第27卷 第6期　　作 物 学 报　　Vol. 27, No. 6
2001年11月　　ACTA AGRONOMICA SINICA　　Nov., 2001

Methane Emission from Irrigated Rice Fields and Its Control*

WANG Zeng-Yuan[1]　XU Yu-Chang[1]　LI Zhen[1]　GUO Yi-Xian[1]　R Wassmann[2]
H U Nene[2]　R S Lantin[2]　L V Buendia[2]

([1] *Institute of Crop Breeding and Cultivation, CAAS, Beijing* 100081, *China*; [2] *International Rice Research Institute, Los Banos, Laguna, Philippines*)

Abstract　Methane emission from irrigated rice fields as affected by water management, organic amendment and rice cultivar was measured using an automatic sampling-measuring system with a closed chamber method in 1995～1998. The results showed that methane emission from irrigated rice fields in North China ranged from 4 to 364 mg m^{-2} day^{-1}, with average emission of 82 mg m^{-2} day^{-1}. Only one methane emission peak was observed during the whole rice season. Seasonal maximum occurred at tillering stage. Methane emission at this stage accounted for 85% of the annual methane emission rate. Methane emission was very limited from mid season field drying until harvest. Field drying at early and midseason stage had a strong effect on methane emission. Intermittent irrigation reduced methane emission by 46% and 59% as compared to local farmer's practice of irrigation and continuous flooding, respectively. Application of organic amendments highly increased methane emission. However, on the same carbon basis, methane emission potential varied highly among different organic amendments. Methane production potentials of cattle manure and compost were much lower than those of pig manure and rice straw. Application of cattle manure and compost reduced methane emission by 86% and 90% respectively, as compared to pig manure; and the same treatments reduced methane emission by 72% and 80% respectively, as compared to rice straw. Rice cultivars were efficient for reducing methane emission. Use of cultivar Zhongzhuo 93 (modern *japonica*) reduced methane emission by 55% and 50% respectively, as compared to Jingyou (*japonica* hybrid) and Zhonghua 94-1017 (tall *japonica*). Generally, methane emission affected by the organic amendments under different water regimes was much potent than the effect of rice cultivar. It was also shown that mitigation options practiced at early growth stage were more effective than those practiced at late stage. These findings provide a better mitigation strategy for methane emission from rice fields.

Key words　Methane emission; Rice field; Water regime; Rice cultivar; Organic amendment

Methane is an important greenhouse gas and it affects the chemistry and oxidation capacity of the atmosphere[1～3]. The methane concentration in the atmosphere has doubled during the last 200 years[4]. Rice fields have been identified as major source of atmospheric

---

* The research described in this paper was funded by the UNDP-Global Environment Facility GLO/91/G31 under agreement with the International Rice Research Institute (IRRI) and the Institute of Crop Breeding and Cultivation, Chinese Academy of Agricultural Sciences Collaborative Project.
Received on: 2000-08-29, Accepted on: 2001-02-15

methane. Recent estimate of global methane emission from rice fields ranges from 20 to 100 Tg (1Tg = 1 million ton) year^{-1}, which contributes about 10%～15% to global methane emission[5～6]. Owing to the rice demand of rapidly growing population, rice cultivation and productivity will continue to increase in the coming decades. This increase in the yield and harvest area of rice may further increase methane emission if the present practices are continued.

China is the largest rice producing country in the world. Rice harvest area in 1994 was estimated at 30.1 million ha and average rice yield was 5.83 t ha^{-1}[7]. Chinese rice fields are considered as an important source of methane and have been a major concern in context of increasing methane concentration in the atmosphere. In recent years, research on methane emission from Chinese rice paddy fields was accumulating[8～17].

The study presented here was conducted within an international network of measuring stations for determining methane emissions from rice fields[18]. The station represents typical area of single rice cropping system in North China and was the only network station in a temperate climate. The objectives of the studies at the station in Beijing were:

1) to quantify methane fluxes from rice fields in North China;
2) to assess the impact of management practices common to this region;
3) to evaluate processes that control methane emission in a temperate climate;
4) to develop mitigation strategies with low methane emission in a sustainable rice system for this region.

