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Discussions

Options for mitigating global warming potential of a double-rice field in China

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Abstract. Traditional land managements (neither drainage nor tillage, NTND) in winter fallow season result in substantial CH_4 and N_2O emissions from the double-rice fields in China. For investigating the effects of drainage and tillage in winter fallow season on global warming potentials (GWPs) of CH_4 and N_2O emissions and developing mitigation options, a field experiment with four treatments: NTND, drainage but non-tillage (NTD), tillage but non-drainage (TND), and both drainage and tillage (TD) were carried out from 2010 to 2014 in a Chinese double-rice field. In winter fallow season total precipitation and mean daily temperature had important effects on CH_4 emission, and significant correlations were observed between them and CH_4 emission. Compared with NTND, drainage and tillage reduced CH_4 emission 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 emission in winter fallow season while reduced it in early- and late-rice seasons, causing annual N_2O emission unaffected. Accordingly, the GWPs were decreased by 1.49 and 0.92 t CO_2-eq ha^{-1} yr^{-1}, respectively, and they were far more reduced by combining drainage with tillage, with a mitigation potential of 1.96 t CO_2-eq ha^{-1} yr^{-1}. Low total C content and high C/N ratio in rice residues revealed that tillage in winter fallow season reduced CH_4 and N_2O emissions in early- and late-rice seasons. Moreover, drainage and tillage significantly decreased the abundance of methanogens in paddy soil, which was a possible reason for the decrease of CH_4 emission. Greenhouse gas intensity was significantly decreased by drainage and tillage, and it was much more reduced by combining drainage with tillage, with a reduction of 0.17 t CO_2-eq t^{-1} yield yr^{-1}. The results indicate that soil drainage combined with tillage in winter fallow season is an effective mitigating strategy in 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 1824 and 325.9 ppb in 2013, respectively (WMO, 2014). Paddy fields are considered to be the major sources of atmospheric CH_4 and N_2O. Since the 2000s, effective options for mitigating CH_4 and N_2O emissions from paddy fields have been continually explored over the world (McCarl and Schneider, 2001; Yan et al., 2005; Hussain et al., 2015), i.e. modifying irrigation and fertilization patterns (Cai et al., 2003; Hussain et al., 2015; Linquist et al., 2015), setting integrated soil–crop system management practices (Chen et al., 2014; Zhang et al., 2013b), and selection of suitable rice cultivar with high production but low GHGs emissions (Su et al., 2015; Hussain et al., 2015; Ma et al., 2010b), etc. Nevertheless, potential mitigating methods might be still available due to the diversity of rice-based ecosystems and the difference in agronomic management practices (Weller et al., 2016).

China is one of the largest rice producers in the world, and its harvested area contributes 18.5% of the world total (FAOSTAT, 2013). In China, total CH_4 and N_2O emissions from paddy fields were 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 total rice cultivation area (Yearbook, 2013) and emitting ca. 50% of the total paddy CH_4 in China (Zhang et al., 2011b; Chen et al., 2013). Double-rice fields mainly distribute at the south of the Yangtze River where usually has relative large precipitation and high temperature in winter fallow season. Traditionally, the fields are fallow in winter season with the soil neither drainage nor tillage after late-rice harvest, and they are usually subjected to visible floodwater after a heavy or a long-time raining. It is very likely to bring about CH_4 emission from these fields in winter fallow season and further to promote its emission during the following rice growth season. Modeling data had shown that CH_4 emission was significantly correlated with simulated soil moisture and mean precipitation of the preceding non-rice growth season (Kang et al., 2002). Incubation and pot experiments also affirmed that the higher the soil water contents in the non-rice growth season, the higher the CH_4 production rates and the more the CH_4 emissions in the subsequent rice season (Xu et al., 2003). An available mitigating option is hence proposed in this region, that is, the fields are drained to decrease the accumulation of rainwater in winter fallow season and finally to attenuate the positive effect of winter precipitation on CH_4 emission. However, drainage possibly stimulates N_2O emission from paddy field in winter fallow season because soil water content changes more quickly and intensively. It is well recognized that soil moisture regulates the processes of denitrification and nitrification and thus N_2O emission (Lan et al., 2013; Bateman and Baggs, 2005). Since the overall balance between the net exchange of CH_4 and N_2O emissions constitutes global warming potentials (GWPs) of rice ecosystem, the effect of soil drainage in winter fallow season on mitigating GWPs year-round from the double-rice field is not well understood.

Soil tillage is a conventional practice in rice cultivation, and considerable reports have shown that tilling the soil prior to rice transplanting plays a key role in CH_4 and N_2O emissions (Hussain et al., 2015; Zhao et al., 2016). Meanwhile, tillage after rice harvest in winter fallow season probably has very important effects on CH_4 and N_2O emissions. Firstly, it is beneficial for the rainwater to penetrate into the subsoil, which won't lead to the accumulation of rainwater in winter fallow season. It is then difficult to form the strict anaerobic environments in the top soil, which not only reduces CH_4 emission directly during the non-rice growing season, but also indirectly inhibits CH_4 emission during the following rice season. On the contrary, tillage makes rice residues fully contact with the soil and microorganism, which may accelerate the decomposition of organic matters and then in favor of CH_4 production and emission in the non-rice growth season (Pandey et al., 2012; Hussain et al., 2015). Secondly, it may also play a key role in CH_4 emission during the following rice season owing to the incompletely decomposed rice residues. In addition, tillage in winter fallow season whether increases N_2O emission from the field or not is still not very clear. There are some contradictive lines of evidence asserting the promotion and reduction in N_2O emissions from rice fields by soil tillage. For instance, tillage changes the soil properties (soil porosity and soil moisture, etc.) and then promotes N_2O emission (Pandey et al., 2012; Mutegi et al., 2010) whereas incorporation of rice residues due to tillage may reduce N_2O emission as a result of N immobilization (Huang et al., 2004; Ma et al., 2010a). Based on a 3-year 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 of drainage combined with tillage in 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.

