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Drainage and tillage practices in the winter fallow season mitigate CH_4 and N_2O emissions from a double-rice field in China

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Abstract. Traditional land management (no tillage, no drainage, NTND) during the winter fallow season results in substantial CH_4 and N_2O emissions from double-rice fields in China. A field experiment was conducted to investigate the effects of drainage and tillage during the winter fallow season on CH_4 and N_2O emissions and to develop mitigation options. The experiment had four treatments: NTND, NTD (drainage but no tillage), TND (tillage but no drainage), and TD (both drainage and tillage). The study was conducted from 2010 to 2014 in a Chinese double-rice field. During winter, total precipitation and mean daily temperature significantly affected CH_4 emission. Compared to NTND, drainage and tillage decreased annual CH_4 emissions in early- and late-rice seasons by 54 and 33 kg CH_4 ha^{-1} yr^{-1}, respectively. Drainage and tillage increased N_2O emissions in the winter fallow season but reduced it in early- and late-rice seasons, resulting in no annual change in N_2O emission. Global warming potentials of CH_4 and N_2O emissions were decreased by 1.49 and 0.92 t CO_2 eq. ha^{-1} yr^{-1}, respectively, and were reduced more by combining drainage with tillage, providing a mitigation potential of 1.96 t CO_2 eq. ha^{-1} yr^{-1}. A low total C content and high C / N ratio in rice residues showed that tillage in the winter fallow season reduced CH_4 and N_2O emissions in both early- and late-rice seasons. Drainage and tillage significantly decreased the abundance of methanogens in paddy soil, and this may explain the decrease of CH_4 emissions. Greenhouse gas intensity was significantly decreased by drainage and tillage separately, and the reduction was greater by combining drainage with tillage, resulting in a reduction of 0.17 t CO_2 eq. t^{-1}. The results indicate that drainage combined with tillage during the winter fallow season is an effective strategy for mitigating greenhouse gas releases from double-rice fields.

1 Introduction

Methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases (GHGs). According to the Greenhouse Gas Bulletin of World Meteorological Organization, the concentrations of atmospheric CH_4 and N_2O reached 1833 and 327 ppb in 2014, respectively (WMO, 2015). Rice paddy fields are major sources of atmospheric CH_4 and N_2O. Effective options for mitigating CH_4 and N_2O emissions from rice paddy fields worldwide have been studied over the last two decades (McCarl and Schneider, 2001; Yan et al., 2005; Hussain et al., 2015). Ideas have included modifying irrigation and fertilization patterns (Cai et al., 2003; Hussain et al., 2015; Linquist et al., 2015), establishing integrated soil–crop system management practices (Zhang et al., 2013; Chen et al., 2014), and selection of rice cultivars with high yields but low GHGs emissions (Ma et al., 2010; Hussain et al., 2015; Su et al., 2015), etc. Nevertheless, other potential mitigation methods might be useful due to the diversity of rice-based ecosystems and the variety of agronomic management practices (Weller et al., 2016).

China is one of the largest rice producers in the world, and its harvested area contributes 18.9 % of the world rice total (FAOSTAT, 2014). In China, total CH_4 and N_2O emissions from paddy fields are estimated to be 6.4 Tg yr^{-1} and 180 Gg yr^{-1}, respectively (Zhang et al., 2014). Double rice is the major rice-cropping system in China, accounting for over 40 % of the total cultivation area (Yearbook, E. B. O. C. A., 2014) and emitting ca. 50 % of the total paddy CH_4 in China (Zhang et al., 2011; Chen et al., 2013). Double-rice fields mainly occur south of the Yangtze River where relatively high precipitation and warm temperatures occur during the winter fallow season. Traditionally, the fields are fallow in winter season with the soil being neither drained nor tilled after the late-rice harvest, which are often flooded after a heavy or prolonged rain. It is very likely to bring about CH_4 emissions from these fields during the winter fallow season and further to promote emissions during the following rice growth season. Modeling data show that CH_4 emission levels were significantly correlated with simulated soil moisture and mean precipitation during the preceding non-rice growth season (Kang et al., 2002). Incubation and pot experiments also showed that high soil water content in the non-rice growth season was associated with high CH_4 production rates and greater CH_4 emissions in the subsequent rice season (Xu et al., 2003). An available mitigation option is proposed for this region. Fields can be drained to decrease the accumulation of rainwater in the winter fallow season and to reduce the effect of winter precipitation on CH_4 emission. However, drainage possibly stimulates N_2O emission from paddy fields in winter because soil water content changes more rapidly. Soil moisture regulates the processes of denitrification and nitrification and thus N_2O emission (Bateman and Baggs, 2005; Lan et al., 2013). Since the overall balance between the net exchange of CH_4 and N_2O emissions constitutes the global warming potentials (GWPs) of the rice ecosystem, the effects of soil drainage in the winter fallow season on mitigating the yearly GWPs from double-rice fields are unclear.

Soil tillage is a conventional practice in rice cultivation, and tilling the soil prior to rice transplanting can play a key role in CH_4 and N_2O emissions (Hussain et al., 2015; Zhao et al., 2016). Tillage after rice harvest in the winter fallow season is also likely to have important effects on CH_4 and N_2O emissions. It is beneficial for rainwater to penetrate into the subsoil because this minimizes rainwater accumulation in winter. However, tillage makes it difficult to establish a strict anaerobic environment in the top soil, which would directly reduce CH_4 emissions during the non-rice growing season and indirectly inhibit CH_4 emissions during the following rice season. On the contrary, tillage allows rice residues to contact the soil, and soil microorganisms accelerate the decomposition of organic matter and facilitate CH_4 production and emission in the fallow season (Pandey et al., 2012; Hussain et al., 2015). Tillage may also play a key role in CH_4 emission during the following rice season owing to the incompletely decomposed rice residues (Tang et al., 2016). In addition, tillage during the winter fallow season may increase N_2O emissions, but the extent of this is not clear. The evidence for the promotion or reduction in N_2O emissions from rice fields by soil tillage is contradictory. For example, tillage changed the soil properties (soil porosity and soil moisture, etc.) and then promoted N_2O emissions (Mutegi et al., 2010; Pandey et al., 2012), whereas incorporation of rice residues by tillage reduced N_2O emissions as a result of N immobilization (Huang et al., 2004; Ma et al., 2010). A possible mitigating strategy that includes crop residues plowed into the soil along with drainage in the winter fallow season has been proposed for a double-rice field (Shang et al., 2011). Nevertheless, the mitigation potential of drainage combined with tillage in the winter fallow season on annual CH_4 and N_2O emissions from double-rice fields remains unclear.

An in situ field measurement was conducted continuously for 4 years (2010 to 2014) to study the CH_4 and N_2O emissions from a typical double-rice field in China. The objectives were to (1) investigate the effects of soil drainage and tillage during the winter fallow season on CH_4 and N_2O emissions, (2) estimate the mitigation potential of drainage and tillage, and (3) suggest optimal land management strategies during the winter fallow season for reducing GWPs of CH_4 and N_2O emissions.