Table 1 Some characteristics of rice soil in Beijing site

pH	7.99
Organic carbon (g/kg)	9.95
Total nitrogen (g/kg)	0.91
CEC (cmol/kg)	13.20
Olsen phosphorus (mg/kg)	133.00
Exchangeable potasium (cmol/kg)	0.11

1 Materials and Methods

1.1 Field preparation Field experiments were conducted on silty clay loam at ICBC farm, Beijing, China for four rice seasons starting in 1995. Some characteristics of the soil are shown in Table 1. The details of field trials conducted from 1995 to 1998 are shown in Table 2. Experiment in each rice season consisted of four treatments in randomized complete block design with four replicates. Field was flooded one or two days before transplanting for harrowing and leveling. The individual plot was 4.5 m × 5 m.

1.2 Methane emission Methane emissions were monitored by an automatic sampling and measuring system[18]. This system consisted of the automatic chambers (1 m × 1 m × 1.2 m) and the sampling-measuring system, which are both controlled by a micro-computer. Methane emission was continuously measured every two hours from each chamber during the whole rice season. Methane concentrations of air samples were measured with Shimadzu GC-8A equipped with Porapak N column and a flame ionization detector.

1.3 Temperature, soil pH and Eh Temperatures of air, floodwater and soil at 5, 10 and 15 cm depths were measured by temperature probes connected to a datalogger. Soil pH and soil Eh at 7.5 cm depth were measured manually with Philips pH/Eh meter every two days from transplanting until harvest.

Table 2 Treatments of experiment in the rice field

Year	Water management	AS(kgN/ha)		Organic manure			Variety	Trans-plant &	Harvest
		Basal	Topdr.	Type	Org. N (kg/ha)	Org. C (kg/ha)			
1995	3) Continuos Irriga.	30	60	Pig manure	60	1783	Modern japonica (Zhongzhuo 93)	06/04	10/17
	1) Local Practice	30	60	Pig manure	60	1783			
	4) Local Practice	40	110	None					
	2) Intermittent Irrig.	30	60	Pig manure	60	1783			
1996	Local practice	40	80	None			1) Modern japonica (Zhongzhuo 93)	05/24	10/08
		40	80	None			2) Japonica Hybrid(Jingyou)		
		40	80	None			3) Tall japonica (Zhonghua 94-1017)		
		40	80	None			4) Modern indica (IR72)		
1997	Local practice	40	80	4) None			Modern Japonica (Zhong zhuo 93)	05/214	10/06
		20	60	1) pig Manure	40	1059			
		27	80	2) cattle Manure	13	1059			
		31	80	3) Rice straw	9	1059			
1998	1) Local Practice	28	60	Compost	32	1059	Modern japonica (Zhongzhuo 93)	05/19	10/06
	2) Early and mid season drainage (type A) *	28	60	Compost	32	1059			
	4) Early and mid season drainage (type B) *	28	60	Compost	32	1059			
	5) Early season drainage(type C)	28	60	Compost	32	1059			

&Date(mm/dd)

* Local practice drying at 55-68 DAT; type A: Drying at 25-31 dat & 45-51 dat; type B: Drying at period of 35-41 dat & 55-61 dat; type C: Drying at 35-48 DAT

1.4 Methane ebullition and soil dissolved methane Methane ebullition was measured weekly by installing plexiglass boxes (size of 40 cm × 15 cm × 20 cm) between rice hills. Boxes were held by PVC pegs, which were sunk into the paddy right after flooding the soil. The PVC pegs remained at the same position during the season. Gas samples were collected after 24 hours of box installation and immediately analyzed for CH_4. Dissolved methane in soil solution was measured weekly from soil depths of 0, 5, 10 and 15 cm with porous tubing system for soil solution sampling. About 5 ml of soil solution was collected in 10 ml vacutainers. The soil solution samples were shaken for 30 second and gas samples in headspace was taken for methane analyzed.

2 Results and Discussions

2.1 Characterization of seasonal fluxes A typical pattern of methane emissions under a local crop management is displayed in Fig. 1 jointly with patterns of water depth, temperature, soil Eh and pH. The fertilizers in this experiment, conducted in 1997, consisted of a mineral and organic (cattle manure) amendments (Table 2). Local water management encompassed persistent flooding (at 4 cm water depth) that was both interrupted by a mid-season field drainage and dried at the end of the season.

