Drainage and tillage practices in the winter fallow season mitigate global warming potential of CH_4 and NO_2 emissions from a double-rice field in China

Guangbin Zhang[1], Haiyang Yu[1,2], Xianfang Fan[1,2], Yuting Yang[1,2], Jing Ma[1], and Hua Xu[1]

[1] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China

[2] University of Chinese Academy of Sciences, Beijing 100049, China

Correspondence to: Hua Xu (hxu@issas.ac.cn)

Abstract. Traditional land managements (neither drainage normanagement (no tillage, no drainage, NTND) induring the winter fallow season resultresults in substantial CH_4 and N_2O emissions from the double-rice fields in China. For investigatingA field experiment was conducted to investigate the effects of drainage and tillage induring the winter fallow season on global warming potentials (GWPs) of CH_4 and N_2O emissions and developingto develop mitigation options, a field. The experiment withhad four treatments: NTND, NTD (drainage but nonno-tillage (NTD),), TND (tillage but nonno-drainage (TND),, and TD (both drainage and tillage (TD) were carried out). The study was conducted from 2010 to 2014 in a Chinese double-rice field. InDuring winter fallow season, total precipitation and mean daily temperature had important effects on CH_4 emission, and significant correlations were observed between them and significantly affected the level of CH_4 emission. Compared withto NTND, drainage and tillage reduced decreased annual CH_4 emissionemissions in early-- and late-- rice seasons and decreased annual emission by 54 and 33 kg CH_4 ha^{-1} yr^{-1}, respectively. Drainage and tillage increased N_2O emissionemissions in the winter fallow season whilebut reduced it in early-- and late-- rice seasons, causing resulting in no annual change in N_2O emission unaffected. Accordingly, the GWPs. Global Warming Potentials of CH_4 and N_2O emissions gases were decreased by 1.49 and 0.92 t CO_2-eq ha^{-1} yr^{-1}, respectively, and they were farreduced more reduced by combining drainage with tillage, withproviding a mitigation potential of 1.96 t CO_2-eq ha^{-1} yr^{-1}. LowA low total C content and high C/N ratio in rice residues revealedshowed that tillage in the winter fallow season reduced CH_4 and N_2O emissions in both early-- and late-- rice seasons. Moreover, drainageDrainage and tillage significantly decreased the abundance of methanogens in paddy soil, which was a possible reason for and this may explain the decrease of CH_4 emissionemissions. Greenhouse gas intensity was levels were significantly decreased by drainage and tillage separately, and itthe reduction

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was much more reducedgreater by combining drainage with tillage, with resulting in a reduction of 0.17 t CO_2-eq t^{-1} yield. The results indicate that soil drainage combined with tillage in TD treatment during the winter fallow season is an effective strategy for mitigating strategy ingreenhouse gas releases from double-rice fields.

1 Introduction

Methane (CH_4) and nitrous oxide (N_2O) are two of the most important greenhouse gases (GHGs) after carbon dioxide (CO_2) in the atmosphere.). According to the Greenhouse Gas Bulletin of World Meteorological Organization, the concentrations of atmospheric CH_4 and N_2O reached at 1833 and 327 ppb in 2014, respectively (WMO, 2015). PaddyRice paddy fields are considered to be the major sources of atmospheric CH_4 and N_2O. Since the 2000s, effectiveEffective options for mitigating CH_4 and N_2O emissions from rice paddy fields worldwide have been continually exploredstudied over the worldlast two decades (McCarl and Schneider, 2001; Yan et al., 2005; Hussain et al., 2015), i.e.. Ideas have included modifying irrigation and fertilization patterns (Cai et al., 2003; Hussain et al., 2015; Linquist et al., 2015), settingestablishing integrated soil–crop system management practices (Zhang et al., 2013; Chen et al., 2014), and selection of suitable rice cultivarcultivars with high productionyields but low GHGs emissions (Ma et al., 2010; Hussain et al., 2015; Su et al., 2015), etc. Nevertheless, other potential mitigatingmitigation methods might be still availableuseful due to the diversity of rice-based ecosystems and the difference invariety 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 wereare 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 rice cultivation area (Yearbook, 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 distribute at theoccur south of the Yangtze River where usually has relative large relatively high precipitation and high temperature in warm temperatures occur during the winter fallow season. Traditionally, the fields are fallow in winter season with the soil being neither drainagedrained nor tillagetilled after the late-rice harvest, and they. The fields, which are usually subjected to visible floodwateroften flooded after a heavy or a long-time raining. It is very likely to bring about CH_4 emissions from emissions occur in these fields induring the winter fallow season and further to promote its

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emissionalso during the following early rice growth season. Modeling data had shownshows that CH_4 emission waslevels were significantly correlated with simulated soil moisture and mean precipitation ofduring the preceding non-rice growth season (Kang et al., 2002). Incubation and pot experiments also affirmedshowed that the higher thehigh soil water contentscontent in the non-rice growth season, the higher the was associated with high CH_4 production rates and the more thegreater CH_4 emissions in the subsequent rice season (Xu et al., 2003). An available mitigatingmitigation option is hence proposed infor this region, that is, the fields are. Fields can be drained to decrease the accumulation of rainwater in the winter fallow season and finally to attenuatereduce the positive effect of winter precipitation on CH_4 emission. However, drainage possibly stimulatescan stimulate N_2O emission from paddy fieldfields in winter fallow season because soil water content changescan change more quickly and intensively. It is well recognized that soilrapidly. 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 potentialspotential (GWPs) of the rice ecosystem, the effecteffects of soil drainage in the winter fallow season on mitigating the yearly GWPs year-round from the double-rice fieldfields is not well understoodunclear.

