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ORIGINAL PAPER

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Spatial and seasonal distribution of organic amendments affecting methane emission from Chinese rice fields

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Abstract The effect of fertilizers on methane emission rates was investigated using an automated closed chamber system in Chinese rice fields (Hunan Province). Each of three experiments compared two fields treated with a first uniform fertilizer dose and a second fertilizer dose which was different for each of the two fields. The uniform fertilizer doses for both fields in each experiment comprised mineral (experiment 1), organic (experiment 2) and combined mineral plus organic components (experiment 3). In all three experiments the second fertilizer dose comprised organic amendments for field 1 and no organic amendments for field 2. The rate of increase in methane emission with a given amount of organic manure was found to depend on the total amount of organic manure applied. A single dose of organic manure increased the emission rates by factors of 2.7 to 4.1 as compared to fields without organic manure (experiment 1). In rice fields that had already been treated with organic manure, the application of a second dose of organic manure only slightly enhanced the emission rates in experiment 2 by factors of 1.1 to 1.5 and showed no detectable increase in experiment 3. The net reduction achieved by separation of organic and mineral fertilizers was maximized by concentrating the organic amendments in the season with low emission rates, i.e. early rice, and using exclusively mineral fertilizers on late rice when emission rates were generally higher. This distribution pattern, which was not associated with significant yield losses, resulted in an annual methane emission corresponding to only 56% of the methane emitted from fields treated with blended fertilizers.

Key words Methane emission · Wetland rice · Fertilization · Mitigation of greenhouse gases

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Introduction

The quantification of methane emissions from rice fields has attracted increasing attention in recent years (Schütz et al. 1989; Khalil et al. 1990; Parashar et al. 1991). Rice fields represent one of the main sources of the greenhouse gas methane, but their exact contribution to the global methane budget remains highly uncertain (Watson et al. 1992; Duxbury et al. 1993). Even though the previously observed trend of increasing methane abundance in the atmosphere has currently been reversed (Dlugocenky et al. 1994), discussion of the global source strength of rice fields and possible mitigation options is likely to remain lively.

Fertilizer use has been found to be a crucial factor in determining the magnitude of methane emission from rice fields; organic amendments generally increase methane emissions (Wassmann et al. 1993b; Neue et al. 1994; Yagi and Minami 1990). However, the quantitative relationship between organic input and methane emission rates remains unclear. This article extracts information from extensive measuring campaigns in Hunan Province, China, in order to assess the effect of different spatial and seasonal distribution patterns of organic and mineral fertilizer use on methane emissions. This investigation aimed to clarify the impact of organic amendments on the regional source strength in one of the main rice-growing areas of China and to evaluate the potential of mitigating methane emissions by management of fertilizer use.

Site description and methods

The field site of Taoyuan (110 30'E, 28°55'N) is located in Hunan Province, one of the Chinese centres for rice production. The site is typical of the red earth region of central China regarding climatic and edaphic parameters. The total content of organic carbon in the paddy

Table 1 Fertilizer treatments, seasonal averages of methane emission rates (∅) (mg CH_4 m^{-2} h^{-1}) and cumulative methane emission (Σ) (g CH_4 m^{-2}) in fields 1 and 2 of each experiment [*M* mineral fertilizer (early rice 140 kg N, 65 kg P_2O_5, 103 kg K_2O, late rice 140 kg N, 85 kg P_2O_5, 140 kg K_2O), *GM* 15 ha^{-1} green manure (*Astralagus sincus*), *RS* 3t ha^{-1} rice straw, *AM* 15 t ha^{-1} animal manure (pig slurry)]

mg CH_4 / $m^2 \cdot h$

Experiment	1 a		1 b		2 a		2 b		3 a		3 b	
	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2
First dose	M		M		GM		RS		M+RS		2×M+RS	
Second dose	GM	M	RS	M	AM	M	AM	M	RS	–	R	–
∅ late rice 1990									25.9 (±11.5)	22.6 (±11.3)	20.1 (±10.4)	20.7 (±11.7)
∅ early rice 1991	26.5 (±18.6)	6.5 (±3.1)			38.6 (±30.6)	26.5 (±18.6)						
∅ late rice 1991			50.1 (±22.3)	14.3 (±5.4)			56.2 (±23.7)	14.3 (±5.4)				
∅ early rice 1992	8.0 (±3.2)	3.0 (±1.3)			9.5 (±4.1)	8.0 (±3.2)						
∅ late rice 1992			14.2 (±14.1)	3.2 (±2.5)			18.8 (±21.9)	14.2 (±14.1)				
Σ early rice 1992	15	6			18	15						
Σ late rice 1992			30	7			41	30				

soil was 1.52%; the total contents of N, P_2O_5 and K_2O were 0.15%, 0.13% and 0.14%, respectively. The average annual precipitation in this area is 1448 mm, the mean annual temperature is 16.5°C and the mean annual sunshine period is 1515 h.

