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Methane and Nitrous Oxide Emissions from Three Paddy Rice Based Cultivation Systems in Southwest China

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ABSTRACT

To understand methane (CH_4) and nitrous oxide (N_2O) emissions from permanently flooded rice paddy fields and to develop mitigation options, a field experiment was conducted in situ for two years (from late 2002 to early 2005) in three rice-based cultivation systems, which are a permanently flooded rice field cultivated with a single time and followed by a non-rice season (PF), a rice-wheat rotation system (RW) and a rice-rapeseed rotation system (RR) in a hilly area in Southwest China. The results showed that the total CH_4 emissions from PF were 646.3±52.1 and 215.0±45.4 kg CH_4 hm^{-2} during the rice-growing period and non-rice period, respectively. Both values were much lower than many previous reports from similar regions in Southwest China. The CH_4 emissions in the rice-growing season were more intensive in PF, as compared to RW and RR. Only 33% of the total annual CH_4 emission in PF occurred in the non-rice season, though the duration of this season is two times longer than the rice season. The annual mean N_2O flux in PF was 4.5±0.6 kg N_2O hm^{-2} yr^{-1}. The N_2O emission in the rice-growing season was also more intensive than in the non-rice season, with only 16% of the total annual emission occurring in the non-rice season. The amounts of N_2O emission in PF were ignorable compared to the CH_4 emission in terms of the global warming potential (GWP). Changing PF to RW or RR not only eliminated CH_4 emissions in the non-rice season, but also substantially reduced the CH_4 emission during the following rice-growing period (ca. 58%, $P<0.05$). However, this change in cultivation system substantially increased N_2O emissions, especially in the non-rice season, by a factor of 3.7 to 4.5. On the 100-year horizon, the integrated GWP of total annual CH_4 and N_2O emissions satisfies PF$\gg$RR$\approx$RW. The GWP of PF is higher than that of RW and RR by a factor of 2.6 and 2.7, respectively. Of the total GWP of CH_4 and N_2O emissions, CH_4 emission contributed to 93%, 65% and 59% in PF, RW and RR, respectively. These results suggest that changing PF to RW and RR can substantially reduce not only CH_4 emission but also the total GWP of the CH_4 and N_2O emissions.

Key words: cultivation systems, permanently flooded rice fields, CH_4, N_2O, global warming potential (GWP)

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1. Introduction

Atmospheric methane (CH_4) and nitrous oxide (N_2O) are two major greenhouse gases along with carbon dioxide (CO_2). All of these three gases have a potential contribution to current global warming, since their atmospheric concentrations have been increasing in the troposphere (IPCC, 2001). About 70%–90% of the recent increasing concentrations of CH_4 and N_2O in the atmosphere have come from biological sources, especially from agro-ecosystems (Iserman, 1994). As an important source of CH_4 and N_2O in the atmosphere, rice paddy soil has been widely considered by scientists worldwide (Chen et al., 1997; Abao et al., 2000; Xu et al., 2002; Ghosh et al., 2003; Yang et al., 2003; Zheng et al., 2000, 2004; Li et al., 2005). Many previous results have shown that permanently flooded rice fields were one of the rice field types with the largest CH_4 emission rates during the rice-growing season in China (Chen et al., 1993; Khalil et al., 1998a,

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1998b; Wei et al., 2000; Cai et al., 2003). Permanently flooded rice fields, which are flooded continuously in the cropping as well as fallow periods, are a special type of rice field in China. Their total area ranges from 2.7×10^6 to 4.0×10^6 hm^{-2} (Li, 1992), with no reliable, exact data so far. Permanently flooded rice fields are mainly distributed in mountainous areas of southern and southwestern China. They are formed for either one of the following two reasons: (1) difficulty in drainage because of hollow topography with a high ground water table; and (2) for the purpose of water stock in a rainfed area. Cai (1999) reported that permanently flooded rice fields, accounting for ca. 12% of the Chinese rice harvested area, release 45% of the CH_4 emission from Chinese paddy rice fields. While there is some preliminary knowledge about CH_4 emission from permanently flooded rice fields, N_2O emission from this type of rice field is not yet clear. Previous studies have found that changing permanently flooded rice fields into other cultivation systems may mitigate CH_4 emission (Yagi et al., 1997; Wang et al., 2000; Cai et al., 2003). But how this change may impact N_2O emission still remains unknown. To address these issues, we conducted a field experiment in situ for two years in a hilly area in southwestern China, in which we investigated CH_4 and N_2O emissions from three paddy rice based cultivation systems, which are a cropping system of rice cultivated once in a permanently flooded paddy field that remains fallow during the rest periods of the year (hereinafter referred to as PF), a rotation system of paddy rice and winter wheat (hereinafter referred to as RW), and a rotation system of paddy rice and oilseed rape (herein after referred to as RR).

