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REGULAR ARTICLE

Methane and nitrous oxide emissions from direct-seeded and seedling-transplanted rice paddies in southeast China

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Abstract
Background and aims The rice production is experiencing a shift from conventionally seedling-transplanted (TPR) to direct-seeded (DSR) cropping systems in Southeast Asia. Besides the difference in rice crop establishment, water regime is typically characterized as water-saving moist irrigation for DSR and flooding-midseason drainage-reflooding and moist irrigation for TPR fields, respectively. A field experiment was conducted to quantify methane (CH_4) and nitrous oxide (N_2O) emissions from the DSR and TPR rice paddies in southeast China.
Methods Seasonal measurements of CH_4 and N_2O fluxes from the DSR and TPR plots were simultaneously taken by static chamber-GC technique.
Results Seasonal fluxes of CH_4 averaged 1.58 mg m^{-2} h^{-1} and 1.02 mg m^{-2} h^{-1} across treatments in TPR and DSR rice paddies, respectively. Compared with TPR cropping systems, seasonal N_2O emissions from DSR cropping systems were increased by 49 % and 46 % for the plots with or without N application, respectively. The emission factors of N_2O were estimated to be 0.45 % and 0.69 % of N application, with a background emission of 0.65 and 0.95 kg N_2O-N ha^{-1} under the TPR and DSR cropping regimes, respectively. Rice biomass and grain yield were significantly greater in the DSR than in the TPR cropping systems. The net global warming potential (GWP) of CH_4 and N_2O emissions were comparable between the two cropping systems, while the greenhouse gas intensity (GHGI) was significantly lower in the DSR than in the TPR cropping systems.
Conclusions Higher grain yield, comparable GWP, and lower GHGI suggest that the DSR instead of conventional TPR rice cropping regime would weaken the radiative forcing of rice production in terms of per unit of rice grain yield in China, and DSR rice cropping regime could be a promising rice development alternative in mainland China.

Keywords CH_4 · Fertilizer application · GWP · GHGI · N_2O · Rice cropping regime

Introduction

Methane (CH_4) and nitrous oxide (N_2O) are two potent greenhouse gases (GHGs) contributing greatly to global warming. Globally, agriculture is considered to be a major anthropogenic source of atmospheric CH_4 and N_2O, which constitutes 50 % and 60 % of the total CH_4 and N_2O emissions in 2005, respectively (Smith et al. 2007). Rice paddies have been identified as a major source of CH_4, amounting to 11 % of the total anthropogenic CH_4 emissions (Smith et al. 2007). Midseason drainage and moist irrigation incur substantial N_2O emissions from rice paddies (Cai et al. 1997; Zheng et al. 2000; Zou et al. 2005a, 2007; Liu et al. 2010).

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Rice is the staple food for people in Asia. There are two main types of rice cropping regime, i.e., seedling-transplanted (TPR) and direct-seeded (DSR) cropping systems, in southeast Asia (Luat 2000; Kim et al. 2001; Pandey and Velasco 2002; Azmi et al. 2005; Farooq et al. 2006a, b). Recently, the shift from TPR to DSR cropping systems has been increasingly adopted in southeast China. At present, DSR rice cropping system accounts for nearly 23 % of the total rice cultivation area (Rao et al. 2007). Besides the difference in direct-seeding vs. seedling-transplanting, water regime is typically distinguished by water-saving moist irrigation for the DSR and flooding-midseason drainage-reflooding and moist irrigation (F-D-F-M) for the TPR fields. Several advantages for DSR over TPR may account for the ongoing shift in rice cropping regime: (i) In addition to higher economic returns, DSR crops are faster and easier to plant, less labor and water resources consumed (Chan and Nor 1993; Jehangir et al. 2005; Bhushan et al. 2007; Pandey and Velasco 2005); (ii) DSR crops flower earlier leading to shorter crop duration (mature about 7–10 days earlier than TPR) and conducive to mechanization (Khade et al. 1993; Santhi et al. 1998; Farooq et al. 2006a, b); (iii) Seedling growth injured by transplanting in TPR cropping systems is avoided in DSR cropping systems (Tuong et al. 2000); (iv) DSR offers the alternative to resolve seasonal cropping conflicts between rice and the following non-rice upland cropping system (Ladha et al. 2003; Singh et al. 2005; Farooq et al. 2006a, b). Generally, direct-seeded crops often perform better than transplanted crops (Singh et al. 1983; Reddy and Panda 1988). On the other hand, among the vulnerabilities for direct-seeded rice cropping regime, weed management and insects control often exert a more severe threat to crop establishment relative to transplanted crops.

