Greenhouse gas emissions in response to straw incorporation, water management and their interaction in a paddy field in subtropical central China

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Abstract

A field experiment was conducted to study the effects of combination of straw incorporation and water management on fluxes of CH$_4$, N$_2$O and soil heterotrophic respiration (Rh) in a paddy field in subtropical central China, by using a static opaque chamber/gas chromatography method. Four treatments were set up: two rice straw incorporation rates at 0 (S1) and 6 (S2) t ha$^{-1}$ combined with two water managements of intermittent irrigation (W1, with midseason drainage) and continuous flooding (W2, without midseason drainage). The cumulative seasonal CH$_4$ emissions for the treatments of S1W2, S2W1, S2W2 increased...
significantly by 1.84, 5.47 and 6.63 times, respectively, while seasonal N$_2$O emissions decreased by 0.67, 0.29 and 1.21 times, respectively, as compared to S1W1 treatment. The significant increase in the cumulative Rh for the treatments S1W1, S2W1 and S2W2 were 0.54, 1.35 and 0.52 times, respectively, in comparison with S1W2. On a seasonal basis, both the CO$_2$-equivalents (CO$_2$e) and yield-scaled CO$_2$e (GHGI) of CH$_4$ and N$_2$O emissions increased with straw incorporation and continuous flooding, following the order: S2W2>S2W1>S1W2>S1W1. Thus, the practices of in season straw incorporation should be discouraged, while midseason drainage is recommended in paddy rice production from a point view of reducing greenhouse gas emissions.

**Keywords:** CH$_4$; N$_2$O; soil CO$_2$ emission; straw retention; water regime

**Introduction**

Rice paddy is one of the important sources of greenhouse gas emissions. Due to the waterlogging condition, the fermentation of the organic materials in the paddy soils generates lots of CH$_4$ as the methanogens can use the intermediate products (e.g. H$_2$/CO$_2$, acetic acid) to form CH$_4$ (Conrad 2002; Kravchenko & Yu 2006), and most of the generated CH$_4$ will be released to atmosphere through the aerenchyma (Inubushi et al. 1990). Thus, paddy fields contribute to large quantity of global CH$_4$ emissions. It was estimated that the annual CH$_4$ emissions from rice paddy were as high as 20-100 Tg in the globe, which accounted for 5-20% of the total CH$_4$ emissions from all anthropogenic sources (IPCC 1997). With the application of nitrogen fertilizers, rice paddy also emits lots of N$_2$O, a potent greenhouse gas with a global warming potential 298 times of CO$_2$ and 8.8 times of CH$_4$ in the 100-year time horizon (Myhre et al. 2013), though the emission factors of N$_2$O in the paddy soils is smaller than those in upland soils (Akiyama et al. 2005). Globally, the estimated N$_2$O emissions from
paddy soils with rice cultivation was 82 Gg N yr\(^{-1}\) based on a mean seasonal emission of 667 g N ha\(^{-1}\) (Akiyama et al. 2005) and the global rice paddy area harvested annually of 123 million hectares (IPCC 1997).

Straw incorporation and water management (practices of irrigation and drainage) are both important factors influencing GHG emissions from paddy fields (Zou et al. 2005; Wang et al. 2011). Straw incorporation is a common practice in rice production in China to recycle nutrients and to increase soil organic carbon (C) content (Wang et al. 2015; Zou et al. 2005). This practice can also reduce N\(_2\)O emissions from paddy fields (Wang et al. 2011; Shen et al. 2014). However, due to the anaerobic condition in paddy fields as caused by waterlogging, straw incorporation can largely enhance CH\(_4\) emissions from paddy fields (Ma et al. 2009; Yao et al. 2013; Zou et al. 2005). Compared with the continuous flooding, mid-season drainage could reduce CH\(_4\) emissions and may also raise N\(_2\)O emissions (Akiyama et al. 2005; Cai et al. 1997; Zou et al. 2005; Wang et al. 2011), although the reduction rate of CH\(_4\) emissions or the increase rate of N\(_2\)O emissions may be different if the time or duration of mid-season aeration varies (Li et al. 2011; Ma et al. 2013). Furthermore, the effects of midseason aeration on mitigating CH\(_4\) and N\(_2\)O emissions from paddy soils may be different between straw incorporation and without straw incorporation. Compared with normal midseason aeration, Li et al. (2014) found that early aeration reduced the net greenhouse gas emissions of CH\(_4\) and N\(_2\)O under straw incorporation. Therefore, it will be worthwhile to examine the combined effects of straw incorporation and water regime on greenhouse gases emissions from paddy fields.

Though the effects of straw incorporation and water management on CH\(_4\) and N\(_2\)O emissions from paddy fields are well quantified, the soil CO\(_2\) emissions from paddy fields as affected by straw and water management are still less known (Li et al. 2005; Iqbal et al. 2009). Soil CO\(_2\) emission is closely related to global carbon cycling because changes in soil CO\(_2\) emission can
also alter atmospheric CO$_2$ concentration as well as the rates of soil carbon sequestration (Lal 2004). Agricultural management practices (such as straw incorporation, nitrogen fertilizer application and water management) can affect soil CO$_2$ emissions by changing soil chemical and physical properties such as soil aeration, soil pH, soil moisture, soil temperature, C/N ratio of substances, etc (Iqbal et al. 2009). Former studies have showed that straw incorporation into paddy soils can not only increase soil CO$_2$ emissions due to mineralization of the organic materials from straw but also cause the increase of soil CO$_2$ emissions by the priming effects of increasing the mineralization of soil original organic carbon (Yuan et al. 2012; Ye et al. 2015).