2 Methods and materials

2.1 Field site and experimental design

The experimental field is located at Yujiang Town, Yingtan City, Jiangxi Province, China (28°15′ N, 116°55′ E). The region has a typical subtropical monsoon climate with an annual mean temperature of 18 °C and an annual mean precipitation of 1800 mm. Prior to the experiment, the field was cultivated with early rice from April to July and late rice from July to November, and then kept fallow until spring planting. The soil type at the experimental field is classified as Typic Haplaquepts (Soil Survey Staff, 1975). The initial properties of the soil (at 0–15 cm) were pH (H_2O) 4.74, organic carbon (SOC) 17.0 g kg^{-1}, and total N 1.66 g kg^{-1}. Daily air temperature (°C) and rainfall (mm) throughout the entire observational period were provided by the Red Soil Ecological Experiment Station, Chinese Academy of Sciences (Supplement Fig. S1).

Four treatments, laid out in a randomized block design with three replicates, were conducted in the experimental field from 2010 to 2014 after late-rice harvest: NTND plots were neither drained nor tilled during the entire winter fallow season. This is the traditional winter land management in the region. NTD plots had drainage but were not tilled. TND plots were tilled but not drained. TD plots were both drained and tilled. Rice stubble in all treatments was 25–35 cm long and 3.0–4.0 t ha^{-1} during the four winter fallow seasons. After the entire winter fallow season in 2012 and 2013, a small sample of rice stubble was collected before early-rice transplanting and the total C and N contents were measured using the wet oxidation–redox titration method and the micro-Kjeldahl method, respectively (Lu, 2000). Soil water content in the winter fallow season was determined gravimetrically after drying at 105 °C for 8 h.

Local rice (*Oryza sativa* L.) cultivars, Zhongzao 33 and Nongxiang 98, were planted in the following early-rice and late-rice seasons, respectively. Seeds were sown in the seedling nursery and then transplanted to the experimental plots at the third to fourth leaf stage. Each season, nitrogen (N) and potassium (K) fertilization in the form of urea and potassium chloride (KCl) were split into three applications, namely, basal fertilizers consisting of $90\,kg\,N\,ha^{-1}$ and $45\,kg\,K\,ha^{-1}$, tillering fertilizers consisting of $54\,kg\,N\,ha^{-1}$ and $60\,kg\,K\,ha^{-1}$, and panicle initiation fertilizers consisting of $36\,kg\,N\,ha^{-1}$ and $45\,kg\,K\,ha^{-1}$. Phosphorus (P) fertilization in the form of phosphorus pentoxide (P_2O_5) was applied to all treatments as a basal fertilizer at a rate of $75\,kg\,P\,ha^{-1}$. After early-rice harvest, rice straw and stubble were removed from the plots. A more detailed description of the water management and fertilization in early- and late-rice seasons is provided in Supplement Table S1.

2.2 CH_4 and N_2O fluxes sampling and measurements

Both CH_4 and N_2O fluxes were measured once every 2–6 and 7–10 days during the rice and non-rice seasons, respectively, using the static chamber technique (Zhang et al., 2011). The flux chamber measured 0.5 × 0.5 × 1 m, and a plastic base (0.5 × 0.5 m) for the chamber was installed before initiation of the experiment. Four gas samples from each chamber were collected using 18 mL vacuum vials at 15 min intervals. Soil temperature and soil redox potential (Eh) at 0.1 m depth were simultaneously measured during gas collection. Rice grain yields were determined in each plot at early- and late-rice harvests.

The concentrations of CH_4 and N_2O were analyzed with a gas chromatograph equipped with a flame ionization detector (Shimadzu GC-12A, Shimadzu Co., Japan) and with an electron capture detector (Shimadzu GC-14B, Shimadzu Co., Japan), respectively. Both the emission fluxes were calculated from the linear increase of gas concentration at each sampling time (0, 15, 30 and 45 min during the interval of chamber closure) and adjusted for area and volume of the chamber. Sample sets were rejected unless they yielded a linear regression value of $r^2 > 0.90$. The amounts of CH_4 and N_2O emissions were calculated by successive linear interpolation of mean CH_4 and N_2O emissions on the sampling days. This assumed that CH_4 and N_2O emissions followed a linear trend during the periods when no samples were taken.

2.3 GWPs and greenhouse gas intensity estimates

The 100-year GWPs (CH_4 and N_2O) in different treatments were calculated by using IPCC factors (100-year GWPs $(CH_4 + N_2O) = 28 \times CH_4 + 265 \times N_2O$) (Myhre et al., 2013). The greenhouse gas intensity (GHGI) represented the GWPs per unit rice grain yield (Li et al., 2006): GHGI = GWPs/grain yield.

2.4 Soil sampling and DNA extraction

During the 2013–2014 winter fallow and early- and late-rice seasons, soil samples were collected at the beginning, middle, and end of each season from the experimental plots and analyzed for levels of methanogens and methanotrophs. In total, there were 108 soil samples (3 seasons × 3 stages in each season × 4 treatments × 3 replicates). Each sample was a combined mixture of three subsamples collected at 0–5 cm depth. All samples were stored at 4 °C for analyses of soil characteristics, and subsamples were maintained at −80 °C for DNA extraction.

For each soil sample, genomic DNA was extracted from 0.5 g soil using a FastDNA spin kit for soil (MP Biomedicals LLC, Ohio, USA) according to the manufacturer instructions. The extracted soil DNA was dissolved in 50 µL of elution buffer, checked by electrophoresis on 1 % agarose, and then quantified using a spectrophotometer (NanoDrop Technologies, Wilmington, DE, USA) (Fan et al., 2016).

2.5 Real-time polymerase chain reaction (PCR) quantification of *mcrA* and *pmoA* genes

The abundance of methanogenic *mcrA* gene copies and of methanotrophic *pmoA* gene copies was determined by quantitative PCR (qPCR) (Fan et al., 2016). Fragments of the *mcrA* and *pmoA* genes, encoding the methyl coenzyme-M reductase and the α subunit of the particulate methane monooxygenase, respectively, were amplified using primers according to Hales et al. (1996) and Costello and Lidstrom (1999), respectively. Real-time quantitative PCR was performed on a CFX96 Optical Real-Time Detection System (Bio-Rad Laboratories, Inc. Hercules, USA). For detailed method descriptions please refer to Fan et al. (2016).

2.6 Statistical analyses

Statistical analysis was performed using SPSS 18.0 software for Windows (SPSS Inc., USA). Differences in seasonal CH_4 and N_2O emissions, 100-year GWPs (CH_4 and N_2O), and grain yields among treatments were analyzed with a repeated-measures one-way analysis of variance (ANOVA) and least significant differences (LSD) test. The significance of the factors (land management and year) was examined by using a two-way analysis of variance (ANOVA). Statistically significant differences and correlations were set at $P < 0.05$.

