Biogeochemistry **56:** 75–91, 2001.

CH_4 emissions from rice paddies managed according to farmer's practice in Hunan, China

ZUCONG CAI[1,*], HARUO TSURUTA[2], XIANMIN RONG[3], HUA XU[1] & ZHENGPING YUAN[3]
[1]*LMCP, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China;*
[2]*National Institute of Agro-environmental Sciences, 3-1-1, Kannondai, Tsukuba, 305 Japan;*
[3]*Division of Agricultural Chemistry, Hunan Agricultural University, Changsha, 410128, China (*Author for correspondence; e-mail: zccai@ns.issas.ac.cn)*

Key words: farmer's practice, flooded fallow, green manure, methane emission, rice fields

Abstract. We measured CH_4 emissions from rice paddies managed by farmer's practices in Changsha, Hunan Province, China, from 1995 to 1997. During the winter season, rice fields were left fallow under either drained (C-Fallow) or flooded conditions (C-Flood), and planted with either Chinese milk vetch (C-GM) or oil-seed rape (C-Rape). The organic manure produced in the winter (weeds, Chinese milk vetch, or oil-seed rape straw) was incorporated *in situ* before the early-rice transplanting. Both early-rice and late-rice straws were removed and the soil was not amended with any exogenous organic manure. For 1996 to 1997, the average seasonal CH_4 emission for the double rice cropping period was the highest from the plot that was flooded in the winter (103.5 g CH_4 m^{-2}) and lowest from the plot planted and incorporated with Chinese milk vetch (32.6 g CH_4 m^{-2}). Precipitation in the winter not only affected growth of green manure, which was incorporated *in situ*, but might also affect CH_4 emissions during the subsequent rice growing period. Therefore, a simple relationship could not be found between the incorporated amount of green manure and CH_4 emission. In the plots incorporated with vetch and oil-seed rape straw CH_4 emissions were significantly less during the subsequent late-rice period than during the early-rice period. This phenomenon might be attributed to a 'priming effect' of green manure, which exhausted soil labile organic matter. Based on the CH_4 flux measurements, the total CH_4 emissions from rice fields in Hunan Province during the rice growing season were estimated as 1.56 Tg CH_4 in 1996 and 1.06 Tg CH_4 in 1997. Large variation of precipitation in the winter would be an important factor controlling the annual variation of CH_4 emissions from the treatments.

Introduction

Wetland and irrigated rice fields are recognized as among the most important sources of atmospheric CH_4 (Cicerone & Oremland 1988). Since the early 1980s, great efforts have been made to estimate CH_4 emissions from rice fields around the world (Cicerone & Shetter 1981). CH_4 emission from rice fields is the net result of CH_4 production, oxidation, and transport. Many factors such as the water regime (Yagi et al. 1997), fertilization practices (Banik et al. 1996), rice cultivars (Watanabe et al. 1995; Sigren et al. 1997; Ding et al. 1999), plant density (Schutz et al. 1989a), and soil properties (Watanabe & Kimura 1999) affect CH_4 emissions from rice fields by influencing CH_4 production, oxidation, transport, or all three. Options for mitigating CH_4 emissions from rice fields have also been intensively discussed (Yagi et al. 1997). However, CH_4 emissions from actual farmer's practice have been measured scarcely. Farmer's practice for rice cultivation is comprehensive. The measurements in the rice fields managed according to actual farmer's practice are imperative for estimating CH_4 emissions from rice fields and verifying model simulation.

China is an important rice-producing country, accounting for 22.6% of the world's rice-harvested area and 36.3% of the world's rice production in 1990 (International Rice Research Institute 1991). Early field measurements reported by Khalil et al. (1991) revealed that CH_4 emissions from Chinese rice fields, which they estimated to be as high as 30 Tg CH_4, were substantially higher than emissions elsewhere in the world. Sass (1994) estimated that CH_4 emissions from Chinese rice fields accounted for 37.6% of the total emissions from the wetland rice fields of the world. Recently, Cai et al. (2000) attributed high CH_4 emissions from some types of rice fields in China to the flooding of those rice fields in the winter season.

The land use and management in the winter season is multiple and varies in region to region in China. Generally, the land uses of rice fields in the winter include planting upland winter crops, such as wheat, barley, green manure crops, oil-seed rape, and so on, and fallow under either well-drained or flooded conditions. Growing crops such as Chinese milk vetch in the winter season after rice harvesting and incorporating them *in situ* as green manure before rice transplanting next year is a traditional practice. Although such land use and management is still practiced, the area in which green manure is grown has been dramatically reduced in the past two decades (see Cai 1997). That an increase in CH_4 emissions from rice fields can result from the application of green manure is well documented (Lauren et al. 1994). Therefore, a decrease in the area in which green manure is planted and applied *in situ* would probably lead to a decrease in CH_4 emissions as rice production in China due to changes from traditional to modern methods (Denier van der Gon 1999). However, the mixed effect of land use and water management in the winter season on CH_4 emissions has rarely been assessed under field conditions.