For better quantifying the greenhouse gas emission effects caused by straw incorporation and water management in rice paddy, it is needed to measure the emissions of CH$_4$, N$_2$O and CO$_2$ simultaneously. The double rice cropping system (two rice seasons per year) is an important cropping system in Southern China. For mitigating the air pollution caused by straw burning and also for increasing soil fertility, straw incorporation is encouraged by the local governments in the regions with double rice cropping. The straw incorporation in the double rice cropping system usually carries out in the late rice season because the time interval between the early rice season and late rice season is very short (usually less than one week) and the fresh rice straw from early rice season can be fast decomposed, which favors for a higher grain yield (Huang et al. 2005). In the early rice season, as the temperature is relatively low in the seedling establishment and tillering stages and the straw from late rice season in the last year usually become dry, the incorporated straw cannot be decomposed fast and thus may decrease rice yield. Therefore, rice straw is usually not incorporated in the early rice season in the double rice cropping system. In this study, a field experiment was conducted in a late rice season in a typical double-cropped paddy rice field in southern China, with the aims (i) to quantify the individual emissions of CH$_4$ and N$_2$O and the rates of soil
heterotrophic respiration (Rh) with contrasting straw incorporation and water management, and (ii) to determine the key factors influencing CH₄, N₂O emissions and Rh rates from rice fields as affected by straw incorporation and water management and their interaction.

**Materials and methods**

**Experimental site and treatments**

The field experiment was carried out from July to October, 2011, during a late rice season at the Changsha Research Station for Agricultural and Environmental Monitoring of the Chinese Academy of Sciences in Hunan Province, China (112°80′N, 28°37′E, elevation of 80 m). The region has a subtropical monsoon climate, with a mean annual precipitation of 1330 mm (1955-2010) and a mean air temperature of 17.5 °C (1955-2010), about 300 days of frost-free period. A typical double rice field, which has been cropped with the double rice for more than 50 years, was chosen for the field experiment. In the early rice season before the field experiment, no fertilizer was used and no straw was incorporated in the experimental field to uniform the soil fertility, and the water regime followed the local practice. The soil at the experimental field is classified as Stagnic Anthrosol in Chinese soil taxonomy (Gong et al. 2007) or Ultisol in USDA soil taxonomy and Hydragric Anthrosol in World Reference Base for Soil Resources (FAO 2015). Selected soil characteristics for the 0-20 cm depth include: soil organic carbon content, 18.4 g kg⁻¹; total N content, 1.98 g kg⁻¹; total P content, 0.03 g P kg⁻¹; total K content, 28.9 g K kg⁻¹; pH value, 5.31; bulk density, 1.20 g cm⁻³; clay, 26.1%; silt, 27.9%; and sand, 45.9%.

Four treatments were designed in this study by combining the common straw incorporation rate or without straw incorporation and two common water regimes, which included (1) no straw incorporation and intermittent flooding (S1W1), (2) rice straw incorporation at a rate of 6 t ha⁻¹ as dry matter (equivalent to all the straw from early rice season been incorporated) and intermittent flooding (S2W1), (3) no straw incorporation and continuous flooding
(S1W2) and (4) rice straw incorporation at a rate of 6 t ha\(^{-1}\) as dry matter and continuous flooding (S2W2). Treatments were laid out in a randomized completed block design with triplicates (plot size: 7 m × 5 m). Rice straw from early rice season was cut into 10-cm pieces, spread evenly in the experimental plots, and then incorporated into the plow layer at ploughing during July 21 to July 22. Chemical fertilizers were applied at the same rate for all the treatments at the end of ploughing. Urea was used as nitrogen fertilizer at the rate of 150 kg N ha\(^{-1}\) and broadcasted at three times in the rice season, with a split of 50% of the total as basal fertilizer, 30% at tillering stage and 20% at booting stage for rice. Full dose of P and K was applied as the basal fertilizer at the rate of 40 kg P\(_2\)O\(_5\) ha\(^{-1}\) and 100 kg K\(_2\)O ha\(^{-1}\) in the form of single calcium superphosphate and potassium sulphate, respectively. The rice cultivar used in this study was T-YOU 207. Rice was sown in a nursery bed and was transplanted to each of the plot at a hill density of 20 cm × 20 cm on July 23. For the water regime of intermittent flooding, after rice seedling transplanting, the experimental plots remained flooded until the rice plant has the largest tillers (approximately 30 days after transplanting). Then, a 10-day mid-season drainage was imposed, followed by re-flooded for 20 days and kept moist but non-waterlogged until one week before harvest. For the water regime of continuous flooding, the rice paddy was continuously flooded until one-week before harvest. For convenience at rice harvest, the experimental plots were drained one week before rice harvest, which was conducted on 22 October 2011.