Soil tillage is a conventional practice in rice cultivation, and considerable reports have shown that tilling the soil prior to rice transplanting playscan play a key role in CH_4 and N_2O emissions (Hussain et al., 2015; Zhao et al., 2016). Meanwhile, tillageTillage after rice harvest in the winter fallow season probably has very is also likely to have important effects on CH_4 and N_2O emissions. Firstly, itIt is beneficial for the rainwater to penetrate into the subsoil, which won’t lead to the because this minimizes rainwater accumulation of rainwater in winter fallow season. It is then . However, tillage makes it difficult to form theestablish a strict anaerobic environmentsenvironment in the top soil, which not only reduces CH_4 emissionwould directly reduce CH_4 emissions during the non-rice growing season, but also and indirectly inhibitsinhibit CH_4 emissionemissions during the following spring rice season. On the contrary, tillage makes Tillage allowsallows rice residues fullyto contact with the soil, and microorganism, which maysoil microorganisms accelerate the decomposition of organic mattersmatter and then in favor offacilitate CH_4 production and emission in the non-rice growthfallow season (Pandey et al., 2012; Hussain et al., 2015). Secondly, itTillage 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 induring the winter fallow season whether increasesmay increase N_2O emission fromemissions but the field orextent of this is

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not is still not very clear. There are some contradictive lines of The evidence assertingfor the promotion andor reduction in N_2O emissions from rice fields by soil tillage is contradictory. For instanceexample, tillage changeschanged the soil properties (soil porosity and soil moisture, etc.) and then promotespromoted N_2O emissionemissions (Mutegi et al., 2010; Pandey et al., 2012) whereas incorporation of rice residues due toby tillage may reducereduced N_2O emissionemissions as a result of N immobilization (Huang et al., 2004; Ma et al., 2010). Based on 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 3-yeardouble-rice field measurement (Shang et al., 2011), the possible agricultural mitigating strategy that is crop residues incorporated into the soil accompanying with drainage in winter fallow season, has been proposed in a double-rice field.. Nevertheless, the effects mitigation potential of drainage combined with tillage in the winter fallow season on annual CH_4 and N_2O emissions from double-rice fields, in particular on the corresponding mitigation potential are scarcely documented remains unclear.

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An *in situ* field measurementstudy was conducted year-roundcontinuously for 4 years from (2010 to 2014) to study the CH_4 and N_2O emissions from a typical double-rice field in China. The study objectives of this study arewere to: (1) to investigate the effects of soil drainage and tillage induring the winter fallow season on CH_4 and N_2O emissions from the paddy field, (2) to, (2) estimate the mitigation potential of drainage and tillage, and thereby (3) to suggest the optimal land management strategies induring the winter fallow season for reducing GWPs of CH_4 and N_2O emissions in the double rice-cropping systems in China.

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 about 18 ℃ and an annual mean precipitation of about 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 in fallow for the rest of yearuntil spring planting. The soil type at the experimental field is classified as Typical Haplaquepts (Soil Survey Staff 1975). The initial properties (0–15 cm) of the soil are(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 (℃) and rainfall (mm) throughout the wholeentire observational period was provided by the Red Soil Ecological Experiment Station, Chinese Academy of Sciences (Appendix S1).

Four treatments, laid out in a randomized block design in triplicatewith three replicates, were conducted in the experimental field from 2010 to 2014 after late-rice harvest from 2010 to 2014: (1) the: NTND plots were neither drainagedrained nor tillage intilled during the wholeentire winter fallow season as Treatment NTND, which. This is the traditional winter land management in the local region; (2) the.   NTD plots werehad drainage but non-tillage as Treatment NTD; (3) thewere not tilled. TND plots were tillagetilled but non-drainage as Treatment TND; (4) and thenot drained. TD plots were drainage and tillage simultaneously as Treatment TDboth drained and tilled. Rice stubble in all treatments was around 25–35 cm long, about and 3.0–4.0 t ha^{-1} during the 4 winter fallow seasons, respectively. UndergoneAfter the wholeentire winter fallow season in 2012 and 2013, a small portionsample of rice stubble was collected before early-rice transplanting in 2012 and 2013, and the total C and N contents were measured byusing 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 ℃ for 8 hhr.

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Local rice (*Oryza sativa L.*) cultivars, Zhongzao 33 and Nongxiang 98, were planted forin the following early-rice and late-rice seasons, respectively. The seedsSeeds were sown in the seedling nursery and then transplanted intoto the experimental plots at theirthe 3- to 4- leaf stage. Each season, nitrogen (N) and potassium (K) fertilizationsfertilization in 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 form of phosphorus pentoxide (P_2O_5) was applied to all the treatments as a basal fertilizer at a rate of 75 kg P ha^{-1}. After early-rice harvest, rice straw and stubble were all moved out ofremoved from the plots, and. A more detailed descriptions aboutdescription of the water management and fertilization in early- and late-rice seasons are givenis provided in Appendix S2.

2.2 CH_4 and N_2O fluxes sampling and measurements

Both CH_4 and N_2O fluxes were measured once every 2–6 d and 7–10 d during the rice and non-rice seasons, respectively, using the static chamber technique (Zhang et al., 2011). The flux chamber wasmeasured 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.

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The concentrations of CH_4 and N_2O were analyzed with a gas chromatographschromatograph 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 timeinterval 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 greater than> 0.90. The amounts of CH_4 and N_2O emissions were calculated by successive linear interpolation of averagemean CH_4 and N_2O emissions on the sampling days, assuming. This assumed that CH_4 and N_2O emissions followed a linear trend during the periods when no sample wassamples were taken.

2.3 GWPs and GHGI 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 × CH_4 + 265 × 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.