Hunan Province in central China produces more rice than any other provinces in China. The rice-harvested area of the province, dominated by double-rice crops, in 1997 accounted for 12.8% of the rice-harvested area nationally and for 12.4% of the rice product. The total rice-harvested area in the province in 1997 was 4.0758 Mha, of which 1.6512 Mha was for early-rice, 1.9096 Mha was for late-rice, and 0.5150 Mha was for single-rice (Editorial Board for Agricultural Yearbook of China 1998). Wassmann et al. (1993) first reported CH_4 emissions from rice fields in Taoyuan, Hunan Province, but focused on treatment effects and did not estimate total CH_4 emissions. Agricultural Statistics of Hunan Province compiled by Agricultural Department of Hunan Province, Hydraulic Department of Hunan Province, and Forestry Department of Hunan Province (1998) showed that rice fields were either in fallow and drained (accounting for 17.4% of the total) or in fallow and flooded (8.4%) or planted with green manure, usually Chinese milk vetch (38.7%) and oil-seed rape (35.5%) in the winter. Green manure and oil-seed rape straw are commonly incorporated into the soil *in situ* when fields are prepared about two weeks before early-rice transplanting in April. Early rice crop is transplanted in early May and harvested in July. The fields are ploughed and prepared for late rice transplanting immediately after early rice harvesting. The interval between early rice harvesting and late rice transplanting is usually less than one week. Late rice is harvested in middle October. Generally, early-rice and late-rice straws are removed from the fields, and the soil is not further amended with exogenous organic manures. Water regime for early rice is relatively homogenous, i.e. continuously flooded until aerated at a late tillering stage and then so-called wet irrigation that means surface soil is water-saturated but a floodwater layer is not necessary until harvesting. For late rice, the water regime is the same as for early rice but fields are drained before harvesting.

Our previous pot experiment studies have shown that winter land use and management significantly affect CH_4 emissions during the subsequent rice season (Cai & Xu 1998; Xu et al. 2000). To understand the effects of land use and water management in the winter on CH_4 emissions during the subsequent rice growing period, we measured CH_4 emissions from rice fields treated differently in the winter but similarly during the rice season in Hunan Province from 1995 to 1997, following farmer's practice. An estimate was made on CH_4 emission from rice fields in the province using results from the field measurements.

Materials and methods

Our measurements of CH_4 emissions from rice fields were conducted at the Hunan Agricultural University Experimental Farm in Changsha, the capital of Hunan Province. The mean annual precipitation from 1993 to 1997 was 1613

Table 1. Soil properties in the experimental field in Changsha, Hunan Province, China

Properties	Value
pH	5.86
Organic carbon, mg g^{-1}	12.80
Total N, mg g^{-1}	1.46
Total P, mg g^{-1}	1.83
Total K, mg g^{-1}	19.00
Available P*, μg g^{-1}	6.40
Available K*, μg g^{-1}	79.60

*Olson-P and NH_4OAc extractable K.

mm, with a very large annual variation, and the mean annual temperature was 17.0 °C (Editorial Board for Agricultural Year Book of China 1994–1998). The highest temperatures occurred in July and August, when late rice was transplanted. After rice harvest in 1994, we divided a rice field at the experimental farm into four sub-plots, which were then left fallow and drained (C-Fallow), planted with Chinese milk vetch (C-GM), planted with oil-seed rape (C-Rape), or left fallow and flooded (C-Flood). The soil of the field was Epiaquepts. Before the experiment, soil samples were collected and soil properties analyzed (Table 1).

Because of low profit of rice production, farmers manage their land extensively in the winter and do not apply fertilizers for growth of Chinese milk vetch or oil-seed rape. The fertilization and water management followed local farmer's practices throughout the experiment. Weeds grew well in C-Fallow, but did not grow in C-Flood. The fresh weight of weeds, Chinese milk vetch in C-GM, and oil-seed rape straw in C-Rape were measured, and varied from year to year (Table 2). All produced manure was incorporated *in situ* by plowing for early-rice transplanting. After harvest of early rice, the straw about 10 cm above ground was removed and the residues were incorporated by plowing for late-rice transplanting. No exogenous organic manures were incorporated into the soil when the plots were prepared for late-rice transplanting. Water management during the rice-growing seasons followed the local farmer's practice as well and was similar in all plots. The plot drained in the winter was flooded one to two weeks before early-rice transplanting. A floodwater layer was maintained until tillering stage when the first mid-season aeration was conducted. Afterwards, the plots were irrigated and kept soil with water saturated, but not continuously flooded, until harvest. After early rice harvesting, the plots were flooded immediately for plowing. The water regime for late-rice production was similar to that for early-rice production, but the fields were drained before harvesting. Chemical fertilizers used for early-rice and late-rice production are also shown in Table 2.

Methane fluxes were usually measured twice a week (every 3 or 4 days) throughout the period of rice growth using a closed-chamber method as described by Yagi and Minami (1991). Sampling chambers, 51 × 51 × 100 (height) cm, were made of Plexiglas. Gas samples were usually collected in the morning between 1000 and 1200. Chambers were placed on a fixed frame in each plot, and gas samples were collected with a syringe and transferred immediately to evacuated vials (17 ml in volume) stopped with butyl rubber septa.

Methane concentration in the gas samples was determined within six months with a GC/FID (Shimadzu 12A) in the Laboratory of Material Cycling in the Pedosphere, Institute of Soil Science, Chinese Academy of Sciences. A pretest showed that the samples in the vials were stable for at least one year. The standard gases were cross-checked by the Japan National Institute of Agro-environmental Sciences laboratory. Methane fluxes were calculated from the concentration changes in the chamber at 0, 10, 20, and 30 min after the chamber was placed on the fixed frame. Soil properties were analyzed using routine methods (Committee for Agro-chemistry, Soil Science Society of China 1989).