**GHG sampling and measurement**

The GHG fluxes sampling were conducted during July 25 (the second day after rice transplanting) to October 23 (the next day after rice harvesting) using the static opaque chamber-gas chromatograph (GC) method following Zheng et al. (2008). In each experimental plot, a base frame made of stainless steel (covering an area of 0.41 m\(^2\)) was inserted into the soil to a depth of 20 cm after field plowing but before transplanting and the
frame remained in place for the entire rice season. After the base frame was fixed into the soil, rice seedlings were transplanted according to the desired hill density. For measuring soil Rh, which is an indicator of soil CO₂ emission, a small part (1.5 m × 1.5 m) of each plot was left bare, and an additional base frame was inserted into the center of the bare area in each plot according to Iqbal et al. (2009). The chamber (64 cm long × 64 cm wide × 100 cm high) made of stainless steel sheet and coated with heat-isolation material was temporarily mounted onto the installed base frame with water seal on the gas sampling day. Gases were sampled during 9:00 am - 11:00 am every week (twice a week during the first 10 days after the applications of N fertilizers or during the mid-season-drainage periods). Detailed information on the gas sampling and analysis can be found in Shen et al. (2014) and Liu et al. (2014).

**Auxiliary measurements**

In addition to the measurements of gas emissions, soil sample (0-20 cm) from each plot was collected by a 3 cm diameter gauge auger at five points at different rice grown stages and immediately kept in a refrigerator at 4°C, and then mixed into one sample for extraction of soil mineral N (NH₄⁺-N and NO₃⁻-N) and dissolved organic carbon (DOC) concentration. The fresh soil sample (30 g) was extracted by 0.5 M K₂SO₄ (80 ml). The soil suspensions were shaken for 1 h and then filtered. The concentrations of soil mineral N and DOC in the extracts were analyzed using a flow-injection auto-analyzer (Tecator FIA Star 5000 Analyzer, Foss Tecator, Sweden) and a TOC analyzer (TOC-VWP, Shimadzu Corporation, Japan), respectively. Soil redox potential (Eh) and soil temperature (Tsoil) at 5 cm soil depth were measured during the gas sampling period with a portable redox potential meter (RM-30P, DKK-TOA Corporation, Japan) and a portable digital thermocouple (JM624, Tianjin Jinming Instrument Co. Ltd., China), respectively. Water depths in the twelve plots were also recorded during the gas sampling period. At harvest, rice plants were removed from five 1 m² areas in each plot for measuring of rice grain yields.
Air temperature and precipitation were recorded with a weather station (Inteliment Advantage, Dynamax Inc., USA) located approximately 100 m from the sampling fields.

Data analyses

The cumulative GHG emissions ($F$, kg C ha$^{-1}$ or g N ha$^{-1}$) were estimated by the following equation (Fu et al. 2012):

$$F = \left(\frac{f_1 + f_n}{2} + \sum_{i=1}^{n-1} \frac{(f_{i+1} + f_i) \times (DOY_{i+1} - DOY_i)}{2}\right) \times \frac{TD}{DOY_n - DOY_1 + 1} \times \frac{240000}{1000000}$$  \hspace{1cm} (1)

where $f$ stands for GHG flux (mg C m$^{-2}$ h$^{-1}$ or μg N m$^{-2}$ h$^{-1}$), the subscripts $i$ (1…$n$) represent the $i$th sampling of the GHG emissions, $DOY_i$ denotes the date of the $i$th sampling, $TD$ is the total days of the late rice cropping season (93 days), and 240,000/1,000,000 is coefficient used for transforming the flux unit from mg C m$^{-2}$ h$^{-1}$ or μg N m$^{-2}$ h$^{-1}$ to kg C ha$^{-1}$ season$^{-1}$ or g N ha$^{-1}$ season$^{-1}$, respectively. Using the ratio of $TD/(DOY_n-DOY_1+1)$, all days during the rice season were considered in the cumulative emission calculation when the period of the rice season was longer than the sampling period.

The cumulative CO$_2$-equivalent emissions of CH$_4$ and N$_2$O in a rice season (CO$_2$e) was computed by summing the cumulative CO$_2$-equivalent emissions in a 100-year horizon for CH$_4$ and N$_2$O using conversion factors of 34 and 298 for CH$_4$ and N$_2$O, respectively (Myhre et al. 2013), and yield-scaled CO$_2$-equivalent emissions was defined as the CO$_2$e divided by grain yield (GHGI).

All statistical analyses and graphs were performed using R (Version 3.1.3). The significance of differences between the treatments with a one-way ANOVA was tested using the Duncan’s multiple range method ($p < 0.05$). A two-way ANOVA was used to analyze the effects of straw incorporation and water management on cumulative emissions of CH$_4$, N$_2$O and CO$_2$, yields, CO$_2$e and GHGI and environmental variables ($\text{NH}_4^+$-N, NO$_3^-$-N, DOC and Eh) ($p < 0.05$). The non-parametric Spearman correlations between GHG emissions and environmental variables were examined because the GHG data were highly-skewed.
Results and discussion