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2.4 Soil sampling and DNA extraction

During the 2013–2014 winter fallow and early- and late-rice seasons, soil samples were collected inat the beginning, middle and end of each season from the experimental plots and analyzed for analyzing the abundanceslevels of methanogens and methanotrophs. TotallyIn total, there were 108 soil samples (3 seasons × 3 stages in each season × 4 treatments × 3 replicates). Each sample was a combined mixture of 3 subsamples collected at 0–5 cm depth in triplicate and fully mixed. Subsequently, all. All samples were stored at 4 ℃ for analyses of soil characteristics and subsamples were maintained at –80 ℃ 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’smanufacturer 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).

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2.5 Real-time PCR quantification of *mcrA* and *pmoA* genes

The abundancefrequency of methanogenic *mcrA* gene copies and of methanotrophic *pmoA* genesgene 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), and for the). For detailed method descriptions please refer to our previous study (Fan et al., (2016).

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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 $P < 0.05$.

3 Results

3.1 CH_4 emission

ObviousSignificant CH_4 fluxes were observed over the 4 winter fallow seasons, particularly during the 2011–2012 winter fallow season though a small net sink of CH_4 to the atmosphere was measured occasionally (Fig. 1). Total CH_4 emissions of the 4 treatments were highlysignificantly lower ($P < 0.05$) in the 2010–2011 winter fallow season (~0.1–1 kg CH_4 ha^{-1}) than in the following three winter fallow seasons (~1–11 kg CH_4 ha^{-1}), and they were 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 field land managementsmanagement (Table 2, $P < 0.01$). Tillage increased CH_4 emissions by 43–69% relative to non-tillage over the 4 winter fallow seasons. In comparison ofto non-drainage, drainage reduced CH_4 emissions by 40–50%. Consequently, CH_4 emission wasemissions were decreased by 14.8% relative to Treatment NTND with the integratedcombined effects of soil drainage and tillage (Table 1).

During the 4 early- and late-rice seasons, the CH_4 fluxes of all treatments dramatically ascendedincreased under continuous flooding, and the highest CH_4 fluxes were observed on about 20–30 daysd after rice transplanting in early-rice seasons and about 10–30 daysd 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. Apparently, the CH_4 emissionemissions 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 impactedinfluenced by year or their interactioninteractions (Table 2). In contrast, total CH_4 emission did significantly varyvaried with land managementsmanagement and year in the late-rice season (Table 2). In comparison ofto Treatment NTND, CH_4 emission wasemissions were decreased by soil drainage and 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 withto 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 was ranged from 151 to 222 kg CH_4 ha^{-1}, averaged . An average of 46.1% and 52.1% of whichthis 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, averagedthe mean CH_4 emission was decreased by 24.3% and 14.9% by drainage and tillage, separately, and it was highlysignificantly reduced by 32.0% when drainage wasand tillage were combined with tillage simultaneously (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 4 winter fallow seasons varied significantly with land management and year while it did not significantly depended on theirbut the interaction affect 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 combined drainage withand tillage simultaneouslywere combined. Over the 4 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 induring 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 emissionemissions during the following rice seasons (Table 1).

Over the 4 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 nothe differences were not significant difference was observed (Table 1). In contrast, the effects of drainage and tillage seemed to be more important over the 4 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 emission wasemissions ranged from 113 to 167 g N_2O-N ha^{-1}, averaged . An average of 34.4% of whichthis was derived from the winter fallow season (Tables 1 and 3). There was no significant difference in total N_2O emission among the 4 treatments (Table 3).

3.3 Global warming potential (GWP)

Throughout the 4 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, beingranging 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 highlysignificantly increased it. Consequently, soil drainage combined with tillage played a slightlyrather slight role in GWPs relative to Treatment NTND.

In contrast, both soil drainage and tillage decreased GWPs in comparison ofcompared to Treatment NTND over the 4 early-rice seasons, with 16.0–36.2% and 4.2–36.2% lower values in Treatment NTD and Treatment TND, respectively (Table 1). The GWPs was hence farwere more decreased by drainage combined with tillage, being 26.6–42.4% lower in Treatment TD, than in Treatment NTND. Totally, drainageDrainage significantly reduced GWPs by 27.4% for Treatment NTD, in particular onand 34.8% for Treatment TD by 34.8% withthat had the integrated effect of drainage and tillage relative to Treatment NTND. Meanwhile, tillage 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 4 late-rice seasons (Table 1). Compared with Treatment NTND, GWPs was 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 ofto Treatment NTND. On average, drainage and tillage reduced GWPs by 20.6% and 15%, separately, and GWPs was significantly reduced (29.1%) by combining drainage with tillage simultaneously.

Annually, the GWPs averagedaverage ranged from 4.29–6.25 t CO_2-eq ha^{-1}, with 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 was 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 by (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 4 annual cycles (Table 1) though the yields slightly varied with land management and year as well as their interaction (Table 2). OnThe average, the 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 thoseyields of Treatments NTND and NTD during the early- and late-rice seasons, respectively. Annually, there was no significancedifference in the total yields was observed among the treatments over the 4 years (Table 3). Throughout the 4 late-rice seasons, a positive correlation was observed between grain yields of the 4 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 changedvaried significantly among the treatments owing to the GWPs highly controlledstrong control while annual rice yields were slightly influenced by soil drainage and tillage (Table 3). Compared withto Treatment NTND, drainage and tillage reduced GWPs by 23.8% and 14.7%, thus causing GHGI to significantly decreaseddecrease by 22.4% and 18.4%, separately. ExpectedlyaAs expected, soil drainage combined with tillage reduced GHGI much more, with a 34.7% reduction of 34.7% relative to Treatment NTND.