Rice was cultivated according to local farming practice. Early rice (cult. Zheifu 802) was transplanted at the end of April and harvested in mid-July; the growing season of late rice (cult. V64) was from late July to mid-October. The irrigation system provided a relative stable water cover of 3–5 cm. The organic manures were incorporated into the soil by ploughing before transplanting; the mineral fertilizers were broadcast 2 weeks after transplanting.

Mineral fertilizers were divided into discrete units corresponding to 50% of the virtual nutrient demand of the plants (Table 1); one unit of rice straw, green manure (*Astralagus sincus*) and animal manure (pig slurry) was based on the nitrogen content required for 50% of the demand (Table 1). All fertilizer treatments of this investigation supplied sufficient N, P and K, so that rice yields showed no significant differences between treatments within one season (Wassmann et al. 1993c).

Each of the three experiments consisted of a comparison between two fields treated with one fertilizer dose that was identical for both fields and with a second fertilizer dose that differed between the two fields (Table 1). The uniform fertilizer doses were mineral (experiment 1), organic (experiment 2) and combined mineral plus organic (experiment 3). In all experiments the additional fertilizers comprised organic amendments for field 1 and no organic amendments for field 2, and the emission rates from both fields were compared in order to evaluate the effect of one unit of organic manure with a given organic treatment.

The methane emission rates were determined by using an automated system ("closed chamber technique") facilitating continual measurements at 2-h intervals for each box (Wassmann et al. 1993b). The emission rates in each fertilizer treatment were simultaneously recorded from four chambers distributed as replicates in each field of 3×20 m. The automated system consisted of: (1) a pneumatic device for automatic opening and closing of the chambers, (2) a sampling device providing direct air transfer from the inner chamber to the analytical system, (3) a gas chromatograph with a flame ionization detector linked to an integrator and (4) a PC equipped for time control functions and data acquisition.

Results and discussion

The seasonal averages of the emission rates are listed in Table 1 and the relative increments with organic amendments, i.e. field 1 vs. field 2, are shown graphically in Fig. 1. The observation periods in 1991 and 1992 covered approximately 1 month per season (Wassmann et al. 1993c, d) due to technical problems in the remaining periods. The previously unpublished results of 1992 consisted of complete data sets of methane emission rates during the early and late rice season which allowed the cumulative methane emission rates to be computed for each season (Table 1).

Experiment 1

Application of one unit of green manure blended with one unit of mineral fertilizer yielded significantly higher emission rates (26.5 mg CH_4 m^{-2} h^{-1} in 1991 and 8.0 mg CH_4 m^{-2} h^{-1} in 1992) than the corresponding average values in fields treated with two units of mineral fertilizer (6.5 mg CH_4 m^{-2} h^{-1} in 1991 and 3.0 mg CH_4 m^{-2} h^{-1} in 1992). The effect of fertilization with one unit of green manure was quantified by the ratio of the average values of these two treatments (Fig. 1) and amounted to factors of 4.1 (1991) and 2.7 (1992). Application of rice straw in experiment 1b resulted in average values of 50.1 mg CH_4 m^{-2} h^{-1} and 14.2 mg CH_4 m^{-2} h^{-1} in 1991 and 1992, respectively, whereas the simultaneous records in plots treated exclusively with mineral fertilizers yielded significantly lower values (14.3 mg CH_4 m^{-2} h^{-1} in 1991 and 3.2 mg CH_4 m^{-2} h^{-1} in 1992).