Environmental variables

Soil NH$_4^+$-N contents ranged from 0.78 to 23.6 mg N kg$^{-1}$ soil during the late rice season; across all the treatments, soil NH$_4^+$-N contents increased after fertilizer N application and then declined slowly (Figure 1(a)). Soil NO$_3^-$-N contents ranged from 0 to 1.26 mg N kg$^{-1}$ soil, and remained rather low in all the treatments during the late rice season (Figure 1(b)). The seasonal mean contents of both soil NH$_4^+$-N and NO$_3^-$-N did not show significant differences across the treatment ($p > 0.05$) (Table 1). The ANOVA analysis showed that the soil NH$_4^+$-N and NO$_3^-$-N contents did not change significantly with straw incorporation, water management and their interaction ($p > 0.05$) (Table 2). As rice straw usually has a high carbon to nitrogen ratio, former studies (Eagle et al. 2000) had showed that the mineralization of straw may cause the immobilization of soil mineral nitrogen and therefore reduce soil available nitrogen contents. This is probably true during the early stage (e.g. first 30 days after transplanting) after straw incorporated when immobilization of soil mineral nitrogen may be large, but during the late stage (e.g. the second and third 30 days after transplanting) the mineralization of microbial biomass nitrogen may increase and thus rise the soil mineral nitrogen content. Therefore, in the whole rice season, rice straw incorporation did not show significant effects on soil mineral nitrogen contents as found in this study.

[Figure 1 near here]

Soil DOC contents increased rapidly and reached one peak after the first topdressing, and another peak following the second topdressing and field drainage (Figure 1(c)). Mean soil DOC concentration was smallest in the S2W1 treatment, and largest in the S2W2 treatment (Table 1). The two-way ANOVA analysis showed that there was significant interaction between straw incorporation and water management on DOC ($p < 0.05$) (Table 2). The less soil DOC content in the S2W1 treatment may be probably due to the fast mineralization of
straw carbon under intermittent irrigation and the increased mineralization of soil original DOC as caused by straw incorporation. The latter, also called the priming effect, has been demonstrated in former studies (Yuan et al. 2012; Ye et al. 2015).

[Table 1 near here]

Soil Eh showed large differences between the intermittent irrigation treatments and the continuous flooding treatments. For the intermittent treatments, soil Eh values were low during the flooding period after rice transplanting, steadily increased during the mid-season drainage period, decreased again when the fields were re-flooded and increased again when the fields were drained before harvest (Figure 1(d)). Soil Eh values in the continuously flooding treatments increased slightly during the flooding period, but maintained low values (Figure 1(d)). The mean values of soil Eh in the intermittent irrigation treatments were significantly higher than those in continuous flooding treatments ($p < 0.05$) (Table 1). The two-way ANOVA analysis showed that water management had a significant effect on Eh ($p < 0.001$) (Table 2). Though straw incorporation also reduced soil Eh in this study, the differences between the straw treatments and non-straw treatments were no significant. Thus the water regime had a more significant effect on soil Eh than straw incorporation in paddy soils.

[Table 2 near here]

The air temperature ranged from 13.7 to 32.4 °C (Figure 2(a)), while the soil temperature at 5 cm ranged from 16.0 to 34.4 °C during the late rice season (Figure 2(b)). Both the air and soil temperatures showed a decreasing trend after rice transplanting. The total precipitation was 298 mm, resulting from the ten rain events with daily precipitation $> 10$ mm (Figure 2(a)). The water depths were maintained as 2 to 8 cm during the flooding period for both continuous flooding treatments and intermittent irrigation treatments, and were zero during the mid-season drainage period and moist but non-waterlogged stages for the intermittent
irrigation treatments (Figure 2(c)).

[Figure 2 near here]

**GHG fluxes**

*CH₄*

The CH₄ fluxes from the rice fields were between -0.03 and 104.9 mg C m⁻² h⁻¹; there were large variations in CH₄ fluxes during the whole rice season and across the treatments (Figure 2(d)). The correlation analysis showed that CH₄ fluxes were negatively correlated to soil Eh ($p < 0.001$) and positively correlated to soil NH₄⁺ content ($p < 0.001$), soil temperature and water depth ($p < 0.001$) (Table 3). The negative correlation between CH₄ flux and soil Eh had also been found by former studies (Wang et al. 1993; Yagi et al. 1996). This is due to that with the increase of soil Eh, the activities of methanogens are usually depressed while the activities of methanotrophs are promoted, and thus CH₄ emissions decrease (Wang et al. 1993; Conrad 2002). As shown in this study, the higher was the standing water depth, generally the lower was the soil Eh (Figure 1(d) and 2(c)). Therefore, CH₄ emissions also showed a positive correlation with water depth. However, as soil Eh can be affected by other factors (e.g. the existence of oxidants, such as O₂, NO₃⁻, Mn⁴⁺, Fe³⁺, SO₄²⁻, in the soil), they may be some periods when the standing water depth was high, but CH₄ emissions were still low. For example, when the paddy soils were re-flooded after mid-season drainage, a CH₄ emission peak did not occur even though the water depth was the highest (Figure 2(d)). This is because after mid-season drainage, there were large amount of oxidative substances in the paddy soils. It may take several days to reduce these oxidants to favor CH₄ production after the paddy soils were re-flooded (Wang et al. 1993). The positive correlation between CH₄ flux and soil NH₄⁺ content may be due to the competition of NH₄⁺ for the oxidation with CH₄ by methanotrophs (Mosier et al. 1991; Singla & Inubushi 2014). But the soil NH₄⁺ content may be not an important factor affecting soil CH₄ emission in this study because when soil
NH$_4^+$ content was high soil Eh was much low, which means soil methanogens other than methanotrophs influence CH$_4$ emissions in a large content. At the beginning of the experiment, rich crop residues, root exudates and low Eh may lead to larger CH$_4$ emissions. At later stages of the experiment, the CH$_4$ emissions decreased under the conditions of insufficient labile organic carbon and higher Eh, while the decreases of soil NH$_4^+$-N contents were ascribed to the assimilation of rice plant. Consequently, the positive correlation between CH$_4$ flux and NH$_4^+$-N content may not suggest higher NH$_4^+$-N content would increase CH$_4$ flux (Linquist et al. 2012).