An *in situ* field measurement was conducted year-round 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 objectives of this study are (1) to investigate the effects of soil drainage and tillage in winter fallow season on CH_4 and N_2O emissions from the paddy field, (2) to estimate the mitigation potential of drainage and tillage, and thereby (3) to suggest the optimal land management strategies in 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 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 year. 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 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 whole observational period was provided by Red Soil Ecological Experiment Station, Chinese Academy of Sciences (Appendix S1).

Four treatments, laid out in a randomized block design in triplicate, were conducted in the experimental field after late-rice harvest from 2010 to 2014: (1) the plots were neither drainage nor tillage in the whole winter fallow season as Treatment NTND, which is the traditional land management in the local region; (2) the plots were drainage but non-tillage as Treatment NTD; (3) the plots were tillage but non-drainage as Treatment TND; (4) and the plots were drainage and tillage simultaneously as Treatment TD. Rice stubble in all treatments was around 25–35 cm long, about 3.0–4.0 t ha^{-1} during the 4 winter fallow seasons, respectively. A small portion of rice stubble was collected before early-rice transplanting and the total C and N contents were measured by the wet oxidation-redox titration method and the micro-Kjeldahl method, respectively (Lu, 2000). Soil water content in winter fallow season was determined gravimetrically after drying at 105 ℃ for 8 h.

Local rice (*Oryza sativa L.*) cultivars, Zhongzao 33 and Nongxiang 98, were planted for the following early- and late-rice seasons, respectively. The seeds were sown in the seedling nursery and then transplanted into the experimental plots at their 3- to 4-leaf stage. Each season, nitrogen (N) and potassium (K) fertilizations 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 basal fertilizer at a rate of 75 kg P ha^{-1}. Detailed descriptions about the water management and fertilization are shown 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., 2011a). The flux chamber was 0.5 × 0.5 × 1 m, and plastic base (0.5 × 0.5 m) for the chamber was installed before 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 gas chromatographs 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 time 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 average CH_4 and N_2O emissions on the sampling days, assuming that CH_4 and N_2O emissions followed a linear trend during the periods when no sample was 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, 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 in the

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beginning, middle and end of each season from the experimental plots for analyzing the abundances of methanogens and methanotrophs. Totally, there were 108 soil samples (3 seasons × 3 stages in each season × 4 treatments × 3 replicates). Each sample was collected at 0–5 cm depth in triplicate and fully mixed. Subsequently, 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's 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 PCR quantification of *mcrA* and *pmoA* genes

The abundance of methanogenic *mcrA* gene copies and of methanotrophic *pmoA* genes 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 detailed descriptions please refer to our previous study (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 $P < 0.05$.

3 Results

3.1 CH_4 emission

Obvious 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 highly lower ($P < 0.05$) in the 2010–2011 winter fallow season (~0.1–1 kg CH_4 ha^{-1}) than 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 managements (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 of non-drainage, drainage reduced CH_4 emissions by 40–50%. Consequently, CH_4 emission was decreased by 14.8% relative to Treatment NTND with the integrated effects of soil drainage and tillage (Table 1).

During the 4 early- and late-rice seasons, the CH_4 fluxes of all treatments dramatically ascended under continuous flooding, and the highest CH_4 fluxes were observed on 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 reflooding, particularly in the early-rice season. Apparently, the CH_4 emission 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 impacted by year or their interaction (Table 2). In contrast, total CH_4 emission did significantly vary with land managements and year in late-rice season (Table 2). In comparison of Treatment NTND, CH_4 emission was 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 with early-rice season (68.3–105.1 kg CH_4 ha^{-1}), total CH_4 emission in 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 46.1% and 52.1% of which 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, averaged CH_4 emission was decreased by 24.3% and 14.9% by drainage and tillage, separately, and it was highly reduced by 32.0% when drainage was 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 their interaction (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 with tillage simultaneously. 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 in 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 generally reduced N_2O emission 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 by 10–12.9%, although no 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 by 10.3–14.4%. Annually, total N_2O emission was ranged from 113 to 167 g N_2O-N ha^{-1}, averaged 34.4% of which 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 over the 100-year time, although it was, on average, very small, being 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 highly increased it. Consequently, soil drainage combined with tillage played a slightly role in GWPs relative to Treatment NTND.

In contrast, both soil drainage and tillage decreased GWPs in comparison of Treatment NTND over the 4 early-rice seasons, with 16.0–36.2% and 4.2–36.2% lower in Treatment NTD and Treatment TND, respectively (Table 1). The GWPs was hence far more decreased by drainage combined with tillage, being 26.6–42.4% lower in Treatment TD than in Treatment NTND. Totally, drainage significantly reduced GWPs by 27.4% for Treatment NTD, in particular on Treatment TD by 34.8% with the integrated effect of drainage and tillage relative to Treatment NTND. Meanwhile, tillage 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 of 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 averaged 4.29–6.25 t CO_2-eq ha^{-1}, with 46% and 52% of which 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 are 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). On average, the yields in Treatments TND and TD were over 6.5 t ha^{-1}, 4.8%–7.3% and 3.1%–4.4% higher than those of Treatments NTND and NTD during the early- and late-rice seasons, respectively. Annually, no significance in the total yields was observed among the treatments over the 4 years (Table 3). Throughout the 4 late-rice seasons, positive correlation was observed between grain yields of 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 changed significantly among the treatments owing to GWPs highly controlled while annual rice yields slightly influenced by soil drainage and tillage (Table 3). Compared with Treatment NTND, drainage and tillage reduced GWPs by 23.8% and 14.7%, thus causing GHGI significantly decreased by 22.4% and 18.4%, separately. Expectedly, soil drainage combined with tillage reduced GHGI much more, with a reduction of 34.7% relative to Treatment NTND.