2. Materials and methods

2.1 *Location and site description*

The site was selected at the Yanting Purple Soil Experimental Station of Agricultural Ecology (31°16′N, 105°27′E), which is one of the CERN (Chinese Ecosystem Research Network) field stations. The station is about 200 km away from Chengdu (the capital city of Sichuan Province, China) in the northeastern direction. The temporal distributions of daily precipitation and daily mean air temperature of the site within the experimental period are presented in Fig. 1. The total annual precipitation in 2003 and 2004 was 825.9 and 860.0 mm, respectively, and the annual mean air temperature in 2002 and 2003 was 16.4°C and 16.0°C, respectively. The soil for this study was classified as Purplish in the Second Soil Survey of China. It was developed from Jurassic purple shales and calcic purple rock (USSR Academy of Sciences, 1969; Zhao, 1986). The topsoil has been changed by continuous inundation and paddy rice cultivation. The soil properties are described as follows: clay (<0.002 mm) fraction, 8.4%; silt (0.002–0.05 mm) fraction, 69.3%; sand (>0.05 mm) fraction, 22.3%; pH (H_2O), 8.1; organic matter content, 21.0 g kg^{-1}; total N content, 1.22 g kg^{-1}; total P content (as P_2O_5), 0.44 g kg^{-1}; total K content (as K_2O), 17.4 g kg^{-1}; and available N preceding the start of the experiment in 2002, 89.2 mg kg^{-1}.

2.2 *Treatments*

The field used for PF was long-term permanently flooded. The soils used for the other systems were also permanently flooded in the historical period, but they were drained for cultivation of RW and RR twenty

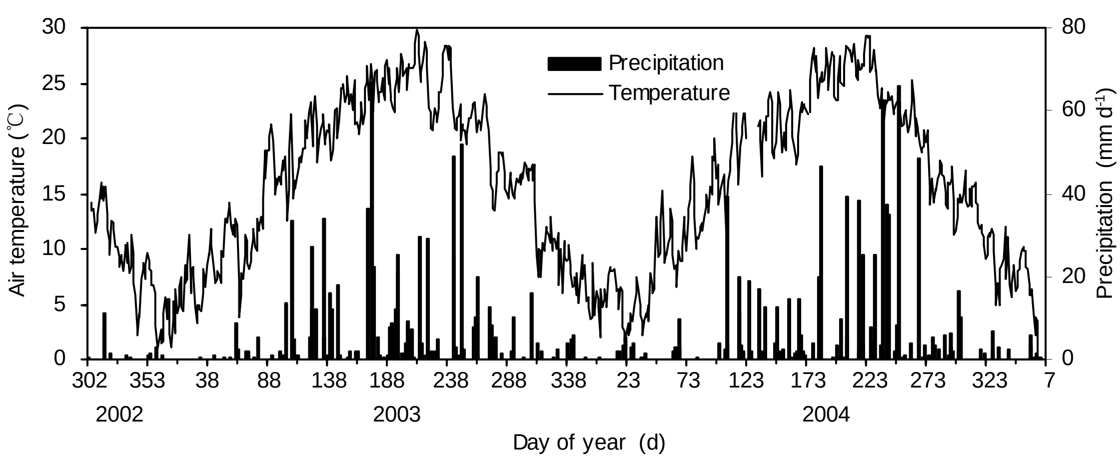

Fig. 1. Seasonal pattern of daily totals for precipitation and daily mean air temperature at the experimental site in Yanting county, China, during the period from late 2002 to early 2005.

Table 1. Field management practices of the three cultivation systems.

Year	Crop Rotation	Date of Transplanting Or Sowing	Basal Fertilization ($kg\ hm^{-2}$) Amounts ($N/P_2O_5/K_2O$)	Basal Fertilization Application date	Top Dressing ($kg\ hm^{-2}$) Amounts ($N/P_2O_5/K_2O$)	Top Dressing Application date	Date of Harvest
2002	Rice	May 8 2002	90/90/142	May 7 2002	60/0/0	May 25 2002	Sep 6 2002
	Wheat/Rape	Oct 29 2002	90/72/45	Oct 28 2002	60/0/0	Jan 6 2003	May 6 2003
2003	Rice	May 9 2003	90/90/142	May 8 2003	60/0/0	May 25 2003	Sep 7 2003
	Wheat/Rape	Oct 26 2003	90/72/45	Oct 25 2003	60/0/0	Jan 9 2004	May 4 2004
2004	Rice	May 14 2004	90/90/142	May 13 2004	60/0/0	May 31 2004	Sep 21 2004
	Wheat/Rape	Nov 4 2004	90/72/45	Nov 3 2004	60/0/0	Jan 9 2004	May 9 2005

Note: The fertilization treatments for rice applied to both the permanently flooded paddy rice cultivation system as well as the rice-wheat or rice-rape cultivation systems.