For the intermittent irrigation treatments (S1W1 and S2W1), CH$_4$ emissions were peaked soon after transplanting, decreased to near zero at approximately 40 days after transplanting (at the end of the mid-season drainage period), showed relatively low values (< 1.2 mg C m$^{-2}$ h$^{-1}$) when the plots were flooded again and decreased to near zero when the plots were drained for harvest. The differences in magnitude of emission fluxes between S1W1 and S2W1 were large before mid-season drainage, whilst were small during the periods of mid-season drainage and after mid-season drainage. This is because the anaerobic decomposition of straw with a high C:N ratio provide enough carbon source to stimulate methanogenesis and CH$_4$ emissions (Bao et al. 2014). Concerning the impact of the water management, the CH$_4$ fluxes decreased to almost zero during the mid-season drainage period due to increased Eh (Figures 1(d) and 2(d)), which inhibited methanogenesis and stimulated CH$_4$ oxidation. Furthermore, during the period after mid-season drainage, Eh values were still high and thus the activities of methanogenic bacteria were inhibited, resulting in low CH$_4$ emission rates.

For the continuous flooding treatments (S1W2 and S2W2), the CH$_4$ emissions fluxes showed similar magnitudes as their counterparts (S1W1 and S2W1) before mid-season drainage, maintained relatively high values when the plots were continuously flooded other than drained. The differences in magnitude of CH$_4$ emission fluxes between S1W2 and S2W2
were large during the first 30 days after transplanting, whilst were small thereafter. This trend was similar to the differences in magnitude of emission fluxes between S1W1 and S2W1, which demonstrated that the increased CH$_4$ emissions due to straw incorporation maybe mostly occur in the first 30 days after straw incorporated in the late rice season and taking measures for reducing CH$_4$ emissions in this period may be effective for mitigating CH$_4$ emissions due to straw incorporation. Large reduction of CH$_4$ emissions from paddy fields with mid-season drainage as compared with the paddy fields with continuous flooding had also been found in a rice-wheat cropping system (Zou et al. 2005), indicating that mid-season drainage can be adopted in various paddy rice cropping systems to reduce CH$_4$ emissions.

On the seasonal basis, the cumulative CH$_4$ emissions were in the order of S2W2>S2W1>S1W2>S1W1, showing significant difference across the treatments ($p < 0.05$, Table 1). Compared with the S1W1 treatment, the S2W2, S2W1 and S1W2 treatments increased CH$_4$ emissions by 6.63, 5.47 and 1.84 times, respectively. For the S2W2 treatment, the cumulative CH$_4$ emissions increased by 1.69 times, compared to the S1W2 treatment during the rice season (Table 1). Two-way ANOVA analysis indicated that both straw incorporation and water management significantly affected total CH$_4$ emissions ($p < 0.001$) (Table 2). The relatively smaller difference of CH$_4$ emissions between S2W2 and S1W2 as compared those between S1W1 and S2W1 was probably related to the high CH$_4$ emissions during the first 30 days after rice transplanting, when straw incorporation caused most of the increased CH$_4$ emissions. This indicates the influence of straw incorporation on CH$_4$ emissions under continuous flooding may be weakened with the increase of flooding days in paddy soils.

$N_2O$

The measured $N_2O$ fluxes across the treatments ranged from -9.23 to 9.30 μg N m$^{-2}$ h$^{-1}$ and also showed large temporal and treatment variations (Figure 2(e)). The correlation analysis
showed that N₂O fluxes were positively correlated to soil NH₄⁺ content (p < 0.05) and soil temperature (p < 0.01), which was consistent with former studies in upland soils (Fu et al. 2012; Chen et al. 2015). For the S1W1 and S2W1 treatments, the N₂O fluxes showed high values during the period before mid-season drainage when 80% of nitrogen fertilizer was applied in this period, and also showed high values during the period of mid-season drainage. This indicates that high nitrogen input and aeration, which create suitable conditions for N₂O production by nitrification and denitrification (Yan et al. 2000), are two important factors that increase N₂O emissions in paddy soils. After mid-season drainage when the plots were flooded again, the N₂O fluxes were relatively low even if the left 20% of nitrogen fertilizer was top-dressed in this period. The low N₂O emissions during this period may be due to the high nitrogen fertilizer use efficiency during the period as paddy rice usually uptakes more than 40% of the total needed nitrogen from jointing to heading (Huang et al. 2010). Former studies also showed that when the nitrogen use efficiencies of crops were high, the soil N₂O emission fluxes were low accordingly (Adviento-Borbe et al. 2007; Liu et al. 2013). For the S1W2 and S2W2 treatments, the N₂O fluxes were high during the period before mid-season drainage and were comparable to those of their counterpart treatments, then showed low values during the period before moisture irrigation and were also lower than those of their counterpart treatments, and showed relatively high values thereafter and were comparable to those of their counterpart treatments. Generally, the N₂O fluxes for the straw treatments were lower than those for the no straw incorporation treatments under the same water regime. The decrease in N₂O emissions after straw application was most likely due to immobilization of mineral N by the high C:N ratio amendment (Jesen 1996). In addition, straw incorporation is also known to increase the soil Fe²⁺ content, facilitating the further reduction of N₂O to N₂ and the decrease of N₂O fluxes (Wang et al. 2011).