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

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Over the 4 winter fallow seasons, total precipitation changed remarkably, which was varied greatly and ranged from ~400 mm to ~750 mm during 2010–2012. Subsequently, it was relatively stable around at ~600 mm in 2012–2014 (Table 4). In contrast, mean daily air temperature varied slightlylittle, with values of ca. 9.0 ℃ to 10.0 ℃. Soil Eh, on average, fluctuated obviouslygreatly from the 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 generally higher in Treatment NTND than in Treatments NTD and TND, and it was lowest in Treatment TD (Fig. 3a), with a mean valuevalues of 55%, 50%, 44% and 38%, respectively. It is easy to seeWe found that the higher the precipitation and temperature, the lower the soil Eh, and thus the moregreater the CH_4 emission in the winter fallow season (Table 4). Statistical analyses showshowed that a significant exponential relationship was observedexisted between mean CH_4 emission and total precipitation (Fig. 3b, $P < 0.01$), and mean CH_4 emission was positively and negatively correlated with mean temperature (Fig. 3c, $P < 0.05$) and negatively correlated with soil Eh (Fig. 3d, $P < 0.01$), respectively.).

3.7 Abundance of methanogens and methanotrophs populations

The abundancelevel 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 withto non-drainage (Treatments NTND and TND), the drainage (Treatments NTD and TD) generally decreased the abundancelevel 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 treatments (NTND and NTD), he tillage (Treatments 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 gradually (Fig. 4b). Drainage (Treatments treatments (NTD and TD) relative to non-drainage (Treatments treatments (NTND and TND) significantly decreased the abundance of methanotrophs over the winter fallow and early-rice seasons (Fig. 4b, $P < 0.05$) though no significancethis was not significant during the late-rice season. In addition, tillage (Treatments 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 ofto non-tillage (Treatments treatments (NTND and

NTD), except in the late-rice season.

4 Discussion

4.1 CH$_4$ emission from double-rice fields

It is reported that *inIn situ* measurementmeasurements of CH$_4$ emissionemissions in China was firstly carried outwere first made from 1987 to 1989 in a double-rice field in Hangzhou City (Shangguan et al., 1993b). Subsequently, more and more CH$_4$ emissions from double-rice fields were observedmeasured (Cai et al., 2001; Shang et al., 2011). However, few investigations were referred tomade related measurements induring the non-rice growth season. Fortunately, Shang et al. (2011) found that the double-rice fields in Hunan province, China usually actingacted 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 occasionallyoccasional negative CH$_4$ flux was also observed over the 4 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 emitted fromoccurred during the winter fallow season.

Because of the residues (mainly including roots and stubble) of early rice as well as high temperaturetemperatures resulting in substantial CH$_4$ production in paddy fields (Shangguan et al., 1993a; Yan et al., 2005), the CH$_4$ emission offrom the late-rice season was generally higher than that of early-rice season. More importantly, a very high CH$_4$ flux peak was usually observed in shortly (a couple offew 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}, beingand 8.0–17.9% largergreater than that of early-rice seasons (Table 1) though total CH$_4$ emission in the last two early-rice seasons was found to be slightslightly greater than thoseemission 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 (Cai et al., 2001; Shang et al., 2011). Great differences. Differences in these CH$_4$ measurements were probably attributeddue to different water and rice straw managementsmanagement 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 the interannual CH$_4$ emission. It is believed that the climatic variation 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, and the. The higher the rainfall, the greater the CH$_4$ emission throughout the 4

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winter fallow seasons (Table 4). And anAn 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 could be demonstrated by the negative relationships between mean soil Eh and CH_4 emission (Fig. 3d). According toIn different rice fields from the 4 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)(Kang et al., 2002).

NeverthelessHowever, we did not found anyno correlations between rainfall in the winter fallow season and CH_4 flux in early-or late-rice seasonseasons in this study, suggesting. This suggests that rainfall in the winter fallow season just significantly regulated CH_4 flux on-season, but didn'tnot off-season. In contrast, a significant linear relationship was found ($P < 0.01$) between CH_4 emissions and corresponding yields over the 4 late-rice seasons, demonstratingindicating that good crop growth benefited rice yield and biomass and thus stimulated CH_4 emission. It is reported that seasonal Seasonal CH_4 emission dependedcan 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 4 winter fallow seasons (Table 4) were supposedexpected to play a key role in CH_4 emission, and the positive correlation had demonstrated supported this wellexpectation (Fig. 3c). Many field measurements have showndemonstrated 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

ConsiderableMany measurements of CH_4 emission as affected by soil drainage induring the winter fallow season have been reported from made in single-rice fields, and most. Most of whichthese were taken from the permanently flooded fields. ObviouslyClearly, drainage significantly decreases CH_4 emission (Table 5). Draining the flooded fields inhibits CH_4 production and CH_4 emission in the winter fallow season directly, and more importantly, 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), and over). Over the 4 years-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- rice season,- and late-rice seasonsseason by

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soil drainage (Fig. 4a) because drainage). Drainage increases soil aeration and hence effectively reduces the survival rate and activity of methane-producing bacteria. According toIn 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 further revealedshowed 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 highly decreasedsignificantly 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 may promotepromotes the decomposition of rice residues, and thenwhich stimulates CH_4 production and emission in the winter fallow season. By contrast, as the readily decomposable partportion of the residues has largely been decomposed after a wholean entire winter fallow season, the remaining hardlyless-decomposable part of organic matter doesn’t have muchhas little effect on promoting CH_4 emission nextthe following year (Watanabe and Kimura, 1998). The total C content of total C in rice residues was generally lower in Treatments TND and TD than in Treatments NTND and NTD (Table 6) and has well demonstrated thatand tillage decreased the carbon substrates necessary for methanogenesis. It thereforeTillage, relative to non-tillage, significantly reduced CH_4 emission (Table 3). In a rice-wheat rotation system, our 2-year field measurements also showed that the carbon content of rice straw incorporated into the soil in the winter fallow season was decreased sharply in comparisoncompared of thatstraw applied to the field just prior to rice transplanting (Zhang et al., 2015). In addition, tillage highlysubstantially reduced the abundance of methanogens throughout the winter fallow and early- and late-rice seasons (Fig. 4a) should be a probable reason for the decrease ofand this 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 in the periods ofduring 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). It is estimated that most of croplandsMost cropland N_2O emission comes from uplands and just 20–25% of whichthis is from rice fields in China (Zhang et al., 2014). In China, field measurements of N_2O emission began in 1992