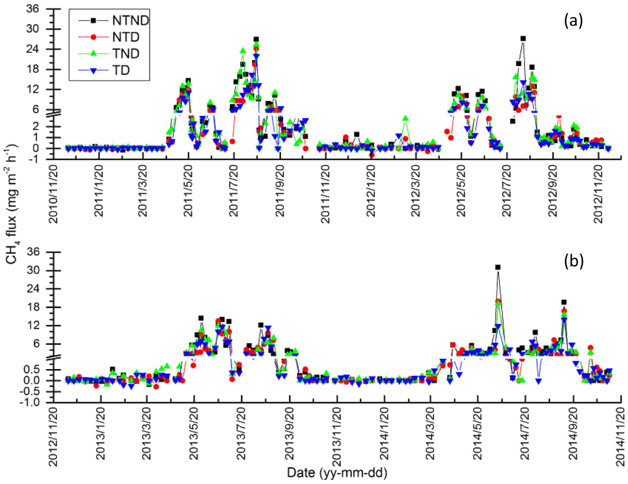

Figure 1. Seasonal variation of CH_4 emission from 2010 to 2014.

3 Results

3.1 CH_4 emission

Significant CH_4 fluxes were observed over the four winter fallow seasons, particularly during the 2011–2012 season, though a small net sink of CH_4 to the atmosphere was measured occasionally (Fig. 1). Total CH_4 emissions of the four treatments were significantly lower ($P < 0.05$) in the 2010–2011 winter fallow season ($\sim$ 0.1–1 kg CH_4 ha^{-1}) than in the following three winter fallow seasons ($\sim$ 1–11 kg CH_4 ha^{-1}), and they ranged from 1.73 to 4.91 kg CH_4 ha^{-1} on average (Table 1). Seasonal CH_4 emissions varied significantly with year and land management (Table 2, $P < 0.01$). Tillage increased CH_4 emissions by 43–69 % relative to non-tillage over the four winter fallow seasons. In comparison to non-drainage, drainage reduced CH_4 emissions by 40–50 %. Consequently, CH_4 emissions were decreased by 14.8 % relative to treatment NTND with the combined effects of soil drainage and tillage (Table 1).

During the four early- and late-rice seasons, the CH_4 fluxes of all treatments dramatically increased under continuous flooding, and the highest CH_4 fluxes were observed about 20–30 days after rice transplanting in early-rice seasons and about 10–30 days after rice transplanting in late-rice seasons (Fig. 1). Subsequently, they sharply decreased after midseason aeration. An obvious flux peak was observed again approximately 1–2 weeks after re-flooding, particularly in the early-rice season. CH_4 emissions always showed a higher flux peak in treatment NTND than in treatment TD.

Seasonal CH_4 emissions in early-rice season varied significantly with land managements, but it was not highly influenced by year or interactions (Table 2). In contrast, total CH_4 emission significantly varied with land management and year in the late-rice season (Table 2). In comparison to treatment NTND, CH_4 emissions were decreased by soil drainage and

Table 1. Seasonal CH_4 and N_2O emissions, global warming potentials (GWPs), and rice grain yields over the 4 years from 2010 to 2014.

Year	Treatment	Winter fallow season			Early-rice season				Late-rice season			
		CH_4 emission (kg CH_4 ha^{-1})	N_2O emission (g N_2O–N ha^{-1})	GWPs (t CO_2 eq. ha^{-1})	CH_4 emission (kg CH_4 ha^{-1})	N_2O emission (g N_2O–N ha^{-1})	GWPs (t CO_2 eq. ha^{-1})	Yield (t ha^{-1})	CH_4 emission (kg CH_4 ha^{-1})	N_2O emission (g N_2O–N ha^{-1})	GWPs (t CO_2 eq. ha^{-1})	Yield (t ha^{-1})
2010–2011	TD	0.46 ± 0.02	46.4 ± 1.5	0.03 ± 0.01	61.3 ± 12.5	49.0 ± 7.2	1.74 ± 0.39	6.44 ± 0.82	133.9 ± 18.6	98.5 ± 4.3	3.79 ± 0.17	7.13 ± 0.07
	TND	1.05 ± 0.13	30.4 ± 3.1	0.04 ± 0.02	80.6 ± 2.4	46.6 ± 7.1	2.28 ± 0.06	6.29 ± 0.20	158.5 ± 28.3	67.4 ± 2.1	4.46 ± 0.40	7.33 ± 0.09
	NTD	0.11 ± 0.19	42.7 ± 5.3	0.02 ± 0.02	70.6 ± 6.1	45.3 ± 11.1	2.00 ± 0.16	6.08 ± 0.60	147.0 ± 15.6	62.8 ± 5.1	4.14 ± 0.02	6.72 ± 0.22
	NTND	0.38 ± 0.07	32.2 ± 5.1	0.02 ± 0.01	84.9 ± 14.3	38.9 ± 12.3	2.38 ± 0.29	5.82 ± 0.34	179.6 ± 26.2	44.5 ± 11.0	5.05 ± 0.15	6.83 ± 0.84
2011–2012	TD	5.06 ± 1.18	42.0 ± 1.8	0.16 ± 0.04	64.0 ± 12.5	17.7 ± 7.9	1.80 ± 0.35	6.67 ± 0.08	79.6 ± 8.8	45.2 ± 7.8	2.25 ± 0.24	6.63 ± 0.09
	TND	11.1 ± 2.51	35.1 ± 2.7	0.33 ± 0.07	90.6 ± 8.2	16.2 ± 7.2	2.54 ± 0.23	7.03 ± 0.50	103.1 ± 6.0	35.4 ± 8.0	2.90 ± 0.16	6.70 ± 0.21
	NTD	4.54 ± 0.32	27.3 ± 11.3	0.14 ± 0.04	68.1 ± 11.8	28.2 ± 6.1	1.92 ± 0.22	6.36 ± 0.36	81.0 ± 4.3	63.0 ± 9.6	2.30 ± 0.80	6.57 ± 0.35
	NTND	7.09 ± 1.08	14.1 ± 4.4	0.20 ± 0.05	107.1 ± 9.9	23.4 ± 4.8	3.01 ± 0.27	6.67 ± 0.47	126.4 ± 12.2	47.2 ± 11.0	3.56 ± 0.66	6.53 ± 0.14
2012–2013	TD	1.40 ± 0.21	88.2 ± 14.7	0.08 ± 0.02	79.7 ± 15.2	27.5 ± 4.1	2.24 ± 0.49	6.33 ± 0.50	44.3 ± 2.1	32.3 ± 3.7	1.25 ± 0.07	6.46 ± 0.41
	TND	3.75 ± 0.21	59.7 ± 18.0	0.13 ± 0.02	101.1 ± 14.8	17.7 ± 15.0	2.84 ± 0.42	6.48 ± 0.78	52.7 ± 11.1	15.3 ± 3.5	1.48 ± 0.31	6.30 ± 0.23
	NTD	0.73 ± 0.22	52.0 ± 9.1	0.04 ± 0.01	80.6 ± 9.6	36.4 ± 13.1	2.27 ± 0.27	6.05 ± 0.47	60.8 ± 11.8	38.1 ± 2.4	1.72 ± 0.34	6.27 ± 0.50
	NTND	2.11 ± 0.23	56.5 ± 13.0	0.08 ± 0.00	108.7 ± 5.8	24.1 ± 14.9	3.05 ± 0.15	6.38 ± 0.73	65.9 ± 12.9	32.3 ± 6.7	1.86 ± 0.36	6.08 ± 0.24
2013–2014	TD	2.94 ± 0.78	96.1 ± 22.9	0.12 ± 0.04	68.1 ± 7.0	76.0 ± 15.1	1.94 ± 0.29	7.07 ± 0.34	62.6 ± 4.7	49.5 ± 2.8	1.77 ± 0.14	6.64 ± 0.31
	TND	3.73 ± 0.85	44.7 ± 26.0	0.12 ± 0.08	76.2 ± 5.0	42.1 ± 8.0	2.15 ± 0.11	6.43 ± 0.60	72.1 ± 9.2	42.1 ± 12.9	2.04 ± 0.25	6.38 ± 0.47
	NTD	1.52 ± 0.48	52.0 ± 28.4	0.06 ± 0.02	88.4 ± 6.3	85.4 ± 10.9	2.51 ± 0.21	6.19 ± 0.23	70.6 ± 13.6	99.7 ± 7.5	2.02 ± 0.39	6.46 ± 0.61
	NTND	2.01 ± 0.09	42.9 ± 10.6	0.07 ± 0.04	119.7 ± 10.8	49.4 ± 13.6	3.37 ± 0.33	6.16 ± 0.36	82.2 ± 3.1	54.4 ± 9.5	2.32 ± 0.08	6.16 ± 0.12
Mean*	TD	2.47 ± 0.10bc	68.2 ± 16.4a	0.10 ± 0.02b	68.3 ± 11.4b	42.5 ± 11.2a	1.93 ± 0.32b	6.62 ± 0.25a	80.1 ± 2.7c	56.4 ± 17.4ab	2.27 ± 0.08c	6.71 ± 0.14a
	TND	4.91 ± 0.43a	42.5 ± 12.3ab	0.16 ± 0.02a	87.2 ± 13ab	30.6 ± 15.0a	2.45 ± 0.37ab	6.56 ± 0.49a	96.6 ± 8.3b	40.0 ± 4.3b	2.72 ± 0.23b	6.68 ± 0.24a
	NTD	1.73 ± 0.37c	43.5 ± 18.4ab	0.07 ± 0.00c	76.2 ± 6.9b	48.8 ± 18.1a	2.15 ± 0.19b	6.17 ± 0.27a	89.9 ± 1.2bc	65.9 ± 6.6a	2.54 ± 0.03bc	6.51 ± 0.39a
	NTND	2.90 ± 0.21b	36.4 ± 13.5b	0.10 ± 0.02b	105.1 ± 15.5a	34.0 ± 6.9a	2.96 ± 0.44a	6.26 ± 0.33a	113.5 ± 8.0a	44.6 ± 8.0b	3.20 ± 0.22a	6.40 ± 0.20a

