, and each treatment had 3 replicates. The \( ^{15}\text{N} \)-urea and \( ^{15}\text{N} \)-S were added to the soil. The results showed that \( \text{N}_2\text{O} \) emissions were primarily affected by urea application and irrigation methods, with urea application being most important. Compared with CF irrigation, mild AWD irrigation increased cumulative \( \text{N}_2\text{O} \) emissions, with an average increase of 28.8 %. In addition, adding rice straw to mild AWD irrigation further stimulated \( \text{N}_2\text{O} \) emissions by 18.1 %. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation increased the yield-scaled \( \text{N}_2\text{O} \) emissions by 17.9 %, and the addition of rice straw further promoted the yield-scaled \( \text{N}_2\text{O} \) emissions under mild AWD irrigation by 17.4 % but reduced the global warming potential (GWP) (methane (\( \text{CH}_4 \)) + \( \text{N}_2\text{O} \)) by 62.9 %. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation reduced the uptake of soil-derived N and aboveground biomass of rice but did not reduce rice yield. Therefore, mild AWD irrigation combined with rice straw return may be a promising agronomic method to maintain rice yield, reduce GHGs, and protect or improve soil fertility.
1 Introduction

Rice is a staple food for more than half of the world’s population and ensuring rice production is crucial to food security (Tang and Cheng, 2018). More than 135 × 10^6 ha of rice are cultivated worldwide, and approximately 90% of paddy fields are submerged (J. Wang et al., 2017). Feeding a growing population under water scarcity will be a major challenge to Asia’s food security in the coming decades (Lampayan et al., 2015). In China, more than 60% of freshwater resources are consumed by rice cultivation every year, which represents a great waste of freshwater and causes many environmental problems, such as nonpoint source pollution, eutrophication, and greenhouse gas (GHG) emissions (Liao et al., 2020). Therefore, it is urgent to explore new methods for managing paddy field fertilization that can ensure high rice yield and reduced water waste and pollution.

Alternate wetting and drying (AWD) irrigation is an effective water-conserving irrigation method that can save approximately 23% of freshwater resources compared with CF irrigation (Bouman and Tuong, 2001; Chu et al., 2014). There are usually two approaches to AWD irrigation: severe AWD irrigation (soil water potential ≥ −30 ± 5 kPa) and mild AWD irrigation (soil water potential ≥ −15 ± 5 kPa) (Zhou et al., 2017). Severe AWD irrigation could reduce rice yield by 22.6% due to water stress, but under mild AWD irrigation, rice yield can be stable or slightly increased (Carrijo et al., 2017). Severe AWD irrigation combined with rice straw return on rice cultivation can achieve the optimal goals of water saving, yield increase and reduction in GHG emissions has remained unclear. Therefore, the purpose of this study was to investigate the effect of mild AWD irrigation combined with rice straw return on N_2O emissions and rice yield in rice cultivation and to explore the supply of N to rice growth from the soil, urea and rice straw using 15N labeling technology. Our initial hypotheses were as follows: (1) mild AWD irrigation would promote N_2O emissions in rice cultivation; and (2) mild AWD irrigation would maintain or promote rice yield.

2 Materials and methods

2.1 Experimental setup

A pot experiment was conducted in an open greenhouse at the Shenyang Experimental Station of the Institute of Applied Ecology, Liaoning Province, China (43°32′N, 123°23′E) from 17 June to 27 October 2020. The test soil was an Alfisol with a total C content of 16.01 g kg^{-1} and a total N content of 1.36 g kg^{-1}.