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from a single-rice field in Liaoning province (Chen et al., 1995), and considerable. Considerable observations have since been made from double-rice fields had been performed (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, varied betweenranged from 70.6 and 114.7 g N_2O-N ha^{-1} yr^{-1} over the 4 years (Table 1), beingand these data were significantly lower than thosevalues reported by Shang et al. (2011) and Zhang et al. (2013) but similar to our previous measurements (Ma et al. (2013). Furthermore, over 1/333% 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 wasis very important. EarlyEarlier field observations even 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, it is found that in China, 41 Gg N_2O-N yr^{-1} is emitted in the non-rice growth period, contributingand 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 interannualbetween-year variation were still not wellare poorly known. In order to specify rules for interannual changeunderstand yearly changes in N_2O emission, it is essential to maintain all-the-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 thesoil nitrogen transformation of soil nitrogen.. Soil drainage can cut downreduce the soil water content and accelerate soil dry/-wet alternation, thus promoting N_2O emission from paddy fields (Davidson, 1992; Cai et al., 1997). It is because thatThe soil dry/-wet alternation stimulates the transformation of C and N in the soil, in particular on the microbial biomass C and N turnover (Potthoff et al., 2001). Expectedly, drainage usually 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). Noted that drainage Drainage in the previous winter fallow season also had an important positive effect on N_2O emission from paddy fields during the following rice seasons, namely, it. Drainage increased N_2O emission both in early- and late-rice seasons (Table 1). It was possibly attributed tois possible that drainage in the winter fallow season would createcreated soil moisture more beneficial to N_2O production in the subsequent rice-growing seasons. Early report had wellreports demonstrated that the production and emission of soil N_2O

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was not only related to the soil moisture regime at the time, but and also strongly affected by the previous soil moisture regime (Groffman and Tiedje, 1988). Regardless of how the water conditions were at thatan 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). Totally,The annual total N_2O emission was increased by 37–48% in drainage treatments compared drainage withto non-drainage treatments though there was no significant difference among the 4 treatments (Table 3).

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

Compared to non-tillage, tillage usuallytreatments increased N_2O emission in the winter fallow season, on by an average, by of 39% over the 4 years (Table 1), which might be ascribed to). At least two reasonsfactors help explain this. First, tillage increases soil aeration, which possibly promotes the process of nitrification process. A soil column experiment has well demonstrated that moderate O_2 concentration is conducive to N_2O production (Khdyer and Cho, 1983). Second, tillage accelerates rainwater percolation from the plowplowed layer percolating into the subsoil layer, stimulating the processes of soil dry/wet alternation and thenthus 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) could validate), and this to some extent.supports the second point. In contrast, ittillage 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 contentlevel 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). Because theThe decomposition of rice residues with a high C/N ratio probably resulted in more N immobilization in the soil and less N available tofor nitrification and denitrification for N_2O production (Huang et al., 2004; Zou et al., 2005). As a whole, however, soil tillage played a slightrelatively 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 highlygreatly

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reduced GWPs, with a decrease of 1.49 t CO_2-eq ha^{-1} annually (Table 3). ConsiderableMany studies have showeddemonstrated that drainage results in a trade-off between CH_4 and N_2O emissions from rice fields (Table 5), and itbut drainage is widely considered to be an effective mitigation option. Annually, the mitigation potential of GWPs from paddy fields byusing drainage in the winter fallow season is over> 50%. However, these measurements are mostly related to the single-rice fields with continuous flooding (Table 5), and fewlittle information areis available about the effect on GWPs from double rice-cropping systems. In this study, we found that as high as 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 withthere is a 24% ofannual mitigation potential annually (Table 3).

In contrast, tillage obviouslyclearly increased both CH_4 and N_2O emissions, thus 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, ittillage significantly decreased CH_4 and N_2O emissions both in early-and late-rice seasons, and, as a result, with a reduction ofit reduced GWPs by 17% and 15%, respectively (Table 1). Annually, the 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 rangesrange of previous results reported by Zhang et al. (2012) and Zhang et al. (2015) in single-rice fields (Table 5). It is obvious that the soil drainage together with tillage simultaneously in the winter fallow season might beis an effective option for mitigating the GWPs of CH_4 and N_2O emissions from the double rice-cropping systems.

More importantly, noNo significant differencedifferences in rice grain yields waswere observed among the 4 treatments over the 4 years (Tables 1 and 3). It suggests that we would notThis indicates a low risk of rice yield loss when we try to decrease the GWPs of CH_4 and N_2O emissions are decreased by means of soil drainage or tillage in the winter fallow season. So, soilSoil 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 yield reduction of 0.17 t CO_2-eq t^{-1} yield (Table 3). Based on a long-term fertilizer experiment, balanced Balanced fertilizer management, in particular on P fertilizer supplement, was suggested to beas an available strategy infor double rice-cropping systems (Shang et al., 2011). In this study, the effective mitigation option in double-rice fields we proposedpropose is that soil drainage

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combined with tillage in the winter fallow season.

