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Effect of controlled drainage in the wheat season on soil CH_4 and N_2O emissions during the rice season

B. Jiang[a], Sh.Y. Yang[a,*], X.B. Yang[a], Y.H. Ma[a], X.L. Chen[a], H.F. Zuo[a], D.F. Fan[a], L. Gao[a], Q. Yu[a,b], W. Yang[a]

[a]*Anhui Agriculture University, Hefei, Anhui, China.*
[b]*Plant Functional Biology and Climate Change Cluster, University of Technology, Sydney, PO Box 123, Broadway, NSW 2007, Australia.*
*Corresponding author. E-mail: yangshy@ahau.edu.cn

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Abstract

The effect of draining crop fields during the wheat season on the soil CH_4 and N_2O emissions during the rice season in this article. There were four treatments: traditional cultivation during the wheat season + cultivation without fertilization during the rice season (CK_1 field), traditional cultivation during the wheat season + traditional cultivation during the rice season (CK_2 field), draining the fields through shallow furrows + traditional cultivation during the rice season (CQ field) and draining the fields through deep furrows + traditional cultivation during the rice season (CS field). The results are listed as follows. (1) Draining the field through furrows during the wheat season significantly reduced the CH_4 and N_2O emissions during the rice season. Compared with the CK_1 field, the total CH_4 emissions from the CQ and CS fields decreased by 43.1% and 39.9%, respectively; compared with the CK_2 field, the total CH_4 emissions from the CQ and CS fields decreased by 58.1% and 55.7%, respectively; compared with the CK_2 field, the total N_2O emissions from the CQ and CS fields decreased by 33.6% and 32.7%, respectively. N_2O emissions from the CQ and CS fields caused by fertilization declined by 44.0% and 42.9% compared with that from the CK_2 field. (2) Draining the wheat field in winter changed the CH_4 emission pattern during the following rice season. The daily average CH_4 emission flux from the winter flooded CK_1 and CK_2 fields were comparable before the field sunning and after the re-flooding and the fluxes from the drained CQ and CS fields before the field sunning were close to that from the CK_1 and CK_2 fields but were significantly greater than that from the drained CQ and CS fields after the field re-flooding. (3) The soil CH_4 emission flux was significantly negatively correlated to the soil E_h. But the correlation was weakened by the drainage treatment in the wheat season. In summary, draining the crop field in the wheat season should be an effective approach to reducing soil greenhouse gas emissions in the rice season.

Keywords: Quarterly paddy fields; CH_4; N_2O; Draining the wheat field in winter; Comprehensive greenhouse effect.

Introduction

Methane (CH_4) and nitrous oxide (N_2O) are the major contributors to global warming (Chakraborty et al., 2000; Rodhe, 1990) and rice fields are the major sources of CH_4 and N_2O in the atmosphere (Cai et al., 1997; Li et al., 2008; Xiong et al., 2007; Xu et al., 2000). The yearly global CH_4 emission from rice fields is 31-112 Tg, which accounts for 5-19% of the total global CH_4 emissions. It was estimated that the yearly China's CH_4 emission from rice fields is 7.6-10 Tg (Wang, 2001) and fields at the middle and lower reaches of the Yangtze River are the main rice fields (2012) in China, approximately 14.85 million hectare (Statistical Yearbook of China, 2013), which accounts for 50% of the total rice fields area in China or 10% of that in the world. Hence, China's CH_4 emission from rice fields is an important part of the global CH_4 emissions and the investigation of CH_4 reduction technology fitting the rice fields plays a positive role in controlling global warming. When the rice field is flooded, the soil layer within a depth of 2-20 cm is a reduced soil layer and produces CH_4 when $Eh \leq -300$ mmV. Under such conditions, the crop field primarily releases CH_4. When the field is dried, the soil exhibits oxidizability in which the CH_4 production is suppressed and N_2O production increases. Under such conditions, the crop field primarily releases N_2O (Xu et al., 2002; Cai et al., 2001). The application of the management method of soil water can control greenhouse gas's emissions (Marja et al., 2001; Jia et al., 2001). Xu et al. (2001) found that soil water control during the non-rice season can attenuate the amount of reducing substances in soil and after being flooded in the rice season decline rate of the soil E_h can be retarded, which eventually leads to the reduction of CH_4 emissions during the rice season. The study by Cai et al. (2003) demonstrated that in the winter irrigation field, the cultivation of winter wheat after field drainage could prolong time of the soil E_h decline and reduce the average CH_4 emission flux by 63-72% during the rice-growing period in the following year (Cai et al., 2003), but the drainage during the non-rice season could increase N_2O emissions (Zheng et al., 1997). The above studies primarily used winter-flooded fields in the southwest areas of China as study subjects. In such areas, irrigation of the rice fields primarily occurs through precipitation, thus requiring water preservation throughout the entire year. Once the fields are drained, precipitation insufficiency causes drought conditions that may become a threat to normal production. Therefore, based on the local farmers' experience, permanent flooding for water preservation is adopted in these areas. The "winter wheat /winter rape plus single-cropping rice" farming areas in the middle and lower reaches of the Yangtze River are primarily flat low-lying areas with abundant surface water sources. In these areas, surface water is the major source for irrigation, so the winter controlled drainage does not impose negative effects on the rice production of the subsequent rice season, but there is still a condition of the winter controlled drainage. In addition (Celik et al., 2012; Shabani et al., 2013), rice fields in these areas accounts for a large proportion of the total global rice field areas (Xiong et al., 1992; Shan et al., 2006; Montemurro et al., 2014), thus possessing a huge potential for reducing rice field greenhouse gas emissions. However, compared to the winter flooded rice fields in the southwest of China, the tradition in these areas is of rainfed crop cultivation in winter. The reduction of greenhouse gas emissions during the rice season that occurs because of the controlled drainage in the winter rainfed crop season has yet to be reported.