Mean* ± SD, different letters within the same column indicate statistical differences in variables mean among treatments over the 4 years by LSD multiple range test ($P < 0.05$).

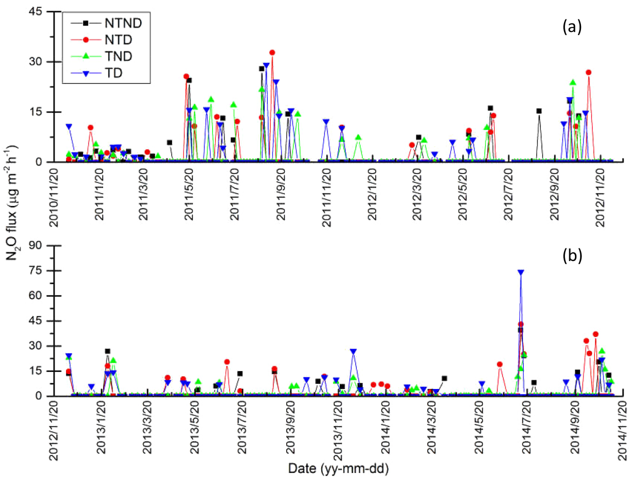

Figure 2. Seasonal variation of N_2O emission from 2010 to 2014.

tillage and, on average, reduced by 22.2 and 17.8 % in early- and late-rice seasons, respectively (Table 1). Soil drainage combined with tillage further reduced CH_4 emission by 35.0 and 29.4 % in early- and late-rice seasons, respectively. Compared to the early-rice season (68.3–105.1 kg CH_4 ha^{-1}), total CH_4 emission in the late-rice season was 8.0–17.9 % greater.

Annually, total CH_4 emission ranged from 151 to 222 kg CH_4 ha^{-1}. An average of 46.1 and 52.1 % of this came from the early- and late-rice seasons, respectively (Tables 1 and 3). Soil drainage and tillage played important roles in decreasing CH_4 emission. Relative to treatment NTND, the mean CH_4 emission was decreased by 24.3 and 14.9 % by drainage and tillage, separately, and it was significantly reduced by 32.0 % when drainage and tillage were combined (Table 3).

3.2 N_2O emission

Substantial N_2O emission was measured in the non-rice growth season though the fields were fallowed with no N-fertilization (Fig. 2 and Table 1). Total N_2O emissions over the four winter fallow seasons varied significantly with land management and year, but the interaction effect was not significant (Table 2). Seasonal N_2O emissions were relatively lower in the 2010–2012 winter fallow seasons than the following two winter fallow seasons. Compared with treatment NTND, soil drainage and tillage generally increased N_2O emissions, separately, and N_2O emissions were significantly stimulated when drainage and tillage were combined. Over the four winter fallow seasons, seasonal N_2O emissions averaged 36.4–68.2 g N_2O–N ha^{-1}, being 87.3, 64.5 and 57.5 % higher in treatment TD than in treatments NTND, TND, and NTD, respectively (Table 1).

After rice transplanting, pronounced N_2O fluxes were observed with N-fertilization and midseason aeration, particularly during the period of dry–wet alternation (Fig. 2). Two-way ANOVA analyses indicated that seasonal N_2O emissions during the early- and late-rice seasons were not highly influenced by land management, and the interactions of land management and year, except that N_2O emissions depended significantly on year (Table 2). Compared with treatments NTND and NTD, tillage increased N_2O emission in 2011 early- and late-rice seasons, whereas there were generally reduced N_2O emissions during the following rice seasons (Table 1).

Over the four early-rice seasons, drainage increased seasonal N_2O emissions by 38.9–43.5 % while tillage decreased N_2O emissions by 10–12.9 %, although the differences were not significant (Table 1). In contrast, the effects of drainage and tillage seemed to be more important over the four late-rice seasons. For instance, drainage increased seasonal N_2O emissions by 41.0–47.8 % while tillage decreased N_2O emissions by 10.3–14.4 %. Annually, total N_2O emissions ranged from 113 to 167 g N_2O–N ha^{-1}. An average of 34.4 % of this was derived from the winter fallow season (Tables 1 and 3). There was no significant difference in total N_2O emission among the four treatments (Table 3).

3.3 Global warming potential (GWP)

Throughout the four winter fallow seasons, soil drainage and tillage had important effects on GWPs (CH_4 and N_2O) over the 100-year time, although it was, on average, very small, ranging from 0.07 to 0.16 t CO_2 eq. ha^{-1} yr^{-1} (Table 1). Compared with treatment NTND, drainage significantly decreased GWPs while tillage significantly increased it. Consequently, soil drainage combined with tillage played a rather slight role in GWPs relative to treatment NTND.