In Conclusion, the conclusion, this study demonstrated that in the winter fallow season large differences in CH_4 emissions wereare probably due to the changesvariation in total precipitation and temperature. Soil drainage and tillage in , either separately or in combination, during the winter fallow season separately, in particular on combining both of them, significantly decreased CH_4 emission and thenthe GWPs of CH_4 and N_2O emissions from the double-rice field. OneA possible explanation for this phenomenon is that drainage and tillage decreased the abundance of methanogens in the paddy soil. Moreover, low Low total C content in rice residues due to tillage wasand subsequent decomposition is a potential reason for the decrease ofreduced 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 and this would be important to thehelp decrease of N_2O emissionemissions. For both achieving both high rice grain yield and low GWPs in double-rice fields, land management strategies in this study we proposed, includingwe propose that the fields werebe drained immediately after late-rice harvest, and meanwhile, the fields were tilled with rice residues incorporated into the soil. The results would benefitThese practices can aid in the development of optimal management strategies in thefor double-rice systems and the interpretation of the corresponding mechanisms.

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Figure captions:

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

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

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 4 winter fallow seasons (Data from Table 4).

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

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.

		Winter fallow season			Early-rice season				Late-rice season			
Year	Treatment	CH_4 emission ($kg\ CH_4\ ha^{-1}$)	N_2O emission ($g\ N_2O\text{-}N\ ha^{-1}$)	GWPs ($t\ CO_2\text{-eq}\ ha^{-1}$)	CH_4 emission ($kg\ CH_4\ ha^{-1}$)	N_2O emission ($g\ N_2O\text{-}N\ ha^{-1}$)	GWPs ($t\ CO_2\text{-eq}\ ha^{-1}$)	Yield ($t\ ha^{-1}$)	CH_4 emission ($kg\ CH_4\ ha^{-1}$)	N_2O emission ($g\ N_2O\text{-}N\ ha^{-1}$)	GWPs ($t\ CO_2\text{-eq}\ ha^{-1}$)	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 ±0.10 bc	68.2 ±16.4 a	0.10 ±0.02 b	68.3 ±11.4 b	42.5 ±11.2 a	1.93 ±0.32 b	6.62 ±0.25 a	80.1 ±2.7 c	56.4 ±17.4 ab	2.27 ±0.08 c	6.71 ±0.14 a
	TND	4.91 ±0.43 a	42.5 ±12.3 ab	0.16 ±0.02 a	87.2 ±13 ab	30.6 ±15.0 a	2.45 ±0.37 ab	6.56 ±0.49 a	96.6 ±8.3 b	40.0 ±4.3 b	2.72 ±0.23 b	6.68 ±0.24 a
	NTD	1.73 ±0.37 c	43.5 ±18.4 ab	0.07 ±0.00 c	76.2 ±6.9 b	48.8 ±18.1 a	2.15 ±0.19 b	6.17 ±0.27 a	89.9 ±1.2 bc	65.9 ±6.6 a	2.54 ±0.03 bc	6.51 ±0.39 a
	NTND	2.90 ±0.21 b	36.4 ±13.5 b	0.10 ±0.02 b	105.1 ±15.5 a	34.0 ±6.9 a	2.96 ±0.44 a	6.26 ±0.33 a	113.5 ±8.0 a	44.6 ±8.0 b	3.20 ±0.22 a	6.40 ±0.20 a

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

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

			CH_4 (kg CH_4 ha^{-1})			N_2O (g N_2O-N ha^{-1})			Yield (t ha^{-1})		
Season	Factors	df	*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					

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

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

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

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

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

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

Type	Traditional management	Suggested practice	GHGs	[a] Mitigation potential (%)				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 means 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 × 28) + (N_2O × 265) + (CO_2 × 1); [b] N.m. indicates no measurements.

Table 6 Measurements of totalTotal 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

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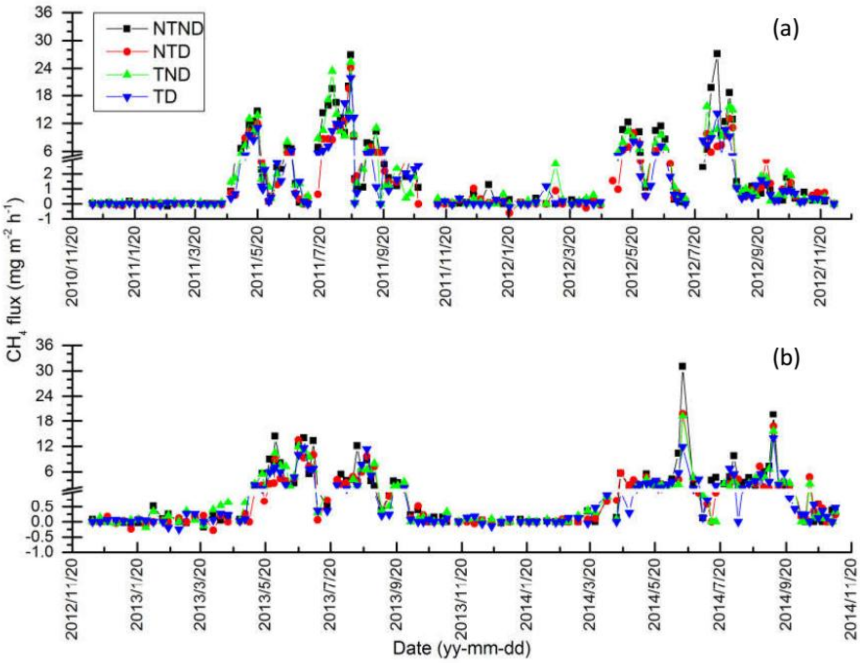


Figure 1 Seasonal variation of CH$_4$ emission from 2010 to 2014.