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

Over the 4 winter fallow seasons, total precipitation changed remarkably, which was ranged from ~400 mm to ~750 mm during 2010–2012. Subsequently, it was relatively stable around 600 mm in 2012–2014 (Table 4). In contrast, mean daily air temperature varied slightly, with values of ca. 9.0 ℃ to 10.0 ℃. Soil Eh, on average, fluctuated obviously from the highest (~150 mV) in 2010–2011 to the lowest (~90 mV) in 2013–2014. Soil water content in 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 value of 55%, 50%, 44% and 38%, respectively. It is easy to see that the higher the precipitation and temperature, the lower the soil Eh, and thus the more the CH_4 emission in winter fallow season (Table 4). Statistical analyses show that a significant exponential relationship was observed between mean CH_4 emission and total precipitation (Fig. 3b, $P < 0.01$), and mean CH_4 emission positively and negatively correlated with mean temperature (Fig. 3c, $P < 0.05$) and soil Eh (Fig. 3d, $P < 0.01$), respectively.

3.7 Abundance of methanogens and methanotrophs populations

The abundance of methanogens in paddy soil decreased significantly from winter fallow season to the following early-rice season, but it increased again during the late-rice season (Fig. 4a). Compared with non-drainage (Treatments NTND and TND), drainage (Treatments NTD and TD) generally decreased the abundance 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 winter fallow season, and then it decreased gradually (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 no significance 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 of non-tillage (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 *in situ* measurement of CH_4 emission in China was firstly carried out 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 observed (Cai et al., 2001; Shang et al., 2011). However, few investigations were referred to related measurements in the non-rice growth season. Fortunately, Shang et al. (2011) found the double-rice fields in Hunan province China usually acting as a small net sink of CH_4 emission (as low as –6 kg CH_4 ha^{-1}) in winter fallow season. Although an occasionally 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 annual CH_4 emission emitted from the winter fallow season.

Because of the residues (mainly including roots and stubble) of early rice as well as high temperature resulting in substantial CH_4 production in paddy fields (Shangguan et al., 1993a; Yan et al., 2005), CH_4 emission of 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 a couple of 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}, being 8.0–17.9% larger than that of early-rice seasons (Table 1) though total CH_4 emission in the last two early-rice seasons was found to be slight greater than those in 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 in these CH_4 measurements were probably attributed to different water and rice straw managements.

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 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 higher the rainfall, the greater the CH_4 emission throughout the 4 winter fallow seasons (Table 4). And an exponential relationship was observed between mean CH_4 emission and total rainfall in winter fallow season (Fig. 3b). The importance of rainfall in controlling CH_4 emission in winter fallow season, to some extent, also could be demonstrated by the negative relationships between mean soil Eh and CH_4 emission (Fig. 3d). According to different rice fields from 4 main rice growing regions in China, similar correlation was found between rainfall in winter fallow season and CH_4 emission in the rice growth season (Kang et al., 2002).

Nevertheless, we did not found any correlations between rainfall in winter fallow season and CH_4 flux in early-or late-rice season in this study, suggesting that rainfall in winter fallow season just significantly regulated CH_4 flux on-season, but didn’t 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, demonstrating that crop growth benefited rice yield and biomass and thus stimulated CH_4 emission. It is reported that seasonal CH_4 emission depended greatly on rice biomass based on a long-term fertilizer experiment (Shang et al., 2011). Furthermore, changes in temperature over the 4 winter fallow seasons (Table 4) were supposed to play a key role in CH_4 emission, and the positive correlation had demonstrated this well (Fig. 3c). Many field measurements have shown the importance of temperature to CH_4 emission (Cai et al., 2003; Parashar et al., 1993; Zhang et al., 2011a).

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

Considerable measurements of CH_4 emission as affected by soil drainage in winter fallow season have been reported from single-rice fields, and most of which were from the permanently flooded fields. Obviously, drainage significantly decreases CH_4 emission (Table 5). Draining the flooded fields inhibits CH_4 production and CH_4 emission in 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., 2011a). Compared with non-drainage, drainage in this study significantly decreased CH_4 emission both in previous winter fallow seasons and following early- and late-rice seasons (Table 1), and over the 4 years, 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, early- and late-rice seasons by soil drainage (Fig. 4a) because drainage increases soil aeration and hence effectively reduces the survival rate and activity of methane-producing bacteria. According to 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 revealed 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 winter fallow season on CH_4 emission

Although CH_4 emission in winter fallow season was increased by soil tillage, it was highly decreased 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 promote the decomposition of rice residues, and then stimulates CH_4 production and emission in winter fallow season. By contrast, as the readily decomposable part of the residues has largely been decomposed after a whole winter fallow season, the remaining hardly-decomposable part of organic matter doesn't have much effect on promoting CH_4 emission next year (Watanabe and Kimura, 1998). The content of total C in rice residues generally lower in Treatments TND and TD than in Treatments NTND and NTD (Table 6) has well demonstrated that tillage decreased the carbon substrates for methanogenesis. It therefore, 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 winter fallow season was decreased sharply in comparison of that applied to the field just prior to rice transplanting (Zhang et al., 2015). In addition, tillage highly 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 of 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 of midseason aeration and subsequent dry/wet alternation in rice-growing season, and in winter crop or fallow season (Zheng et al., 2004; Cai et al., 1997; Ma et al., 2013; Yan et al., 2003). It is estimated that most of croplands N_2O emission comes from uplands and just 20–25% of which 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), and considerable observations from double-rice fields had been performed (Xu et al., 1997; Shang et al., 2011; Zhang et al., 2013a). The total N_2O emission of early- and late-rice seasons in this study, on average, varied between 70.6 and 114.7 g N_2O-N ha^{-1} yr^{-1} over the 4 years