Agriculture releases significant amount of CH_4 and N_2O emissions to the atmosphere, meanwhile shifts in agricultural cropping regime may also provide opportunities for GHGs mitigation (Robertson et al. 2000; Pandey and Velasco 2002; Mosier et al. 2006; Smith et al. 2008; Qin et al. 2010). Emission of GHGs from rice fields is highly sensitive to rice management practice, and thereby the shift in rice cropping system has become an important concern in this context (Wassmann et al. 2004). It is reported that the water-saving DSR relative to TPR rice cropping regime has a high potential to reduce CH_4 emissions (Ko and Kang 2000). For example, Corton et al. (2000) found that, compared with TPR cultivation practice, the DSR rice production decreased CH_4 emissions by 18 %. In addition, Wassmann et al. (2004) proposed that CH_4 emissions may be suppressed by up to 50 % when midseason drainage occurring in DSR fields. However, a trade-off between CH_4 and N_2O fluxes due to water regime has been well documented (Zheng et al. 2004; Yan et al. 2003, 2009; Zou et al. 2009; Zhang et al. 2011; Shang et al. 2011), suggesting that decrease of CH_4 may be offset by enhanced N_2O emissions in the DSR relative to TPR rice fields. To our knowledge, literatures comparing agricultural GHGs emission from the DSR and TPR rice cropping systems are extremely limited, although the water- and cost-saving DSR rice cropping regime is increasingly practiced for rice production in China. Therefore, further studies are highly needed to update our knowledge on CH_4 and N_2O emissions from rice paddies as influenced by the shift in rice cropping regime.

In this study, we presented field measurements of CH_4 and N_2O fluxes from the DSR and conventional TPR rice cropping systems in southeast China in 2011, which were under the water regime of moist irrigation (M) and flooding-midseason drainage-reflooding-moisture irrigation (F-D-F-M), respectively. The CH_4 and N_2O fluxes were simultaneously measured using static chamber method. We predicted that CH_4 emissions would be greater, while N_2O emissions would be lower in the TPR cropping systems under the water regime of F-D-F-M than in the DSR cropping systems with moist irrigation. The objectives of this study are to gain an insight into an accounting of global warming potential (GWP) and greenhouse gas intensity (GHGI) derived from CH_4 and N_2O emissions as affected by the shift in rice cropping regime, and thereby to optimize agricultural management practices for achieving high grain yield and mitigating climatic impacts of rice production in China.

Materials and methods

Site description

The field plot experiment was established in a typical rice cropping system located on the experimental farm of Nanjing Agricultural University, Nanjing, Jiangsu province, China (31° 52′ N, 118° 50′ E) in 2011. The field site was overwhelmingly dominated by an annual paddy rice-winter wheat cropping rotation. Soil of the experimental site was classified as hydromorphic, consisting of 6 % sand, 40 % silt and 54 % clay. Initial soil pH was 6.7 (1:2.5, water/soil, w/w), an average bulk density was 1.24 g cm^{-3}, and total N and organic C contents were 1.5 g kg^{-1} and 14.8 g kg^{-1}, respectively. Climate information was recorded by the weather station, which was established on the experimental farm of Nanjing Agricultural University. The region displays a typical monsoonal climate with seasonal mean temperature of 25.4 °C and precipitation of 560 mm during the rice growing season, and annual mean temperature and precipitation of 16.5 °C and 1,080 mm in 2011, respectively.

Cropping regime and water management

After the wheat crop, the experimental fields were waterlogged with shallow water depth (0.5–2 cm) during the fallow season. The wheat stubble was identically retained at about 10 cm height in both rice cropping systems. For seedling-transplanted rice (TPR) cropping systems, seeds (Oryza sativa L., cv. Wuyunjing 7) were sown in a nursery bed on May 30, seedlings were transplanted to the paddy fields on July 1 and harvested on October 20, 2011. We plowed, mixed the soil surface and leveled the ground before rice transplanting in the TPR cropping systems. In the TPR plots, transplanting ridge spacing was 0.25×0.15 m, with three seedlings per ridge. All the TPR plots were dominated by a typical water regime of flooding-midseason drainage-reflooding-moisture irrigation (F-D-F-M) over the whole rice-growing season (Figs. 1 and 2). Initially, the level of flooding was kept from 1 week before rice transplanting until August 1, and was then followed by mid-season drainage for 10 days. Thereafter, all the field plots were re-flooded until September 30, 2011 and finally followed by maintaining moist soil status but without waterlogging (a dry-wet alteration with intermittent irrigation).

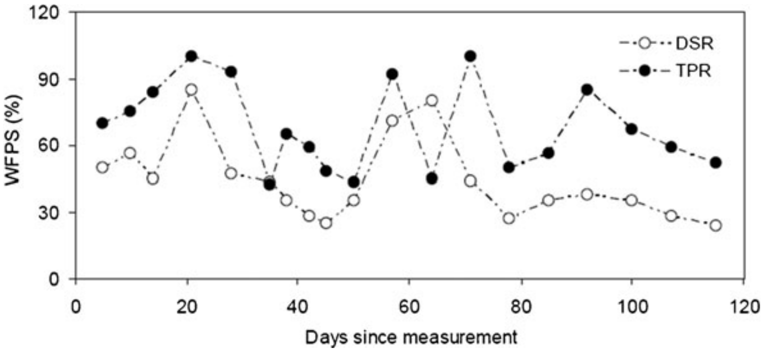
In direct-seeded rice (DSR) cropping systems, no tillage was required for the fields prior to sowing, seeds of the rice cultivar Wuyunjing 7 were soaked in water for 12 h to improve seedling quality and then broadcast at the rate of 400 seeds m^{-2} (representing the standard seed rate for local DSR production) on well prepared wet soil surface after water drainage, which was then mechanically harrowed to incorporate the seeds on June 15, and harvested on October 18, 2011. We matched the number of seedlings and tillers in the DSR plots according to transplanting density in the TPR plots on July 10. Moist irrigation without waterlogging (M), as a water-saving irrigation regime, was practiced throughout the whole rice growing season for DSR cropping systems, except that low-level (0–1 cm) flooding was entailed for the short-term episodes during fertilization and rainfall, which was controlled by an irrigation trench (Figs. 1 and 2).