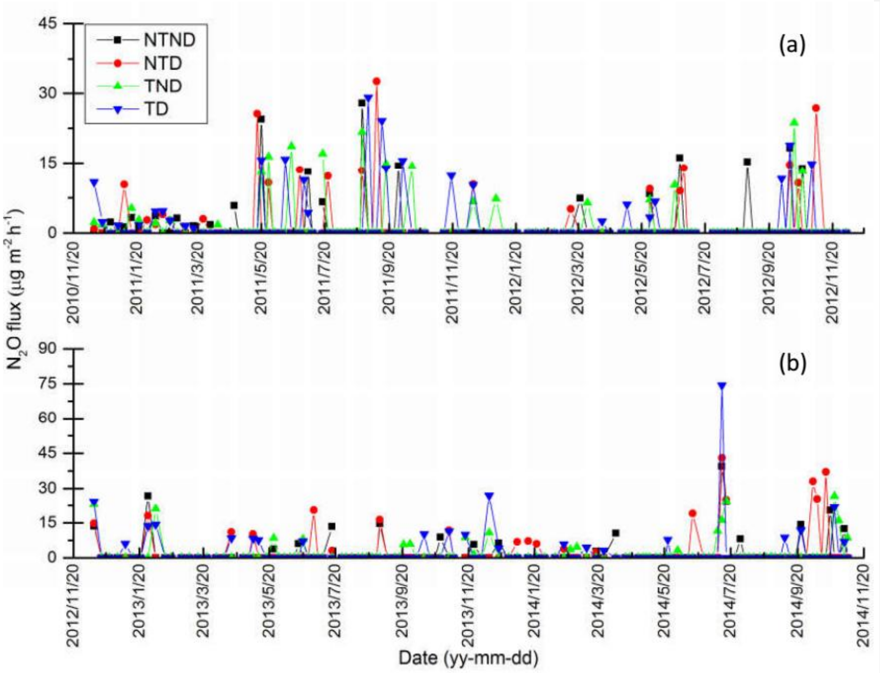


Figure 2 Seasonal variation of N_2O emission from 2010 to 2014.

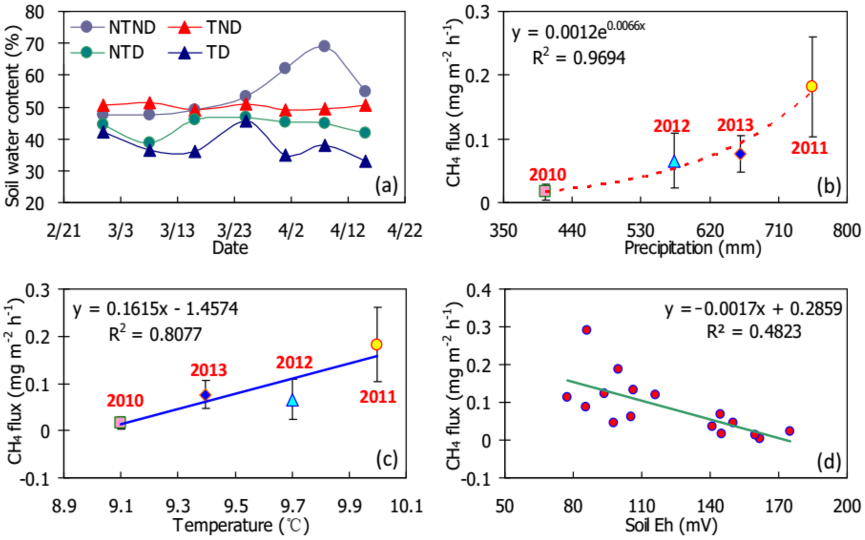


Figure 3 Soil water content in 2010 winter fallow season (a) and the relationships between mean CH_4 emission and total winter precipitation (b), and mean daily air temperature (c) and soil Eh (d) over the 4 winter fallow seasons (Data from Table 4).

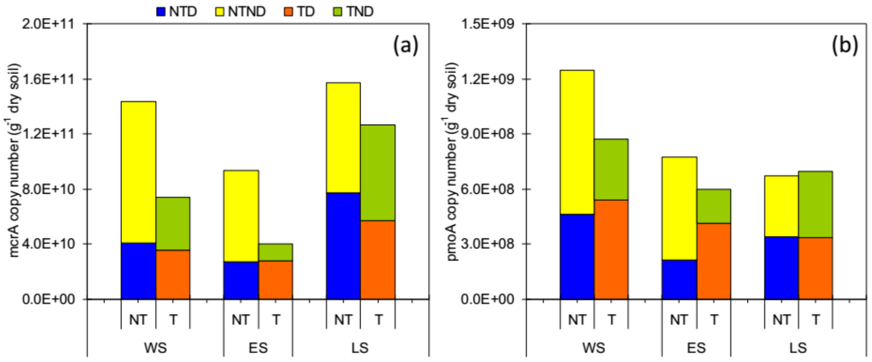
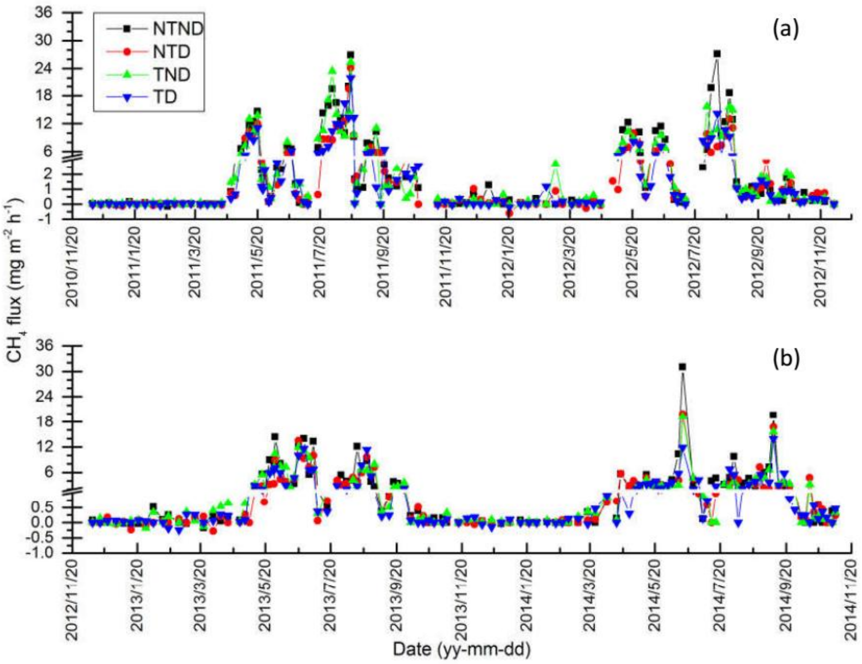