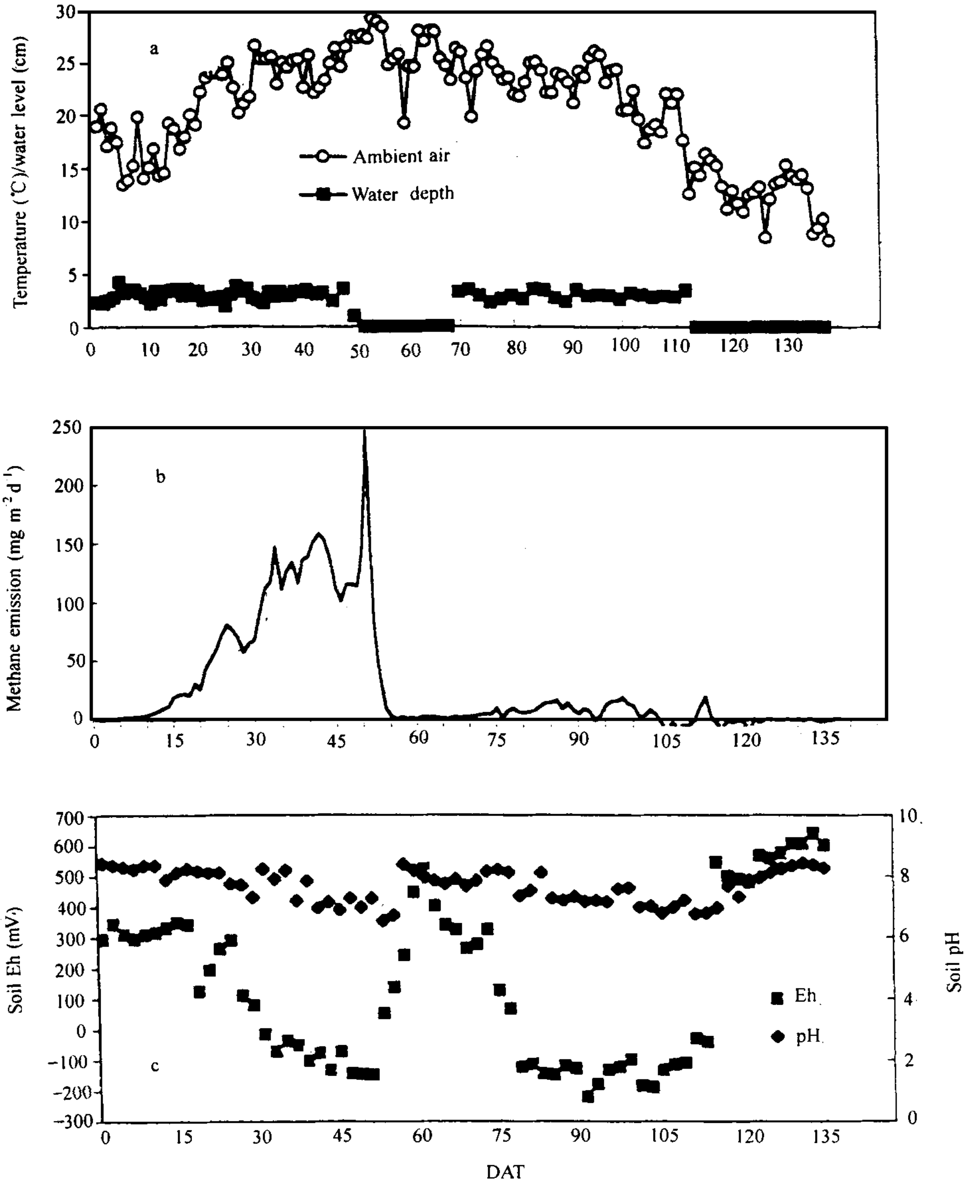

Fig. 1 Seasonal pattern of temperature and water level (a), methane emission (b), and soil pH and Eh (c) of T2 (cattle manure+ mineral fertilizer) during the 1997 rice season.

Methane emission rates rapidly increase in the first 35 days after transplanting (DAT) (Fig. 1b). In this period, temperature shows an increasing tendency and reached seasonal maximum at late tillering stage (Fig. 1a). Methane emission flux sharply decreased when field was drained at mid-season stage (50 DAT). After reflooding, methane emission remained at a very low level. At the end of the season, temperatures were below 15℃ and methane emission was virtually zero. Methane emission in early season accounted for 85% of total seasonal emission. Methane emission after mid season field drainage until harvest is only a small fraction of the total methane emitted from rice fields in the temperate zone of China.