In agreement with the local conventional fertilization practices (Cai et al. 1997; Zheng et al. 2000; Zou et al. 2004, 2005a, b, 2007; Liu et al. 2012b), seasonal N input identically totaled 250 kg N ha^{-1} for all the fertilized field plots (D-F and T-F). Urea was broadcasted on the field during the rice growing season with split applications of 40 % of the total as basal fertilizer, 40 % at turning-green and 20 % at tillering stage during rice season (Figs. 2 and 3). Plots without synthetic N fertilizer applied were designed as the controls in the DSR and TPR cropping systems (D-C and T-C). For all the experimental plots, calcium superphosphate (P_2O_5) at a rate of 120 kg ha^{-1} and potassium chloride (K_2O) at a rate of 90 kg ha^{-1} were applied with the basal fertilizer. All the field treatments were set up with three replications.

Gas flux measurements

The CH_4 and N_2O fluxes were determined by the static chamber-GC method (Wang and Wang 2003; Zou et al. 2005a, b). Prior to initial flooding special made boardwalks, guaranteeing access to randomly selected greenhouse gas sampling sites were installed at the edge of the boardwalks to minimise soil disturbance during flux measurements. Three aluminum flux collars (0.5 m length×0.5 m width×0.15 m height) for each plot were permanently installed near the boardwalks to ensure reproducible placement of gas collecting chambers during successive gas emission measurements over the whole rice growing season. The top edge of the collar base exhibits a groove (5 cm in depth) that can be filled with water to seal the rim of the chamber during gas sampling. The chamber with a cross-sectional area of 0.25 m^2 (0.5×0.5 m) was equipped with a circulating fan to ensure complete gas mixing and wrapped with a layer of sponge and aluminum foil to minimize air temperature changes inside the chamber during the period of sampling. When gas sampling, the chamber was placed over the six ridges of rice vegetation with

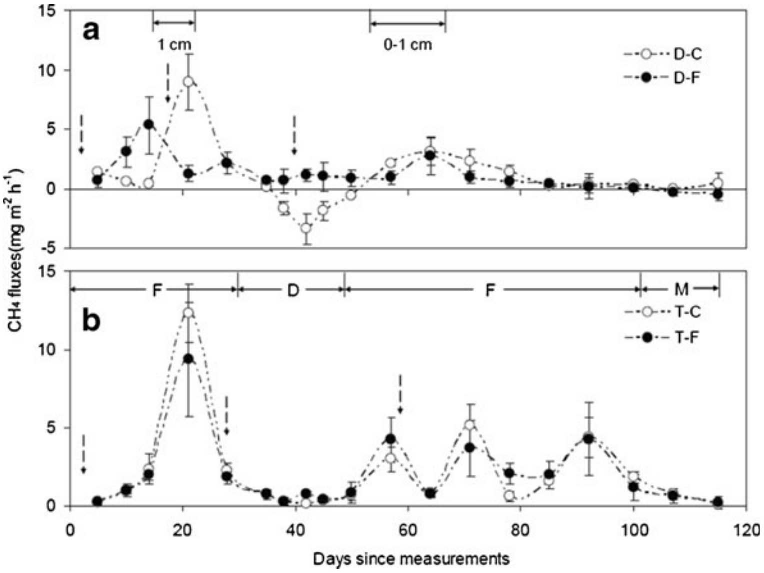
Fig. 1 Soil WFPS at the depth of 5–10 cm during direct-seeded (DSR) and conventionally seedling-transplanted (TPR) rice cropping seasons



the rim of the chamber fitted into the groove of the collar. The planting density inside the chamber was the same as that outside the chamber. In order to cover the whole rice growing season and minimize the uncertainties in comparing the seasonal total of CH_4 and N_2O emissions between the DSR and TPR cropping systems, gas sampling was simultaneously initiated in the two rice cropping systems, i.e., 1-week after sowing in the DSR cropping systems or 10 days before seedling transplanting in the TPR rice paddies. Gas samples were taken once a week except that they were taken once a day during the period of mid-season drainage and after precipitation events. We collected gas samples from inside the chambers using 60-mL plastic syringes fitted with three-way stop-cocks at 0, 5, 10, 15 and 20 min after chamber closure (Zou et al. 2005a, b). Gas samples were taken within 20 min after chamber closure starting any time between 0800 and 1000 LST on each sampling day (Zou et al. 2009; Liu et al. 2010). Gas samples in the syringes were transported to the laboratory for analysis by GC within a few hours.