In this paper, the mean CH_4 flux over a rice growing period was the average of the individual fluxes weighted by an interval of two measurements. Seasonal emission for one rice growing season was the product of the mean CH_4 flux and the duration of the rice growing period, and seasonal emission for double-cropped rice was the sum of the early-rice and late-rice seasonal emissions.

Results

As shown in Table 2, both the chemical fertilizers used and the application rates varied greatly from season to season. The biomasses of Chinese milk vetch and oil-seed rape straw were affected by the precipitation during the growing season (from November to April). Large precipitation depressed the growth of vetch and oil-seed rape (Figure 1). During the period of experiment, the smallest biomasses of vetch and rape straw produced were corresponding to the largest precipitation in 1994/1995 (663.7 mm) and the largest biomasses to the smallest precipitation in 1995/1996 (509.3 mm). Large amount of weeds produced in the winter, consisting of *Alopecurus L.* (about 90%, dominated by *A. aequalis sobol*) with *Cardamine L.* (about 4–5%), *Erigeron L.*, and *Stellaria L.* But the biomass of weeds produced seems

Table 2. Agronomic parameters for rice production of the experiment in Changsha, Hunan Province, China from 1995 to 1997

Treatment	Year	Early rice					Late rice			
		Cultivar	Transplanting/ Harvesting on	CF* kg ha^{-1}	Dose of manure t ha^{-1}	Yield kg ha^{-1}	Cultivar	Transplanting/ Harvesting on	CF* kg ha^{-1}	Yield kg ha^{-1}
C-Fallow	1995	91-264	6 May/17 Jul.	N: 86;	5.25	5625	931080	24 Jul./20 Oct.	N: 86; P: 18.8;	3750
C-GM			7 May/17 Jul.	K: 70	3.75	5250		29 Jul./23 Oct.	K: 88	4875
C-Fallow	1996	92A-97	4 May/21 Jul.	N: 69	2.25	∼4500	208	30 Jul./17 Oct.	Same as in 1995	∼6000
C-GM					13					
C-Flood					Nil					
C-Rape					26.9					
C-Fallow	1997	9297	1 May/14/ Jul.	N: 86;	4.5	∼4875	386	20 Jul/21 Oct.	N: 210; K: 70	5250
C-GM				K: 70	12.6					5625
C-Flood					Nil					
C-Rape					10.9					

*CF, Chemical fertilizers: K is KCl; N is urea and ammonium bicarbonate; P is superphosphate.

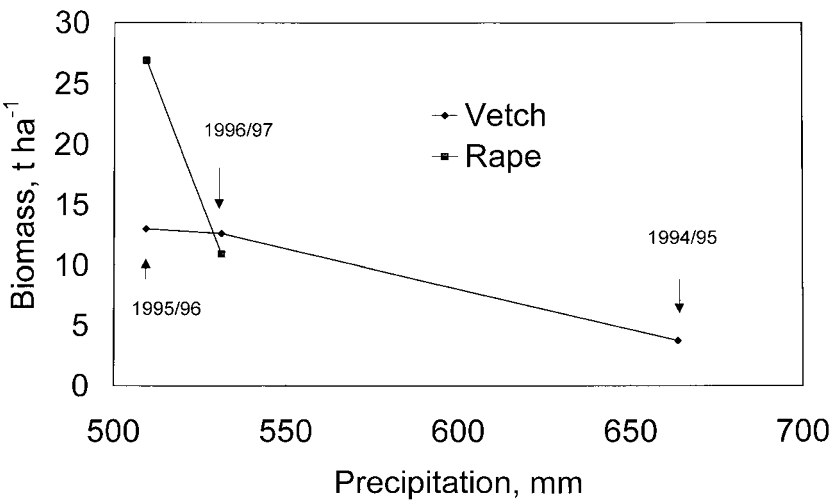

Figure 1. Relationship between precipitation in the winter season (November to April) and products of Chinese milk vetch and oil-seed rape.

to be independent on the precipitation in the winter. Because all biomasses (weeds in C-Fallow, Chinese milk vetch in C-GM, and oil-seed rape straw in C-Rape) produced in the winter were incorporated *in situ*, the amounts of green manure incorporated *in situ* into the soil varied greatly as well. The biomass of weeds produced in C-Flood was negligible, probably due to the reason that the flooding prevented weed growth.

The seasonal variations in the CH_4 fluxes in the treatment plots during the rice growing periods from 1995 to 1997 are shown in Figure 2. The patterns of seasonal variation varied from season to season. The measured CH_4 flux varied from 0 to 237 mg CH_4 m^{-2} h^{-1}. The mean flux over one-rice crop season ranged from 3.83 to 54.6 mg CH_4 m^{-2} h^{-1} (Table 3). The highest mean flux was observed in C-Rape during the early rice growing period in 1996 and the lowest in C-GM during the late-rice period in the same year (Table 3).