In this study, the typical rice-wheat double cropping fields in the Chaohu low-lying areas with a relative high underground water level was used to represent the single-cropping rice fields at the middle and lower reaches of the Yangtze River and the effect of controlled drainage via furrows in the wheat season on the CH_4 and N_2O emissions in the following rice season was investigated. Our findings are of theoretical significance to research on the reduction of greenhouse gas emissions from rice fields in the study area.

Materials and Methods

Overview of the study area

This study was conducted in the Chaohu Experiment Station of Anhui Agriculture University during the period between October 2012 and October 2013 (117° 40′ E, 31° 39′ N, altitude 17 m). This area is a typical low-lying polder area and belongs to the northern humid subtropical climate zone. The yearly average temperature is 16.8 °C and the yearly average precipitation is 1358.3 mm. The soil is a gley-type paddy soil and its physiochemical properties are as follows: pH (H_2O) value is 6.18, the content of organic carbon is 23.64 g kg^{-1}, the content of total nitrogen (N) is 1.30 g kg^{-1} and the content of physical clay particles is 490 g kg^{-1}.

Experimental design

The experiment included two phases: the wheat season and rice season. There were four treatment groups and each was performed in triplicate.
(1) Blank treatment (the CK_1 field): absence of controlled furrow drainage in the wheat season, traditional water management and absence of fertilization in the rice season. The soil fertility of the treated field originated from the wheat season residue, so this treatment was used for the fertility exhaustion experiment. This treatment was applied to as a comparison with effects of the absence of fertilization in the rice season on greenhouse gas emissions.
(2) Traditional treatment (the CK_2 field): absence of controlled furrow drainage in the wheat season and traditional water and fertilization management in the rice season. This treatment was used to investigate the greenhouse gas emissions from the rice field under the traditional cultivation conditions.
(3) Shallow-furrow treatment (the CQ field): controlled drainage through 20 cm deep row furrows and 30 cm deep perpendicular furrows in the wheat season and traditional water and fertilization management in the rice season. This treatment was used to investigate the greenhouse gas emissions from the rice field under shallow-furrow water management conditions in the wheat season.
(4) Deep-furrow treatment (the CS field): controlled drainage through the 30 cm deep row furrows and the 40 cm deep perpendicular furrows in the wheat season and traditional water and fertilization management in the rice season. This treatment was used to investigate the greenhouse gas emissions from the rice field under deep-furrow water management conditions in the wheat season.

A randomized block design was adopted. Each block had an area of 4×7.5 m and the furrows around the blocks were all 40 cm in depth. The protection belts outside of the furrows had a width of 2 m and the ditches outside of the protection belts were 0.6-0.8 m deep.

During the wheat season, all of study fields received local traditional fertilization treatment as follows: on October 20 before the seeding, the crop fields were fertilized with 72.03 kg·hm^{-2} of pure nitrogen, 72 kg·hm^{-2} of P_2O_5 and 50.4 kg·hm^{-2} of K_2O; on January 15, the fields were fertilized with 68.985 kg·hm^{-2} of pure nitrogen and 21.6 kg·hm^{-2} of K_2O and on February 25, the fields were fertilized with 68.985 kg·hm^{-2} of pure nitrogen. The fields were irrigated with only natural precipitation. According to water monitoring from November 5, 2012 to May 26, 2013, the average volumetric water content of CK_1, CK_2, CQ and CS were 32.1%, 31.3%, 25.2% and 23.9%. The effects of water management by furrowing was remarkable.

During the rice season, the CK_2, CQ and CS fields received local traditional fertilization treatment as follows: on June 12, the crop fields were fertilized with 67.5 kg·hm^{-2} of pure nitrogen, 67.5 kg·hm^{-2} of P_2O_5 and 180 kg·hm^{-2} of K_2O; on June 28, the fields were fertilized with 67.5 kg·hm^{-2} of pure nitrogen and on July 27, the fields were fertilized with 45 kg·hm^{-2} of pure nitrogen.

The rice used in this study was super rice 0293. The cultivation and water management processes were as follows: land soaking began on June 10 and was followed by rice transplantation on June 13, land sunning on July 11 and re-flooding on July 17. The rice was harvested on September 27. Based on the time points for land sunning and re-flooding, the rice-growing period was divided into three phases: before land sunning (twenty-eight days), during land sunning (seven days) and after re-flooding (seventy-two days). The average soil volumetric water content decreased from 35.2% to 22.4% during land sunning and the depth of submergence on the surface of soil at other times was 2-5 cm.

Gas collection and analysis

Gas samples were collected using a sealed static chamber. The sealed sampling chamber was made of 5 mm thick transparent plexiglass with a size of 50×50×60 cm or 50×50×120 cm, which was selected based on the rice plant height. The chamber was equipped with a thermometer on the top to measure the temperature inside the chamber. During the sampling, the sampling chamber was tapped on the base and water was added into the "凹"-shaped gap on the base for sealing.