The mixing ratios of CH_4 and N_2O were simultaneously analyzed with a modified gas chromatograph (Agilent 7890) equipped with a flame ionization detector (FID) and an electron capture detector (ECD) (Wang and Wang 2003) immediately after gas sampling from the experimental site. Nitrogen and a gas mixture of argon and methane (Ar-CH_4) were used as the carrier gas for CH_4 and N_2O, respectively. To remove CO_2 and water vapor in the air samples entering the ECD detector, a filter column filled with ascarite was connected to the beginning of the separation column for N_2O (Zheng et al. 2008). Fluxes were determined from the slope of the mixing ratio change in five samples, taken at 0, 5, 10, 15 and 20 min after chamber closure. The configuration of GC and procedures for simultaneously measuring CH_4

Fig. 2 Seasonal patterns of CH_4 fluxes (mean ± 1 S.D.) from direct-seeded (**a**) and conventionally seedling-transplanted (**b**) rice cropping systems under moist irrigation and the F-D-F-M (*F*, flooding; *D*, midseason drainage; *M*, moist irrigation without waterlogging) water regimes, respectively. *Vertical arrows* indicate fertilizer application; number range refers to the water layer above the soil surface during fertilization and rainfall



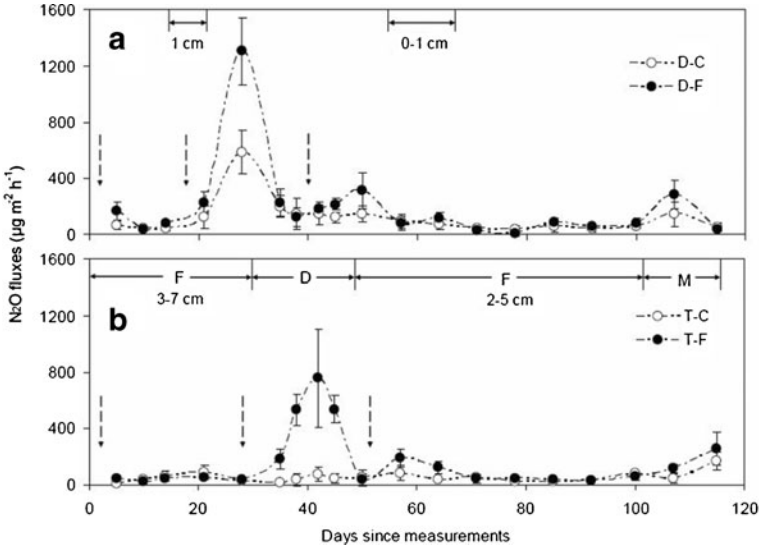


Fig. 3 Seasonal patterns of N_2O fluxes (mean ± 1 S.D.) from direct-seeded (**a**) and conventionally seedling-transplanted (**b**) rice cropping systems under moist irrigation and the F-D-F-M (*F*, flooding; *D*, midseason drainage; *M*, moist irrigation without waterlogging) water regimes, respectively. *Vertical arrows* indicate fertilizer application; number range refers to the water layer above the soil surface during fertilization and rainfall

and N_2O fluxes were detailed in our previous studies (Zou et al. 2004, 2005a, b).

Determination of GWPs and GHGI

The concept of global warming potential (GWP), as one type of simplified index based upon radiative forcing, was introduced to estimate the potential future impacts of emissions of different gases upon the climate system in a relative sense (Lashof and Ahuja 1990). In GWP estimation, CO_2 is generally taken as the reference gas, and an increase or reduction in emission of CH_4 and N_2O is converted into 'CO_2-equivalents' by means of their GWPs. Recently, the net GWP has been estimated to complete understanding the agricultural impacts on radiative forcing (Frolking et al. 2004; Robertson and Grace 2004; Mosier et al. 2006; Qin et al. 2010; Shang et al. 2011). We calculated the combined GWPs from CH_4 and N_2O emissions for each treatment in the DSR and TPR cropping systems using the IPCC factors over the 100-year time scale ($GWP = CH_4 \times 25 + N_2O \times 298$, Forster et al. 2007).

Particularly, greenhouse gas intensity (GHGI) as another concept was recently proposed to associate agricultural practices with GWP (Mosier et al. 2006). The GHGI is calculated by dividing GWP by grain yield (Li et al. 2006; Mosier et al. 2006; Shang et al. 2011). To better understand the impacts of shift in rice cropping regime on GHGI, we thereby calculated GHGI to assess the radiative forcing of CH_4 and N_2O emissions in terms of rice production (Table 2).

Auxiliary measurements

The field topsoil samples (10–15 cm) were collected before rice transplanting or sowing to measure soil pH, bulk density, total organic carbon, total nitrogen and soil mineral nitrogen (NH_4^+-N + NO_3^--N) contents. Soil properties analyses were directed by the Chinese Soil Society Guidelines (Lu 2000). Soil moisture on each sampling day was measured with a portable rod probe (MPM-160) and the values were further converted into water filled pore space (WFPS, %) by the formula (soil volumetric water content/(1 − (soil bulk density/2.65)) × 100 %), where 2.65 Mg m^{-3} is the assumed soil particle density (Liu et al. 2013). Grain yields were measured at physiological maturity by hand harvesting two rows 2 m long per plot. Aboveground biomass and grain yields of the rice for each treatment were determined at harvest by oven drying to a constant weight at approximately 70 %.

Statistical analyses

Statistical analyses were carried out using JMP version 7.0 (SAS Institute, USA, 2007). Differences in grain yield, cumulative CH_4 and N_2O emissions, GWP and GHGI over the whole rice growing season as affected by cropping regime, fertilizer application and their interaction were examined by using a two-way analysis of variance (ANOVA). The differences among treatments were further examined by the Tukey's multiple range tests. We conducted an ANCOVA on CH_4 and N_2O emissions with rice cropping system as the main effect and rice biomass as the covariate. A significant interaction (difference in regression slope) was interpreted as difference in the contribution of crop to CH_4 or N_2O emissions between the two cropping systems. Statistical significance was determined at the 0.05 probability level.