During the entire observed period, the cumulative N₂O emissions were significantly different
between the treatments with the ranking sequence of S1W1>S1W2>S2W1>S2W2 ($p < 0.05$) (Table 1). As compared to the cumulative N$_2$O emissions from the S1W1 treatment, the S1W2, S2W1 and S2W2 treatments decreased cumulative N$_2$O emissions by 0.29, 0.67 and 1.21 times, respectively. Furthermore, the cumulative N$_2$O emissions from the treatment S2W2 were 1.29 times lower than those from the treatment S1W2 in the entire growing season (Table 1). There were significant separate influences of straw incorporation and water management on N$_2$O emission ($p < 0.001$), as well as a significant interaction between these two management factors on N$_2$O emissions in this study ($p < 0.05$) (Table 2), which indicates that combining straw incorporation and continuous flooding can further reduce N$_2$O emissions from paddy fields as compared with the separate N$_2$O reduction effects caused by straw incorporation and continuous flooding.

$Rh$

The measured rates of Rh varied between 5.00 and 91.7 mg C m$^{-2}$ h$^{-1}$, and also showed large temporal and treatment variations (Figure 2(f)). The correlation analysis showed that the Rh fluxes showed a positive correlation with soil temperature ($p < 0.05$) and a negative correlation with water depth ($p < 0.01$). For the S1W1 and S2W1 treatments, Rh rates showed high values during the drainage period while showed low values during the flooding period. For the S1W2 and S2W2 treatments, the Rh rates were relatively high in the first one and half months after transplant and showed low values thereafter. There were higher Rh rates in the straw treatments (S2W1 and S2W2) than in the counterpart no-straw treatments (S1W1 and S1W2) during the first two months after transplanting. Former studies also showed that straw incorporation increased soil CO$_2$ emissions as most of the organic carbon in the straw will be mineralized and be released as CO$_2$ (Yuan et al. 2012; Ye et al. 2015). Besides, from the start of midseason drainage until rice harvest, the Rh rates in the intermittent treatments were consistently higher than those in the continuously flooding treatments. This may be probably
due to that the mineralization of soil organic carbon was restrained under the waterlogging conditions (Devüvre & Horwáth 2000).

The cumulative Rh on seasonal basis was in the order of S2W1>S1W1>S2W2>S1W2, and significant differences in Rh rates were found between the treatments, except for between S1W1 and S2W2 (p < 0.05) (Table 1). The cumulatively Rh from the S2W1, S1W1 and S2W2 treatments was 1.35, 0.54 and 0.52 times greater than the S1W2 treatment, respectively; moreover, the cumulative flux in the S2W1 treatment was raised by 53%, compared with the S1W1 treatment (Table 1). Two-way ANOVA analysis showed that there were significant influences of straw incorporation and water regime (p < 0.001) and their interactions on total Rh (p < 0.05) (Table 2). This indicates that although straw incorporation can increase soil Rh, under the continuous flooding condition, both the mineralization of straw organic carbon and soil organic carbon will be restrained, and a large part of the increased soil CO$_2$ emissions caused by straw incorporation can be mitigated by continuous flooding. Therefore, adopting a continuous flooding water regime may favor for carbon sequestration in paddy fields.

**CO$_2$e and GHGI**

Considering the distinct effects of both straw incorporation and water regime on CH$_4$ and N$_2$O emissions from paddy fields in this study, the net greenhouse emissions of CH$_4$ and N$_2$O (CO$_2$e) during the whole late rice season was also calculated. The CO$_2$e were significantly larger in treatments with straw incorporation and continuously flooding and occurred in the following the order: S2W2>S2W1>S1W2>S1W1 (Table 1). S2W2, S2W1 and S1W2 significantly increased total CO$_2$e by 6.54, 5.40 and 1.82 times, respectively, compared with S1W1. Furthermore, the CO$_2$e from the S2W2 treatment was increased significantly by 1.68 times, compared with S1W2 (p < 0.05) (Table 1). Straw incorporation and water management significantly affected total CO$_2$e (p < 0.001) (Table 2). The magnitudes of CO$_2$e across the
treatments showed similar trends as the cumulative CH$_4$ emissions for the treatments, indicating that CH$_4$ emissions from paddy fields during this late rice season contributing to most of the greenhouse effect. Therefore, effects to reduce CH$_4$ emissions from paddy fields (e.g. avoiding straw incorporation, extending the water regime of mid-season drainage) would be effective to mitigate the greenhouse effect cause by paddy rice production. Besides, our results also showed that soil Rh varied across the treatments. Soil Rh is closely related to soil organic carbon balance (Iqbal et al. 2009). In the future studies, it would be meaningful to consider the net greenhouse effect of CH$_4$, N$_2$O and soil organic carbon balance to give a comprehensive evaluation of the greenhouse effect from paddy fields as affected by straw incorporation and water regime (Li et al. 2005; Liu et al. 2014).