Gas samples were collected at the time points of 0, 10, 20 and 30 min after the installation during the period of 9:00-12:00 in the morning. The sampling methods referenced the research of Cai et al. (2009). A medical syringe was used for gas sample collection and 60 mL of gas was collected in each collection period.

Gas samples were collected once every seven days and were collected more frequently during the fertilization and land sunning periods. Gas samples were collected on the day of fertilization, Days 1, 3, 5, 7 and 9 after fertilization and daily during land sunning. Gas samples were collected a total of 35 times.

The samples were analyzed within 24 h. Gas chromatography (GC) was performed on a 450-GC system (Bruker Daltonics Inc., U.S.A.). CH_4 was detected by a flame ionization detector and N_2O was detected with an Nl^{63} electron capture detector (ECD).

The CH_4 or N_2O emission flux was calculated using the following formula: $F=\rho\times V/A\times dc/dt\times 273/T$, where F is the emission flux in units of $mg.m^{-2}.h^{-1}$ for CH_4 and $\mu g.m^{-2}.h^{-1}$ for N_2O, ρ is the density of CH_4 or N in the form of N_2O under standard conditions (0.714 $kg.m^{-3}$ and 1.25 $kg.m^{-3}$, respectively), V is the effective volume of the sampling chamber (m^3), A is the area covered by the sampling chamber (m^2), dc/dt is the change of CH_4 or N_2O concentration ($\mu L.L^{-1}.h^{-1}$ or $nL.L^{-1}.h^{-1}$, respectively) in the sampling chamber per unit of time (positive value: gas emission; negative value: gas absorption), T is the temperature inside the chamber (K) and 273/T is the temperature impact factor.

CH_4 or N_2O emissions were calculated using a trapezoidal method according to the following formula: $Q=(F_1+F_2)\times(t_2-t_1)/2\times 24$, where Q is the total emission amount of CH_4 or N_2O ($mg.m^{-2}$ and $\mu g.m^{-2}$, respectively) and F_1 and F_2 are the corresponding emission fluxes at day t_1 and t_2.

The temperature inside the chamber was measured simultaneously for the standardized correction of the volume of gas. Soil E_h was measured using a FJA-6 automated oxidation-reduction potential (ORP) analyzer (Nanjing Chuan-Di Instrument & Equipment CO., LTD. Nanjing, China).

Results and Analysis

Effect of controlled drainage during the wheat season on CH_4 emissions during the rice season

CH_4 Emission flux

The changing patterns of CH_4 emission flux from the CK_1 and CK_2 fields were generally consistent except that the overall value of the CK_2 field was slightly higher. Using the day of land sunning as a dividing time point, CH_4 emission fluxes from the CK_1 and CK_2 fields peaked during Days 6-29 (from June 18 to July 11) before land sunning and both exhibited two peaks after land sunning on Days 45-62 (from July 27 to August 13) and on Days 76-93 (from August 27 to September 13). The amplitude of the two post-sunning peaks were comparable to those before land sunning and the emission flux between the two peaks was greater than half of the peak value, indicating that the CH_4 emissions from both CK_1 and CK_2 fields was persistent and stable. Because the only difference in the treatment between the CK_2 and CK_1 fields is the absence or presence of fertilization, the above results indicate that the absence of fertilization may reduce the CH_4 emission flux from the rice field but does not alter its changing trend.

The changing patterns of CH_4 emission flux from the CQ and CS fields were generally consistent except that the overall value of the CS field was slightly higher. CH_4 emission flux Both the CQ and CS fields only had one CH_4 emission peak during Days 6-29 after the transplantation of seedlings. The peak value was slightly higher than that of the CK_1 field and slightly lower than the CK_2 field; the peak duration was not different from that of the CK_1 and CK_2 fields. After land re-flooding, the CH_4 emission flux from both the CQ and CS fields showed a continuously declining trend and the maximum value did not exceed the average level during land sunning. Even with more frequent monitoring after fertilization on Day 45 (July 27), drastic fluctuations of the CH_4 emission flux were not found. This phenomenon was completely different from the observation of the CK_1 and CK_2 fields in which the CH_4 emission flux began to increase in a stable manner after land sunning. This result indicated that the controlled drainage during the wheat season did not significantly affect the pre-sunning CH_4 emissions but dramatically reduced the CH_4 emissions after the re-flooding; the reduction caused by the drainage is greater than that caused by the absence of fertilization.