Results

CH_4 emissions

Seasonal pattern of CH_4 fluxes differed greatly between the DSR and TPR cropping systems, which was determined by irrigation regime over the rice growing season (Fig. 2). In the TPR plots, CH_4 fluxes gradually increased until the peak fluxes achieved approximately 2–3 weeks after rice transplanting when the fields were waterlogged. Thereafter, CH_4 fluxes decreased after midseason drainage and then remained at a level between 1–5 mg m^{-2} h^{-1}. In contrast to the TPR cropping systems, the relatively lower soil water content greatly decreased CH_4 flux in the DSR cropping systems under the water regime of moist irrigation, and even the phenomenon of frequent CH_4 uptake appeared as a result of drainage episodes (Figs. 1 and 2).

Seasonal total of CH_4 emissions from rice paddies significantly differed between the TPR and DSR cropping systems (Tables 1 and 2), Across treatments, seasonal fluxes of CH_4 averaged 1.58 mg m^{-2} h^{-1} and 1.02 mg m^{-2} h^{-1} in the TPR and DSR cropping systems, respectively. Relative to the DSR cropping regimes, on average, seasonal CH_4 emissions from the TPR cropping systems were increased by 39 % across field treatments. For the TPR cropping regime, seasonal fluxes of CH_4 averaged 1.68 mg m^{-2} h^{-1} and 1.49 mg m^{-2} h^{-1} for the plots with or without chemical N addition, respectively. In contrast, CH_4 fluxes averaged 0.98 mg m^{-2} h^{-1} for the plots applied with N fertilizer and 1.05 mg m^{-2} h^{-1} for the control without fertilizer application under the DSR cropping regime. However, seasonal total CH_4 emissions from rice paddies were independent of fertilizer application, or the interaction between fertilizer application and cropping regime (Tables 1 and 2), Compared with the control without fertilizer application, chemical N fertilizer application increased CH_4 emissions by 15 %, while decreased CH_4 emissions by 3 % for the plots under conventional TPR and DSR cropping regimes, respectively, but the differences were not statistically significant (Table 2).

N_2O emissions

Seasonal dynamics of N_2O fluxes was mainly regulated by field water status in the TPR and DSR cropping systems. In the TPR cropping systems, a large amount of N_2O emission was observed during the non-waterlogged period of rice growing season, i.e. the drainage and moist episodes (Fig. 3). Especially, midseason drainage led to an obvious trade-off between CH_4 and N_2O emissions, incurring a substantial peak flux of N_2O emission. In contrast, only a smaller N_2O emission was detected under the conditions of waterlogging, and flooding generally resulted in negligible N_2O flux throughout the rice growing season. In the DSR cropping systems under moist irrigation, substantial N_2O

Table 1 Yield, CH_4 and N_2O emissions and their net GWP (kg CO_2-equivalent ha^{-1}) and GHGI (kg CO_2-equivalent kg^{-1} grain yield) from seedling-transplanted (112 days) and direct-seeded rice cropping seasons (125 days) with (F) or without (C) N fertilization

Cropping system	Treatment[a]	Biomass (t ha^{-1})[b]	Yield (t ha^{-1})	CH_4 (kg ha^{-1})	N_2O-N (kg N ha^{-1})	GWP[c]	GHGI[d]
Seedling-transplanted	T-C	8.15±2.01b	4.25±0.21c	28.4±2.4ab	0.65±0.19c	1015±160a	0.24±0.02bc
	T-F	10.36±1.63ab	4.78±0.32b	32.5±8.2a	1.79±0.67ab	1651±458a	0.34±0.08a
Direct-seeded	D-C	12.58±3.89ab	4.86±0.23b	18.9±1.7b	0.95±0.26bc	920±157a	0.19±0.01c
	D-F	13.21±1.23a	5.93±0.48a	18.4±3.4b	2.69±1.21a	1722±147a	0.29±0.01ab

[a] *T-C* control plots in transplanted rice cropping system; *T-F* N fertilized plots in transplanted rice cropping system; *D-C* control plots in direct-seeded rice cropping system; *D-F* N fertilized plots in direct-seeded rice cropping system

[b] Different letters in a single column represent significant difference between treatments at the 0.05 probability level

[c] The IPCC GWP factors (mass basis, kg CO_2-equalivent ha^{-1}) for CH_4 and N_2O are 25 and 298 in the time horizon of 100 years, respectively (Forster et al. 2007)

[d] GHGI (kg CO_2-equivalent kg^{-1} grain yield) is calculated by dividing GWP of CH_4 and N_2O emissions by rice grain yield

Table 2 A two-way ANOVA for the effects of rice cropping system (CS) and fertilizer application (F) on yield, CH_4 and N_2O emissions, GWP and GHGI

Factors	DF	Yield (t ha^{-1})			CH_4 (kg ha^{-1})			N_2O-N (kg ha^{-1})			GWP (kg CO_2-equalivent ha^{-1})			GHGI (kg CO_2-equalivent kg^{-1} yield)		
		SS	*F*	*P*	*SS*	*F*	*P*	*SS*	*F*	*P*	*SS*	*F*	*P*	*SS*	*F*	*P*
Cropping system (CS)	1	11.18	22.25	<0.001	6102	9.89	0.01	2.46	5.89	0.02	465	0.007	0.94	0.01	7.17	0.03
Fertilizer (F)	5	16.08	6.40	<0.001	5715	1.85	0.14	14.91	7.14	<0.001	1549805	22.0	0.002	0.03	24.60	0.001
CS × F	5	2.86	1.14	0.36	3255	1.06	0.40	1.18	0.57	0.06	20825	0.30	0.60	0.00	0.003	0.95
Model	11	30.12	5.45	<0.001	15074	2.22	0.04	18.55	4.03	0.002	1571094	7.45	0.02	0.04	10.59	0.004
Error	24	12.06			14799			10.02			562680			0.01		

SS sum of squares; *F* F-value indicating the level of significant difference within or between variate groups; *P* P-value indicating statistical significance

flux was observed when N fertilizer was applied to the non-waterlogged fields (Fig. 3).