The pot experiment used a random block design, including 30 pots (30 cm diameter × 20 cm height). This experiment included two irrigation methods, two N application levels and two rice straw return levels, with three replicates of each combination, for a total of 30 rice pots (urea and straw were labeled with 15N, respectively). The two irrigation methods were continuous flooding (CF) irrigation and mild AWD irrigation. The CF irrigation maintained a water level depth of approximately 3–5 cm throughout the rice-growing season. Mild AWD irrigation water management in the first 7 d was consistent with CF irrigation and was allowed to evaporate under monitoring; when the soil negative pressure gauge reached −15 kPa, it was sub-flooded to a depth of 3–5 cm again and was then naturally allowed to dry again. This step was repeated until harvest. The CF and mild AWD irrigation were halted 2 weeks before harvest. Nitrogen was applied at 0 kg N ha^{-1} (control check (CK) and rice straw (15S)) and 225 kg N ha^{-1} (106.13 mg kg^{-1} dry soil) (urea (15U), urea + rice straw (U15S) and urea + rice straw (15US)). The abundance of urea 15N was 10.20%. Urea was applied three times: base fertilizer 40% (17 June), tiller topdressing 30% (4 August) and heading topdressing 30% (25 August). Rice straw return was applied at 0 kg ha^{-1} (CK and 15U) and 9000 kg ha^{-1} (4.25 g kg^{-1} dry soil) (15S, U15S and 15US). The total N content of unlabeled rice straw was 0.72%, and the isotope abundance of 15N was 0.59%. The total N content of labeled rice straw was 0.73%, and the 15N isotope abundance was 22.94%. The rice straw was ground and applied together with the base fertilizer. Phosphate fertilizer was superphosphate (150 kg P_2O_5 ha^{-1}), and potassium fertilizer was potassium chloride (185 kg K_2O ha^{-1}) as one-time application of basic fertilizer. Every pot was filled with 10.51 kg (9 kg dry soil) of sieved (2 mm) fresh soil. Two hills
of rice were planted in each pot. At maturity, the rice yield and aboveground biomass were recorded after being oven-dried (105°C for 0.5 h and 60°C for 12 h).

2.2 Soil sample collection and analysis

At the stages of regreening, tillering, jointing, booting, filling and maturity, five points were randomly selected from the 0–10 cm soil layer of each pot and mixed. The soil NH$_4^+$-N and NO$_3^-$-N were extracted with 2 mol L$^{-1}$ KCl solution (Wu et al., 2019), filtered and analyzed with a continuous flow analyzer (AA3, Bran + Luebbe, Germany). The extraction of soil $^{15}$N-NH$_4^+$-N followed Yu et al. (2020). Soil microbial biomass N (MBN) was fumigated with chloroform, extracted with 0.5 mol L$^{-1}$ K$_2$SO$_4$ (soil: solution = 5 g : 20 mL) (Joergensen and Mueller, 1996), and determined by a total organic carbon (TOC) analyzer (Elementar vario TOC Analyzer, Germany). The soil $^{15}$N-NH$_4^+$-N content, $^{15}$N-MBN and $^{15}$N of rice aboveground biomass were determined by a stable isotope ratio mass spectrometer (253 MAT, Thermo Finnigan, Germany).

2.3 Gas sampling and calculation

The static chamber method was used to determine the N$_2$O flux (J. L. Li et al., 2018). The static chamber with a top seal made of transparent plexiglass consisted of two parts, namely, the base and the gas-collecting chamber. The base had a diameter of 31 cm, a groove in the middle, and a height of 10 cm. The gas-collecting chamber had a diameter of 30 cm with a height of 70 cm. A small fan and a thermometer were installed in the gas-collecting chamber. Nitrous oxide (N$_2$O) was collected every 2 d in the first week after fertilization or irrigation and every 7 d during other periods; N$_2$O was sampled at 08:00–11:00 LT each sampling day. Every pot was sealed with water when N$_2$O was collected. Three gas samples were collected at 0, 30 and 60 min after the chamber was airtight, and N$_2$O was collected with a 50 mL injector and then injected into 200 mL gasbags.

The N$_2$O concentration was analyzed using a gas chromatograph (Agilent 7890B, Gas Chromatograph, Delaware, USA). The calculation of N$_2$O fluxes was as follows (J. L. Li et al., 2018):

$$F = \rho \times h \times \frac{dc}{dt} \times 273/(273 + T),$$

where $F$ is the N$_2$O flux (µg m$^{-2}$ h$^{-1}$); $\rho$ is the N$_2$O standard-state density (1.964 kg m$^{-3}$); $h$ is the chamber height above the soil (m); $c$ is the N$_2$O concentration; $\frac{dc}{dt}$ is the slope of the N$_2$O concentration curve, estimated using a linear regression model (Vitale et al., 2017); 273 is the gas constant; and $T$ is the average air temperature inside the chamber during N$_2$O collection (°C).