(Table 1), being significantly lower than those reported by Shang et al. (2011) and Zhang et al. (2013a) but similar to our previous measurements Ma et al. (2013). Furthermore, over 1/3 of annual N_2O emission came from the winter fallow season (Table 1), indicating that N_2O emission from paddy fields in winter fallow season was very important. Early field observations even showed that as high as 60–90% of N_2O emission occurred in winter fallow season (Shang et al., 2011). On a national scale, it is found that 41 Gg N_2O-N yr^{-1} emitted in the non-rice growth period, contributing 45% of the total N_2O emission from rice-based ecosystems (Zheng et al., 2004). Although N_2O emission from rice fields significantly affected by year (Table 2), reasons for the interannual variation were still not well known. In order to specify rules for interannual change 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 by the microbial processes of nitrification and denitrification while soil water content determines the general direction of the transformation of soil nitrogen. Soil drainage can cut down 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 that 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 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 winter fallow season (Table 1). Noted that drainage in previous winter fallow season also had an important effect on N_2O emission from paddy fields during the following rice seasons, namely, it increased N_2O emission both in early- and late-rice seasons (Table 1). It was possibly attributed to that drainage in winter fallow season would create soil moisture more beneficial to N_2O production in the subsequent rice-growing seasons. Early report had well demonstrated that the production and emission of soil N_2O was not only related to the soil moisture regime at the time, but also strongly affected by the previous soil moisture regime (Groffman and Tiedje, 1988). And regardless of how the water conditions were at that 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, annual N_2O emission was increased by 37–48% compared drainage with non-drainage 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 usually increased N_2O emission in winter fallow season, on average, by 39% over the 4 years (Table 1), which might be ascribed to two reasons. First, tillage increases soil aeration, which possibly promotes the process of nitrification. 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 from the plow layer percolating into the subsoil layer, stimulating the processes of soil dry/wet alternation and then 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 this to some extent. In contrast, it 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 content of total N in rice residues, which probably reduced the substrates for nitrification and denitrification. More importantly, the ratio of C/N in rice residues was increased by tillage (Table 6). Because the decomposition of rice residues with high C/N ratio probably resulted in more N immobilization in the soil and less N available to nitrification and denitrification for N_2O production (Huang et al., 2004; Zou et al., 2005). As a whole, soil tillage played a slight 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 highly reduced GWPs, with a decrease of 1.49 t CO_2-eq ha^{-1} annually (Table 3). Considerable studies have showed that drainage results in a trade-off between CH_4 and N_2O emissions from rice fields (Table 5), and it is widely considered to be an effective mitigation option. Annually, the mitigation potential of GWPs from paddy fields by drainage in winter fallow season is over 50%. However, these measurements are mostly related to the single-rice fields with continuous flooding (Table 5), and few information are 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 reduced by drainage in winter fallow season throughout the previous winter fallow and following early- and late-rice seasons, and with 24% of mitigation potential annually (Table 3).

In contrast, tillage obviously increased both CH_4 and N_2O emissions, thus highly increased GWPs in 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 winter fallow season (Table 5). Fortunately, it significantly decreased CH_4 and N_2O emissions both in early-and late-rice seasons, and as a result, with a reduction of 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 ranges 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 winter fallow season might be an effective option for mitigating the GWPs of CH_4 and N_2O emissions from the double rice-cropping systems.

More importantly, no significant difference in rice grain yields was observed among the 4 treatments over the 4 years (Tables 1 and 3). It suggests that we would not risk rice yield loss when we try to decrease the GWPs of CH_4 and N_2O emissions by means of soil drainage or tillage in winter fallow season. So, 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 yr^{-1} (Table 3). Based on a long-term fertilizer experiment, balanced fertilizer management, in particular on P fertilizer supplement, was suggested to be an available strategy in double rice-cropping systems (Shang et al., 2011). In this study, the effective mitigation option in double-rice fields we proposed is that soil drainage combined with tillage in winter fallow season.

In Conclusion, the study demonstrated that in winter fallow season large differences in CH_4 emissions were probably due to the changes in total precipitation and temperature. Soil drainage and tillage in winter fallow season separately, in particular on combining both of them, significantly decreased CH_4 emission and then GWPs of CH_4 and N_2O emissions from double-rice field. One possible explanation for this phenomenon is that drainage and tillage decreased the abundance of methanogens in paddy soil. Moreover, low total C content in rice residues due to tillage was a potential reason for the decrease of CH_4 emission in the following early- and late-rice seasons. Finally, tillage reduced total N content but increased C/N ratio in rice residues would be important to the decrease of N_2O emission. For both achieving high rice grain yield and low GWPs in double-rice fields, land management strategies in this study we proposed, including the fields were drained immediately after late-rice harvest, and meanwhile, the fields were tilled with rice residues incorporated into the soil. The results would benefit the development of optimal management strategies in the double-rice systems and the interpretation of the corresponding mechanisms.

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Reference

Bateman, E. J., and Baggs, E. M.: Contributions of nitrification and denitrification to N2O emissions from soils at different water-filled pore space, Biol. Fert. Soils., 41, 379-388, 10.1007/s00374-005-0858-3, 2005.

Bayer, C., Zschornack, T., Pedroso, G. M., Rosa, C. M. D., Camargo, E. S., Boeni, M., Elio Marcolin b, Reis, C. E. S. d., and Santos, D. C. d.: A seven-year study on the effects of fall soil tillage on yield-scaled greenhouse gas emission from flood irrigated rice in a humid subtropical climate, Soil Till. Res., 145, 118-125, 2015.

Cai, Z. C., Xing, G. X., Yan, X. Y., Xu, H., Tsuruta, H., Yagi, K., and Minami, K.: Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management, Plant Soil, 196, 7-14, 10.1023/a:1004263405020, 1997.

Cai, Z. C., Xu, H., Lu, W. S., Liao, Z. W., Wei, C. F., and Xie, D. T.: Influence of water management in winter crop season on CH_4 emission during the rice growing seaosn, Chinese Journal of Applied Ecology, 9, 171-175 (In Chinese), 1998.