In contrast, both soil drainage and tillage decreased GWPs in compared to treatment NTND over the four early-rice seasons, with 16.0–36.2 and 4.2–36.2 % lower values in treatment NTD and treatment TND, respectively (Table 1). GWPs were more decreased by drainage combined with tillage, being 26.6–42.4 % lower in treatment TD, than in treatment NTND. Drainage significantly reduced GWPs by 27.4 % for treatment NTD, and 34.8 % for treatment TD that had the integrated effect of drainage and tillage relative to treatment NTND. Tillage also tended to decrease GWPs relative to treatment NTND, but this effect was not statistically significant.

Similar effects of soil drainage and tillage on GWPs were observed over the four late-rice seasons (Table 1). Compared with treatment NTND, GWPs were 7.5–35.4 and 11.7–20.4 % lower in treatments NTD and TND, respectively. Soil drainage combined with tillage significantly decreased GWPs by 23.7–36.8 % for treatment TD in comparison to treatment NTND. On average, drainage and tillage reduced GWPs by 20.6 and 15 %, separately, and GWPs were significantly reduced (29.1 %) by combining drainage with tillage simultaneously.

Table 2. Two-way ANOVA for the effects of land management (L) and year (Y) on CH_4, N_2O emissions, and rice grain yields.

			CH_4 (kg CH_4 ha^{-1})			N_2O (g N_2O–N ha^{-1})			Yield (t ha^{-1})		
Season	Factors	d*f*	ss	*F*	*P*	ss	*F*	*P*	ss	*F*	*P*
Early-rice	L	3	3052.7	5.196	0.005	820.1	1.007	0.403	0.603	2.361	0.090
	Y	3	692.3	1.178	0.333	4357.4	5.349	0.004	0.598	3.340	0.092
	L × Y	9	254.2	0.433	0.907	267.0	0.328	0.959	0.161	0.631	0.762
	Model	15	901.5	1.535	0.151	1195.7	1.468	0.176	0.337	1.319	0.248
	Error	32	587.5			814.7			0.256		
Late-rice	L	3	2379.4	4.700	0.008	1635.2	1.528	0.226	0.259	1.522	0.228
	Y	3	22545.7	44.534	0.000	3515.8	3.286	0.033	1.193	7.015	0.001
	L × Y	9	223.0	0.440	0.903	826.9	0.806	0.614	0.057	0.338	0.955
	Model	15	5118.8	10.111	0.000	1547.9	1.447	0.185	0.325	1.910	0.061
	Error	32	506.3			1070.0			0.170		
Winter	L	3	21.582	5.215	0.005	2367.6	4.537	0.009			
	Y	3	86.036	20.788	0.000	3265.9	6.259	0.002			
	L × Y	9	4.020	0.971	0.481	314.4	0.603	0.785			
	Model	15	23.935	5.783	0.000	1315.4	2.521	0.014			
	Error	32	4.139			521.8					

Table 3. Mean annual CH_4 and N_2O emissions, global warming potentials (GWPs) of CH_4 and N_2O emissions, rice grain yields, and greenhouse gas intensity (GHGI) over the 4 years from 2010 to 2014.

Treatment	CH_4 emission (kg CH_4 ha^{-1} yr^{-1})	N_2O emission (g N_2O–N ha^{-1} yr^{-1})	GWPs (t CO_2 eq. ha^{-1} yr^{-1})	Rice yields (t ha^{-1} yr^{-1})	GHGI (t CO_2 eq. t^{-1} yield)
TD	151 ± 10d	167 ± 28a	4.29 ± 0.27d	13.3 ± 0.3a	0.32 ± 0.02c
TND	189 ± 15b	113 ± 13a	5.33 ± 0.41b	13.2 ± 0.6a	0.40 ± 0.05b
NTD	168 ± 6cd	158 ± 27a	4.76 ± 0.17cd	12.7 ± 0.6a	0.38 ± 0.02b
NTND	222 ± 9a	115 ± 38a	6.25 ± 0.26a	12.7 ± 0.1a	0.49 ± 0.02a

Note: different letters within the same column indicate statistical differences among treatments at $P < 0.05$ level by LSD test.

Annually, the GWP average ranged from 4.29 to 6.25 t CO_2 eq. ha^{-1}, 46 and 52 % of which was derived from the early-rice and late-rice seasons, respectively (Tables 1 and 3). Compared with treatment NTND, GWPs were significantly reduced by 0.92–1.49 t CO_2 eq. ha^{-1} in treatments TND and NTD, respectively, and it was decreased much more (1.96 t CO_2 eq. ha^{-1}) in treatment TD (Table 3).

3.4 Rice grain yields

Grain yields of treatments TND and TD were generally higher than those of treatments NTND and NTD over the four annual cycles (Table 1) though the yields varied with land management and year as well as their interaction (Table 2). The average yields in treatments TND and TD were over 6.5 t ha^{-1}, which was 4.8–7.3 and 3.1–4.4 % higher than yields of treatments NTND and NTD during the early- and late-rice seasons, respectively. Annually, there was no difference in total yields among the treatments over the 4 years (Table 3). Throughout the four late-rice seasons, a positive correlation was observed between grain yields of the four treatments and the corresponding CH_4 emissions ($r = 0.733$, $P < 0.01$).

3.5 Greenhouse gas intensity (GHGI)

Annual GHGI ranged from 0.32 to 0.49 t CO_2 eq. t^{-1} yield, and it varied significantly among the treatments owing to the GWPs' strong control while annual rice yields were slightly influenced by soil drainage and tillage (Table 3). Compared to treatment NTND, drainage and tillage reduced GWPs by 23.8 and 14.7 %, thus causing GHGI to significantly decrease by 22.4 and 18.4 %, separately. As expected, soil drainage combined with tillage reduced GHGI much more, with a 34.7 % reduction relative to treatment NTND.

3.6 Precipitation, temperature, soil Eh and soil water content in winter fallow season

Over the four winter fallow seasons, total precipitation varied greatly and ranged from ∼ 400 to ∼ 750 mm during 2010–2012. Subsequently, it was relatively stable at ∼ 600 mm in 2012–2014 (Table 4). In contrast, mean daily air temperature

Table 4. Total precipitation, mean daily temperature, mean* soil Eh, CH_4, and N_2O fluxes over the four winter fallow seasons.

Winter fallow season	Precipitation (mm)	Temperature (°C)	Soil Eh (mV)	CH_4 flux ($mg\,CH_4\,m^{-2}\,h^{-1}$)	N_2O flux ($\mu g\,N_2O–N\,m^{-2}\,h^{-1}$)
2010 (2 Dec 2010 to 15 Apr 2011)	404	9.1	152 ± 11	0.02 ± 0.01	5.01 ± 0.26
2011 (3 Nov 2011 to 19 Apr 2012)	754	10.0	102 ± 13	0.18 ± 0.08	3.11 ± 0.31
2012 (5 Dec 2012 to 15 Apr 2013)	574	9.7	141 ± 34	0.07 ± 0.04	8.41 ± 0.54
2013 (11 Nov 2013 to 5 Apr 2014)	661	9.4	92 ± 12	0.08 ± 0.03	7.06 ± 0.38

Note: *mean soil Eh, CH_4, and N_2O fluxes were the average of 4 treatments.