One-way ANOVA analysis showed that the land use and water regime in the winter did not significantly affected three-year mean CH_4 flux during the early rice growing period ($p > 0.05$); while significantly affected the flux during the late rice growing period ($p < 0.05$). During the late rice growing period, the mean CH_4 flux from C-Flood was significantly higher than those from C-GM and C-Rape ($p < 0.05$); the flux from C-Fallow was significantly higher than that from C-GM ($p < 0.05$). When we integrated all the data from all the treatments and years and carried out correlation analyses between the amended amount of organic manure and the mean CH_4 flux during the early

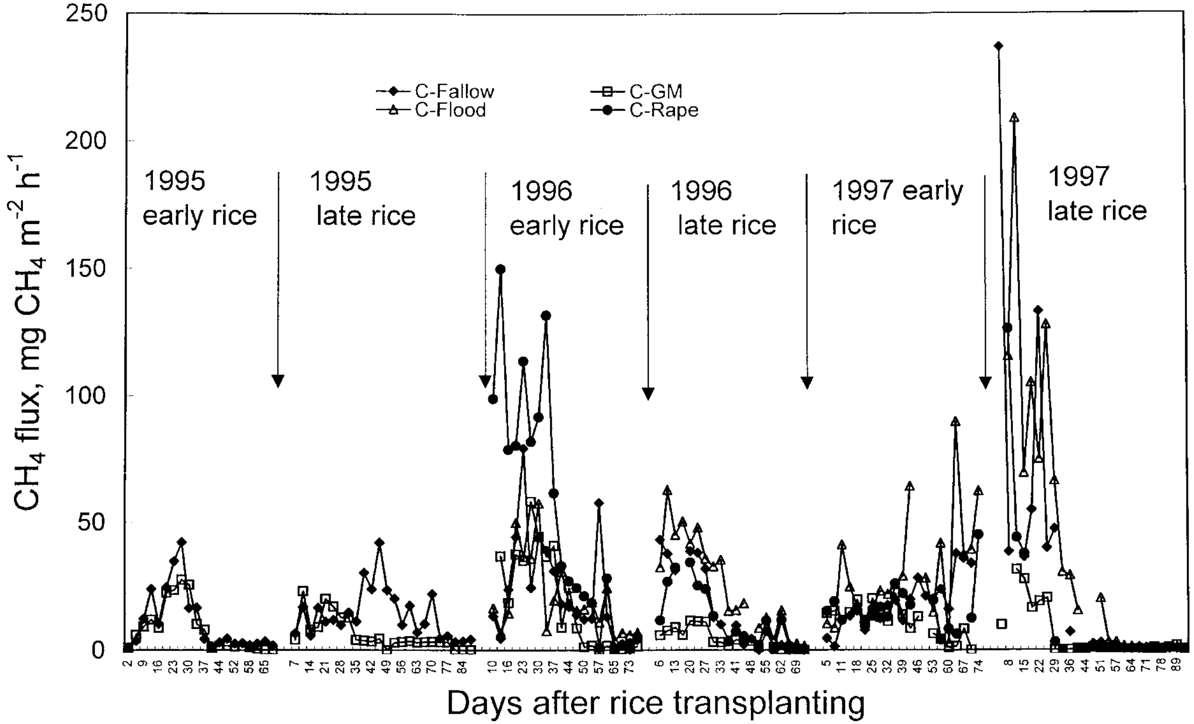

Figure 2. Seasonal variations in CH_4 fluxes during the rice growing period from rice fields treated as fallow and drained (C-Fallow), fallow and flooded (C-Flood), planted with Chinese milk vetch (C-GM) and oil-seed rape (C-Rape) from 1995 to 1997. Organic manure (weeds in C-Fallow and C-Flood, Chinese milk vetch in C-GM, and oil-seed rape straw in C-Rape) produced in the plots during the winter was incorporated into the soil before the early-rice transplanting.

Table 3. Mean CH_4 fluxes and seasonal CH_4emissions from the experimental plots in Hunan Province during the double-cropped rice period

Treatment	Year	Mean flux, mg CH_4 m^{-2} h^{-1}		Seasonal emission, g CH_4 m^{-2}
		Early rice	Late rice	
C-Fallow	1995	11.33	13.74	48.6
C-GM		8.38	6.12	37.0
C-Fallow	1996	18.12	13.12	58.8
C-GM		15.89	3.83	37.0
C-Flood		19.63	22.28	79.0
C-Rape		54.57	9.45	120.0
C-Fallow	1997	15.12	25.49	83.8
C-GM		9.37	5.17	28.2
C-Flood		29.73	33.66	128.0
C-Rape		12.88	7.31	39.2

rice growing period, we found a significant concave parabolic relationship ($R^2 = 0.9254$, $p < 0.01$, Figure 3). In this experiment, only when 26.9 t ha^{-1} fresh oil-seed rape straw (C-Rape in 1996, Table 2) was incorporated into the soil before the early-rice transplanting did the mean CH_4 flux during the early-rice period substantially increase (to 54.6 mg CH_4 m^{-2} h^{-1}).

The mean CH_4 fluxes were always higher during the early rice growing period than during the late-rice growing period in C-GM and C-Rape, into which Chinese milk vetch and oil-seed rape straw were incorporated. The difference in the mean CH_4 fluxes between the early-rice and the late-rice periods was related exponentially to the amount of green manure amendment ($p < 0.05$). This phenomenon was not observed in the C-Flood plot, in which the soil was not amended with any organic manure before the early-rice transplanting, neither in the C-Fallow plot, in which the soil was amended by incorporating the weeds that had grown there in the winter.