years ago, and since then they were only periodically flooded in the rice season. The emission fluxes of CH_4 and N_2O from PF, RW and RR were simultaneously measured throughout the year. For the convenience of data analysis and discussion, we divide the year into two crop seasons: the rice season and the non-rice season. The rice season starts from around early May and ends around mid September, but the exact date slightly varies year by year (see Table 1). In the RW and RR treatments, a floodwater layer was maintained during the rice crop season but was drained in the winter crop season for winter crop growth. Each field plot for a replicate of a treatment was 20 m long by 8 m wide, with a protection zone of 1–2 m wide around each plot to avoid possible edge effects. Each treatment has three replicates. The fields were ploughed one day before rice transplanting. Rice seeds (Oryza sativa L., cv. japonica hybrid II-You 162) were sown around early April in other plots and transplanted into the experimental plots around early May. The seedlings were manually transplanted at a density of 3 seedlings per hill and 24 hills per square meter. The local prevailing agricultural practices, such as water management regime, intermittent irrigation at mid-ripening (except for PF), mid-season drainage at panicle initiation (except for PF), application of insecticide and herbicide at tilling and at the end of the anthesis stages, and so on, were followed in all experimental plots. Winter wheat (Triticum aestivum L., cv. Chuannong 117) and rapeseed (Brassica napus L. cv. Mianyou II) were sown in early November in each year. Wheat was sown by broadcast sowing, and rapeseed was sown with a spacing of 40 cm×2.0 cm. Prior to sowing or transplanting, no straw (rice, wheat or rape) but only stubble (equivalent to ca. 2696, 2180 and 2176 kg hm^{-2} in dry matter, respectively) remained in the fields and was incorporated into the soil by plowing with oxen. The rates and dates of applications of nitrogen, phosphorus, and potassium mineral fertilizers are listed in Table 1. No additional organic fertilizers were applied in these treatments.

2.3 *Measurement of* CH_4 *and* N_2O *fluxes*

For each of the cultivation systems, one mini-plot of 0.5 m×0.5 m was defined for measurements of the CH_4 and N_2O emission fluxes. Each mini-plot included 6 hills of rice (or 5 plants of rapeseed and a 0.5 cm×0.5 cm area of wheat plants). Wooden boardwalks were set up for an access path to each mini-plot, to avoid physical disturbance of the field in measurement operations. A stainless steel base (0.5 m×0.5 m×0.2 m) with a water groove on top was installed at each mini-plot at sowing/transplanting and permanently remained there until harvest field preparation for sowing/transplanting of the following crop. The fluxes of CH_4 and N_2O were determined using the techniques of static opaque chamber and gas chromatography described by Wang and Wang (2003). For gas flux measurements, a portable stainless steel top chamber (0.5 m, 1.0 m or 2.0 m high, depending upon plant height), which fits exactly in the groove, was installed over the base, and a gas tight seal was formed by filling the groove with water. Gas samples from the headspace were taken with 100 mL gas-tight plastic syringes, via a Teflon tube that was connected to a three-port valve. A second tube (Φ1 cm×10 m, here Φ is the diameter) installed at one of the sides of the stainless steel chamber ensured the equilibration of air pressure between the inside and outside of the enclosure. Two ventilators driven by 12 V DC were installed inside the top chamber to avoid the formation of gas concentration gradients. During a period of 30 min, four gas samples were taken at an interval of about 10 min. Simultaneously, the air temperature inside the chamber and the air pressure were measured. The gas samples were analyzed simultaneously for CH_4 and N_2O in the laboratory (within a period of at most 8 hours after sampling), using a gas chromatograph equipped with a flame ionization detector and an electron capture detector (Wang and Wang, 2003). The slope of the linear regression curve for the CH_4 or N_2O concentration in the headspace of an enclosed chamber against enclosure time was directly used to calculate the flux, using measured air temperature and pressure to correct the density of the CH_4 or N_2O gas (Zheng et al., 2000). At a mini-plot, CH_4 (or N_2O) fluxes were measured twice per week, each between 0900 and 1100 LST.

The total seasonal CH_4 and N_2O emissions for each cultivation system in 2003 and 2004 were directly computed from the measured fluxes and by linear interpolation for those days with missing measurement data. This estimation was based on two assumptions: (1) the flux measured during 0900–1100 LST is representative of the daily mean (Zheng et al., 1998; Xu et al., 2004), and (2) the daily CH_4 (or N_2O) emission of the days with measurements absent between any two close days with available data could be represented by the arithmetic mean of the measured fluxes of these two days.

2.4 *Statistical analysis*

Data analyses were performed with SYSTAT 5.0 for Windows (SPSS, Inc.). A flux datum was considered valid only under the condition that the linear regression, on which basis the flux was calculated, was statistically significant ($p<0.05$, F-test). All the results of this paper are based on valid flux data. An one-way variance analysis test (ANOVA) was applied to determine the significant level for the effect of cultivation system on CH_4 and N_2O emissions.