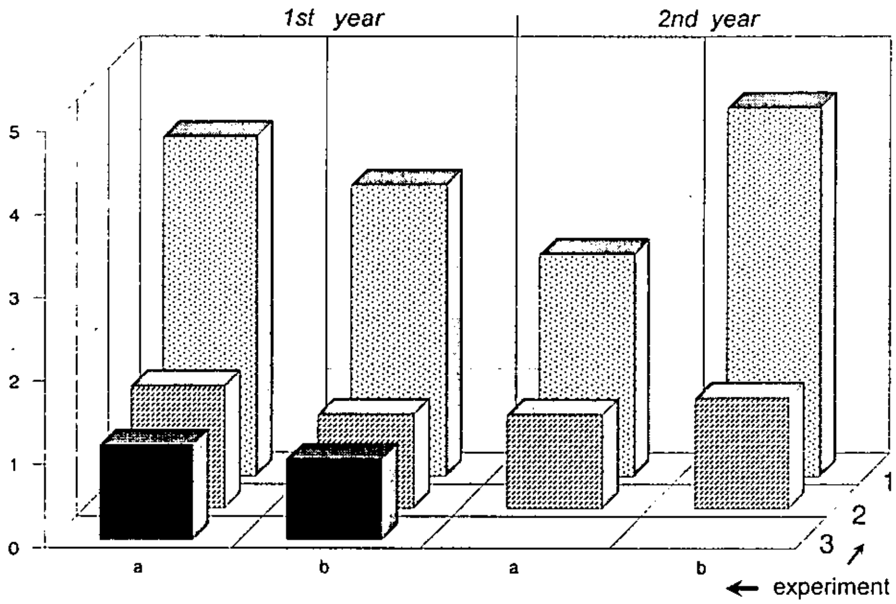

Fig. 1 Ratios between seasonal average of methane emission rates of field 1 vs. seasonal average of field 2 in experiments 1a, 1b, 2a, 2b, 3a and 3b

Experiment 2

One unit of animal manure was used as a complementary fertilizer to other organic amendments, i.e. green manure in the early growing seasons of 1991/1992 (experiment 2a) and rice straw in the late growing seasons of 1991/1992 (experiment 2b). The average emission rates for the treatment with animal manure plus green manure (experiment 2a) were 38.8 (1991) and 9.5 mg CH_4 m^{-2} h^{-1} (1992). The substitution of animal manure by mineral fertilizer yielded average emission rates of 26.5 and 8.0 mg CH_4 m^{-2} h^{-1} in the early seasons of 1991 and 1992, respectively. From these data the specific increment factors of CH_4 emission by supplementary organic amendments can be quantified as 1.5 (1991) and 1.2 (1992).

Addition of animal manure to rice straw (experiment 2b) resulted in average emission rates of 56.2 mg CH_4 m^{-2} h^{-1} (late rice 1991) and 18.8 mg CH_4 m^{-2} h^{-1} (late rice 1992) whereas the corresponding values for a blended application of minerals and green manure were 50.1 mg CH_4 m^{-2} h^{-1} (1991) and 14.2 mg CH_4 m^{-2} h^{-1} (1992). The specific increment factors of CH_4 emission with fertilization with animal manure compared with rice straw (experiment 1b) can be computed as 1.1 (1991) and 1.3 (1992), which are in a similar range to the specific CH_4 emission ratios for the addition of animal manure to green manure (experiment 2a).

Experiment 3

Doubling of the rice straw application rate showed only a minor increase in the methane emission rate in experiment 3a, in which the rice straw was blended with one unit of minerals. The effect of the second unit of rice straw was quantified by the specific CH_4 emission ratio of the average values of field 1 (25.9 mg CH_4 m^{-2} h^{-1}) and field 2 (22.6 mg CH_4 m^{-2} h^{-1}) and amounted to 1.14. Blending rice straw with two units of mineral fertilizer (experiment 3b) yielded the same level of methane emission rates in fields treated with one unit of rice straw (20.7 mg CH_4 m^{-2} h^{-1}) and with two units of rice straw (20.1 mg CH_4 m^{-2} h^{-1}).

Spatial distribution

A statistical analysis of experiment 1a and 1b, i.e. *t*-test with a 1% confidence level, yielded significant differences between the methane emissions from field 1 and field 2. On the other hand, the results obtained in experiments 2a, 2b, 3a and 3b showed no significant differences between the methane emissions from both fields even using a confidence level of 5%. Hence, a pronounced difference between mineral and organic fertilizers was observed in fields that were previously treated with mineral compounds only, whereas amendment to a previously high background level of organic compounds in the field did not result in statistically significant differences in methane emission.