Based on our field measurements, we estimated CH_4 emissions from rice fields in Hunan province for 1996 and 1997. We did not estimate the emission for 1995 because the CH_4 emission rates from two treated plots (C-Flood and C-Rape) were not measured that year. For estimating the total CH_4 emissions from rice fields in Hunan Province, the area ratios of four types of land use and water management in the winter were used from Agricultural Statistics of Hunan Province (Agricultural Department of Hunan Province, Hydraulic Department of Hunan Province, and Forestry Department of Hunan Province,

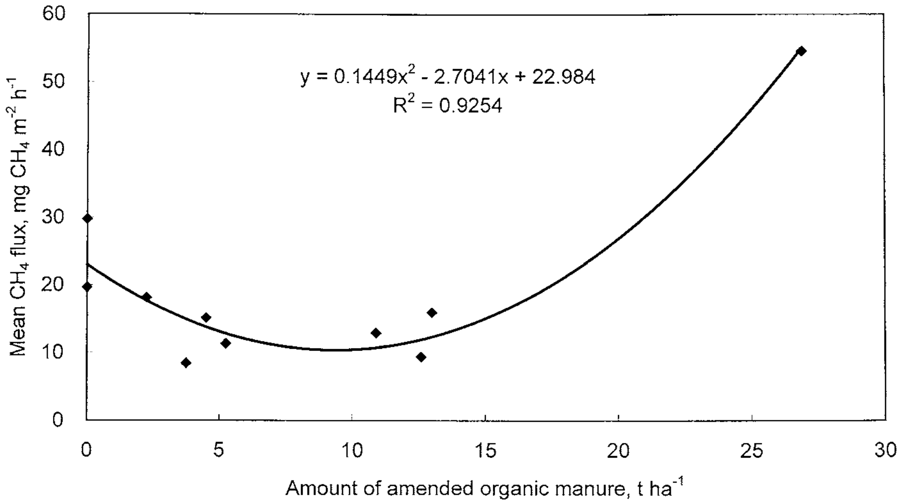

Figure 3. The relationships between the amount of organic manure produced in the winter and incorporated *in situ* before early-rice transplanting and the mean CH_4 fluxes over the early rice growing period.

1998). That was 17.4% in C-Fallow, 8.4% C-Flood, 38.7% in C-GM, and 35.5% in C-Rape. Three types of rice crops, early-rice, late-rice, and single-rice, are grown in the province. The harvested area of the single-rice crop accounted for 12.6% of the total rice-harvested area in 1996 and 1997. There were no field measurements available for CH_4 emissions from fields used for single-rice, so to estimate the CH_4 emissions from single-rice fields, we used the same land-area ratios for rice field winter-management practices. The duration of single-rice growing period is shorter than that of double-rice growing period. Normally, single-rice period is about 120 days and the sum of the early- and late-rice growing periods is about 155 days. We then calibrated the seasonal CH_4 emissions obtained for double-cropped rice fields (Table 3) by using a growing-period ratio of 120/155 to estimate the corresponding emissions for fields planted with single-rice. In this way, we estimated total CH_4 emissions from rice fields in Hunan Province as 1.56 Tg CH_4 in 1996 and 1.06 Tg CH_4 in 1997.

Discussion

Effect of water management in the winter season

The effect of mid-season aeration during the rice period on CH_4 has been studied intensively, and the results show that CH_4 emission from rice fields is suppressed by mid-season aeration (Yagi & Minami 1990; Sass et al. 1992; Chen et al. 1993; Cai et al. 1994; Bronson et al. 1997; Yagi et al. 1997). Plot experiments have shown that flooding between the two rice crop seasons significantly stimulates both methanogenesis (Trolldenier 1995) and CH_4 emissions during the subsequent rice growing period (Xu et al. 2000). However, very few field measurements are available on the effects of the winter water regime on CH_4 emissions during the subsequent rice growing period (Cai et al. 2000).

Flooding rice fields or leaving them fallow and drained in the winter are common practices in south and southwest China. The total area of rice fields flooded in the winter is between 2.7 and 4.0 Mha in China (Lee 1992). The Second Soil Survey of China, which was carried out in the early 1980s, showed that the area of waterlogged paddy soils (those which were usually permanently flooded) was about 0.4 Mha in Hunan Province, accounting for 14.42% of the total area of paddy soils (Agricultural Department of Hunan Province 1989). The area of waterlogged paddy soils greatly decreased with the efforts of improving irrigation and drainage systems after the Second Soil Survey. However, rice fields in Hunan Province flooded in the winter during the middle 1990s were still accounted for 8.4% of the total (Agricultural Department of Hunan Province, Hydraulic Department of Hunan Province, and Forestry Department of Hunan Province 1998). There are several reasons for keeping rice fields flooded after the late-rice harvest. First, in the plains area, the groundwater table may be too high to drain the fields completely. Second, in hilly areas, water may invade the fields from the surrounding slopes. Third, where there is a shortage of irrigation water or the irrigation system is not well developed, water is allowed to stand in the fields, because if there is insufficient rain when the fields are prepared for early-rice transplanting, the fields cannot be flooded and prepared for the transplanting at that time.