As shown in Figure 2, the soil CH_4 emission flux was close to zero on Days 1-4 after the transplantation of rice seedlings (Figure 1) and the soil E_h remained positive during the same time period (≥133.7 mV), with a daily maximum variation of -40.5 mV/d. During Days 6-8, the CH_4 emission flux from all of the study fields rapidly increased and reached the maximum value of the current phase. The soil E_h rapidly declined at the same time, with a daily minimum reduction of 50.5 mV/d and maximum reduction of 91.7 mV/d. The soil E_h of the CK_1 and CK_2 fields declined to a negative value. During this phase, although the soil E_h of the CQ and CS fields remained positive and the declination rate was far below that of the CK_1 and CK_2 fields, the CH_4 emission flux reached a peak level of 17.13 $mg·m^{-2}h^{-1}$ from the CQ field and 18.23 $mg·m^{-2}h^{-1}$ from the CS field, which was similar to the peak level from the CK_1 and CK_2 fields (18.50 $mg·m^{-2}h^{-1}$ and 24.34 $mg·m^{-2}h^{-1}$). During Days 8-16, the declination speed of the soil E_h became slower and the CH_4 emission flux was dramatically reduced by more than 50% from the highest level. During Days 16-19, the soil E_h rapidly dropped again and the CH_4 emission flux of all four treatment groups gradually increased at a rate significantly slower than that during Days 6-8. During land sunning that began on Day 29 (July 11), although the soil E_h of the CK_1 and CK_2 fields was slightly elevated, the CH_4 emission flux rapidly dropped. For the CQ and CS fields, the soil E_h increased at a relatively high speed and the CH_4 emission flux declined at a speed greatly lower than that of the CK_1 and CK_2 fields. After re-flooding, the soil E_h of all four treatment groups returned to the levels of Days 17-29 and the CH_4 emission flux from the CK_1 and CK_2 field returned to a high level and reached an emission peak on Days 45-93. The peak value was 19.57 $mg·m^{-2}h^{-1}$ for the CK_1 field and 26.48 $mg·m^{-2}h^{-1}$ for the CK_2 field, which were close to or above the maximum value before land sunning. The CH_4 emission flux from the CQ and CS field was no higher than 4.05 $mg·m^{-2}h^{-1}$ and 4.66 $mg·m^{-2}h^{-1}$, respectively, a noticeable emission peak was not found. An analysis of the relationship between the variations of the CH_4 emission flux and soil E_h during this phase revealed that the elevated CH_4 emission flux usually occurred along with a dramatic declination of soil E_h, but a significant relation was not found with the absolute value of soil E_h. This finding was inconsistent with the results reported by Xu et al. (1999). Another finding of the present study was that the CH_4 emission flux was negatively correlated to the soil E_h in all of the treatment groups and this finding was consistent with the research results reported by Xu et al. (1999). In terms of the correlation of the variations of the CH_4 emission flux with soil E_h, the comparison between the CQ and CS fields with the CK_1 and CK_2 fields indicated that controlled drainage in winter significantly attenuates the effect of soil E_h on CH_4 emissions, in particular after the re-flooding (Table 1).

Table 1. The correlation of the variations of the CH_4 emission flux with soil E_h.

Treatment	CK_1	CK_2	CQ	CS
E_h	-0.252*	-0.291*	-0.313**	-0.250*

N=72; * At the 0.05 level significantly correlated (bilateral);
** At the 0.01 level significantly correlated (bilateral)

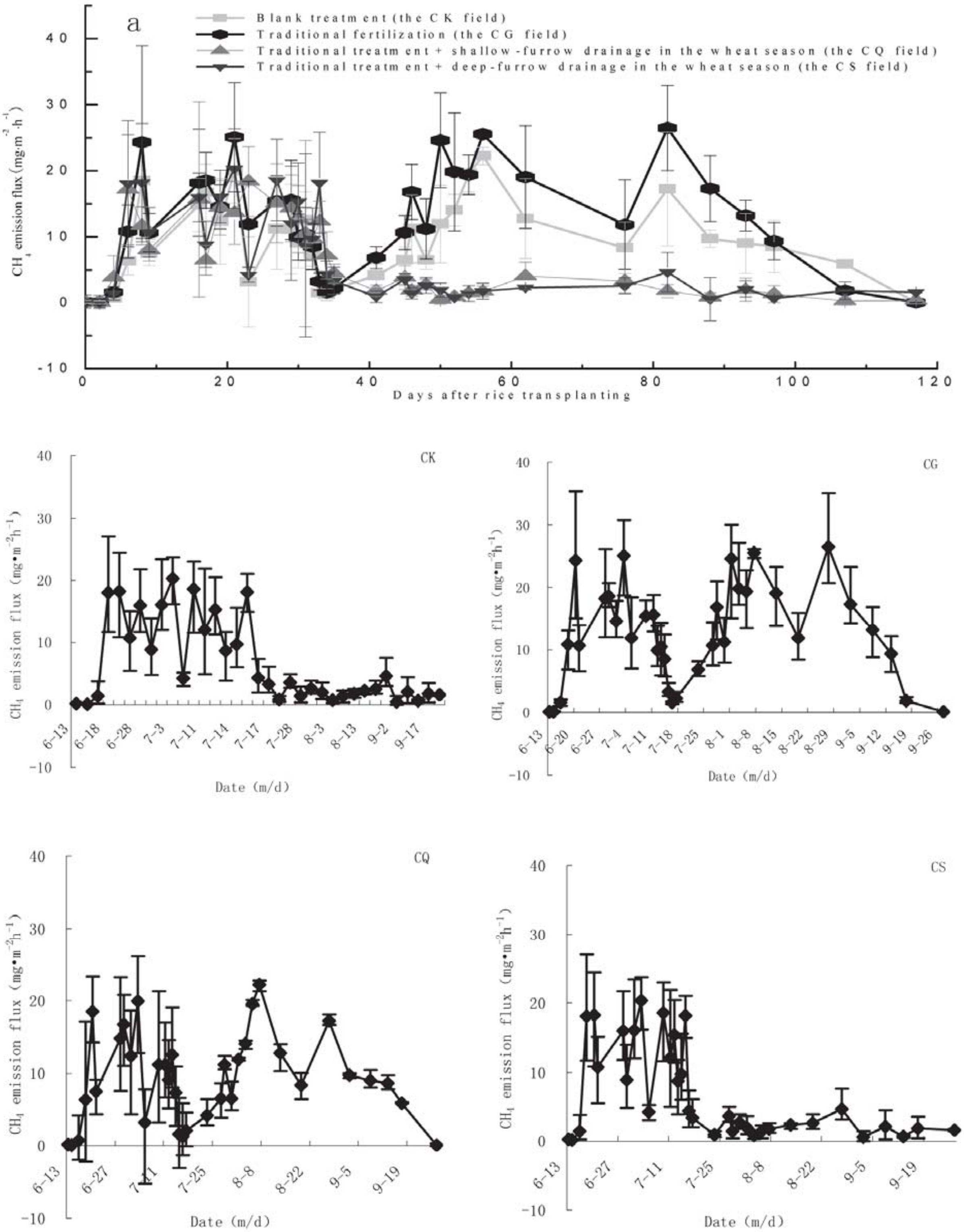

Figure 1. Seasonal variation of the CH_4 emission flux.