Because one of the main functions of agricultural land is to provide food for human consumption, the yield-scaled net greenhouse gas effect should also be considered when evaluating different management measures for GHG emission mitigation (Linquist et al. 2012). The grain yields on seasonal basis were in the order of S2W2>S1W2>S1W1>S2W1, there was no significant difference in grain yield between treatments (Tables 1). The crop yields from the S2W2 and S1W2 treatments were 9% and 7% greater than the S1W1 treatment, respectively. Furthermore, the grain yield in the S2W1 treatment was decreased by 6%, compared with the S1W1 treatment (Table1). GHGIs were in the order of S2W2>S2W1>S1W2>S1W1 and significantly different between the treatments, except for the difference between S2W1 and S2W2 ($p < 0.05$) (Table 1). Compared with S1W1, the GHGIs from S2W2, S2W1 and S1W2 during the rice growing season were increased by 5.94, 5.84 and 1.64 times, respectively. Additionally, the GHGI from S2W2 increased significantly, by 1.63 times, compared with S1W2 ($p < 0.05$) (Table 1). The GHGIs significantly increased with straw incorporation in this study ($p < 0.001$) (Table 2). The relatively larger increase of GHGI between the straw incorporation treatment and no straw incorporation treatment (as
compared with the difference of GHGI between the intermittent irrigation treatment and continuous flooding treatment) indicated that straw incorporation should be avoided priorly in the paddy rice production for reducing yield-scale greenhouse effect.

[Table 3 near here]

**Conclusions**

The straw incorporation strongly increased the CH$_4$ fluxes and Rh rates, and significantly decreased the N$_2$O emissions from paddy fields compared with the no straw incorporation. The CH$_4$ emissions from the continuous flooding treatment were significantly higher than those from the intermittent irrigation treatment. In contrast to CH$_4$, continuously flooding obviously reduced the cumulative N$_2$O emissions and Rh. The interaction of straw incorporation and continuously flooding significantly reduced the total N$_2$O emissions and Rh, and no significant interaction on cumulative CH$_4$ emissions. The CO$_2$e and GHGI were lowest in the no straw incorporation and intermittent irrigation and the highest in the straw incorporation and continuously flooding treatment. Therefore, to reduce GHGI, straw incorporation and continuously flooding are not suggested, but alternates like amendment of biochar made from rice straw and mid-season drainage in paddy fields may need to have a try. Moreover, long-term experiment is still needed to quantify the net greenhouse gas emissions (the CO$_2$e of CH$_4$, N$_2$O and soil organic carbon change) as caused by different straw incorporation rates and water regimes in paddy fields.

**References**


Yan X, Du L, Shi S, Xing G. 2000. Nitrous oxide emission from wetland rice soil as affected by the application of controlled availability fertilizers and midseason aeration. Biol Fert


Table 1. Cumulative CH$_4$, N$_2$O emissions and soil heterotrophic respiration (Rh), grain yield, total GHG emissions (CH$_4$ plus N$_2$O) as CO$_2$-equivalents (CO$_2$e), and yield-scaled CO$_2$e (GHGI) and average concentrations of NH$_4^+$-N, NO$_3^-$-N and DOC, and average values of soil Eh during the 2011 late rice season.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>CH$_4$ (kg C ha$^{-1}$)</th>
<th>N$_2$O (g N ha$^{-1}$)</th>
<th>Rh (kg C ha$^{-1}$)</th>
<th>Yield (t ha$^{-1}$)</th>
<th>CO$_2$e $^\dagger$ (kg CO$_2$-eq ha$^{-1}$)</th>
<th>GHGI $^\dagger$ (kg CO$_2$-eq t$^{-1}$)</th>
<th>NH$_4^+$-N (mg kg$^{-1}$)</th>
<th>NO$_3^-$-N (mg kg$^{-1}$)</th>
<th>DOC (mg kg$^{-1}$)</th>
<th>Eh (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1W1</td>
<td>41.6±4.9$^a$</td>
<td>47.3±4.0$^a$</td>
<td>550.3±17.2$^b$</td>
<td>6.7±0.3$^a$</td>
<td>1,906.2±221.9$^d$</td>
<td>287.8±45.2$^c$</td>
<td>6.5±1.9$^a$</td>
<td>0.2±0.0$^a$</td>
<td>149.2±14.0$^{ab}$</td>
<td>73.3±44.9$^a$</td>
</tr>
<tr>
<td>S2W1</td>
<td>268.9±13.5$^b$</td>
<td>15.4±2.4$^c$</td>
<td>841.1±14.8$^a$</td>
<td>6.3±0.3$^a$</td>
<td>12,196.4±612.9$^b$</td>
<td>1,946.2±70.3$^a$</td>
<td>5.2±1.5$^a$</td>
<td>0.2±0.1$^a$</td>
<td>113.7±8.6$^b$</td>
<td>38.0±44.8$^a$</td>
</tr>
<tr>
<td>S1W2</td>
<td>118.1±15.0$^c$</td>
<td>33.8±0.2$^b$</td>
<td>358.6±25.3$^c$</td>
<td>7.2±0.6$^a$</td>
<td>5,368.4±680.9$^c$</td>
<td>760.2±108.5$^b$</td>
<td>5.5±1.3$^a$</td>
<td>0.2±0.1$^a$</td>
<td>144.6±14.7$^{ab}$</td>
<td>-68.1±7.5$^b$</td>
</tr>
<tr>
<td>S2W2</td>
<td>317.1±8.1$^a$</td>
<td>-9.8±0.4$^d$</td>
<td>544.4±20.2$^b$</td>
<td>7.3±0.8$^a$</td>
<td>14,372.2±365.4$^a$</td>
<td>2,023.4±228.0$^a$</td>
<td>6.2±1.1$^a$</td>
<td>0.3±0.1$^a$</td>
<td>173.0±19.0$^a$</td>
<td>-79.9±10.6$^b$</td>
</tr>
</tbody>
</table>