The mean CH_4 flux from C-Flood during the early-rice period was about the same as the fluxes measured in the plots amended with different amounts of organic manure even though no organic manure was incorporated into the soil of the C-Flood plot. If without incorporation of organic manure in the non-flooded treatments (C-GM, C-Fallow, and C-Rape), CH_4 emissions during the early rice growing period would be much higher from C-Flood than from the non-flooded treatments. Since the yields of the early-rice crops were similar among the differently treated plots (Table 2), the residues incorporated into the soil when the plots were prepared for the late-rice transplanting should be similar among the treatments. But the mean CH_4 fluxes were significantly higher from C-Flood than from C-GM and C-Rape during the late-rice period ($p < 0.05$). Pot experiments have shown that during the rice growing period, the difference in CH_4 flux between treatments flooded or drained and left fallow during the preceding winter is much more significant at the early stage than at the late stage of rice growth (Xu et al. 2000). However, our field measurements showed that the effect on CH_4 emission of flooding a field in the winter could persist to the second crop season. These results clearly indicate that flooding in the winter substantially stimulates CH_4 emissions in regions where rice is double cropped. In this experiment, we did not measure CH_4 emissions from C-Flood during the winter. We infer from measurements carried out in Chongqing (Cai et al. 2000) that CH_4 emissions might continue during the winter. Therefore, we expect that the annual CH_4 emission from C-Food during the winter would be higher than the seasonal CH_4 emission determined for the rice growing periods (Table 3).

Effect of organic manure amendment

The stimulating effect of organic manure amendments on CH_4 emissions from rice fields has been well documented (Yagi & Minami 1990; Chen et al. 1993; Lauren et al. 1994; Oyediran et al. 1996). In most previous experiments on the effect of organic manure on CH_4 emission, the different amounts of organic manure were realized through either the application of exogenous organic manure or the partial removal of endogenously produced organic manure (Schutz et al. 1989b; Yagi & Minami 1990; Wassmann et al. 1993; Lauren et al. 1994; Denier van der Gon & Neue 1995; Oyediran et al. 1996; Wassmann et al. 1998). In this way, the factors influencing CH_4 emission other than the amendment rate of organic manure were relatively homogenous. When Denier van der Gon and Neue (1995) integrated all the data available in the literature on the effects of organic manure on CH_4 emission from rice fields, they found no relationship between the amount of organic manure amendment and CH_4 emissions. But when they plotted the amount of organic manure amendment against the fraction of CH_4 emissions from the field treated with organic manure by CH_4 emissions from the fields without organic manure, they found a significant relationship between them. Their results indicate that the effect of organic manure is easily masked and can only be seen when the effects of other parameters such as temperature, soil properties, and cultivars are excluded. The interaction of factors masking the effect of organic manure on CH_4 emission is also supported by the results reported by Bosse and Frenzel (1998). They found no significant difference in CH_4 production between microcosms planted with rice and those not planted because the rice plants not only release root exudates but also transport O_2 from the atmosphere into the submerged soil. The former provides organic substrates for methanogenesis, while the latter stimulates aerobic oxidation and decomposition of complex organic substrates (MacRae & Castro 1996).

In the present experiment, organic manure was produced endogenously in the winter season, and the soil was amended by its incorporation before the early-rice transplanting. The differences in the amounts of organic manure amendment to the soil in the different plots and in different years resulted from the different amounts of biomass produced. Because of the high winter precipitation (the mean precipitation was 627 mm from November to April from 1993 to 1997 in Changsha), drainage is essential for the production of green manure in Hunan Province (Agricultural Department of Hunan Province 1989). Since extensive management in the winter, soil moisture is mainly controlled by precipitation in the winter. In winter with less precipitation, vetch and oil-seed rape grew well (Figure 2) and the incorporated amount of organic manure was larger. Thus, the contribution of incorporated manure would be larger to CH_4 emissions, as well-documented previously (Schutz et al. 1989b; Yagi & Minami 1990; Wassmann et al. 1993; Lauren et al. 1994; Oyediran et al. 1996; Wassmann et al. 1998). On the contrary, larger precipitation in the winter was not favor for growth of vetch and oil-seed rape and less amount of green manure produced and incorporated. Thereby, the contribution of green manure to CH_4 emission was smaller as well. However, soil moisture in the winter not only affects growth of vetch and oil-seed rape, but might also affect CH_4 emission during the subsequent rice growing period. Xu (2001) found from a pot experiment that the mean CH_4 emissions during the rice growing period increased from 3.72 ± 0.64, 8.70 ± 1.28, 12.68 ± 1.38 to 19.22 ± 1.49 mg CH_4 m^{-2} h^{-1}, respectively, with the increasing in soil moisture of a paddy soil at 25–35, 50–60, 75–85% field capacity, and flood in the proceeding winter. This meant that the contribution to CH_4 emission of larger incorporated amount of organic manure produced under lower soil moisture condition would be partially or completely traded off by the depressive effect of lower soil moisture on CH_4 emission. Therefore, the concave relationship between the amount of organic manure and mean CH_4 flux during the early rice growing period (Figure 3) could be attributed to the interaction of water regime in the winter and organic manure. Because the soil moisture in the non-flooded treatments was mainly controlled by the precipitation in the winter, this result implied that precipitation in the winter might be an important factor controlling the annual variation of CH_4 emissions during the rice growing periods in Hunan Province. It is needed to understand the underlying mechanisms for the interaction of water regime in the winter and green manure produced and incorporated on CH_4 emissions during the subsequent rice growing period under strict controlled conditions.