Figure 4 The abundance of methanogens and methanotrophs populations in paddy soil from 2013 to 2014, WS, ES, and LS means winter fallow season, early-rice season, and late-rice season, respectively.



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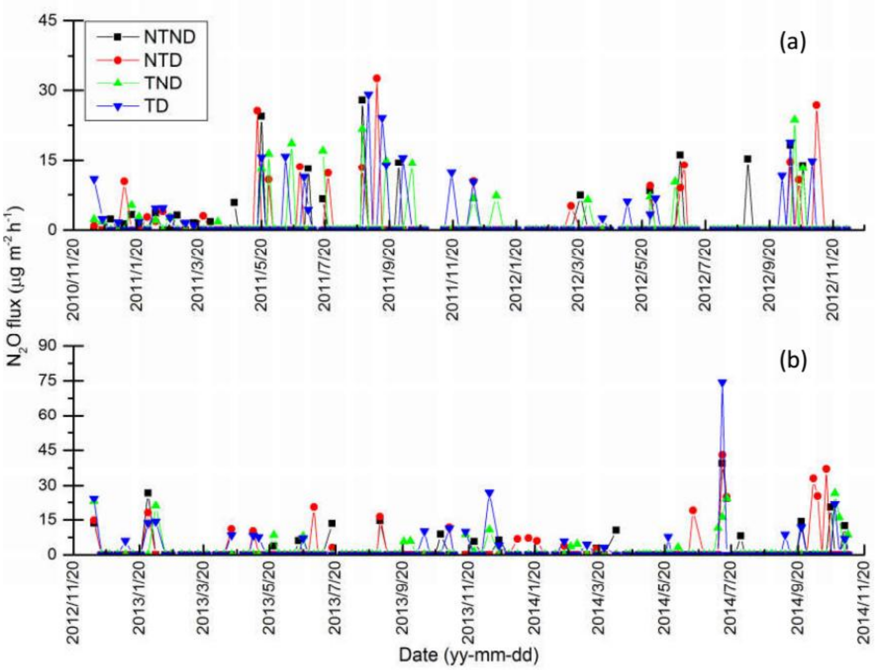

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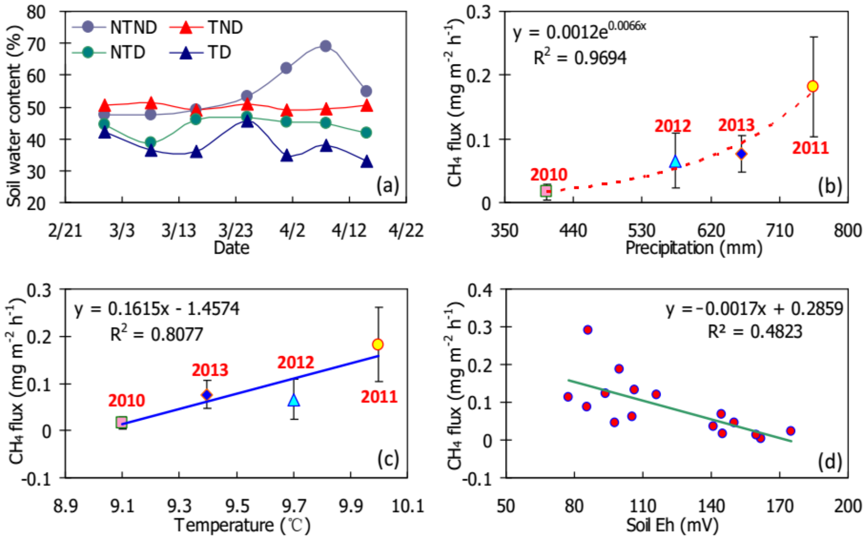

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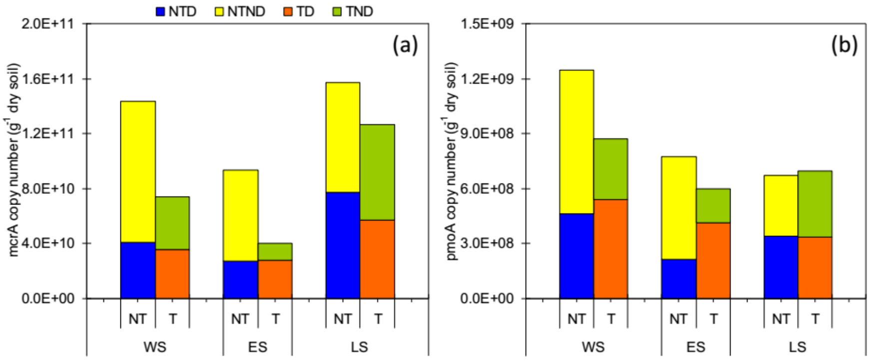

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