The seasonal pattern of methane emission is reflected the influence of temperature changes and mid-season field drainage. The pattern can be broken up into 3 phases (Fig. 1b): (1) emissions increase at tillering stage triggered by rising temperature; (2) emissions fluctuate at a high level in the hot season; (3) emissions decrease at late growth stages due to a temperature drop and field drainage.

The redox potential was governed by the local practice in water management. Flooding resulted in soil Eh decrease while field drying promote soil Eh increase (Fig. 1c). Generally, soil Eh decreased from positive values to the critical value of methane formation (- 120 to - 150 mv) within 1 to 3 weeks after field flooding. Anaerobic conditions promoted methane formation. Drainage resulted in a sudden increase in redox potentials (Fig. 1c).

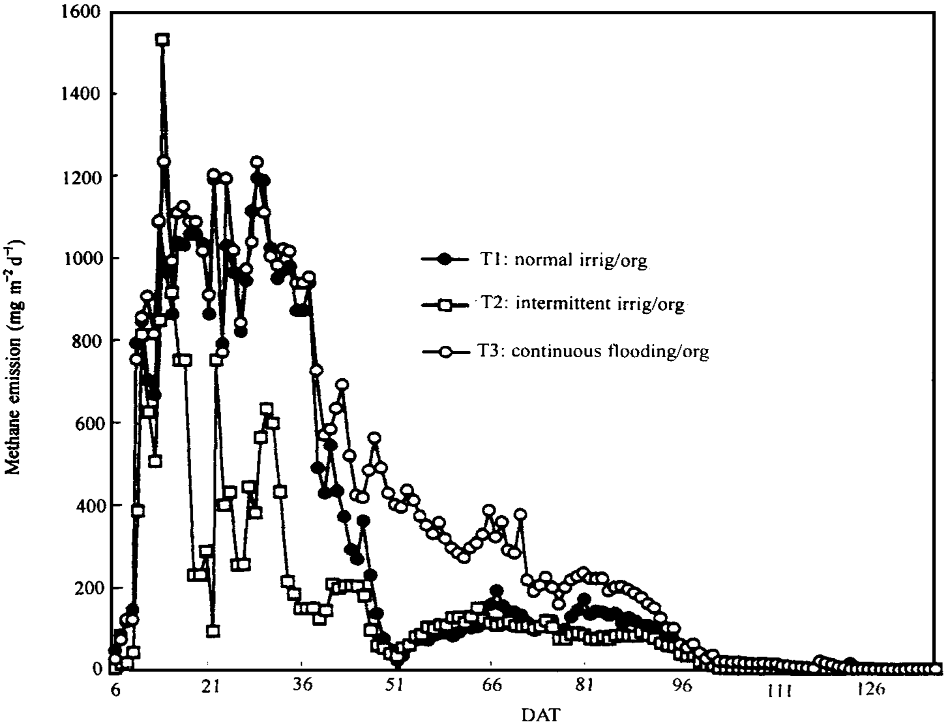

Fig. 2 Seasonal patterns of methane emission as affected by water regime during the 1995 rice season

The effect of soil pH on methane emission was negligible under field condition in Beijing. These findings were corroborated by similar trends in Eh and pH throughout the entire observation period from 1995 to 1998.

2.2 Effect of water regime The patterns of methane emission from rice fields as affected by water regime are shown in Fig. 2. The experiment in 1995 compared three different water regimes: (1) local practice, i.e. normal irrigation with mid-season field drainage, (2) intermittent irrigation with alternate flooding and drainage in app. 10-days interval, and (3) continuous flooding. All fields were fertilized with pig manure. Methane emission started to increase after about one week of flooding and became relatively constant after five days. For all treatments, seasonal maximum occurred at the tillering stage. Continuous flooding resulted in the highest emission rates while intermittent irrigation plots gave the lowest methane fluxes among 3 water regimes. The plots with mid-season field drainage-that were essentially replicates of continuous flooding during the first 40 days-shifted from high values to low values roughly corresponding to the emission rates in intermittent flooding. Low temperatures during the period before harvest resulted in uniformly low emission rates.