Seasonal total N_2O emissions were significantly affected by rice cropping regime, fertilizer application and tended to be affected by their interaction (Tables 1 and 2). Across field treatment plots, seasonal fluxes of N_2O averaged 138.19 μg N_2O-N m^{-2} h^{-1} in the DSR cropping systems, 49 % greater than those in the TPR cropping systems. Seasonal N_2O emissions from the controls, representing the background emissions of N_2O, totaled 0.95 kg N_2O-N ha^{-1} and 0.65 kg N_2O-N ha^{-1} in the DSR and TPR cropping systems, respectively. Relative to the control, fertilizer application increased N_2O emissions by 183 % and 175 % in the DSR and TPR cropping systems, respectively (Table 1). The interaction of fertilizer with rice cropping regime on N_2O emissions tended to be significant (p=0.06, Table 2), suggesting that the fertilizer-induced direct N_2O emissions were slightly greater in the DSR cropping systems than in the TPR cropping systems. The direct emission factor of fertilizer N for N_2O was estimated by the equation [(N_2O-N emissions from fertilized plots − N_2O-N emissions from control plots)/fertilized N × 100 %], which was estimated to be 0.69 % and 0.45 % under the DSR and TPR rice cropping systems, respectively.

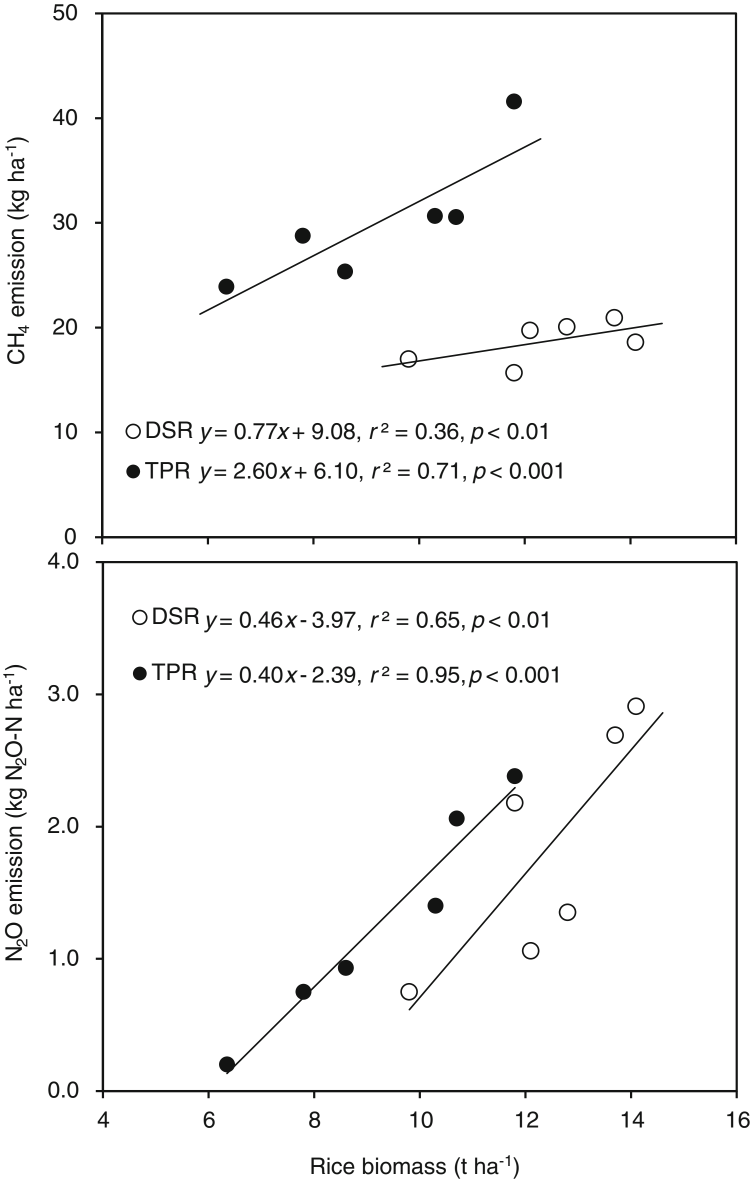
Correlation of CH_4 and N_2O emissions to rice biomass