$^\dagger$ Based on the global warming potential factors of CH$_4$ (34) and N$_2$O (298) in the 100-year time horizon (Myhre et al. 2013). $^\ddagger$ Yield-scaled CO$_2$e (GHGI) was defined as the CO$_2$e divided by the yield. * Values with the same letter within the column are not significantly different ($p < 0.05$). * means±se within the same column followed by different characters indicate significance at the 5% level according to Duncan’s multiple range test.
Table 2. Summary ($F$ value) of two-way ANOVA on the effects of straw incorporation (S), water management (W) and their interactions on the cumulative CH$_4$, N$_2$O emissions and soil heterotrophic respiration (Rh), total GHG emissions (CH$_4$ plus N$_2$O) as CO$_2$-equivalents (CO$_2$e), yields and yield-scaled CO$_2$e (GHGI), average concentrations of soil NH$_4^+$-N, NO$_3^-$-N and DOC, and average values of soil Eh during the 2011 late rice season.

<table>
<thead>
<tr>
<th>Factor</th>
<th>df</th>
<th>CH$_4$</th>
<th>N$_2$O</th>
<th>Rh</th>
<th>CO$_2$e</th>
<th>Yield</th>
<th>GHGI</th>
<th>NH$_4^+$-N</th>
<th>NO$_3^-$-N</th>
<th>DOC</th>
<th>Eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1</td>
<td>365.8***</td>
<td>262.5***</td>
<td>145.6***</td>
<td>364.2***</td>
<td>0.1</td>
<td>120.7***</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>W</td>
<td>1</td>
<td>31.3***</td>
<td>69.2***</td>
<td>152.9***</td>
<td>31.1***</td>
<td>1.8</td>
<td>4.3</td>
<td>0.0</td>
<td>0.8</td>
<td>3.5</td>
<td>16.0***</td>
</tr>
<tr>
<td>S×W</td>
<td>1</td>
<td>1.6*</td>
<td>6.2*</td>
<td>7.1*</td>
<td>1.6</td>
<td>0.3</td>
<td>2.2</td>
<td>0.4</td>
<td>0.1</td>
<td>4.8*</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*a* $p < 0.05$, **$p < 0.01$, ***$p < 0.001$. †Yield-scaled CO$_2$e (GHGI) was defined as the CO$_2$e divided by the yield.
Table 3. Correlation coefficients between daily CH$_4$, N$_2$O and soil heterotrophic respiration (Rh) fluxes with soil NH$_4^+$-N, NO$_3^-$-N and DOC contents, soil Eh, soil temperature (Tsoil) and water depths (Depth)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NH$_4^+$-N (n=48)</th>
<th>NO$_3^-$-N (n=48)</th>
<th>DOC (n=48)</th>
<th>Eh (n=60)</th>
<th>Tsoil (n=64)</th>
<th>Depth (n=64)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>0.64***</td>
<td>-0.01</td>
<td>-0.14</td>
<td>-0.80***</td>
<td>0.64***</td>
<td>0.45***</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.29*</td>
<td>-0.02</td>
<td>-0.21</td>
<td>-0.21</td>
<td>0.37**</td>
<td>0.15</td>
</tr>
<tr>
<td>Rh</td>
<td>-0.10</td>
<td>0.16</td>
<td>-0.15</td>
<td>0.10</td>
<td>0.27*</td>
<td>-0.40**</td>
</tr>
</tbody>
</table>

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Figure captions

Figure 1. Seasonal variation of concentration for (a) NH$_4^+$-N, (b) NO$_3^-$-N, (c) DOC, and (d) Eh values in the S1W1, S2W1, S1W2 and S2W2 treatments during the 2011 late rice season.

The vertical bars represent standard errors (n=3). T1 and T2 represent the first and second dates of urea top-dressings, respectively. Dates of flooding (F), mid-season drainage (D), flooding (F) and moist but non-waterlogged (M) for the rice growing season are indicated, respectively.
Figure 2. Seasonal variation of (a) air temperature and precipitation, (b) soil temperature (5 cm), (c) water depth, (d) CH$_4$, (e) N$_2$O and (f) soil heterotrophic respiration (Rh) fluxes in the S1W1, S2W1, S1W2 and S2W2 treatments during the 2011 late rice season.

The vertical bars represent standard errors (n=3). T1 and T2 represent the first and second dates of urea top-dressings, respectively. Periods of flooding (F), mid-season drainage (D), flooding (F) and moist but non-waterlogged (M) for the rice growing season are indicated, respectively.
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