Table 3 Methane emission rates, biomass and yields (1995～1998)

Year		Modifying treatment	Mean emission (mg/m^2·d)	Cumulated emission (kg/ha·yr)	Biomass (t/ha)	Grain yield (t/ha)
1995	1	Continuos irrigation/pig manure	364	503	18.73	8.14
	2	Local practice/pig manure	279	385	20.66	9.24
	3	Intermittent irrigation/pig manure	150	207	19.98	9.09
	4	Local practice/mineral fertilizer	19	26	17.73	7.84
1996	1	Modern japonica (Zhongzhuo 93)	16	22	16.62	8.17
	2	Japonica hybrid (Jingyou)	36	49	15.06	7.27
	3	Tall japonica (Zhonghua94-1017)	32	44	18.14	7.75
	4	Modern indica (IR72)	23	32	14.17	6.35
1997	1	Pig manure	139	191	15.83	7.76
	2	Cattle manure	31	43	14.72	7.43
	3	Rice straw	102	141	14.71	7.23
	4	Mineral fertil	4	6	15.27	7.68
1998	1	Local practice irrigation	20	28	17.05	7.73
	2	Early and mid s drainage (type A)*	15	21	16.94	7.75
	3	Early and mid s drainage (type B)*	19	26	17.61	7.82
	4	Early season drainage	11	15	15.68	7.60

* Type A: Drying at period of 25-31 DAT & 45-51 DAT; type B: Drying at period of 35-41 DAT & 55-61 DAT

Table 3 presents the mean and seasonal methane fluxes, biomass and grain yields for 4 years. In 1995, methane emission from the local practice of irrigation was 86 % higher than intermittent irrigation and 23 % lower than continuous flooding. Farmer's practice of irrigation provided the highest biomass and grain yields, although only differences with continuous flooding were significant ($P < 0.05$). These results reveal that mid-season field drainage and alternate flooding/drying can be a promising mitigation strategy that does not affect yields.

This result stimulated another experiment to explore different modes of drainage for further reducing emission rates. In 1998, the field experiment included 4 different types of field drainage (Table 2). As in previous years, local practice (T1) encompassed drying at 55～68 days after transplanting (DAT). T2 had a slightly shorter drying period at late tillereing stage (55～61 DAT) plus a preceding one from 35～41 DAT. T3 encompassed two drainage periods (25～31 DAT & 45～51 DAT) with an earlier timing than T2. T4 consisted of one early, but slightly prolonged drainage period (35～48 DAT). All fields received mineral fertilizer and compost resulting in relatively low levels of emission rates even before the drying periods (Fig. 3 a, b). Local practice of irrigation gave the highest methane emission flux, which was obviously related to the relatively late onset of the drainage period after 55 days. The most effective drainage period for mitigating methane emission is 35～48 DAT as conducted for T4. An earlier drainage (T2) as well as a slight shortening of this drainage period (T3) yielded higher emission rates (Tab. 3). The second drainage period in