Cumulative N$_2$O emissions (CE) were calculated using the following formula according to Wang et al. (2011):

$$CE (kg N_2O ha^{-1}) = \sum_{i=1}^{n} \left( \frac{F_i + F_{i+1}}{2} \right) (t_{i+1} - t_i) \times 24 \times 10^{-2},$$

where $i$ is the various sampling times, $t$ is the sampling date, $n$ is the total measurement time and 10$^{-2}$ is the conversion factor.

The contribution of $^{15}$N markers to NH$_4^+$-N and MBN as well as the calculation of the N source of the aboveground biomass of rice followed Ma et al. (2015). Yield-scaled N$_2$O was calculated as the ratio between N$_2$O and rice yield (J. L. Li et al., 2018).

2.4 Statistical analysis

All analyses were performed using SPSS Statistics 16.0 (SPSS, Inc., Chicago, USA). One-way ANOVA was conducted to test the treatment effects with Duncan’s test. Significance was set at $P < 0.05$. Univariate analysis of variance was used to analyze the response of cumulative N$_2$O emissions to irrigation method, N level and rice straw application (Table 2). Tables and figures were prepared with Excel 2016 (Microsoft Corp., USA) and Origin 8 (Origin Lab Corp., USA), respectively. The data in the figures and tables are the average value ± standard error.

3 Results

3.1 N$_2$O flux

Three higher N$_2$O flux peaks appeared after basal fertilizer and two topdressing treatments (Fig. 1), and the N$_2$O flux peak after basal fertilizer application was significantly larger than the last two peaks. After basal fertilizer was applied, the N$_2$O flux peaks of CF irrigation and mild AWD irrigation were similar. After the first topdressing, the N$_2$O flux peak of mild AWD irrigation was significantly greater than that of CF irrigation, approximately 1.4 and 9.1 times under the U and US treatments, respectively. In contrast, the N$_2$O flux peak of CF irrigation after the second topdressing was 3.5 and 1.6 times higher than that of mild AWD irrigation under the U and US treatments, respectively. In addition to the above three peaks, the N$_2$O flux of CF irrigation was close to zero, and mild AWD irrigation had a lower flux peak with alternating wet and dry conditions. The flux of N$_2$O ranged from −103.93 to 2770.50 µg m$^{-2}$ h$^{-1}$. The N$_2$O flux appeared negative in the late stage of rice growth. The N$_2$O fluxes of CF irrigation and mild AWD irrigation were similar in the later stage of rice growth, indicating that drainage had little effect on it. During the entire rice growth cycle, the N$_2$O flux of the CK and S treatments was low. There were significant differences in the peak N$_2$O fluxes between the different treatments. Compared with CK, the application of
S alone significantly promoted the $\text{N}_2\text{O}$ flux on the first day after CF irrigation and mild AWD irrigation. Compared with $\text{U}$, the addition of $\text{S}$ in CF irrigation reduced the $\text{N}_2\text{O}$ flux, while the addition of $\text{S}$ in mild AWD irrigation increased the $\text{N}_2\text{O}$ flux.

### 3.2 Soil $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$ and MBN concentrations

The soil $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and MBN concentrations varied with the growing stage of rice (Figs. 2a, c and 3a). The soil $\text{NH}_4^+\text{-N}$ concentration first increased and then decreased. The $\text{NH}_4^+\text{-N}$ concentration under CF irrigation and mild AWD irrigation was low in the late rice growth period (Fig. 2a). The concentration of $\text{NO}_3^-\text{-N}$ in CF-irrigated soil showed a trend of first increasing and then decreasing and was at a low level in the later growth period of rice, while the concentration of $\text{NO}_3^-\text{-N}$ in mild AWD irrigation showed a trend of first decreasing and then increasing, with repeated decreases and increases (Fig. 2c). The concentration of MBN in CF-irrigated soil first decreased and then increased and then decreased to a lower level, while the concentration of MBN in mild AWD-irrigated soil decreased with the growth stage of rice (Fig. 3a).