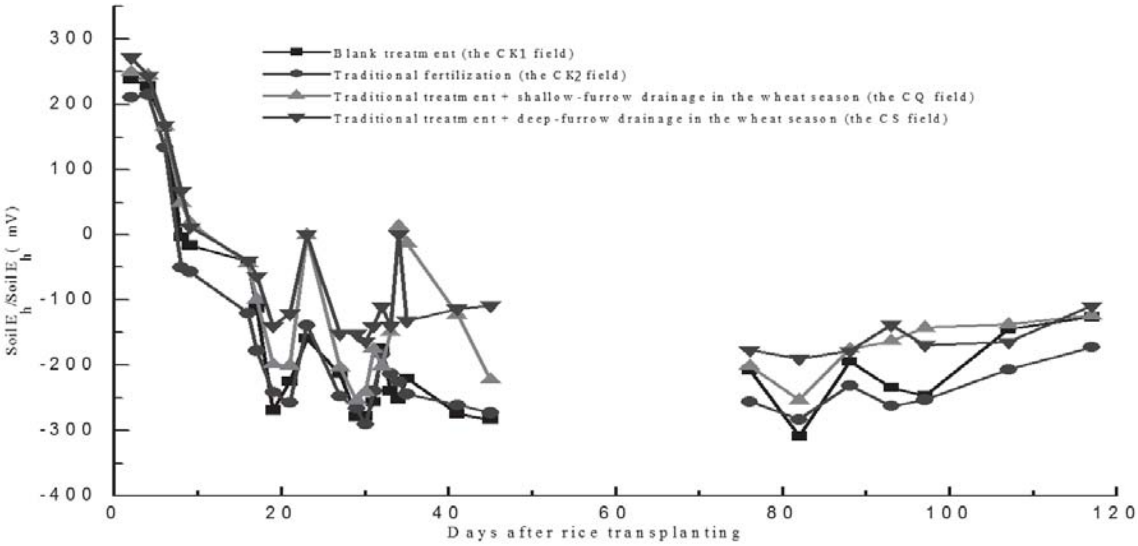

Figure 2. Seasonal variation of the soil E_h.

Total CH_4 emission

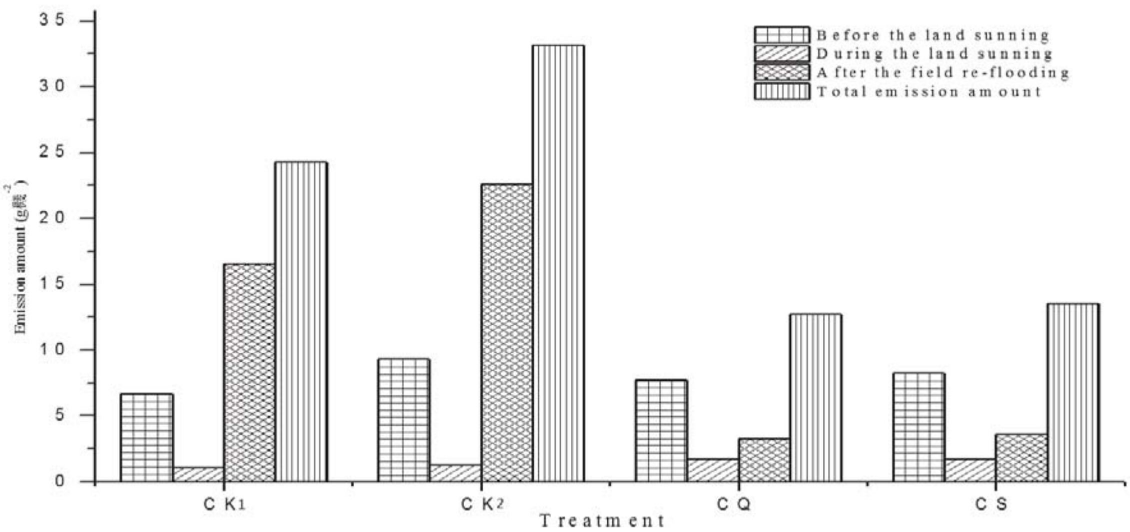

Figure 3. CH_4 Emissions ($g \cdot m^{-2}$) at different phases.