In addition, we note that the CH_4 emissions during the late-rice season in response to organic manure incorporated into the soil before the early-rice transplanting were substantially different (Table 3). The mean CH_4 fluxes from C-GM and C-Rape were substantially lower during the late-rice period than during the early-rice period, and the difference was significantly related to the amount of green-manure amendment ($p < 0.01$). The same phenomenon was not observed in C-Flood and neither in C-Fallow (Table 3). These results are consistent with the previous finding that the effect of green manure on increasing CH_4 emissions is not as long lasting as that of other organic materials. Denier van der Gon and Neue (1995) found that toward the end of the season, the difference in CH_4 production between soil treated with green manure and untreated soil is less pronounced. These results indicate that the stimulating effect of Chinese milk vetch and oil-seed rape straw on CH_4 emission lasted for a shorter term than that of weeds. The substantially lower mean CH_4 fluxes during the late-rice growing period compared with mean fluxes during the early-rice period in the C-GM and C-Rape plots might have been resulted from a 'priming effect,' which exhausted active organic matter in the soil (Hauck & Bremner 1976). Chinese milk vetch and oil-seed rape straw might have a stronger priming effect than weeds. These different effects might be attributed to the different components of the organic materials (Yagi & Minami 1990; Watanabe et al. 1993).

Estimate of CH_4 emissions from rice fields in Hunan Province

Based on our field measurements, we estimated CH_4 emissions from rice fields in Hunan Province as 1.56 Tg CH_4 in 1996 and 1.06 Tg CH_4 in 1997. Two-year average was closely agreement with the estimate made by a model (Huang et al. 1998). Because the field measurements were carried out under farmer's practice without any special treatments, the estimated CH_4 emission should be close to the actual emission in the province during the rice growing periods. However, the annual CH_4 emissions from rice fields in Hunan Province should be higher than our estimate, because from measurements made in Chongqing (Cai et al. 2000), we infer that CH_4 emissions also occur during the winter from flooded rice fields.

If we assume CH_4 emissions from the rice fields in Hunan Province to be typical of CH_4 emissions from Chinese rice fields, total CH_4 emissions from rice fields in China during the rice growing period would have been 12.2 Tg CH_4 in 1996 and 8.28 Tg CH_4 in 1997. The estimate was also close to the estimation of the total CH_4 emission from rice fields in China made by Neue and Sass (1998). However, our field measurements showed that the CH_4 emissions from rice fields in Changsha fell in the upper range of CH_4 emissions from rice fields in China (Cai et al. 2000). Therefore, total CH_4 emissions from the rice fields in China would actually have been less than those estimated from the CH_4 emissions of Hunan Province.

Acknowledgements

This project was supported by the National Key Basic Research Development Foundation (G1999011805), and the Global Environmental Research Program of the Environmental Agency of Japan. We thank Ruizhi Hu, Yunxiang Huang, Hongmei Zhu, Qing Zhou, Yangzhu Zhang, and Yonglan Xiao of Hunan Agricultural University for their help with gas sampling and the recording of field parameters.

References

Agricultural Department of Hunan Province (1989) Soils of Hunan. Agricultural Press, Beijing, 399 pp

Agricultural Department of Hunan Province Hydraulic, Department of Hunan Province, and Forestry Department of Hunan Province (1998) Agricultural Yearbook of Hunan Province. Changsha

Banik A, Sen M & Sen SP (1996) Effects of inorganic fertilizers and micronutrients on methane production from wetland rice (*Oryza sativa L.*). Biol. Fert. Soils 21: 319–322

Bosse U & Frenzel P (1998) Methane emissions from rice microcosms: The balance of production, accumulation and oxidation. Biogeochem. 41: 199–214

Bronson KF, Neue HU, Single U & Abao EBJ (1997) Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil, I, Residue, nitrogen, and water management. Soil Sci. Soc. Am. J. 61: 981–987

Cai ZC (1997) A category for estimate of CH_4 emission from rice paddy fields in China. Nutrient Cycling in Agroecosystem 49: 171–179

Cai ZC, Tsuruta H & Minami K (2000) Methane emission from rice fields in China: Measurements and influencing factors. J. Geophys. Res. 105(D13): 17,231–17,242

Cai ZC & Xu H (1998) Effect of land management in winter crop season on methane emission from following rice growth period. In: Pawlowski L et al. (Ed.) Chemistry for the Protection of the Environment, Vol. 3 (pp 43–50). Plenum, New York

Cai ZC, Xu H, Zhang HH & Jin JS (1994) Estimate of methane emission from rice paddy fields in Tai-hu region, China, Pedosphere 4(4): 297–306

Chen ZL, Li DB, Shao KS & Wang BJ (1993) Features of CH_4 emission from rice paddy fields in Beijing and Nanjing. Chemosphere 26(1/4): 239–245

Cicerone RJ & Oremland RS (1988) Biogeochemical aspects of atmospheric methane. Global Biogeochem. Cycles 2: 299–327

Cicerone RJ & Shetter JD (1981) Sources of atmospheric methane: measurements in rice paddies and discussion. J. Geophys. Res. 86: 7203–9209