Grain yields and biomass were significantly affected by rice cropping regime and fertilizer application, but were not significantly affected by their interaction (Tables 1 and 2). Relative to the TPR cropping regime, the DSR cropping system increased rice grain yields by 18 % across treatments. Compared with the controls, fertilizer application enhanced grain yields by 12 % and 22 % in the TPR and DSR cropping system, respectively. Seasonal CH_4 emissions linearly increased with rice biomass (or grain yield) in both rice cropping systems (Fig. 4, DSR: slope=0.77, $p<0.01$; TPR: slope=2.60, $p<0.001$). However, a difference in the slopes of the regression lines suggested that rice crop growth played a more important role for CH_4 emissions in the TPR system than in the DSR cropping system (ANCOVA, interaction term: p=0.05). Similar to CH_4, linear regressions of seasonal N_2O emission to rice biomass (or grain yield) were also pronounced in both rice cropping systems (Fig. 4). However, no significant difference in the slopes of the regression line suggested that rice crop growth played similar roles for N_2O emissions in the TPR and DSR cropping systems (ANCOVA, DSR: slope=0.46, $p<0.01$; TPR: slope=0.40, $p<0.001$; interaction term: p=0.86).

Net GWP and GHGI

Over the 100-year time scale, the net GWPs of seasonal CH_4 and N_2O emissions were significantly affected by fertilizer application, but independent of rice cropping regime and their interaction (Table 2). Compared with the TPR cropping systems, the DSR cropping regime decreased the net GWPs by 9 % but increased by 4 % for the control and fertilizer applied plots, respectively (Table 1). Relative to the controls, the net GWPs of CH_4 and N_2O emissions from the fertilizer applied plots were increased by 63 % and 87 % in the TPR and DSR

Fig. 4 Correlation of seasonal CH_4 and N_2O emissions with rice biomass under direct-seeded (DSR) and conventionally seedling-transplanted (TPR) rice cropping regimes



cropping systems, respectively. On the other hand, the GHGI relating GWP to crop yield was significantly affected by rice cropping regime, fertilizer application, but independent of their interaction (Table 2). Relative to the TPR cropping regime, the GHGI was decreased by 15 % and 23 % for the plots with or without N application in the DSR cropping systems (Table 1). Fertilizer N application increased GHGI by 40 % and 53 % in the TPR and DSR cropping systems, respectively. Overall, the comparable net GWP and lower GHGI from the DSR rice cropping system suggest that the DSR instead of TPR rice cropping system would mitigate the climatic impacts derived from CH_4 and N_2O emissions in terms of per unit of rice grain yield.

Discussion

Effects of rice cropping regime on CH_4 and N_2O emissions

Although CH_4 and N_2O emissions from rice paddies have been well documented over the past decades (Cai et al. 1997; Yan et al. 2005; Zou et al. 2005a, 2009;

Qin et al. 2010; Liu et al. 2010, 2012b), few measurements of CH_4 and N_2O fluxes were simultaneously taken from both DSR and TPR rice cropping systems in China. In turn, this study gives an insight into the effects of currently predominant rice cultivation practices on CH_4 and N_2O emissions from rice paddies. Clearly, CH_4 and N_2O emissions from croplands are generally associated with soil properties, cropping practice (e.g. crop cultivation practice), and climate. In this study, in view of the similar physicochemical properties of soils and climate between the two cropping systems, differences in seasonal CH_4 and N_2O emissions are presumably attributed to the distinct differences in rice cropping practice between the DSR and TPR rice cropping systems, particularly in water regime.

The seasonal patterns and intensities of CH_4 and N_2O emissions from the TPR cropping systems in this study were generally comparable to those previously reported on conventional rice paddies under a similar water regime in this area (Zheng et al. 2000; Zou et al. 2004, 2005a, 2009; Liu et al. 2010). Moist irrigation in the DSR cropping systems instead of F-D-F-M water regime in the TPR cropping systems mainly influenced CH_4 and N_2O emissions between the two cropping systems. Compared with DSR cropping regime, CH_4 emissions were significantly increased under the conventional TPR rice cultivation practice (Tables 1 and 2). Several reasons may account for the higher CH_4 emissions. Firstly, continuous waterlogging mostly dominated over the whole TPR rice growing season would benefit CH_4 production (Cai et al. 1997; Zheng et al. 2000; Zou et al. 2005a; Liu et al. 2012a, b). Moist irrigation in the DSR cropping systems would create an aerobic soil environment favorable for CH_4 oxidization, in contrast to anaerobic soil conditions aiding CH_4 production in the TPR cropping systems. Secondly, the rice plant serves as a main pathway of CH_4 emission, especially when fields are waterlogged, and the dependence of CH_4 emission on crop growth in rice paddies has been well documented (Huang et al. 2004; Zou et al. 2004; Yan et al. 2005; Ma et al. 2009). The difference in linear slope of relationship between seasonal CH_4 emission and rice biomass (Fig. 4) suggest that CH_4 emissions were more closely associated with rice crop growth in the TPR cropping system than in the DSR cropping system. In addition, the differences in CH_4 emissions between the two cropping systems might be influenced by some other biotic and abiotic factors characteristic to the rice cropping regime in this study, such as rice growth status, temperature, and soil characteristics, which are involved in the entire process of CH_4 emission, including production, oxidation and transport to the atmosphere (e.g. Schutz et al. 1989; Li and Lin 1993; Kumaraswamy et al. 2000; Mitra et al. 2002; Elder and Lal 2008).