Cai, Z. C., Tsuruta, H., Rong, X. M., Xu, H., and Yuan, Z. P.: CH_4 emissions from rice paddies managed according to farmer's practice in Hunan, China, Biogeochemistry, 56, 75-91, 10.1023/a:1011940730288, 2001.

Cai, Z. C., Tsuruta, H., Gao, M., Xu, H., and Wei, C. F.: Options for mitigating methane emission from a permanently flooded rice field, Glob. Change Biol., 9, 37-45, 2003.

Cai, Z. C., Xu, H., and Ma, J.: Methane and nitrous oxide emissions from rice-based ecosystems (In Chinese), Science and Technology University of China Press, Hefei, China, 2009.

Chen, G. X., Huang, G. H., Huang, B., Wu, J., Yu, K. W., Xu, H., Xue, X. H., and Wang, Z. P.: CH_4 and N_2O emission from a rice field and effect of *Azolla* and fertilization on them, Chinese Journal of Applied Ecology (In Chinese), 6, 378-382, 1995.

Chen, H., Zhu, Q. A., Peng, C. H., Wu, N., Wang, Y. F., Fang, X. Q., Jiang, H., Xiang, W. H., Chang, J., Deng, X. W., and Yu, G. R.: Methane emissions from rice paddies natural wetlands, lakes in China: synthesis new estimate, Glob. Change Biol., 19, 19-32, Doi 10.1111/Gcb.12034, 2013.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Ma, L., and Zhang, F.: Producing more grain with lower environmental costs, Nature, 514, 486-489, nature13609 [pii]
10.1038/nature13609, 2014.

Costello, A. M., and Lidstrom, M. E.: Molecular characterization of functional and phylogenetic genes from natural populations of methanotrophs in lake sediments, Appl. Environ. Microb., 65, 5066-5074, 1999.

Davidson, E. A.: Sources of nitric oxide and nitrous oxide following wetting of dry soil, Soil Sci. Soc. Am. J., 56, 95-102, 1992.

Dendooven, L., and Anderson, J. M.: Maintenance of denitrification potential in pasture soil following anaerobic events, Soil Biol. Biochem., 27, 1251-1260, Doi 10.1016/0038-0717(95)00067-O, 1995.

Dendooven, L., Duchateau, L., and Anderson, J. M.: Gaseous products of the denitrification process as affected by the antecedent water regime of the soil, Soil Biol. Biochem., 28, 239-245, Doi 10.1016/0038-0717(95)00132-8, 1996.

Fan, X., Yu, H., Wu, Q., Ma, J., Xu, H., Yang, J., and Zhuang, Y.: Effects of fertilization on microbial abundance and emissions of greenhouse gases (CH_4 and N_2O) in rice paddy fields, Ecol Evol, 6, 1054-1063, 10.1002/ece3.1879, 2016.

Groffman, P. M., and Tiedje, J. M.: Denitrification hysteresis during wetting and drying cycles in soil, Soil Sci. Soc. Am. J., 52, 1626-1629, 1988.

Hales, B. A., Edwards, C., Ritchie, D. A., Hall, G., Pickup, R. W., and Saunders, J. R.: Isolation and identification of methanogen-specific DNA from blanket bog peat by PCR amplification and sequence analysis, Appl. Environ. Microb., 62, 668-675, 1996.

Huang, Y., Zou, J. W., Zheng, X. H., Wang, Y. S., and Xu, X. K.: Nitrous oxide emissions as influenced by amendment of plant residues with different C : N ratios, Soil Biol. Biochem., 36, 973-981, DOI 10.1016/j.soilbio.2004.02.009, 2004.

Hussain, S., Peng, S. B., Fahad, S., Khaliq, A., Huang, J. L., Cui, K. H., and Nie, L. X.: Rice management interventions to mitigate greenhouse gas emissions: a review, Environ. Sci. Pollut. R, 22, 3342-3360, 10.1007/s11356-014-3760-4, 2015.

Jiang, C. S., Huang, Y. S., Zheng, X. H., Zhu, B., and Huang, Y.: Effects of tillage-cropping systems on methane and nitrous oxide emissions from permanently flooded rice fields in a cen tral Sichuan hilly area of south west China, Environmental Science, 27, 207-213 (In Chinese), 2006.

Kang, G. D., Cai, Z. C., and Feng, Z. H.: Importance of water regime during the non-rice growing period in winter in regional variation of CH_4 emissions from rice fields during following rice growing period in China, Nutr. Cycl. Agroecosys., 64, 95-100, Doi 10.1023/A:1021154932643, 2002.

Khdyer, I. I., and Cho, C. M.: Nitrification and denitrification of nitrogen fertilizers in a soil column, Soil Sci. Soc. Am. J., 47, 1134-1139, 1983.

Lan, T., Han, Y., Roelcke, M., Nieder, R., and Cai, Z. C.: Processes leading to N2O and NO emissions from two different Chinese soils under different soil moisture contents, Plant Soil, 371, 611-627, 10.1007/s11104-013-1721-1, 2013.

Li, C. S., Salas, W., DeAngelo, B., and Rose, S.: Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in china over the next twenty years, J. Environ. Qual., 35, 1554-1565, 10.2134/jeq2005.0208, 2006.

Liang, W., Shi, Y., Zhang, H., Yue, J., and Huang, G. H.: Greenhouse gas emissions from northeast China rice fields in fallow season, Pedosphere, 17, 630-638, Doi 10.1016/S1002-0160(07)60075-7, 2007.

Linquist, B. A., Anders, M. M., Adviento-Borbe, M. A. A., Chaney, R. L., Nalley, L. L., da Rosa, E. F. F., and van Kessel, C.: Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems, Glob. Change Biol., 21, 407-417, 10.1111/gcb.12701, 2015.

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Lu, R.: Soil agro-chemical analyses (In Chinese), Agricultural Technical Press, Beijing, 2000.