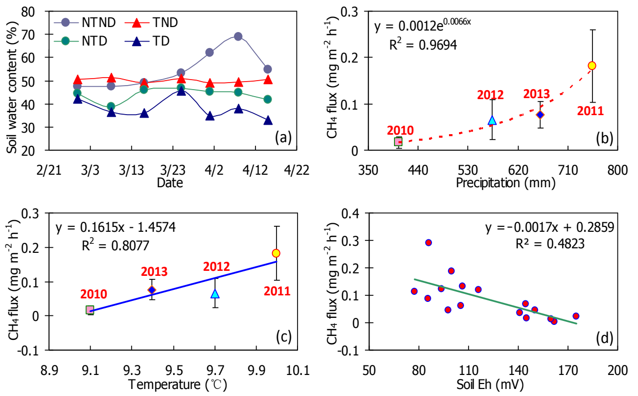

Figure 3. Soil water content in the 2010 winter fallow season **(a)** and the relationships between mean CH_4 emission and total winter precipitation **(b)**, and mean daily air temperature **(c)** and soil Eh **(d)** over the four winter fallow seasons (data from Table 4).

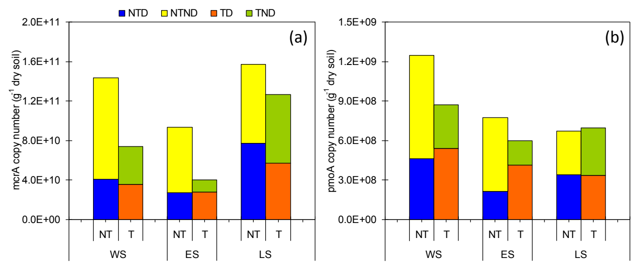

Figure 4. The abundance of methanogen and methanotroph populations in paddy soil from 2013 to 2014. WS, ES, and LS mean winter fallow season, early-rice season, and late-rice season, respectively.

varied little, with values of ca. 9.0 to 10.0 °C. Soil Eh, on average, fluctuated greatly from highest values (∼ 150 mV) in 2010–2011 to the lowest values (∼ 90 mV) in 2013–2014. Soil water content in the 2010 winter fallow season was higher in treatment NTND than in treatments NTD and TND, and lowest in treatment TD (Fig. 3a), with mean values of 55, 50, 44, and 38 %, respectively. We found that the higher the precipitation and temperature, the lower the soil Eh, and thus the greater the CH_4 emission in the winter fallow season (Table 4). Statistical analyses showed that a significant exponential relationship existed between mean CH_4 emission and total precipitation (Fig. 3b, $P < 0.01$), and mean CH_4 emission was positively correlated with mean temperature (Fig. 3c, $P < 0.05$) and negatively correlated with soil Eh (Fig. 3d, $P < 0.01$).

3.7 Abundance of methanogen and methanotroph populations

The level of methanogens in paddy soil decreased significantly from the winter fallow season to the following early-rice season, but it increased again during the late-rice season (Fig. 4a). Compared to non-drainage (treatments NTND and TND), the drainage (treatments NTD and TD) generally decreased the level of methanogens throughout the winter fallow (Fig. 4a, $P < 0.001$) and following early- and late-rice seasons (Fig. 4a, $P < 0.05$). Relative to non-tillage treatments (NTND and NTD), tillage treatments (TND and TD) also significantly decreased the abundance of methanogens throughout the winter fallow and following early- and late-rice seasons (Fig. 4a, $P < 0.001$).

The abundance of methanotrophs was highest in the winter fallow season, and then it gradually decreased (Fig. 4b). Drainage treatments (NTD and TD) relative to non-drainage treatments (NTND and TND) significantly decreased the abundance of methanotrophs over the winter fallow and early-rice seasons (Fig. 4b, $P < 0.05$) though this was not significant during the late-rice season. In addition, tillage treatments (TND and TD) significantly decreased the abundance of methanogens during the previous winter (Fig. 4b, $P < 0.001$) and following early-rice seasons (Fig. 4b, $P < 0.01$) in comparison to non-tillage treatments (NTND and NTD), except in the late-rice season.

4 Discussion

4.1 CH_4 emission from double-rice fields

In situ measurements of CH_4 emissions in China were first made from 1987 to 1989 in a double-rice field in Hangzhou City (Shangguan et al., 1993b). Subsequently, more CH_4 emissions from double-rice fields were measured (Cai et al., 2001; Shang et al., 2011). However, few investigations have made related measurements during the non-rice growth season. Fortunately, Shang et al. (2011) found that the double-rice fields in Hunan Province, China, usually acted as a small net sink of CH_4 emission (as low as $-6\,kg\,CH_4\,ha^{-1}$) in the winter fallow season. Although an occasional negative CH_4 flux was also observed over the four winter fallow seasons (Fig. 1), the double-rice field in this study was an entire source of CH_4 emission, in particular during the 2011–2012 winter fallow season (Table 1). On average, around 2 % of the annual CH_4 emission occurred during the winter fallow season.

Because of the residues (mainly roots and stubble) of early rice as well as high temperatures resulting in substantial CH_4 production in paddy fields (Shangguan et al., 1993a; Yan et al., 2005), the CH_4 emission from the late-rice season was higher than that of early-rice season. More importantly, a very high CH_4 flux peak was usually observed shortly (a few days) after late-rice transplanting (Cai et al., 2001; Shang et al., 2011). In the present study, CH_4 emission in late-rice seasons was 80.1–113.5 kg $CH_4\,ha^{-1}$, and 8.0–17.9 % greater than that of early-rice seasons (Table 1) though total CH_4 emission in the last two early-rice seasons was slightly greater than emission in the late-rice seasons (Fig. 1). Mean annual CH_4 emission varied between 151 and 222 kg $CH_4\,ha^{-1}$ over the 4 years (Table 3), which was much lower than previous results. Differences in these CH_4 measurements were probably due to different water and rice straw management practices.

Significant differences in CH_4 emission from the fields in winter fallow and late-rice seasons were observed (Table 2), indicating large changes in interannual CH_4 emission. Climatic variability may be the major factor leading to interannual variation of CH_4 emission at the macroscopic scale (Cai et al., 2009). In this study we found that total winter rainfall had an important effect on CH_4 emission. The higher the rainfall, the greater the CH_4 emission throughout the four winter fallow seasons (Table 4). An exponential relationship was observed between mean CH_4 emission and total rainfall in the winter fallow season (Fig. 3b). The importance of rainfall in controlling CH_4 emission in the winter fallow season, to some extent, was also demonstrated by the negative relationships between mean soil Eh and CH_4 emission (Fig. 3d). In different rice fields from the four main rice growing regions in China, a similar correlation was found between rainfall in the winter fallow season and CH_4 emission in the rice growth season (Kang et al., 2002).

However, we found no correlations between rainfall in the winter fallow season and CH_4 flux in early- or late-rice seasons in this study. This suggests that rainfall in the winter fallow season significantly regulated CH_4 flux on-season, but not off-season. In contrast, a significant linear relationship was found ($P < 0.01$) between CH_4 emissions and corresponding yields over the four late-rice seasons, indicating that good crop growth benefited rice yield and biomass and thus stimulated CH_4 emission. Seasonal CH_4 emission can depend greatly on the amount of rice biomass based on results from a long-term fertilizer experiment (Shang et al., 2011). Furthermore, changes in temperature over the four winter fallow seasons (Table 4) were expected to play a key role in CH_4 emission, and the positive correlation supported this expectation (Fig. 3c). Many field measurements have demonstrated the importance of temperature to CH_4 emission (Parashar et al., 1993; Cai et al., 2003; Zhang et al., 2011).