There were significant differences in the $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and MBN concentrations between the different treatments. In CF irrigation and mild AWD irrigation, the $\text{U}$ treatment had a higher $\text{NH}_4^+\text{-N}$ concentration in the early stage of rice growth, while the other treatments had no significant difference, but as rice grew, the $\text{NH}_4^+\text{-N}$ concentration of the US treatment increased, which was significantly greater than that of the $\text{U}$, $\text{S}$ and $\text{CK}$ treatments (Fig. 2a). In CF irrigation, the $\text{NO}_3^-\text{-N}$ concentration of the $\text{U}$ treatment was slightly higher than that of the other treatments, and all treatments had little variance. In mild AWD irrigation, the $\text{NO}_3^-\text{-N}$ concentration of the $\text{US}$ treatment was significantly higher than that of the $\text{U}$, $\text{S}$ and $\text{CK}$ treatments. The $\text{U}$ treatment had a higher $\text{NO}_3^-\text{-N}$ concentration than the $\text{S}$ and $\text{CK}$ treatments in the later
Figure 3. Changes in the concentration of microbial biomass N (MBN) (a) in the soil during the growth period of rice and the contribution of $^{15}$N markers to MBN (b) ($n = 3$).

stage of rice growth (Fig. 2c). The US treatment in CF irrigation and mild AWD irrigation had the highest MBN concentration during the growth period of rice (Fig. 3a).

Figure 2b shows that the NH$_4^+$-N in CF irrigation and mild AWD irrigation mainly came from urea rather than rice straw, and the combined application of urea and rice straw further promoted the release of NH$_4^+$-N from urea. Regardless of CF irrigation or mild AWD irrigation, rice straw N was difficult to utilize by microorganisms in the first year under single rice straw application, but the combined application of rice straw and urea significantly promoted the utilization of rice straw N by microorganisms. The application of urea combined with rice straw may be more easily utilized by microorganisms than urea applied alone (Fig. 3b).

### 3.3 Sources of aboveground biomass N in rice

As shown in Fig. 4, under CF irrigation and mild AWD irrigation, compared with CK, a single application of rice straw did not increase the aboveground N absorption of rice, while the U and US treatments significantly promoted the aboveground N absorption of rice. Under mild AWD irrigation, the US treatment reduced N uptake in rice shoots compared with the U treatment. The U and US treatments under CF irrigation promoted the N uptake of the aboveground rice more than those under mild AWD irrigation.

With different irrigation methods, the effects of urea and rice straw addition on the N absorption of the aboveground rice were varied. Compared with the CK and S treatments, the U and US treatments under CF irrigation significantly promoted the absorption of soil-N by rice, while only the S and U treatments had significant differences under mild AWD irrigation. Compared with mild AWD irrigation, the U and US treatments under CF irrigation significantly promoted the absorption of soil-N by rice. Regardless of the irrigation and fertilization method, the soil was the main source
of N in the aboveground parts of rice, followed by urea and finally rice straw (Fig. 4).

3.4 Cumulative N$_2$O emissions, rice agronomic properties and yield-scaled N$_2$O emissions

In addition to the CK treatment, compared with CF irrigation, mild AWD irrigation significantly promoted the accumulation of N$_2$O during the growth period of rice, with an average increase of 28.8% (Table 1). Under CF irrigation, there was no significant difference in the accumulation of N$_2$O between S and CK or between US and U. However, the addition of rice straw under mild AWD irrigation significantly increased the accumulation of N$_2$O by 18.1% (Table 1). Compared with the CK and S treatments, the U and US treatments significantly promoted cumulative N$_2$O emissions under the two irrigation modes. As shown in Table 2, irrigation methods, N application level, and rice straw return affected cumulative N$_2$O emissions, of which the N application level had the greatest impact. The interaction between irrigation level and N fertilizer or rice straw significantly affected cumulative N$_2$O emissions.

As shown in Table 1, compared with CF irrigation, mild AWD irrigation significantly reduced rice aboveground biomass under US treatment but had no effect on other treatments. Regardless of whether CF irrigation or mild AWD irrigation was applied, there was no significant difference in the rice aboveground biomass between S and CK or between US and U. Compared with the CK and S treatments, the U and US treatments significantly promoted the rice aboveground biomass under the two irrigation modes. Irrigation level had no effect on rice yield under all treatments. Regardless of CF irrigation or mild AWD irrigation, rice yield under the U and US treatments was significantly higher than that under the CK and S treatments, but there was no difference between the former two and the latter two.

In addition to the CK treatment, compared with CF irrigation, mild AWD irrigation significantly promoted yield-scaled N$_2$O emissions during the rice growth period. Under urea application conditions, compared with CF irrigation, mild AWD irrigation increased yield-scale N$_2$O emissions by 17.9%, and the increase of rice straw further promoted yield-scale N$_2$O emissions by 17.4% under mild AWD irrigation conditions (Table 1). Regardless of CF irrigation or mild AWD irrigation, yield-scaled N$_2$O emissions under the U and US treatments were significantly higher than those under the CK and S treatments. Rice straw addition had no effect on the yield-scaled N$_2$O emissions under CF irrigation but significantly increased the yield-scaled N$_2$O emissions under mild AWD irrigation.