Ma, E., Zhang, G., Ma, J., Xu, H., Cai, Z., and Yagi, K.: Effects of rice straw returning methods on N_2O emission during wheat-growing season, Nutr. Cycl. Agroecosys., 88, 463-469, 10.1007/s10705-010-9369-1, 2010a.

Ma, J., Ji, Y., Zhang, G. B., Xu, H., and Yagi, K.: Timing of midseason aeration to reduce CH_4 and N_2O emissions from double rice cultivation in China, Soil Sci. Plant Nutr., 59, 35-45, Doi 10.1080/00380768.2012.730477, 2013.

Ma, K., Qiu, Q. F., and Lu, Y. H.: Microbial mechanism for rice variety control on methane emission from rice field soil, Glob. Change Biol., 16, 3085-3095, DOI 10.1111/j.1365-2486.2009.02145.x, 2010b.

Ma, K., and Lu, Y. H.: Regulation of microbial methane production and oxidation by intermittent drainage in rice field soil, FEMS Microbiol. Ecol., 75, 446-456, DOI 10.1111/j.1574-6941.2010.01018.x, 2011.

Ma, K., Conrad, R., and Lu, Y.: Responses of Methanogen mcrA Genes and Their Transcripts to an Alternate Dry/Wet Cycle of Paddy Field Soil, Appl. Environ. Microb., 78, 445-454, 10.1128/aem.06934-11, 2012.

McCarl, B. A., and Schneider, U. A.: Climate change - Greenhouse gas mitigation in US agriculture and forestry, Science, 294, 2481-2482, DOI 10.1126/science.1064193, 2001.

Mutegi, J. K., Munkholm, L. J., Petersen, B. M., Hansen, E. M., and Petersen, S. O.: Nitrous oxide emissions and controls as influenced by tillage and crop residue management strategy, Soil Biol. Biochem., 42, 1701-1711, 10.1016/j.soilbio.2010.06.004, 2010.

Pandey, D., Agrawal, M., and Bohra, J. S.: Greenhouse gas emissions from rice crop with different tillage permutations in rice-wheat system, Agr. Ecosyst. Environ., 159, 133-144, 10.1016/j.agee.2012.07.008, 2012.

Parashar, D. C., Gupta, P. K., Rai, J., Sharma, R. C., and Singh, N.: Effect of soil temperature on methane emission from paddy fields, Chemosphere, 26, 247-250, http://dx.doi.org/10.1016/0045-6535(93)90425-5, 1993.

Potthoff, M., Joergensen, R. G., and Wolters, V.: Short-term effects of earthworm activity and straw amendment on the microbial C and N turnover in a remoistened arable soil after summer drought, Soil Biol. Biochem., 33, 583-591, Doi 10.1016/S0038-0717(00)00200-5, 2001.

Shang, Q., Yang, X., Gao, C., Wu, P., Liu, J., Xu, Y., Shen, Q., Zou, J., and Guo, S.: Net annual global warming potential and greenhouse gas intensity in Chinese double rice‐cropping systems: a 3‐year field measurement in long‐term fertilizer experiments, Glob. Change Biol., 17, 2196-2210, 2011.

Shangguan, X. J., Wang, M. X., Chen, D. Z., and Shen, R. X.: Methane production in rice paddy fields, Advance in Earth Sciences (In Chinese), 8, 1-12, 1993a.

Shangguan, X. J., Wang, M. X., and Shen, R. X.: Regularity of methane emission from rice paddy fields, Advance in Earth Sciences (In Chinese), 8, 23-36, 1993b.

Shiratori, Y., Watanabe, H., Furukawa, Y., Tsuruta, H., and Inubushi, K.: Effectiveness of a subsurface drainage system in poorly drained paddy fields on reduction of methane emissions, Soil Sci. Plant Nutr., 53, 387-400, 10.1111/j.1747-0765.2007.00171.x, 2007.

Su, J., Hu, C., Yan, X., Jin, Y., Chen, Z., Guan, Q., Wang, Y., Zhong, D., Jansson, C., Wang, F., Schnurer, A., and Sun, C.: Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice, Nature, 523, 602-606, 10.1038/nature14673, 2015.

Watanabe, A., and Kimura, M.: Effect of rice straw application on CH_4 emission from paddy fields IV. Influence of rice straw incorporated during the previous cropping period, Soil Sci. Plant Nutr., 44, 507-512, 1998.

Weller, S., Janz, B., Jörg, L., Kraus, D., Racela, H. S. U., Wassmann, R., Butterbach-Bahl, K., and Kiese, R.: Greenhouse gas emissions and global warming potential of traditional and diversified tropical rice rotation systems, Glob. Change Biol., 22, 432-448, 10.1111/gcb.13099, 2016.

Xu, H., Guangxi, X., Cai, Z. C., and Tsuruta, H.: Nitrous oxide emissions from three rice paddy fields in China, Nutr. Cycl. Agroecosys., 49, 23-28, Doi 10.1023/A:1009779514395, 1997.

Xu, H., Cai, Z. C., and Tsuruta, H.: Soil moisture between rice-growing seasons affects methane emission, production, and oxidation, Soil Sci. Soc. Am. J., 67, 1147-1157, 2003.

Yan, X. Y., Akimoto, H., and Ohara, T.: Estimation of nitrous oxide, nitric oxide and ammonia emissions from croplands in East, Southeast and South Asia, Glob. Change Biol., 9, 1080-1096, DOI 10.1046/j.1365-2486.2003.00649.x, 2003.

Yan, X. Y., Yagi, K., Akiyama, H., and Akimoto, H.: Statistical analysis of the major variables controlling methane emission from rice fields, Glob. Change Biol., 11, 1131-1141, 10.1111/j.1365-2486.2005.00976.x, 2005.