3. Results and discussion

3.1 *Emission fluxes of* CH_4 *and* N_2O *from a permanently flood paddy rice field*

The CH_4 and N_2O fluxes in PF measured between 1 November 2002 and 2 November 2004 are shown in Table 2. During the rice-growing periods of 2003 and 2004, the average CH_4 effluxes were 20.95±2.58 and 21.93±2.66 mg m^{-2} h^{-1}, respectively. These emission rates were remarkably lower than the data previously measured in southwestern China, e.g. 54–79 mg m^{-2} h^{-1} (Leshan, Sichuan Province) reported by Chen et al. (1993), ca. 30 mg m^{-2} h^{-1} (Chongqing) by Wei et al. (2000), and ca. 34 mg m^{-2} h^{-1} (Leshan, Sichuan Province) by Khalil (1998a, b). One possible reason for the difference is that no additional organic fertilizer was applied in this experiment, while organic manure was incorporated into the soil before rice transplantation in the previous experiments (Chen et al., 1993; Khalil et al., 1998a, b; Wei et al., 2000; Cai et al., 2003). It is well known that the application of organic manure usually stimulates CH_4 emission from paddy rice fields (Wang, 2001; Denier van der Gon and Neue, 1995; Wang et al., 2000; Zou et al., 2004). Another reason is that the difference in soil properties and other local climatic or environmental factors may, to some extent, account for the difference in methane emission. Since the latest decade, less and less organic manure has been applied in paddy rice fields of China, including the permanently flooded paddy fields in the southwest. Thus an update of the knowledge on the methane emission from permanently flooded paddy rice fields on the basis of in situ long-term measurement is necessary. As compared with the CH_4 emission fluxes from those paddy rice fields only receiving mineral fertilizers (Khalil et al., 1998b; Wang, 2001), the CH_4 fluxes we measured in this study are somewhat higher.

The CH_4 emission from permanently flooded paddy rice fields occurs not only during the rice-growing period, but also during the fallow periods of the year, which are as long as 230–250 days. The mean CH_4 efflux we measured in this study was 3.77±0.99 mg m^{-2} h^{-1} during the non-rice periods, which is much lower than the value of 13 mg m^{-2} h^{-1} reported by Wei et al. (2000). The CH_4 emissions during the non-rice periods of 2002–2003 and 2003–2004 accounted for 16% and 49% of the total annual emission, respectively. The relatively lower CH_4 effluxes occurring during the non-rice periods, as compared to those in the rice-growing period, can most likely be attributed to three factors: (1) lower temperature, (2) a thicker floodwater layer, and (3) the absence of plant aerenchyma for transferring CH_4 from submerged soil to the atmosphere (Jean and Pierre, 2001; Wang, 2001).

As shown in Table 2, the annual mean N_2O fluxes were 0.038±0.010 and 0.064±0.009 mg m^{-2} h^{-1} in the periods of 2002–2003 and 2003–2004, respectively, with a mean value of 0.05±0.01 mg m^{-2} h^{-1}. The mean N_2O fluxes were 0.13±0.02 and 0.01±0.01 mg m^{-2} h^{-1} during the rice-growing season and the non-rice periods, respectively. The former is about 10 times larger than the latter. The difference may be due to three reasons. Firstly, nitrogen supplies, as the substrates for N_2O formation via nitrification and denitrification (Aulakh et al., 2001), are only available in the rice season, due to basal fertilizer application preceding rice transplantation and fertilizer topdressing at early tillering. Secondly, the temperature, which is one of the major regulatory factors for N_2O production and emission processes (Smith et al., 1998), is remarkably higher in the rice season than during the non-rice periods (25.1°C versus 13.2°C). Thirdly, rice plants in the growing season may produce N_2O itself (Chen et al., 1997) and may also transport N_2O produced in the submerged soil to the atmosphere via aerenchyma (Lensi and Chalamet, 1981; Xu et al., 2001; Mosier et al., 1990). The mean of the total N_2O emission during the rice-growing period was 3.8±0.7 kg hm^{-2}, accounting for 84% of the annual total amount.

Table 2. Fluxes of CH_4 and N_2O emissions from a permanently flooded paddy field.

Period	Time (days)	Observations	Gas	Flux (mg N_2O/CH_4 m^{-2} h^{-1}) Range	Mean±SE	Seasonal emission ($kg\ hm^{-2}$)
Whole year	365	94	CH_4	0.04–54.37	8.02±1.05	702.7±92.3
(1 Nov 2002 to 31 Oct 2003)			N_2O	−0.11–0.51	0.04±0.01	3.4±0.9
Rice	121	41	CH_4	0.10–54.37	20.95±2.58	608.3±74.9
(9 May to 7 Sep)			N_2O	−0.11–0.51	0.09±0.01	2.6±0.3
Fallow	244	53	CH_4	0.04–27.01	1.61±0.37	94.4±21.9
(1 Nov to 8 May, 7 Sep to 31 Oct)			N_2O	−0.09–0.12	0.01±0.01	0.7±0.8
Whole year	365	97	CH_4	0.49–47.18	11.61±0.86	1019.9±75.9
(31 Oct 2003 to 2 Nov 2004)			N_2O	−0.20–0.38	0.06±0.01	5.6±0.8
Rice	130	45	CH_4	0.79–47.17	21.93±2.66	684.4±83.0
(14 May to 21 Sep)			N_2O	−0.04–0.38	0.16±0.03	5.0±1.1
Fallow	235	52	CH_4	0.49–30.26	5.92±0.36	335.6±20.1
(1 Nov to 13 May, 22 Sep to 2 Nov)			N_2O	−0.20–0.15	0.01±0.01	0.6±0.4

Note: SE refers to standard errors for three replicates, the same below.