The total CH_4 emissions from the CK_1, CK_2, CQ and CS fields was 24.26 $g \cdot m^{-2}$, 33.17 $g \cdot m^{-2}$, 12.71 $g \cdot m^{-2}$ and 13.51 $g \cdot m^{-2}$, respectively (Figure 3). Compared with the CK_1 treatment, the CK_2 treatment increased the CH_4 emissions by 35.8% and the CQ and CS treatments decreased the CH_4 emissions by 43.1% and 39.9%, respectively. Compared with the CK_2 treatment, the CQ and CS treatments decreased the CH_4 emissions by 61.7% and 59.3%, respectively. Although these numbers are slightly lower than those obtained by Cai et al. (1998). From their study of winter-flooded fields in Southwestern China, our results still revealed a remarkable reduction of gas emissions by the controlled drainage in the wheat season. This finding confirmed that crop cultivation under controlled drainage may effectively reduce CH_4 emissions during the following rice season in the single-cropping rice farming areas in the middle and lower reaches of the Yangtze River.

CH_4 emissions during the rice season occur primarily before sunning and after re-flooding of the field (Figure 3) and differs significantly at these two phases between the fields with and without controlled drainage. The CK_1 and CK_2 fields without controlled drainage in the wheat season emitted relatively similar daily average amounts of CH_4 and their total emissions relied on the duration of the phase. The growing period of the field was 28 days before land sunning and 72 days after re-flooding, which accounted for 26.2% and 67.3% of the entire growing period of the field, respectively. Accordingly, the CH_4 emissions before land sunning and after re-flooding accounted of 27.5% and 68.3%, respectively, of the total amount in the CK_1 field and 28.1% and 68.2%, respectively, in the CK_2 field. The daily average CH_4 emission flux from the CQ and CS fields with controlled drainage in the wheat season was similar to that of the CK_1 and CK_2 fields before land sunning, but the flux was significantly higher than that after the re-flooding. Accordingly, the CH_4 emissions before land sunning and after re-flooding accounted for 60.7% and 25.9%, respectively, of the total amount during the entire growing period of the CQ field and 61.0% and 26.3%, respectively, in the CS field. These results indicated that the reduction of CH_4 emissions caused by the controlled drainage in the wheat season occurred primarily after the re-flooding.

Effect of controlled drainage in the wheat season on the soil N_2O emissions during the rice season

N_2O Emission flux

The N_2O emission flux in the rice season greatly varied with the different treatments (Figure 4).

The CK_1 treatment led to an overall decreasing trend of N_2O emission flux over time and did not cause significant differences compared to the CK_2, CQ and CS treatments. The average emission flux before land sunning, during land sunning and after re-flooding was 10.34 $\mu g.m^{-2}h^{-1}$, 15.65 $\mu g.m^{-2}h^{-1}$ and 7.57 $\mu g.m^{-2}h^{-1}$, respectively. The average emission flux before land sunning and after re-flooding accounted for 66.1% and 48.4%, respectively, of the flux during land sunning, indicating that drying the land under sunshine may elevate the N_2O emission flux. Although the N_2O emission flux from the CK_1 field during land sunning was relatively high, its maximum value was only 30.9 μg.m^{-2}h^{-1}, which was significantly lower than the peak values of the CK_2, CQ and CS fields.

The N_2O emissions from the CK_2 field reached a peak of 306.28 μg.m^{-2}h^{-1} on June 28 and 133.68 μg.m^{-2}h^{-1} on July 28. The emission flux from this field during land sunning remained in a range of 10.04-54.61 μg.m^{-2}h^{-1}. Although the flux was at a relatively high level overall, it was greatly smaller than the peak value caused by the fertilization. Compared to the CK_1, CQ and CS fields, the average emission flux from the CK_2 field reached 78.42 μg.m^{-2}h^{-1} before land sunning, which was higher than the flux during land sunning by 85.5%, suggesting that the N_2O emissions from the CK_2 field were concentrated primarily at the phase before land sunning.

The changing pattern of the N_2O emission flux from the CQ, CS and CK_2 fields was similar; the emissions peaked after fertilizing twice in all of these fields, but the peak values and time points of the peaks greatly varied. The first emission peak from the CQ and CS fields occurred at post-fertilization Day 5 (June 28), which was two days earlier than that of the CK_2 field. The peak values of the CQ and CS fields were 185.3 μg.m^{-2}h^{-1} and 57.8 μg.m^{-2}h^{-1}, respectively, which was significantly below that of the CK_2 field. The second peak occurred at the same time as that of the CK_2 field (306.3 μg.m^{-2}h^{-1}), but the peak value was significantly smaller.

As demonstrated in Figure 2 and Figure 4, during the period from Day 16 after fertilization (June 28) to the day before land sunning, the soil E_h showed a changing trend from a rapid decrease (from>0 mv to -150 mv) to a rapid increase back to above 0 mv. During the period of rapid increase of the E_h, the N_2O emissions from the CK_2, CQ and CS fields reached the first peak, which occurred earlier than that of the E_h peak. The peak of the CK_2 field lasted for more than seven days, during which the N_2O emissions accounted of 73.8% of the total emissions before land sunning; during the same time period, the N_2O emissions from the CQ, CS and CK_1 fields accounted for 62.1%, 47.2% and 44.1%, respectively, of the total emissions before land sunning. These results indicated that fertilization caused remarkable N_2O emissions from the CK_2 and CQ fields and revealed that the treatment of nitrogen fertilizer may greatly increase the N_2O emissions from the flooded land, in particular from the CK_2 field. In addition, controlled drainage can suppress the N_2O emissions peak and the deeper furrows showed an effect superior to that of the shallow furrows. No significant correlation between soil E_h and N_2O emission was observed, which is inconsistent with the report of Xu et al. (1999).