Primarily, N_2O is produced as a by-product during soil microbial nitrification and denitrification processes (Malla et al. 2005), which are highly dependent on soil water status and fertilizer application (Fig. 2). Consistent with previous studies, N_2O emissions from the TPR cropping systems were negligible when the fields were waterlogged, but midseason drainage and dry-wet alteration episodes induced substantial N_2O emission in rice production (Smith et al. 1982; Zheng et al. 2000; Akiyama et al. 2005; Zou et al. 2005a; Liu et al. 2010). Relative to the conventional TPR rice cropping systems, the DSR rice cropping regime significantly increased N_2O emissions from rice paddies. Several explanations may be given for the higher N_2O emissions from DSR rice cropping systems. Firstly, the water regime of moist irrigation instead of F-D-F-M over the DSR rice cropping season would create soil moisture more beneficial for N_2O production (Liu et al. 2010). Indeed, N_2O emissions have been proved to be significantly higher from aerobic rice paddies as compared to anaerobic paddy fields (Xu et al. 2004). Secondly, the relatively higher crop biomass in the DSR cropping system may improve the interaction of soil–plant system and in turn facilitate N_2O emissions (Chen et al. 2008). Besides, shifts in rice production from conventionally anaerobic TPR to aerobic DSR rice cropping practice would alter a series of key soil factors involved in the processes of N_2O production, such as increased soil redox potential and changes in soil pH (Liu 1996; Gao et al. 2002), which may give rise to the differences in seasonal total N_2O emissions under the two rice cultivation practices.

Emission factor and background emission of N_2O

Nitrous oxide emissions were significantly increased by fertilizer application under both the DSR and TPR cropping regimes (Table 2). The emission factor of N_2O was estimated to be 0.69 % and 0.45 % in the DSR and conventional TPR cropping systems, respectively. The emission factors of N_2O under conventional TPR rice cropping regime are comparable to previous estimates in the rice paddies under the similar water regime (Akiyama et al. 2005; Zou et al. 2005b; Liu et al. 2010). Relatively higher N_2O emission factors from the DSR than conventional TPR rice cropping systems mainly resulted from the increased seasonal N_2O emissions facilitated by favorable soil water status during the DSR rice growing season. However, the values of seasonal emission factors under both rice cropping practices in this study fall within the range of previous estimates (0.42–0.79 %) in rice paddies with midseason drainage in this area (Zheng et al. 2004; Zou et al. 2007, 2009), slightly greater than those estimated by Yan et al. (2003) in the same area.

On the global basis, field- or region-scaled background emission of N_2O has been taken into consideration in N_2O estimation and given more attention in developing an inventory of N_2O emissions in some areas (e.g. Yan et al. 2003; Zheng et al. 2004). In this study, background N_2O emissions refer to those taken from the control plots without N application. The seasonal background emissions of N_2O in present study were estimated to be 0.95 kg N_2O-N ha^{-1} and 0.65 kg N_2O-N ha^{-1} in the DSR and conventional TPR rice paddies, respectively, comparable to the previous reports in rice-based cropping systems (Yan et al. 2003; Gu et al. 2009; Liu et al. 2010). The previous estimates indicated that background N_2O emissions from paddy rice-upland cropping rotation systems accounted for approximately 32–43 % of the total N_2O emissions from agricultural soils in China (Yan et al. 2003; Zheng et al. 2004; Lu et al. 2006; Gu et al. 2007; Liu et al. 2010). Since background N_2O emissions contributed considerably to the overall N_2O emissions from croplands, thus, more studies will be needed to accurately quantify background N_2O emissions from typical rice-based cropping systems under various rice cropping regimes.

Shifts in rice cropping regime and mitigation of GHGs in rice production in China

Recently, rice production is undergoing a shift from traditional TPR to DSR rice cropping regimes in southeast Asia (Pandey and Velasco 2002). This conversion was principally induced by the increasing cost of production mainly due to labor and water resources shortage (Chan and Nor 1993). The TPR rice cropping regime has high labor and water demands for uprooting nursery seedlings, pudding fields and seedling transplanting (Pandey and Velasco 2005). Therefore, DSR instead of the conventional TPR rice cropping practice would significantly decrease the water use and costs of rice production (Flinn and Mandac 1986). Clearly, emission of GHGs from rice paddies is highly sensitive to agricultural management practices (Wassmann et al. 2004). In the present study, higher grain yield, comparable GWP, and lower GHGI derived from CH_4 and N_2O emissions in rice production were simultaneously achieved under the DSR rice cropping regime. Overall, the results of this study suggest that the DSR instead of conventional TPR rice cropping regime would reduce the radiative forcing derived from CH_4 and N_2O emissions in terms of per unit of rice grain yield in China, and DSR rice cropping regime could be a promising rice development alternative in mainland China.

Conclusion

Shifts in current rice cropping regime from the conventional TPR to the increasingly adopted water-saving DSR rice cropping system play a vital role in mitigating CH_4 and N_2O emissions from rice paddies. The DSR rice cropping practice relative to TPR cropping regime significantly decreased CH_4 emissions, although slightly increased N_2O emissions. Chemical N application significantly increased N_2O emissions under both rice cropping systems. The fertilizer N-induced emission factor for N_2O tended to be higher in the DSR than in the TPR cultivation system. Overall, higher grain yield, comparable GWP, and lower GHGI suggest that the DSR instead of the conventional TPR rice cropping regime would lower the radiative forcing derived from CH_4 and N_2O emissions in terms of per unit of rice grain yield in China, and thus the DSR rice cropping system could be a promising rice cropping alternative in mainland China.

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