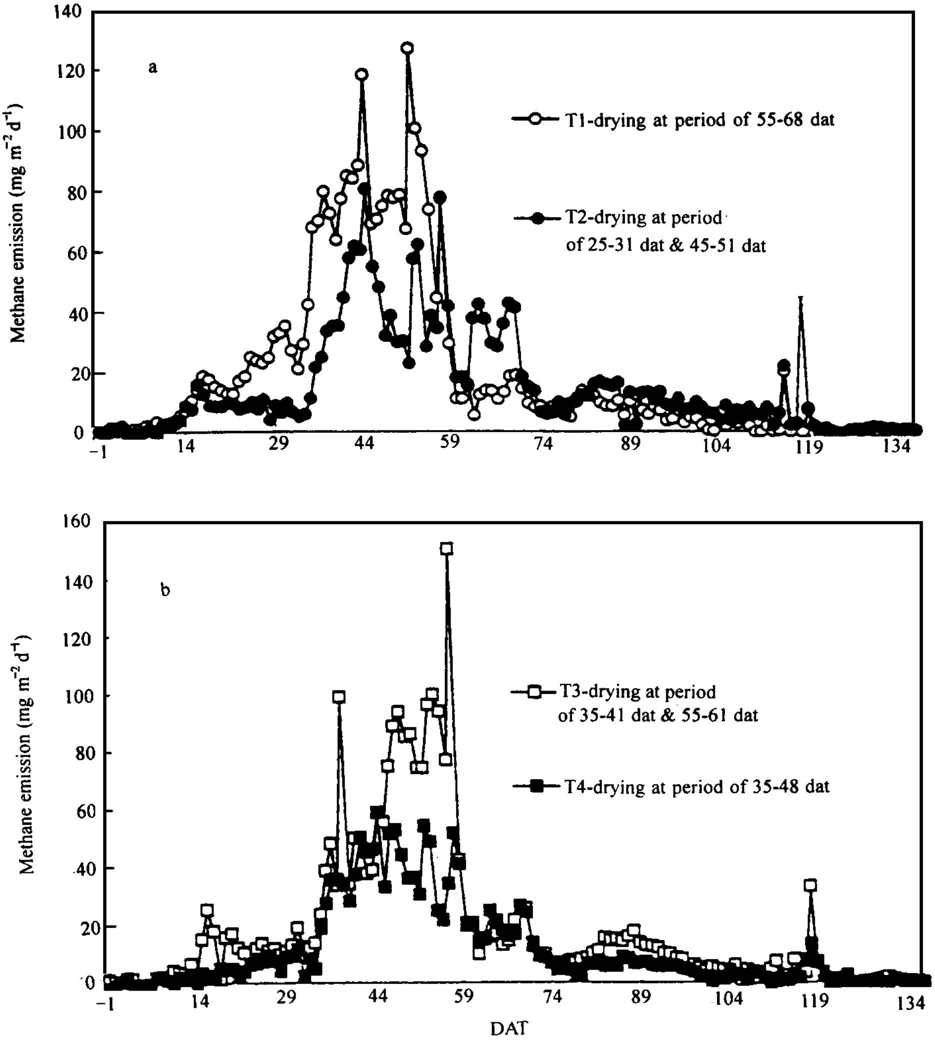

Fig. 3　Methane emission rates as affected by combination of drying time and compost during the 1998 rice season

T2 and T3 apparently had a relatively small impact on emission rates, so that T4 was recorded with the lowest overall emission.

Average emission fluxes were 20 mg m^{-2} day^{-1} in the plots with local practice of irrigation (T1), 15 mg m^{-2} day^{-1} in the plots with early and mid season drainage (T2), 19 mg m^{-2} day^{-1} in the plots with modified early and mid season drainage (T3), and 11 mg m^{-2} day^{-1} in the plots with early season drainage (T4). Methane emissions in T2 and T3 were reduced by 25% and 5%, respectively, as compared to T1 while similar yields were obtained. T4 gave as high as 46% reduction in methane emission as compared to T1 and yields were also similar. The results indicated that early and mid season field drainage can further be optimized to reduce methane emission while sustaining rice yields.