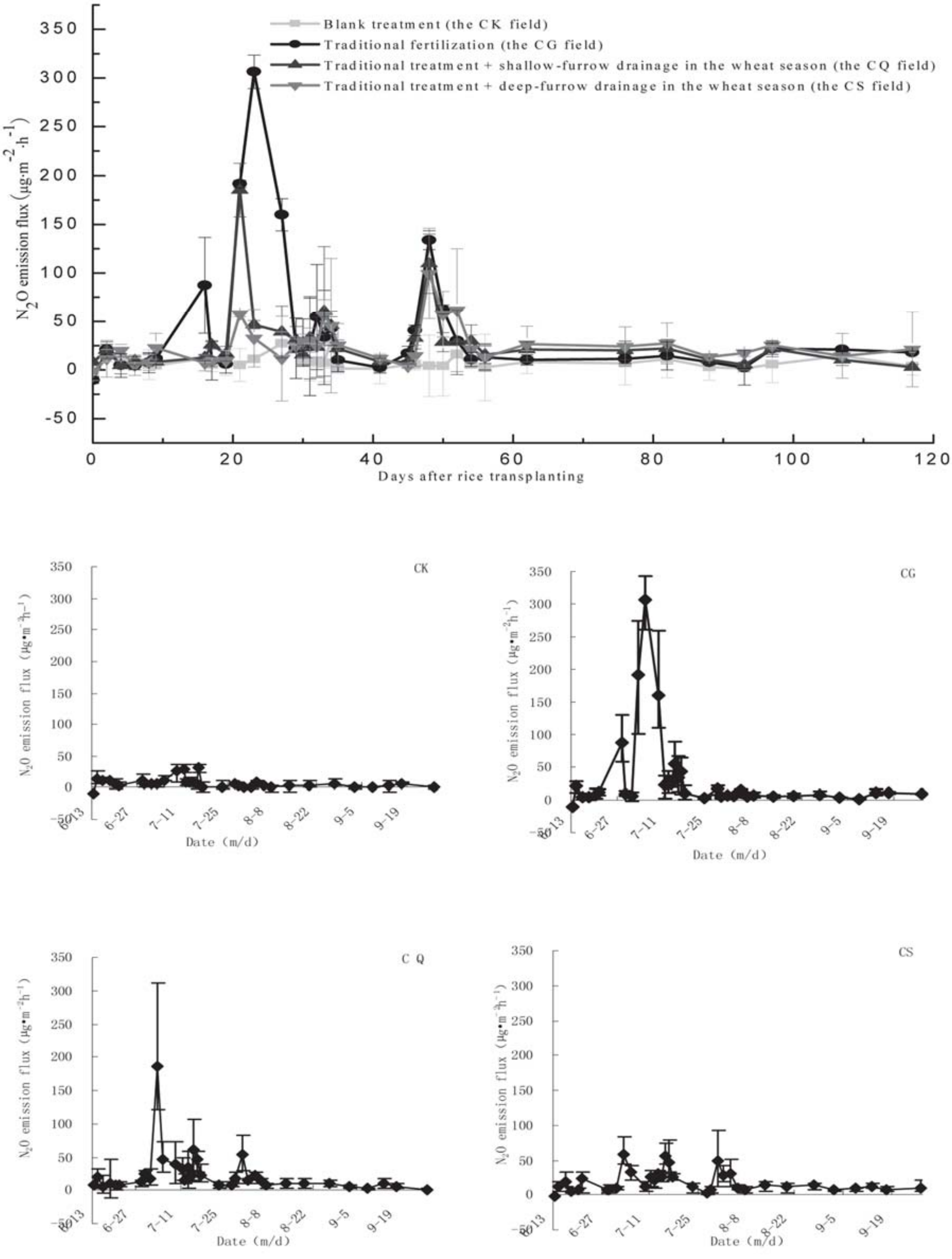

Figure 4. Change of N_2O emission flux.

Total N_2O emissions

The total N_2O emissions during the rice season from the CK_1, CK_2, CQ and CS fields was 22.66 mg·m^{-2}, 95.35 mg·m^{-2}, 63.35 mg·m^{-2} and 64.15 mg·m^{-2} (Table 2), respectively. Compared with the CK_1 treatment, the CK_2, CQ and CS treatments increased the total N_2O emissions by 3.21 times, 1.80 times and 1.83 times, respectively. However, the CK_1 treatment is usually used to reflect nitrogen exhaustion, so this result cannot reflect the actual gas emissions from the rice field under normal cultivation conditions. Instead, the CK_2 treatment simulates the local traditional management of farmland; therefore, the comparison between the CQ and CS fields with the CK_2 field can be used to clarify the effect of controlled drainage in the wheat season on the N_2O emissions from the rice fields under traditional management. Compared with the CK_2 treatment, the CQ and CS treatments reduced the N_2O emissions by 33.6% and 32.7%, respectively, indicating that controlled drainage in the wheat season can significantly suppress N_2O emissions during the rice season.

Table 2. N_2O Emissions from rice soils under different drainage measures during soil drying and soils continuously flooded (mg·m^{-2}).

Treatment	Before the land sunning	During the land sunning	After the field re-flooding	Total emission amount
CK_1	6.95	2.63	13.08	22.66
CK_2	52.70	7.10	35.55	95.35
CQ	20.83	6.08	36.44	63.35
CS	11.76	5.91	46.47	64.15

The difference in the emission amounts among the CK_2, CQ and CS fields suggested that the reduction of N_2O emissions during the rice season caused by controlled furrow drainage in the wheat season primarily occurred during the fertilization phase before land sunning. Hence, the enhanced utilization efficiency of nitrogen fertilizer might be responsible for the reduction of N_2O emissions caused by controlled furrow drainage. The effect occurred only during the period before re-flooding of dried field, which was shown by slightly higher emissions from the field with a furrow drainage system (CQ and CS fields) after re-flooding than that from the CK_2 field.