Yao, Z. S., Zheng, X. H., Wang, R., Xie, B. H., Butterbach-Bahl, K., and Zhu, J. G.: Nitrous oxide and methane fluxes from a riceewheat crop rotation under wheat residue incorporation and no-tillage practices, Atmos. Environ., 79, 641-649, 2013.

Zhang, G. B., Zhang, X. Y., Ma, J., Xu, H., and Cai, Z. C.: Effect of drainage in the fallow season on reduction of CH_4 production and emission from permanently flooded rice fields, Nutr. Cycl. Agroecosys., 89, 81-91, 10.1007/s10705-010-9378-0, 2011a.

Zhang, H. L., Bai, X. L., Xue, J. F., Chen, Z. D., Tang, H. M., and Chen, F.: Emissions of CH_4 and N_2O under different tillage systems from double-cropped paddy fields in southern China, Plos One, 8, 10.1371/journal.pone.0065277, 2013a.

Zhang, J. K., Jiang, C. S., Hao, Q. J., Tang, Q. W., Cheng, B. H., Li, H., and Chen, L. H.: Effects of tillage-cropping systems on methane and nitrous oxide emissions from ago-ecosystems in a purple paddy soil, Environmental Science, 33, 1979-1986 (In Chinese), 2012.

Zhang, W., Yu, Y. Q., Huang, Y., Li, T. T., and Wang, P.: Modeling methane emissions from irrigated rice cultivation in China from 1960 to 2050, Glob. Change Biol., 17, 3511-3523, 2011b.

Zhang, W., Yu, Y., Li, T., Sun, W., and Huang, Y.: Net greenhouse gas balance in China's croplands over the last three decades and its mitigation potential, Environ. Sci. Technol., 48, 2589-2597, 2014.

Zhang, W. F., Dou, Z. X., He, P., Ju, X. T., Powlson, D., Chadwick, D., Norse, D., Lu, Y. L., Zhang, Y., and Wu, L.: New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China, Proceedings of the National Academy of Sciences, 110, 8375-8380, 2013b.

Zhang, Y. F., Sheng, J., Wang, Z. C., Chen, L. G., and Zheng, J. C.: Nitrous oxide and methane emissions from a Chinese wheat-rice cropping system under different tillage practices during the wheat-growing season, Soil Till. Res., 146 261-269, 2015.

Zhao, X., Liu, S.-L., Pu, C., Zhang, X.-Q., Xue, J.-F., Zhang, R., Wang, Y.-Q., Lal, R., Zhang, H.-L., and Chen, F.: Methane and nitrous oxide emissions under no-till farming in China: a meta-analysis, Glob. Change Biol., n/a-n/a, 10.1111/gcb.13185, 2016.

Zheng, X. H., Han, S. H., Huang, Y., Wang, Y. S., and Wang, M. X.: Re-quantifying the emission factors based on field measurements and estimating the direct N_2O emission from Chinese croplands, Glob. Biogeochem. Cycle, 18, 10.1029/2003gb002167, 2004.

Zou, J. W., Huang, Y., Jiang, J. Y., Zheng, X. H., and Sass, R. L.: A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application, Glob. Biogeochem. Cycle, 19, Doi 10.1029/2004gb002401, 2005.

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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 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.

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 ±0.10 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 two-way ANOVA for the effects of land management (L) and year (Y) on CH_4 and N_2O emissions and 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-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 yr^{-1})
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 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.

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Table 5 Relative mitigating GWPs of GHGs emissions from paddy fields with various land management practices as compared to traditional managements in 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, 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 Contents of total C (g kg^{-1}) and total N (g kg^{-1}) in rice stubble.

Tillage time	Treatment	Total C	Total N	C/N	Tillage time	Treatment	Total C	Total N	C/N
After late-rice harvest in 2011	TD	338	6.9	49	After late-rice harvest in 2012	TD	368	8.7	42
	TND	314	7.8	40		TND	364	7.1	51
Before early-rice transplanting in 2012	NTD	356	12.7	28	Before early-rice transplanting in 2013	NTD	404	12.8	32
	NTND	374	10.4	36		NTND	397	13.4	30

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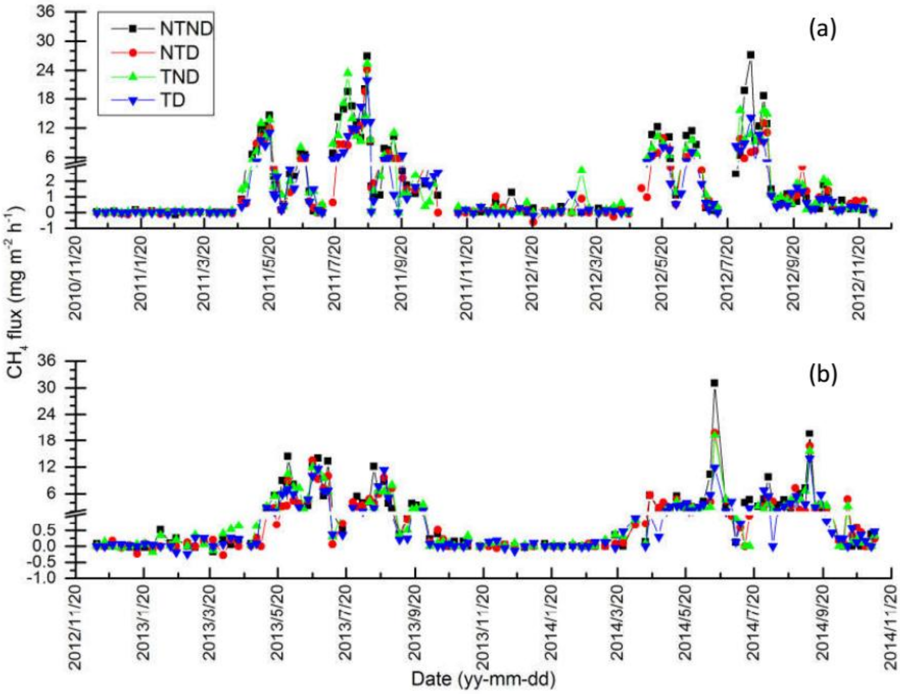

Figure 1 Seasonal variation of CH$_4$ emission from 2010 to 2014.