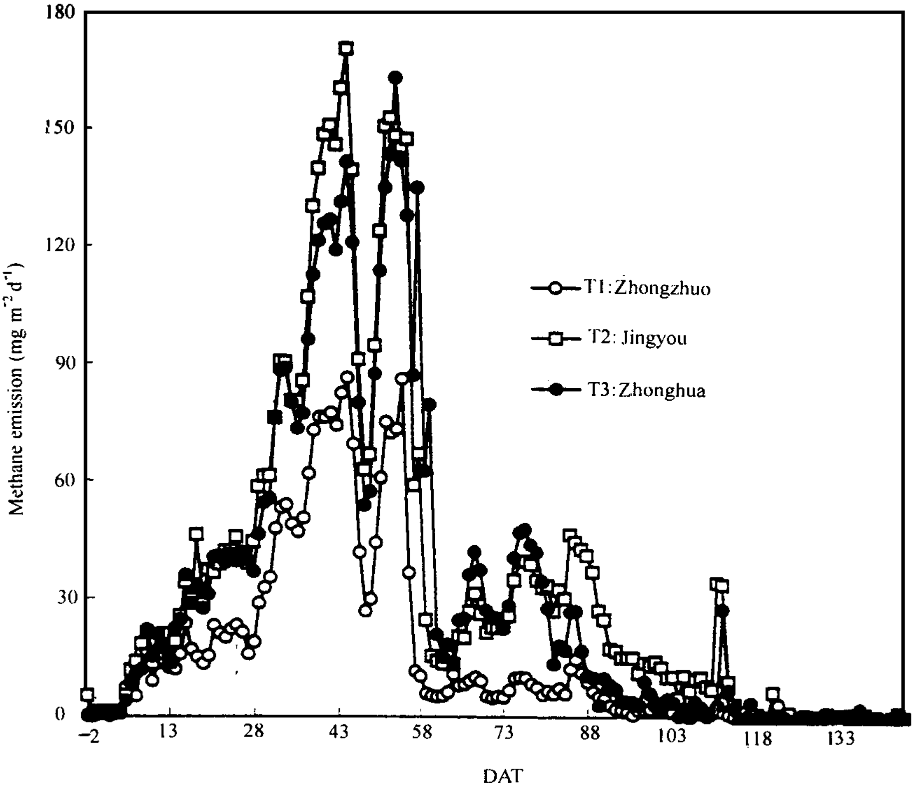

Fig. 4 Seasonal patterns of methane emission as affected by rice cultivars during the 1996 rice season.

2.3 Effect of rice cultivar Seasonal patterns of methane emission from rice cultivars are shown in Fig. 4. Methane fluxes were very low and did not differ among rice cultivars during the first week after transplanting. When methane emission started to increase in the second week after transplanting, rice cultivars differentiated in their methane emission potential. Both of Jingyou (*Japonica* hybrid) and Zhonghua 94-1017 (Tall *japonica*) gave higher methane emission fluxes while the methane emission from Zhongzhuo 93 (Modern *japonica*) was lower. Field drainage and low temperatures at the end of the season substantially reduced methane emissions for all cultivars.

Average emission rates from Zhongzhuo 93, Jingyou and Zhonghua 94- 1017 were 16 mg m^{-2} day^{-1}, 36 mg m^{-2} day^{-1} and 32 mg m^{-2} day^{-1}, respectively (Table 3). Table 3 also lists the results for IR72, a modern *indica* variety. However, the growth of this tropical cultivar was obviously affected by low temperatures, so that the low emission rates may be related to insufficient biomass assimilation. Among the temperate varieties, Zhongzhuo 93 had lowest emission rate and highest yield (Table 3). Therefore, it appears feasible and effective to maintain sustainable yield and to mitigate methane emission by cultivar selection.

2 4 Effect of mineral and organic fertilizers Fertilizer impacts were investigated in the seasons of 1995 and 1997; both experiments were conducted with local farmer's practice of irrigation. Organic manure greatly promoted methane emissions as compared to mineral fertilizers (Table 3). Methane fluxes in the plots with pig manure exceeded those in the plots with ammonium sulfate by a factor of 15 in 1995 and a factor of 35 in 1997 (Table 3). The experiment in 1997 included cattle manure and rice straw (Fig. 5). Methane emission fluxes were low and did not differ among 4 treatments during the first 7 days Methane emissions increased steeply and the difference became wider after 10 days after transplanting The maximum methane emission fluxes were recorded 26 DAT for pig manure, 36 DAT for rice straw and 52 DAT for cattle manure respectively. Pig manure gave the highest methane emission flux, followed by rice straw while methane emission flux in cattle manure treated plot was the lowest among 3 organic amendments As in 1995, the plots treated purely with mineral fertilizers emitted almost no methane gas

Average fluxes were 139 mg m^{-2} day^{-1} in pig manure treated plots, 31 mg m^{-2} day^{-1} in cattle manure treated plots, and 102 mg m^{-2} day^{-1} in rice straw treated plots and 4 mg m^{-2} day^{-1} in pure mineral fertilizer treated plots (Table 3). Quality and quantity of added organic amendments highly affected methane formation. Higher methane emission rates from pig manure and rice straw were due to higher contents of easily decomposable organic carbon than in cattle manure (data not shown). In the 1997 experiments, all organic manure types resulted in similar grain yield, indicating that organic manure management is an important mitigation option in sustainable rice system. Furthermore, it should be noted that compost amendment in 1998 yielded in substantially lower emissions than any other organic amendment tested in 1995 and 1997. Emission rates are even less than some of the experiments with mineral fertilizer in 1995 and 1996, which can be taken as clear indication of the beneficial effect of composting organic amendments for achieving low methane emission from rice fields

2 5 Ebullition and dissolved methane in soil solution The seasonal patterns of methane ebullition and dissolved methane in the 1997 experiment are shown in Fig. 6 Ebullitions of methane in the plots treated pig manure and cattle manure were higher than those treated rice straw and mineral fertilizer. Ebullitions of methane during the 1997 rice season under different organic amendments were averaged 26 51 mg m^{-2} day^{-1} in pig manure treated plots, 16 59 mg m^{-2} day^{-1} in cattle manure treated plots, 6 86 mg m^{-2} day^{-1} in rice straw treated plots and 1.45 mg m^{-2} day^{-1} in pure mineral fertilizer treated plots. These values accounted for 36.3% (mineral), 22.1% (cattle manure), 16.3% (rice straw) and 19.1% (pig manure) of the total methane emission. The difference in methane ebullition among treatments was probably related to the quality and quantity of organic amendment.