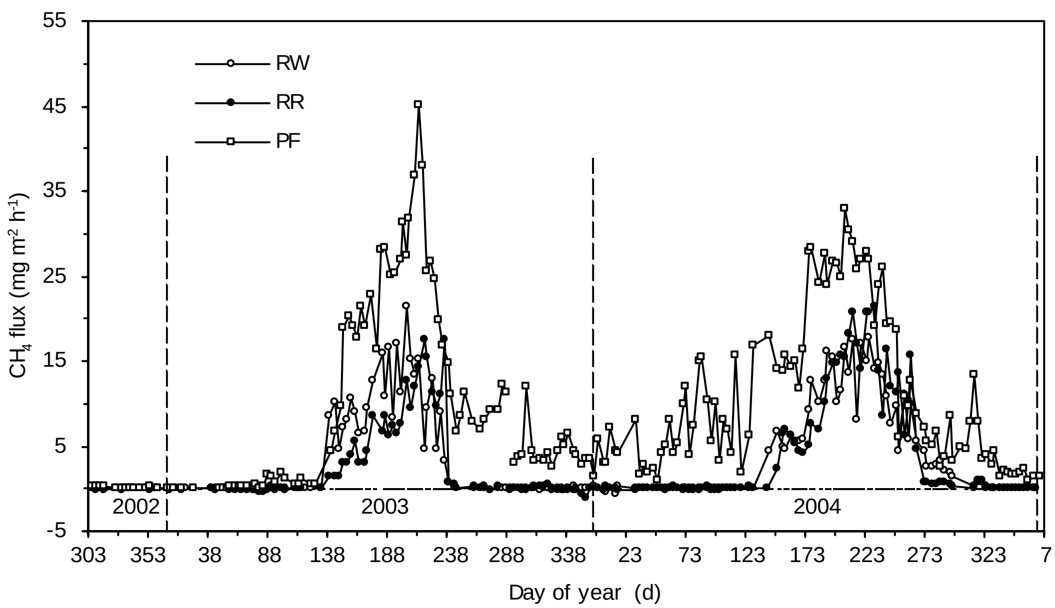

Fig. 2. Seasonal variations of CH_4 fluxes from three cultivation systems in a hilly area of Southwest China (Yanting, mean flux of three triplicates) during the period from late 2002 to early 2005. RW, rice and wheat rotation; RR, rice and rapeseed rotation; PF, permanently flooded rice paddy fields cultivated once and fallow in the non-rice season.

3.2 *Effects of cultivation system on* CH_4 *and* N_2O *emissions*

3.2.1 CH_4 *emission*

The CH_4 fluxes from paddy rice fields under the three cultivation systems are shown in Fig. 2. There was a remarkable common seasonal variation pattern of CH_4 flux for each cultivation system. The CH_4 emission fluxes were low during the non-rice periods, but they increased gradually with time after rice transplantation. The strongest CH_4 emission peak in a year was found at the rice heading and flowering. Then the CH_4 fluxes clearly decreased. In the RW and RR, the fluxes were further reduced to near zero soon after the fields were finally drained. In the PF, the effluxes fluctuated around a certain level for a short period of time before winter, then remained stable at a lower level during winter, and gradually increased for a short period of time before rice transplantation in the following spring.

The seasonal means of CH_4 fluxes from PF, RW and RR were 22.26, 9.74 and 9.04 mg m^{-2} h^{-1}, respectively, during the rice-growing period. The annual means of CH_4 effluxes from PF, RW and RR were 10.13, 3.43 and 3.11 mg m^{-2} h^{-1}, respectively. Both the annual means of CH_4 emission fluxes and the seasonal means in the rice-growing period were significantly different among the three cultivation systems ($p<0.05$, one-way ANOVA). These results suggest that changing a permanently flooded rice cultivation system into a seasonally flooded cultivation system as, e.g., a rotation system of rice-wheat or rice-rapeseed, may remarkably reduce CH_4 emission, while the crop yield is remarkably increased (the total rice yields of RW and RR were 8856 and 8606 kg hm^{-2} during the investigation period, being 43% and 39% higher than that of PF).