4.2 Effect of soil drainage in winter fallow season on CH_4 emission

Many measurements of CH_4 emission affected by soil drainage during the winter fallow season have been made in single-rice fields. Most of these were taken from permanently flooded fields. Clearly, drainage significantly decreases CH_4 emission (Table 5). The drainage of flooded fields inhibits CH_4 production and CH_4 emission in the winter fallow season directly, and it plays an important role in reducing CH_4 production and its emission in the subsequent rice-growing season (Zhang et al., 2011). Compared with non-drainage, drainage in this study significantly decreased CH_4 emission both in the previous winter fallow seasons and the following early- and late-rice seasons (Table 1). Over the 4-year study, mean annual CH_4 emission was reduced by 38–54 kg $CH_4\,ha^{-1}$ (Table 3). Such changes were very likely due to the decrease of methanogens in paddy soils throughout the winter and early- and late-rice seasons by soil drainage (Fig. 4a). Drainage increases soil aeration and hence effectively reduces the survival rate and activity of methane-producing bacteria. In microcosm experiments, Ma and Lu (2011) found that the total abundance of methanogenic archaeal populations decreased by 40 % after multiple drainages, and quantitative PCR analysis showed that both *mcrA* gene copies and *mcrA* transcripts significantly decreased after dry–wet alternation (Ma et al., 2012).

4.3 Effect of soil tillage in the winter fallow season on CH_4 emission

Although CH_4 emission in the winter fallow season was increased by soil tillage, it was significantly reduced during the following early- and late-rice seasons (Table 1), and over the 4 years, on average, it was reduced by 17–33 kg $CH_4\,ha^{-1}\,yr^{-1}$ (Table 3). Compared to non-tillage, tillage promotes the decomposition of rice residues, which stimulates CH_4 production and emission in the winter fallow season. By contrast, as the readily decomposable portion of the residues has largely been decomposed after an entire winter fallow season, the remaining less-decomposable part of organic matter has little effect on promoting CH_4 emission the following year (Watanabe and Kimura, 1998). The total C content in rice residues generally lower in treatments TND and TD than in treatments NTND and NTD (Table 6)

Table 5. Relative mitigating GWPs of GHGs emissions from paddy fields with various land management practices as compared to traditional management in the winter crop season.

Type	Traditional management	Suggested practice	GHGs	Mitigation potential[a] (%)				Reference
				WS	ES	LS	Annual	
Double rice	Winter fallow without drainage nor tillage	Drainage	CH_4 and N_2O	30	27	21	24	This study
		Tillage	CH_4 and N_2O	−60	17	15	15	
		Drainage combined with tillage	CH_4 and N_2O	0	35	29	32	
Single rice	Winter wheat with drainage	Tillage	CH_4 and N_2O	21	14		15	Zhang et al. (2015)
Single rice	Winter ryegrass with drainage	Tillage	N_2O	[b]N.m.	22		N.m.	Bayer et al. (2015)
Single rice	Winter wheat with drainage	Tillage	CH_4 and N_2O	38	N.m.		N.m.	Yao et al. (2013)
Single rice	Winter fallow and continuous flooding	Oil-seed rape with drainage and tillage	CH_4 and N_2O	4	57		43	Zhang et al. (2012)
Single rice	Winter fallow without drainage nor tillage	Drainage	CH_4	N.m.	71		> 71	Shiratori et al. (2007)
Single rice	Winter fallow with drainage but non-tillage	tillage	CH_4, N_2O, and CO_2	−21	N.m.		N.m.	Liang et al. (2007)
Single rice	Winter fallow and continuous flooding	Wheat with drainage	CH_4 and N_2O	59	55		56	Jiang et al. (2006)
		Oil-seed rape with drainage	CH_4 and N_2O	53	57		56	
Single rice	Winter fallow and continuous flooding	Wheat with drainage	CH_4	100	30		59	Cai et al. (2003)
Single rice	Winter fallow and continuous flooding	Wheat with drainage	CH_4	N.m.	68		> 68	Cai et al. (1998)

Note: WS, ES, and LS mean winter fallow season, early-rice season and late-rice season, respectively; annual is the total of winter and rice seasons. [a] Mitigation potential of combined gases was calculated on the basis of CO_2 equivalents by assuming GWPs for CH_4 and N_2O as 28 and 265 times the equivalent mass of CO_2 over a 100-year period (Myhre et al., 2013): GWPs $(CH_4 + N_2O + CO_2) = (CH_4 \times 28) + (N_2O \times 265) + (CO_2 \times 1)$. [b] N.m. indicates no measurements.

Table 6. Total C ($g\,kg^{-1}$) and total N ($g\,kg^{-1}$) contents in rice stubble before early-rice transplanting in 2012 and 2013.

Year	Treatment	Total C	Total N	C / N
2012	TD	338	6.9	49
	TND	314	7.8	40
	NTD	356	12.7	28
	NTND	374	10.4	36
2013	TD	368	8.7	42
	TND	364	7.1	51
	NTD	404	12.8	32
	NTND	397	13.4	30

has well demonstrated that tillage decreased the carbon substrates necessary for methanogenesis. In a rice–wheat rotation system, our field measurements also showed that the carbon content of rice straw incorporated into the soil in the winter fallow season decreased sharply compared to straw applied to the field just prior to rice transplanting (Zhang et al., 2015). In addition, tillage substantially reduced the abundance of methanogens throughout the winter and early- and late-rice seasons (Fig. 4a), which helps to explain the decreased CH_4 emission.

4.4 N_2O emission from double-rice paddy fields

Direct N_2O emission from rice-based ecosystems mainly happens during midseason aeration and subsequent dry–wet alternation in the rice-growing season and in the winter crop or winter fallow season (Cai et al., 1997; Yan et al., 2003; Zheng et al., 2004; Ma et al., 2013). Most cropland N_2O emission comes from uplands, and just 20–25 % of this is from rice fields in China (Zhang et al., 2014). In China, field measurements of N_2O emission began in 1992 from a single-rice field in Liaoning Province (Chen et al., 1995). Considerable observations have since been made from double-rice fields (Xu et al., 1997; Shang et al., 2011; Zhang et al., 2013). The total N_2O emission of early- and late-rice seasons in this study, on average, ranged from 70.6 and 114.7 $g\,N_2O\text{–}N\,ha^{-1}\,yr^{-1}$ over the 4 years (Table 1), and these data were significantly lower than values reported by Shang et al. (2011) and Zhang et al. (2013) but similar to our previous measurements (Ma et al., 2013). Furthermore, over 33 % of annual N_2O emission came from the winter fallow season (Table 1), indicating that N_2O emission from paddy fields in the winter fallow season is very important. Earlier field observations showed that as high as 60–90 % of N_2O annual emission occurred in the winter fallow season (Shang et al., 2011). On a national scale in China, 41 $Gg\,N_2O\text{–}N\,yr^{-1}$ is emitted in the non-rice growth period, and this constitutes 45 % of the total N_2O emission from rice-based ecosystems (Zheng et al., 2004). Although N_2O emission from rice fields was significantly affected by year (Table 2), reasons for the between-year variation are poorly known. In order to understand yearly changes in N_2O emission, it is essential to maintain year-round long-term stationary field observations of N_2O emission from the double-rice fields.