4 Discussion

4.1 Effects of irrigation methods, N levels and rice straw return on N$_2$O emissions

N$_2$O emissions are significantly affected by water-filled pores and mineral N (NH$_4^+$-N and NO$_3^-$-N) content (Allen et al., 2010). The N$_2$O emission peak in CF irrigation occurred only after N application, while mild AWD irrigation caused other N$_2$O emission peaks, which might have been caused by the change in soil moisture conditions by mild AWD irrigation (Zhou et al., 2020). The peak of N$_2$O after fertilization may be because a large amount of N application increases the soil inorganic-N concentration (Fig. 2a and c), which in turn promotes the generation of N$_2$O, which comes from the denitrification process (L. Wang et al., 2017; Yano et al., 2014). During the denitrification process, it is easier for microorganisms to use NO$_3^-$-N as an electron acceptor (Fig. 2c), which affects the reduction process of N$_2$O, resulting in an increase in the ratio of N$_2$O/N$_2$ in the denitrification products (Pérez et al., 2000). Our results showed a negative N$_2$O emission flux at the later stage of rice growth, which may be due to the decrease in surface soil N$_2$O concentration due to the strengthening of the N$_2$O reduction process or the weakening of the N$_2$O diffusion process in the soil profile, which allowed atmospheric N$_2$O to diffuse back into the soil (Chapuis-Lydie et al., 2007). Mild AWD irrigation promoted cumulative N$_2$O emissions by 28.8% on average, which was as proposed in our Hypothesis 1. Similar results were found in previous studies, which may be due to the increased N$_2$O produced by nitrification and denitrification due to water-level alternation (Liang et al., 2017; Zhou et al., 2020) and temperature change (Wu et al., 2019) of mild AWD irrigation. To reduce N$_2$O emissions from paddy fields, researchers generally regulate N$_2$O production by optimizing N management (Liang et al., 2017), applying inhibitors to control the N supply rate of N fertilizers (Wu et al., 2019). In both CF and mild AWD irrigation, there was no obvious N$_2$O emission peak at the later growth stage of rice, which may have been due to the decrease in soil inorganic-N content (Fig. 2a and c) and microbial biomass (Fig. 3a).

Compared with CK and S, N fertilizer application (U and US) significantly increased cumulative N$_2$O emissions and was the most notable factor in N$_2$O generation (Table 2), mainly because N fertilizer application provided sufficient substrates for soil nitrification and denitrification to generate N$_2$O (Fiedler et al., 2017; Wu et al., 2021). The peak of N$_2$O emissions after base fertilizer application was larger than that after two topdressings, which might have been due to a higher N application rate and simultaneous nitrification and denitrification during the initial flooding (Mathieu et al., 2006; L. Wang et al., 2017). The peak of N$_2$O emissions after the two topdressing treatments with CF irrigation was similar, while the peak of N$_2$O emissions after the first topdressing treatment with mild AWD irrigation was signifi-
The change in irrigation method did not cause differences in rice yield (Table 1), but under the US treatment, mild AWD irrigation significantly reduced the aboveground biomass of rice and the uptake of soil N by rice (Table 1 and Fig. 4), which was consistent with our Hypothesis 2. Previous studies have also shown that mild AWD irrigation can stabilize or increase rice yield. This may be because mild AWD irrigation can promote the transport of nutrients from stems and leaves to grains during the reproductive growth stage of rice while inhibiting ineffective tillering and increasing the number of effective panicles, thereby reducing excessive vegetative growth of rice (Carrijo et al., 2017; Z. Li et al., 2018; Liao et al., 2020; Zhang et al., 2009). This may also be an important reason for the decrease in the uptake of soil N by rice under AWD irrigation. Urea application was a key factor in improving rice yield (J. Wang et al., 2017), but it also aggravated soil N uptake by rice, and soil was the largest source of N for rice in all treatments (Fig. 4). Compared with U, under CF irrigation and mild AWD irrigation, US reduced the uptake of soil-derived N by rice, and the trend was more obvious under mild AWD irrigation. Although the trend was significantly larger than that following the second topdressing treatment. This may be because the soil environment (temperature, moisture, etc.) changed little during long-term flooding under CF irrigation (Lagomarsino et al., 2016; Verhoeven et al., 2018; Congreves et al., 2019), while the variations in the soil environment of the two topdressings under mild AWD irrigation changed the utilization of fertilizer N by microorganisms (Fig. 3b). Therefore, reducing the amount of the topdressing can promote the transport of nutrients from stems and leaves to grains during the reproductive growth stage of rice while inhibiting ineffective tillering and increasing the number of effective panicles, thereby reducing excessive vegetative growth of rice (Carrijo et al., 2017; Z. Li et al., 2018; Liao et al., 2020; Zhang et al., 2009). This may also be an important reason for the decrease in the uptake of soil N by rice under AWD irrigation. Urea application was a key factor in improving rice yield (J. Wang et al., 2017), but it also aggravated soil N uptake by rice, and soil was the largest source of N for rice in all treatments (Fig. 4). Compared with U, under CF irrigation and mild AWD irrigation, US reduced the uptake of soil-derived N by rice, and the trend was more obvious under mild AWD irrigation. Although the trend was