Because the dates for the rice transplantation and harvesting varied (Table 2), the duration of the rice crop season was 121 days in 2003 and 130 days in 2004, and that of the winter crop season was 244 days in 2002–2003 and 235 days in 2003–2004. Though the seasonal mean flux during the fallow period was remarkably lower than that of the rice season (Table 2, Fig. 2), the seasonal total CH_4 emissions of the two seasons of PF were comparable in magnitude (Fig. 3), as the fallow duration was much longer. In the rice-growing season, the largest seasonal total CH_4 emission was observed in PF (646.3 kg hm^{-2}), followed by RW (282.89 kg hm^{-2}) and RR (262.64 kg hm^{-2}). The annual total CH_4 emission from PF was also the highest, on average being 888.8 kg hm^{-2}, of which 27% was emitted during the winter fallow season. The net CH_4 exchange amounts in the non-rice season of RW and RR were negligible, being only 6% (18.4 kg hm^{-2}) and 4% (10.0 kg hm^{-2}) of the emission in the rice season, respectively. Consequently, the annual total CH_4 emission was reduced by 66% to 69% ($p<0.05$) due to changing the permanently flooded paddy rice fields to seasonally flooded rice-wheat or rice-rapeseed rotation systems.

A direct inhibitory effect of drainage in the non-rice season on CH_4 emission in the current season is understandable, because the prerequisite condition (anaerobic condition) for CH_4 production is eliminated as long as the floodwater layer disappears. In this field experiment, however, we observed that seasonal drainage during the non-rice period also reduced the CH_4 emission that occurred during the following rice season. This result was consistent with previous reports based on experiments in a greenhouse (Trolldenier, 1995; Xu et al., 2002) and in the field (Kumagai and Konno, 1998). It is most likely caused by two factors. Firstly, it is probably due to the change in soil redox potential (Eh). Drainage in the non-rice season restores the soil Eh that had decreased under submerged conditions during the previous rice-growing period. Methane production is inhibited at high soil Eh and increases gradually with a decrease in soil Eh. If soil is continuously flooded during the entire fallow season, its Eh may always remain at a lower level, which allows for CH_4 production. This explanation may be supported by the experimental evidence that a significant correlation between Eh and CH_4 flux in the rice season was found in the soils with unsaturated moisture in the non-rice season but not observed in those flooded for the entire non-rice season (Xu et al., 2002). Secondly, it may also be due to the change in available carbon. During the aerobic non-rice period, bio-available carbon may be lost as CO_2, and as such, less carbon is available for methanogenesis during the subsequent rice-growing period. In addition, we cannot exclude other possibilities. For instance, the population and activities of methanogens may decrease under aerobic conditions in the non-rice season (Ueki et al., 1997). But recovery of the population and their activities may take some time after re-flooding the soil. This may also delay CH_4 production and emission. However, the effects of the water regime in the non-rice season on the population and activities of methanogens (archaebacteria) have not been fully understood and are worth investigating further.

3.2.2 N_2O *emission*

The N_2O fluxes from the three cultivation systems are shown in Fig. 4. They were significantly lower than the CH_4 fluxes, but there were many strong N_2O emission pulses. The N_2O flux ranged from -268 to 2412 μg m^{-2} h^{-1}. As shown in Fig. 4, N_2O emission pulses were found after the application of basal fertilizers, topdressing fertilizers and final water drainage, indicating that N_2O flux is affected by N fertilizer addition, soil moisture, and soil temperature (Davidson et al., 1996; Kaiser et al., 1998; Zheng et al., 2000; Dobbie and Smith, 2003). In RW and RR, the largest peak of N_2O emission occurred following the application of basal fertilizers for wheat or rapeseed. Due to this

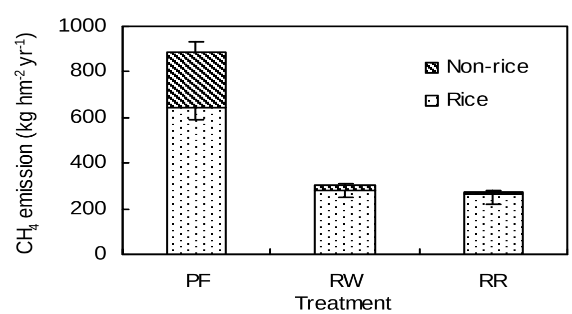

Fig. 3. Total annual and seasonal CH_4 emissions (two-year average) from three cultivation systems in a hilly area of Southwest China. Definitions of PF, RW and RR are found in Fig. 2 and in the text. Bars refer to the standard error of six observations (in two years).