Committee for Agro-chemistry, Soil Science Society of China (1989) Routine Analysis of Soil and Agro-chemistry. Science Press, Beijing

Denier van der Gon HAC (1999) Changes in CH4 emissions from rice fields from 1960 to 1990s. II. The declining use of organic inputs in rice farming. Global Biogeochemical Cycles. 13: 1053–1062

Denier van der Gon HAC & Neue HU (1995) Influence of organic matter incorporation on the methane emission from a wetland rice field. Global Biogeochem. Cycles 9: 11–22

Ding A, Willis CR, Sass RL & Fisher FM (1999) Methane emissions from rice fields: Effect of plant height among several rice cultivars. Global Biogeochem. Cycles 13: 1045–1052

Editorial Board for Agricultural Year Book of China (1994, 1995, 1996, 1997, 1998) Agricultural Year Book of China. Agricultural Press, Beijing

Hauck RD & Bremner JM (1976) Use of tracers for soil nitrogen research. Adv. Agron. 28: 219–266

Huang Y, Sass RL & Fisher FM (1989) Model estimates of methane emission from irrigated rice cultivation of China. Global Change Biology. 4: 809–821

International Rice Research Institute (1991) World Rice Statistics 1990, Manila, Philippines

Khalil MAK, Rasmussen RA, Wang MX & Ren R (1991) Methane emission from rice fields in China. Environ. Sci. Technal. 25: 979–981

Lauren JG, Pettygrove GS & Duxbury JM (1994) Methane emission associated with a green manure amendment to flooded rice in California. Biogeochemistry 24: 53–65

Lee CK (1992) Paddy Soils of China (in Chinese). Science Press, Beijing, China

MacRae IC & Castro TF (1996) Carbohydrates and amino acids in the root exudates of rice seedlings. Phyton. 23: 91–106

Neue HU & Sass RL (1998) The budget of methane from rice fields. IGACtivities Newsletter 12: 3–11

Oyediran G, Adachi K & Senboku T (1996) Effect of application of rice straw and cellulose on methane emission and biological nitrogen fixation in a subtropical paddy field, I, Methane emission, soil-ARA, and rice plant growth. Soil Sci. Plant Nutr. 42: 701–711

Sass RL (1994) Short summary chapter for methane. In: Minami K et al. (ed.) CH_4 and N_2O – Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources (pp 1–7). Yokendo, Tokyo

Sass RL, Fisher FM, Wang YB, Turner FT & Jund MF (1992) Methane emission from rice fields: The effect of floodwater management. Global Biogeochem. Cycles 6: 249–262

Schutz H, Holzapfel-Pschorn A, Conrad R, Rennenberg H & Seiler W (1989a) A 3-year continuous record on the influencing of daytime, season and fertilizer treatment on methane emission rates from an Italian rice field. J. Geophys. Res. 94: 16405–16416

Schutz H, Seiler W & Conrad R (1989b) Processes involved in formation and emission of methane of rice paddies. Biogeochemistry 7: 33–53

Sigren LK, Byrd GT, Fisher FM & Sass RL (1997) Comparison of soil acetate concentrations and methane production, transport, and emission in two rice cultivars. Global Biogeochem. Cycles 11: 1–14

Trolldenier G (1995) Methanogenesis during rice growth as related to water regime between crop seasons. Biol. Ferti. Soil 19: 84–86

Wassmann R, Neue HU, Bueno C, Lantin RS, Alberto MCR, Buendia LV, Bronson K, Papen H & Rennenberg H (1998) Methane production capacities of different rice soil derived from inherent and exogenous substrates. Pland and Soil 203: 227–237

Wassmann R, Wang MX, Shangguan XJ, Xie XL, Wang RX, Wang YS, Papen H, Rennenberg H & Seiler W (1993) First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan-Province (PR China). Geophys. Res. Let. 20: 2071–2074

Watanabe A, Kajiwara M, Tashiro T & Kimura M (1995) Influence of rice cultivar on methane emission from paddy fields. Plant Soil 176: 51–56

Watanabe A, Katoh K & Kimura M (1993) Effect of rice straw application on CH_4 emission from paddy fields, II, Contribution of organic constituents in rice straw, Soil Sci. Plant Nutr., Tokyo 39: 707–712

Watanabe A & Kimura M (1999) Influence of chemical properties of soils on methane emission from rice paddies. Communications in Soil Science and Plant Analysis 30: 2449–2463

Xu H, Cai ZC, Li XP & Tsuruta H (2000) Effect of antecedent soil water regime and rice straw application time on CH_4 emission from rice cultivation. Aust. J. Soil Res. 38: 1–12

Xu H (2001) Effects of soil moisture in the winter on CH_4 emissions during the subsequent rice growing period. PhD thesis. Institute of Soil Science, Chinese Academy of Sciences, Nanjing

Yagi K & Minami K (1990) Effects of organic matter application on methane emission from some Japanese paddy fields. Soil Sci. Plant Nutr. 36: 599–610

Yagi K & Minami K (1991) Emission and production of methane in the paddy fields of Japan. Jpn. Agric. Res. Q. 25: 165–171

Yagi K, Tsuruta H & Minami K (1997) Possible options for mitigating methane emission from rice cultivation. Nutr. Cycles. Agroecosystems 49: 213–220