Table 1. Effects of different treatments on cumulative nitrous oxide (N\(_2\)O) emissions, rice aboveground biomass, rice yield and yield-scaled N\(_2\)O emissions. The values denote means ± standard errors (n = 3). Different lowercase letters indicate significant differences (\(P < 0.05\)).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Cumulative N(_2)O emissions kg ha(^{-1})</th>
<th>Rice aboveground biomass g pot(^{-1})</th>
<th>Rice yield g pot(^{-1})</th>
<th>Yield-scaled N(_2)O emissions g kg(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF</td>
<td>1.48 ± 0.06 ef</td>
<td>37.11 ± 2.53 f</td>
<td>21.63 ± 1.81 b</td>
<td>0.24 ± 0.01 d</td>
</tr>
<tr>
<td></td>
<td>15S</td>
<td>1.24 ± 0.05 f</td>
<td>37.99 ± 2.69 f</td>
<td>20.91 ± 1.63 b</td>
</tr>
<tr>
<td></td>
<td>15U</td>
<td>4.02 ± 0.30 c</td>
<td>82.54 ± 10.39 ab</td>
<td>36.56 ± 2.75 a</td>
</tr>
<tr>
<td></td>
<td>U+15S</td>
<td>3.89 ± 0.09 c</td>
<td>87.58 ± 7.70 a</td>
<td>35.98 ± 1.72 a</td>
</tr>
<tr>
<td></td>
<td>15U+IS</td>
<td>3.76 ± 0.02 c</td>
<td>80.99 ± 19.54 abc</td>
<td>35.85 ± 2.50 a</td>
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<tr>
<td>AWD</td>
<td>CK</td>
<td>1.64 ± 0.15 e</td>
<td>45.31 ± 3.07 ef</td>
<td>22.92 ± 1.07 b</td>
</tr>
<tr>
<td></td>
<td>15S</td>
<td>2.07 ± 0.17 d</td>
<td>34.78 ± 4.86 f</td>
<td>20.42 ± 0.46 b</td>
</tr>
<tr>
<td></td>
<td>15U</td>
<td>4.48 ± 0.12 b</td>
<td>64.44 ± 7.33 bcd</td>
<td>34.81 ± 1.64 a</td>
</tr>
<tr>
<td></td>
<td>U+15S</td>
<td>5.05 ± 0.28 a</td>
<td>62.92 ± 2.49 ede</td>
<td>34.50 ± 1.76 a</td>
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<tr>
<td></td>
<td>15U+IS</td>
<td>5.29 ± 0.25 a</td>
<td>60.44 ± 6.74 de</td>
<td>34.85 ± 1.18 a</td>
</tr>
</tbody>
</table>