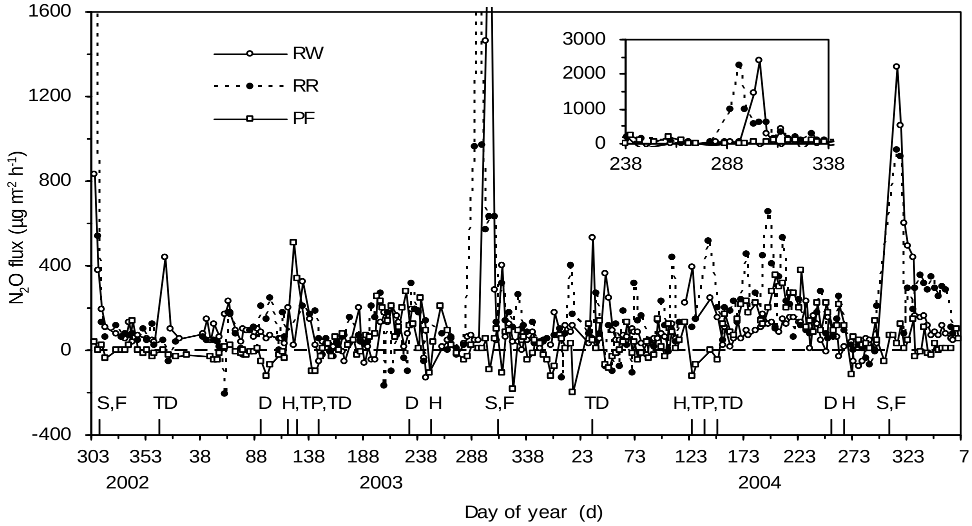

Fig. 4. Seasonal variations of N_2O fluxes from three cultivation systems in a hilly area of Southwest China (Yanting, mean flux of three triplicates) during the period from late 2002 to early 2005. Definitions of PF, RW and RR are found in Fig. 2 and in the text. S, seeding; F, fertilization; TD, top dressing; H, harvest; TP, transplanting; D, drainage.

Table 3. Fluxes of N_2O emissions from rice paddy fields under the three cultivation systems.

Period	Cultivation system	Time (days)	Observations	Mean Flux (μg N_2O m^{-2} h^{-1})	Seasonal emission (kg N_2O hm^{-2})
Whole year	PF	365	97	29.0±3.8	3.1±0.7
(9 May 2003 to 8 May 2004)	RW	365	98	126.4±10.5	11.5±0.9
	RR	365	98	159.0±2.9	13.9±0.2
Rice	PF	124	36	85.4±11.2	2.5±0.3
(9 May to 5 Sep)	RW	119	37	82.3±15.4	2.8±0.4
	RR	119	37	113.3±15.2	3.2±0.4
Non-rice	PF	241	61	9.7±7.3	0.6±0.4
(6 Sep 2003 to 8 May 2004)	RW	246	61	147.8±8.3	8.7±0.5
	RR	246	61	181.2±11.4	10.7±0.7

Note: PF, RW, and RR represent permanently flooded paddy rice fields, rice-wheat and rice-rapeseed rotation cultivation systems, respectively.

pulse emission, about 22% and 25% of the total annual N_2O emissions in RW and RR, respectively, were released during the earliest period of 20 days after the wheat/rapeseed sowing.

The seasonal mean N_2O fluxes and total emissions from the three cultivation systems are shown in Table 3. The data indicate that total annual N_2O emission increased substantially (by a factor of 4–5) after changing the cultivation system from PF to RW or RR. However, the increase in seasonal accumulative N_2O emission due to these changes in cultivation system was only significant in the non-rice season (by a factor of 16–19), but not at all during the rice-growing period. Though the duration of the non-rice season was longer, and the temperature was lower, compared to the rice-growing season, the mean N_2O fluxes of the non-rice season were greater than in the rice season by 79.7% and 59.8% (p<0.05) in RW and RR, respectively, but only by 11.3% (p<0.01) in PF. It is a pleasing result that the mean annual N_2O flux was almost two orders of magnitude less than that of CH_4 in the same cultivation system; and thus the total annual amount of N_2O emission from an individual cultivation system is much lower than that of CH_4.

3.3 *Global warming potential* (*GWP*) *of* CH_4 *and* N_2O *emissions*

The concept of GWP was developed to compare

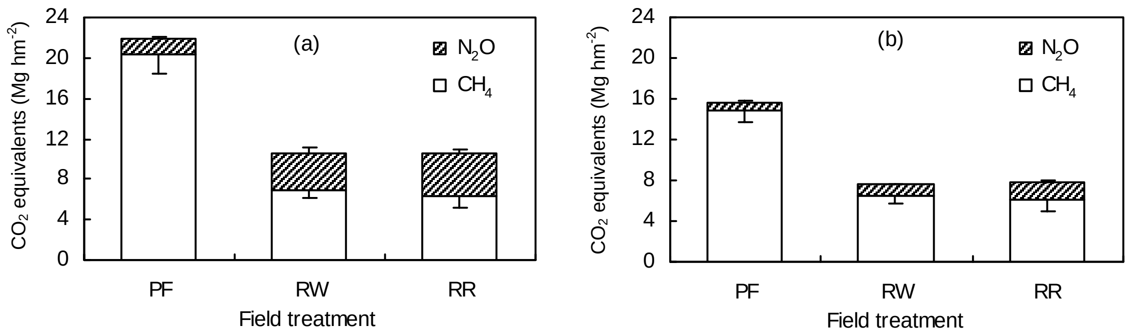

Fig. 5. The total global warming potential (GWP, expressed as CO_2 equivalent) of CH_4 and N_2O emissions in three cultivation systems in a hilly area of Southwest China. (a) In the whole year (from 1st January to 31 Dec; (b) During the rice-growing period. Definitions of PF, RW and RR are given in Fig. 2 and in the text. Bars refer to the standard error of six observations (in two years).