The fertilizer effects observed in this study could either be explained by a stimulation from the organic amendments or by an inhibitory effect of mineral fertilizers. However, other experiments in rice fields have yielded similar levels of methane emission from unfertilized plots and from plots treated with mineral fertilizers (Schütz et al. 1989; Wassmann et al. 1993b). A direct effect of mineral components can most likely be excluded as the cause of such large differences in methane emission rates as observed in our investigation. Methane emission appears to be determined by the availability of substrate for methanogenesis as long as the background level of organic compounds in the soil is low. However, the different effects caused by the first and by the second unit of organic manure indicate a non-linear relationship between organic input and methane emission rates. Even though explicit proof of a saturation level cannot be given with the data available from this field experiment, the findings indicate that the stimulation of methane emission by organic amendments declines at high background levels of organic compounds in the soil.

Fertilizer effects were investigated by using three different types of organic amendment, i.e. green manure, rice straw and animal manure. The comparison between the various experiments demonstrated that the type of organic manure had only a minor effect on methane emission as compared to the background level of organic compounds. The application of one unit of green manure and rice straw (experiments 1a,1b) had a pronounced impact on methane emission rates (Fig. 1); the application of a second unit of organic fertilizer (experiment 2a,b) had a much less marked effect for both rice straw and animal manure (Fig. 1).

Seasonal distribution

For all treatments, average emission rates in the early seasons of 1991 and 1992 were lower than the corresponding values of the following late season (Table 1). Due to incomplete data sets for the two seasons of 1991, the total amount of methane emitted within 1 year under varying fertilizer use patterns can only be evaluated based on the cumulative values available for 1992. The emission in fields with blended mineral and organic fertilizers amounted to 45 g CH_4 m^{-2} (15 g CH_4 m^{-2} h^{-1} in early rice and 30 g CH_4 m^{-2} in late rice) (Table 1). The consecutive use of organic fertilizers in early season (18 g CH_4 m^{-2}) and mineral fertilizers in late season (7 g CH_4 m^{-2}) amounted to 25 g CH_4 m^{-2}, corresponding to only 56% of the total amount emitted from fields with blended fertilizers. The inverse sequence of pure mineral fertilizers in early (6 g CH_4 m^{-2}) and pure organic fertilizers in late rice (41 g CH_4 m^{-2}) yielded an annual emission of 47 g CH_4 m^{-2}, representing no significant alteration in comparison to blended fertilizers in both seasons. The simultaneous use of organic fertilizers in one half and mineral fertilizers in the other half of the rice land for the two seasons of 1992 resulted in a total emission of 36 g CH_4 m^{-2}, corresponding to a 25% decrease in methane emission as compared to application of blended fertilizers. Apparently, the net reduction from separation of organic and mineral fertilizers was maximized by concentrating the organic amendments in the season with low emission rates and using exclusively mineral fertilizers when emission rates were generally higher. In Hunan Province, leguminous plants used as green manure are generally grown in spring and applied in the early rice season. This seasonal pattern implied a lower effect of the methane source strength than the intensive use of organic manure in the late season.

Rice cultivation can be regarded as one of the most promising targets for mitigating greenhouse gas emissions in an economically viable way (Braatz and Hogan 1991; Wassmann et al. 1993a; Neue and Roger 1993). The reduction of greenhouse gas emissions prevails as a paramount objective irrespective of the actual trend in methane concentrations. One approach to effectively reduce methane emissions from rice cultivation is to focus on areas with intense methane release ("hot spots") and to strive for location-specific measures of mitigation. Use of organic manure has been identified as one of the crucial factors in the promotion of high methane emission rates. A complete substitution by mineral fertilizers is not feasible and, furthermore, not desirable in the context of the CO_2 emissions required for fertilizer production. Large areas of wetland rice, e.g. in China, rely on organic manure due to limited financial resources and availability of mineral fertilizers. Previously, the fermentation of animal manure in biogas generators has been shown as one strategy to reduce methane emissions with given quantities of organic amendments (Wassmann et al. 1993c). The results presented here provide evidence that methane emission rates from Chinese rice fields could be reduced by using an appropriate spatial and temporal distribution of organic fertilizers.

The distribution pattern of organic amendments is especially important in rice areas with interseasonal differences in methane emission. Seasons with high and low emission rates are not limited to Chinese rice-growing areas as can be seen from results obtained in the Philippines, where emission rates in the dry season 1992 exceeded emission in the wet season by a factor of 2.4 (Wassmann et al. 1994). However, further research is needed to substantiate the effect of distribution patterns of organic fertilizers on methane emission from different soils and under diverse climatic conditions.

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