4.2 Effects of irrigation methods, N levels and rice straw return on rice production and yield-scaled N\(_2\)O emissions

The change in irrigation method did not cause differences in rice yield (Table 1), but under the US treatment, mild AWD irrigation significantly reduced the aboveground biomass of rice and the uptake of soil N by rice (Table 1 and Fig. 4), which was consistent with our Hypothesis 2. Previous studies have also shown that mild AWD irrigation can stabilize or increase rice yield. This may be because mild AWD irrigation can promote the transport of nutrients from stems and leaves to grains during the reproductive growth stage of rice while inhibiting ineffective tillering and increasing the number of effective panicles, thereby reducing excessive vegetative growth of rice (Carrijo et al., 2017; Z. Li et al., 2018; Liao et al., 2020; Zhang et al., 2009). This may also be an important reason for the decrease in the uptake of soil N by rice under AWD irrigation. Urea application was a key factor in improving rice yield (J. Wang et al., 2017), but it also aggravated soil N uptake by rice, and soil was the largest source of N for rice in all treatments (Fig. 4). Compared with U, under CF irrigation and mild AWD irrigation, US reduced the uptake of soil-derived N by rice, and the trend was more obvious under mild AWD irrigation. Although the trend was

Table 2. Cumulative nitrous oxide (N\(_2\)O) emissions in response to irrigation method, nitrogen level and straw returning. Significant treatment effects within a main category (\(P < 0.05\)) were indicated by * and *** indicated significant treatment effects within a main category (\(P < 0.001\)).

<table>
<thead>
<tr>
<th>Factors</th>
<th>Cumulative N(_2)O emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation method (I)</td>
<td>88.576***</td>
</tr>
<tr>
<td>Nitrogen level (N)</td>
<td>1525***</td>
</tr>
<tr>
<td>Straw (S)</td>
<td>6.393*</td>
</tr>
<tr>
<td>IN</td>
<td>6.275*</td>
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<tr>
<td>IS</td>
<td>26.288***</td>
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<tr>
<td>NS</td>
<td>1.426</td>
</tr>
<tr>
<td>INS</td>
<td>0.178</td>
</tr>
</tbody>
</table>
not significant, rice straw return may be an effective way to maintain long-term soil fertility (Fig. 4).

In our study, mild AWD irrigation, urea application and rice straw return all increased yield-scaled N\(_2\)O emissions (Table 1), mainly due to improved soil aeration and increased inorganic N and rice straw decomposition, resulting in more N\(_2\)O production (Andren et al., 1993; Buchen et al., 2016; Chen et al., 2016; Lagomarsino et al., 2016; Fiedler et al., 2017; Verhoeven et al., 2018; Congreves et al., 2019; Wu et al., 2021). Although mild AWD irrigation had higher yield-scaled N\(_2\)O emissions than CF irrigation, the GWP (CH\(_4\) + N\(_2\)O) under mild AWD irrigation was significantly lower than that under CF irrigation and decreased by 8.1 %, 57.9 %, 11.8 % and 62.9 % under CK, S, U and US, respectively (Table S1 in the Supplement). Therefore, mild AWD irrigation combined with rice straw return may be a promising agronomic measure that maintains rice yield, slows greenhouse effects (CO\(_2\) emissions are not considered), and also reduces soil fertility consumption.

5 Conclusions

The effects of irrigation methods, N levels and rice straw return on N\(_2\)O emissions were explored through pot experiments using rice. We found that N\(_2\)O emissions were affected by urea application and irrigation methods, with urea application being the most important. Compared with CF irrigation, mild AWD irrigation increased cumulative N\(_2\)O emissions, with an average increase of 28.8 %. In addition, adding rice straw to mild AWD irrigation further stimulated N\(_2\)O emissions by 18.1 %. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation increased the yield-scaled N\(_2\)O emissions by 17.9 %, and the addition of rice straw further promoted the yield-scaled N\(_2\)O emissions under mild AWD irrigation by 17.4 % but reduced the GWP (CH\(_4\) + N\(_2\)O) by 62.9 %. Under the condition of urea application, compared with CF irrigation, mild AWD irrigation reduced the uptake of soil-derived N and above-ground biomass of rice but did not reduce rice yield. Therefore, mild AWD irrigation combined with rice straw return may offer a promising agronomic measure to maintain high rice yield, reduce greenhouse effects, and maintain or improve soil fertility.

Data availability. The data that support the findings of this study are available by request from the corresponding author (Lili Zhang).

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Author contributions. KW, WL, ZW and ZD conceived and designed the experiments; YM and NL performed the experiments; KW analyzed the data; KW and LZ wrote the paper and all authors approved submission of the paper. All authors have read and agreed to the published version of the manuscript.

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