the ability of a gas to trap heat in the atmosphere relative to CO_2. The GWP of a greenhouse gas is a CO_2 equivalent. It is determined by multiplying its mass with its GWP coefficient. The GWP coefficient of a gas means that a unit mass of this gas is equivalent to a certain unit mass of CO_2 in terms of the ability to trap heat (Shine et al., 1995). On a 100-year time horizon, the GWP coefficients of CH_4 and N_2O are 23 and 296, respectively (IPCC, 2001). The GWP of CH_4 and N_2O released from each cultivation system is thought to be an integrative criterion to assess the contribution of the system to the global warming effect in terms of CH_4 and N_2O emissions. Figure 5 shows the GWP of CH_4 and N_2O emissions from the three cultivation systems. The total annual GWP satisfies PF$\gg$RR$\approx$RW, with the GWP of PF being higher than that of RW and RR by factors of 2.6 and 2.7 (p<0.01), respectively (Fig. 5a). This suggests that the drainage of floodwater for a subsequent upland crop in the winter season not only eliminates CH_4 emissions from this season, but also largely reduces the total annual GWP of emissions of both gases, as compared to the permanently flooded paddy rice cultivation system.

Of the GWP of total annual N_2O and CH_4 emissions, nitrous oxide contributes a very low share (only 7%) in PF but relatively higher shares in RW (35%) and RR (41%). This suggests that both the CH_4 and N_2O emissions are important in RW and RR, but only CH_4 emission may be a serious concern in PF.

In the rice-growing season, the seasonal total GWP of CH_4 and N_2O emissions also satisfies PF$\gg$RR$\approx$RW (Fig. 5b), with the former significantly higher than the latter two by a factor of 2.0 to 2.1 (p<0.05), though the N_2O emission was enhanced due to the intermittent drainage in the rice-growing season in RW and RR. The intermittent drainage in the rice-growing season is considered as a main option for mitigating CH_4 emission from rice fields in Asia (Van Amstel and Swart, 1994) and as an important approach to suppress the development of a number of non-effective tillers, to promote the growth of rice roots, and to obtain a high yield. In fact, the water regime of most of the irrigated rice fields in China involves alternate flooding and draining after the tilling stage. Nevertheless, previous reports have stated that the reduction and oxidation cycle caused by intermittent drainage would lead to an increase in N_2O emission (Letey et al., 1980) and therefore would offset the mitigation of CH_4 emission resulting from the intermittent drainage of the rice fields (Cai et al., 1997; Chen et al., 1997). However, our field experiment results have showed that the total GWP of CH_4 and N_2O emissions during the rice-growing period were dominated by CH_4 emission, and the shares of N_2O emission were only 6%, 15% and 23% in PF, RW and RR, respectively. This result further confirms that intermittent irrigation in the rice season is an effective measure to reduce the total GWP of CH_4 and N_2O emissions.

4. Summary

Previous field experiment studies have reported that permanently flooded rice fields release CH_4 in the rice season at the largest level of flux. However, our field experiments resulted in much lower CH_4 fluxes, especially in the non-rice period. The CH_4 emission in the rice season was found to be more intensive in the permanently flooded rice fields than in the rice-wheat or rice-rapeseed rotation systems. The total CH_4 emission in the non-rice season of permanently flooded rice fields was 13% to 33% of the total annual CH_4 emission. The amounts of the N_2O emissions were negligible compared to CH_4 in terms of the sum of the CO_2 equivalence of both gases released from the permanently flooded rice fields.

The drainage of floodwater at the rice harvest time and the growing of upland crops (winter wheat or rapeseed) in the non-rice season not only eliminated CH_4 emissions from the non-rice season, but also remarkably reduced the CH_4 emission in the following rice season. However, the N_2O emission was substantially increased after the permanently flooded rice paddy fields were changed into rice-wheat or rice-rapeseed cultivation systems. On the 100-year horizon, the total GWP of CH_4 and N_2O emissions from the three cultivation systems satisfies PF$\gg$RR$\approx$RW, with the value for PF being higher than that for RW and RR by factors of 2.6 and 2.7, respectively. Methane emission contributed more than 90% of the total GWP of the CH_4 and N_2O emissions in PF but only around 60% in RW and RR. Changing the permanently flooded paddy rice cultivation system to a rice-wheat or rice-rapeseed rotation system substantially reduced the CH_4 emission as well as the total GWP of the CH_4 and N_2O emissions.

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