The difference in the total N_2O emissions during the entire growing period between the CQ and CS fields was only 0.80 mg·m^{-2}, which is equal to only 1.24% of the emissions from the CS field, indicating that drainage in the wheat season using 20 cm deep furrows is sufficient to achieve a reduction of N_2O emissions during the rice season and deeper furrows might not necessarily improve the reduction of gas emissions.

The CK_1 field data suggested that there were background N_2O emissions under natural conditions and they could be increased by fertilization. Therefore, the effect of controlled drainage in the wheat season on the N_2O emissions from the rice field should be investigated under a prerequisite of excluding the natural baseline emissions. Based on this consideration, after subtracting the baseline emissions, the N_2O emissions from the CK_2, CQ and CS fields caused by the application of nitrogen fertilizer was 72.69 mg·m^{-2}, 40.68 mg·m^{-2} and 41.48 mg·m^{-2}, respectively. Controlled drainage in the wheat season suppressed the fertilization-caused N_2O emissions during the rice season by 44.0% (CQ) and 42.9% (CS), respectively.

Discussion

Rice cultivation relies on water and fertilizers, which are the major regulatory factors of CH_4 and N_2O emissions from rice fields (Li et al., 1999). Studies have demonstrated that the order of different treatments was as CQ>CK_2>CS>CK_1 in terms of rice production (Table 3). Rice production in the CK_2 field was 1.5% lower than that of the CQ field, 0.3% higher than that of the CS field and 9.9% higher than that of the CK_1 field. The absence of fertilization can greatly decrease rice production immediately; therefore, reducing greenhouse gas emissions by blindly limiting the use of fertilizer is not reasonable. Controlled drainage in the wheat season can attenuate the CH_4 and N_2O emissions simultaneously without decreasing crop production. The studies conducted by Cai et al. (1997) and Xu et al. (1999) have demonstrated that CH_4 emissions over the rice-growing period can be reduced by 63.2%-72.4% by draining the winter-flooded rice fields in winter in Southwestern China. The reduction of CH_4 emissions in this study was less than that in the studies of Cai et al. (2001) which might be caused by productivity habits of winter drainage in the middle and lower reaches of the Yangtze River which led to the difference between the middle and lower reaches of the Yangtze River and Southwestern China in the accumulation of soil matrix generating methane and its change the characteristics of the soil E_h. In addition, relatively weak correlation between the soil E_h and CH_4 emission flux also certified this point. In this study, we found that for single-cropping rice fields in the middle and lower reaches of the Yangtze River, furrow drainage in the wheat season lead to a reduction of CH_4 emissions that were slightly less than that in Southwestern China. Therefore, controlled drainage in the wheat season is an effective approach to reducing greenhouse gas emissions from rice fields. The soils' air capacity were decreased by furrowing during the wheat season, which leads to the decrease of soil matrix generating methane, the accommodation of the soil E_h change and the reduction of greenhouse gas emissions eventually.

Table 3. Rice grain yield of different drainage measures.

Treatment	economic coefficient	economic outputs/kg·hm^{-2}
CK_1	0.37	5176~~A~~
CK_2	0.37	5742~~A~~
CQ	0.38	5828~~A~~
CS	0.42	5726~~A~~

Conclusions

Controlled drainage in the wheat season can significantly suppress CH_4 and N_2O emissions during the rice season. The controlled drainage in the preceding crop season can be an effective approach to reducing greenhouse gas emissions during the following rice season. The CQ and CS treatments decreased the total CH_4 emissions by 43.1% and 39.9%, respectively, compared with the CK_1 field and decreased the total CH_4 emissions by 58.1% and 55.7%, respectively, compared with the CK_2 field. Compared with the CK_2 field, the CQ and CS treatments decreased the total N_2O emissions by 33.6% and 32.7%, respectively and by 44.0% and 42.9%, respectively, when only the fertilizer-caused increase of N_2O emissions was considered.

The CH_4 emissions in the rice season occurred mainly during two phases: before land sunning and after re-flooding. Controlled drainage in the wheat season suppressed the CH_4 emissions primarily after re-flooding. The daily average CH_4 emission flux from the CK_1 and CK_2 fields without the drainage treatment was similar before land sunning and after re-flooding. The emission amount varied with the length of the phase. The duration of the growing period after re-flooding accounted for 67.3% of the total growing period of the field. The CH_4 emission flux from the CK_1 and CK_2 fields after re-flooding accounted for 68.3% and 68.2% of the total emissions, respectively. The CH_4 emissions after re-flooding from the CQ and CS fields with the drainage treatment were inhibited, resulting in a significantly higher daily average CH_4 emission flux before land sunning than after re-flooding. Hence, the emissions primarily occurred before land sunning, which accounted for 60.7% and 61.0% of the total emissions from the CQ and CS fields, respectively.

The soil CH_4 emission flux is negatively correlated to the soil E_h in the single-cropping rice field and this correlation can be attenuated by controlled drainage in the wheat season, in particular after re-flooding. This attenuation results in the alteration of CH_4 emissions, leading to a low emission flux even when the soil E_h is below -150 mv after re-flooding of the CQ and CS fields.

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