4.5 Effect of soil drainage in winter fallow season on N_2O emission

The production of soil N_2O is mainly achieved by the microbial processes of nitrification and denitrification while soil water content determines the general direction of soil nitrogen transformation. Soil drainage can reduce the soil water content and accelerate soil dry–wet alternation, thus promoting N_2O emission from paddy fields (Davidson, 1992; Cai et al., 1997). The soil dry–wet alternation stimulates the transformation of C and N in the soil, in particular the microbial biomass C and N turnover (Potthoff et al., 2001). Drainage typically decreased the soil water content in this study (Fig. 3a) and then increased N_2O emission, on average, by 42 % relative to non-drainage in the winter fallow season (Table 1). Drainage in the previous winter fallow season also had a positive effect on N_2O emission from paddy fields during the following early- and late-rice seasons (Table 1). It is possible that drainage in the winter fallow season created soil moisture more beneficial to N_2O production in the subsequent rice-growing seasons. Early reports demonstrated that the production and emission of soil N_2O was related to the soil moisture regime at the time and also strongly affected by the previous soil moisture regime (Groffman and Tiedje, 1988). Regardless of how the water conditions were at an earlier time, the previous soil moisture conditions affected the concentration of reductase or synthetic ability of the enzymes, thus affecting denitrification (Dendooven and Anderson, 1995; Dendooven et al., 1996). The annual total N_2O emission increased by 37–48 % in drainage treatments compared to non-drainage treatments though there was no significant difference among the four treatments (Table 3).

4.6 Effect of soil tillage in winter fallow season on N_2O emission

Compared to non-tillage, tillage treatments increased N_2O emission in the winter fallow season by an average of 39 % over the 4 years (Table 1). At least two factors help to explain this. First, tillage increases soil aeration, which promotes the nitrification process. A soil column experiment demonstrated that moderate O_2 concentration is conducive to N_2O production (Khdyer and Cho, 1983). Second, tillage accelerates rainwater percolation from the plowed layer into the subsoil layer, stimulating the processes of soil dry–wet alternation and thus promoting the transformation of N and production of N_2O in the soil (Cai et al., 1997; Potthoff et al., 2001). Tillage usually decreased soil water content (Fig. 3a), and this supports the second point. In contrast, tillage had negative effects on N_2O emission during the following early- and late-rice seasons, and mean N_2O emission over the 4 years was reduced by 12 and 13 %, respectively (Table 1). Compared to non-tillage, tillage decreased the level of total N in rice residues, which probably reduced the substrates needed for nitrification and denitrification. More importantly, the ratio of C / N in rice residues was increased by tillage (Table 6). The decomposition of rice residues with a high C / N ratio probably resulted in more N immobilization in the soil and less N available for nitrification and denitrification for N_2O production (Huang et al., 2004; Zou et al., 2005). As a whole, however, soil tillage played a relatively minor role in annual N_2O emission over the 4 years (Table 3).

4.7 Effect of soil drainage and tillage on GWPs and GHGI

Although drainage increased N_2O emission throughout the winter fallow and early- and late-rice seasons, it significantly decreased CH_4 emission from paddy fields (Table 1). As a consequence, it greatly reduced GWPs, with a decrease of 1.49 t CO_2 eq. ha^{-1} annually (Table 3). Many studies have demonstrated that drainage results in a trade-off between CH_4 and N_2O emissions from rice fields (Table 5), but drainage is widely considered to be an effective mitigation option. Annually, the mitigation potential of GWPs from paddy fields using drainage in the winter fallow season is > 50 %. However, these measurements are mostly related to single-rice fields with continuous flooding (Table 5), and little information is available about the effect on GWPs from double rice-cropping systems. In this study, we found that 21–30 % of the GWPs were reduced by drainage in the winter fallow season throughout the previous winter fallow and following early- and late-rice seasons, and there is a 24 % annual mitigation potential (Table 3).

In contrast, tillage clearly increased both CH_4 and N_2O emissions and highly increased GWPs in the winter fallow season (Table 1). Indeed, in a single-rice field, Liang et al. (2007) found that it increased the GWPs of CH_4, N_2O, and CO_2 emissions in the winter fallow season (Table 5). Fortunately, tillage significantly decreased CH_4 and N_2O emissions both in early- and late-rice seasons and, as a result, it reduced GWPs by 17 and 15 %, respectively (Table 1). Annually, GWPs were reduced by 0.92 t CO_2 eq. ha^{-1}, with 15 % of mitigation potential (Table 3). As expected, the integrated effects of soil drainage and tillage decreased GWPs much more, with a further reduction by 1.04 t CO_2 eq. ha^{-1} yr^{-1}. Moreover, the annual mitigation potential (as high as 32 %) of soil drainage combined with tillage in this study was in the range of previous results reported by Zhang et al. (2012) and Zhang et al. (2015) in single-rice fields (Table 5). It is obvious that soil drainage together with tillage in the winter fallow season is an effective option for mitigating the GWPs of CH_4 and N_2O emissions from double rice-cropping systems.

No significant differences in rice grain yields were observed among the four treatments over the 4 years (Tables 1 and 3). This indicates a low risk of rice yield loss when the GWPs of CH_4 and N_2O emissions are decreased by means of soil drainage or tillage in the winter fallow season. Soil drainage and tillage significantly decreased GHGI by 22.4 and 18.4 %, separately, and the GHGI was decreased much more by combining drainage with tillage, with a reduction of 0.17 t CO_2 eq. t^{-1} yield (Table 3). Balanced fertilizer management, in particular on P fertilizer supplement, was suggested as an available strategy for double rice-cropping systems (Shang et al., 2011). In this study, the effective mitigation option in double-rice fields we propose is soil drainage combined with tillage in the winter fallow season.

In conclusion, this study demonstrated that in the winter fallow season large differences in CH_4 emissions are probably due to variation in total precipitation and temperature. Soil drainage and tillage, either separately or in combination, during the winter fallow season significantly decreased CH_4 emission and the GWPs of CH_4 and N_2O emissions from the double-rice field. A possible explanation for this phenomenon is that drainage and tillage decreased the abundance of methanogens in the paddy soil. Low total C content in rice residues due to tillage and subsequent decomposition is a potential reason for reduced CH_4 emission in the following early- and late-rice seasons. Finally, tillage reduced the total N content, but increased the C / N ratio in rice residues would help decrease N_2O emissions. For achieving both high rice grain yield and low GWPs in double-rice fields, we propose that the fields be drained immediately after late-rice harvest and tilled with rice residues incorporated into the soil. These practices can aid in the development of optimal management strategies for double-rice systems.

5 Data availability

Data used in this article can be provided upon request by e-mail to the corresponding author, Hua Xu (hxu@issas.ac.cn), or the first author, Guangbin Zhang (gbzhang@issas.ac.cn).

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