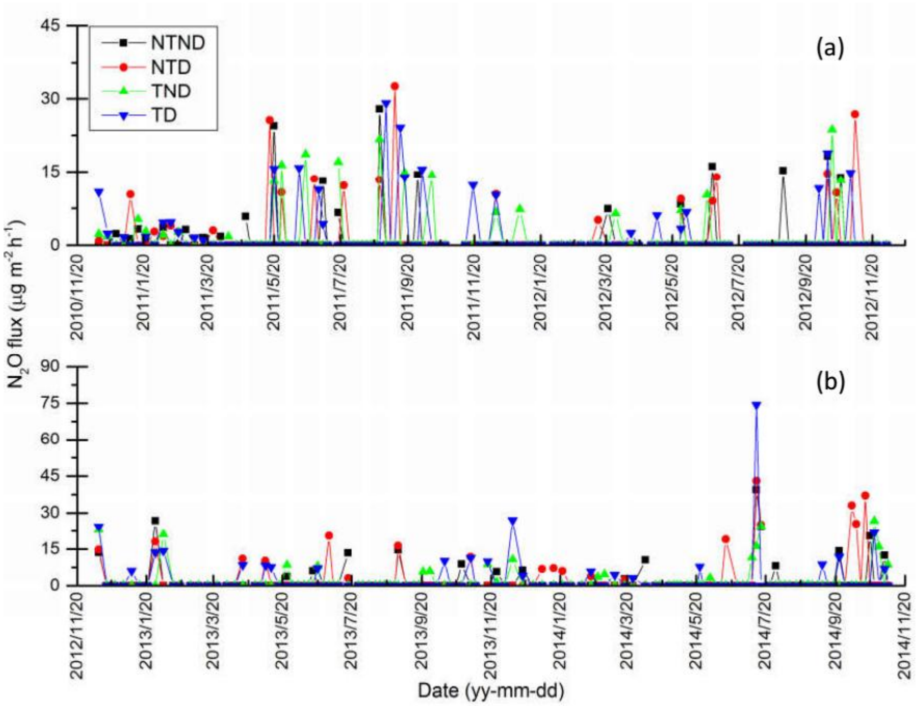

Figure 2 Seasonal variation of N_2O emission from 2010 to 2014.

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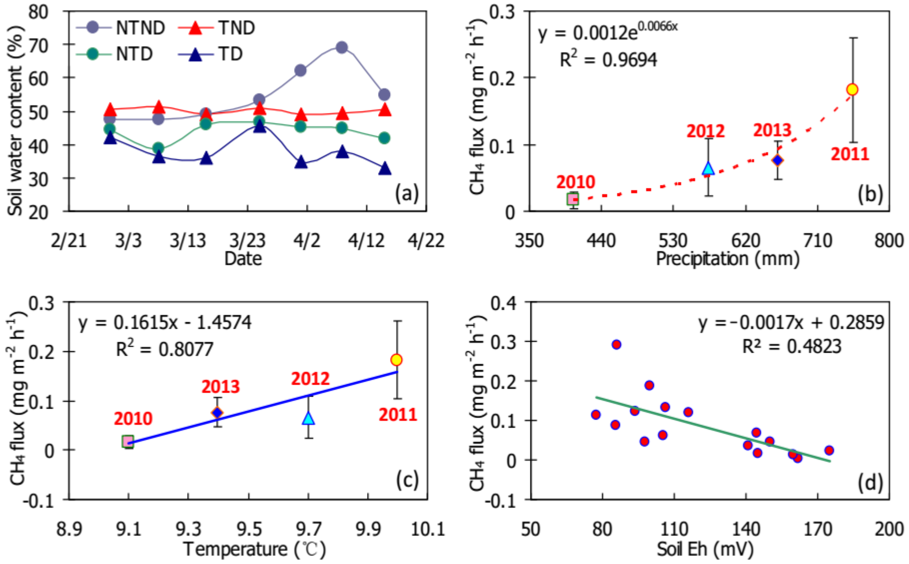

Figure 3 Soil water content in 2010 winter fallow season (a) and the relationships between mean CH_4 emission and total winter precipitation (b), and mean daily air temperature (c) and soil Eh (d) over the 4 winter fallow seasons (Data from Table 4).

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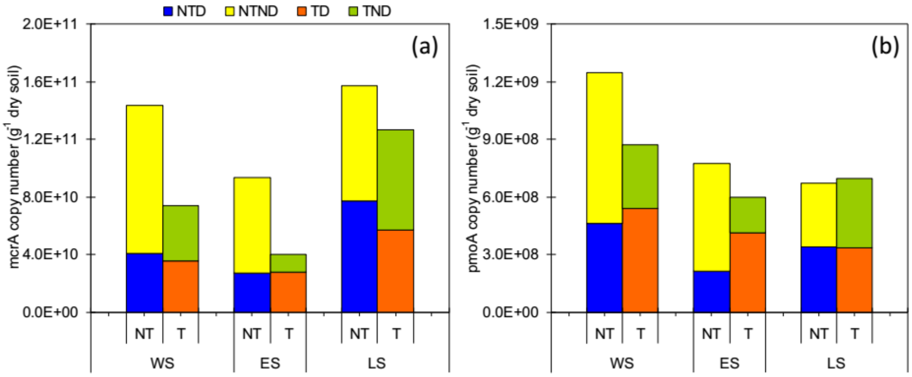

Figure 4 The abundance of methanogens and methanotrophs populations in paddy soil from 2013 to 2014, WS, ES, and LS means winter fallow season, early-rice season, and late-rice season, respectively.