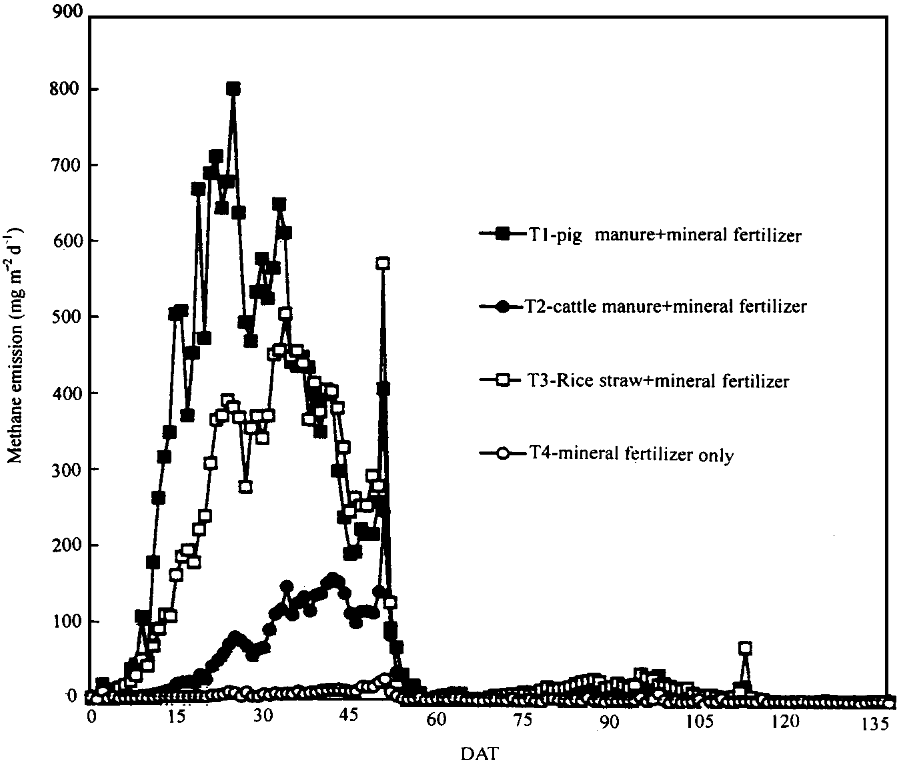

Fig. 5 Impact of organic amendment on methane emission from rice fields during the 1997 rice season.

Dissolved methane concentrations were relatively high in the plots treated organic amendments while the plots treated mineral fertilizer had low methane concentrations (Fig. 6). Seasonal patterns of dissolved methane were similar among treatments. At tillering stage, higher dissolved methane concentration occurred coincided with high ebullition rates of methane. Dissolved methane was positively correlated with methane ebullition ($r^2 = 0.58^{**}$, $n = 32$) and emission ($r^2 = 0.67^{**}$, $n = 32$) at tillering stage. It was observed that dissolved methane concentration was soil Eh dependent ($r^2 = 0.41^{**}$, $n = 56$) and negatively correlated to soil Eh ($r^2 = -0.62^{**}$, $n = 56$).

Dissolved methane concentration was high at soil depth of 5, 10 and 15 cm while the concentration of dissolved methane at floodwater always remained at low level. Dissolved methane concentration in the soil was different from year to year but the seasonal pattern was similar in the measuring years (data not shown).

2.6 Mitigation strategies Methane emission rates under local practice in North China ranged from 4 to 364 mg m^{-2} day^{-1}, with average emission of 82 mg m^{-2} day^{-1}. Seasonal maximum values occurred at tillering stage and the emission during this stage accounted for

85% of the annual methane rate. Therefore, it is crucial to reduce seasonal methane flux by controlling methane emission at early season.

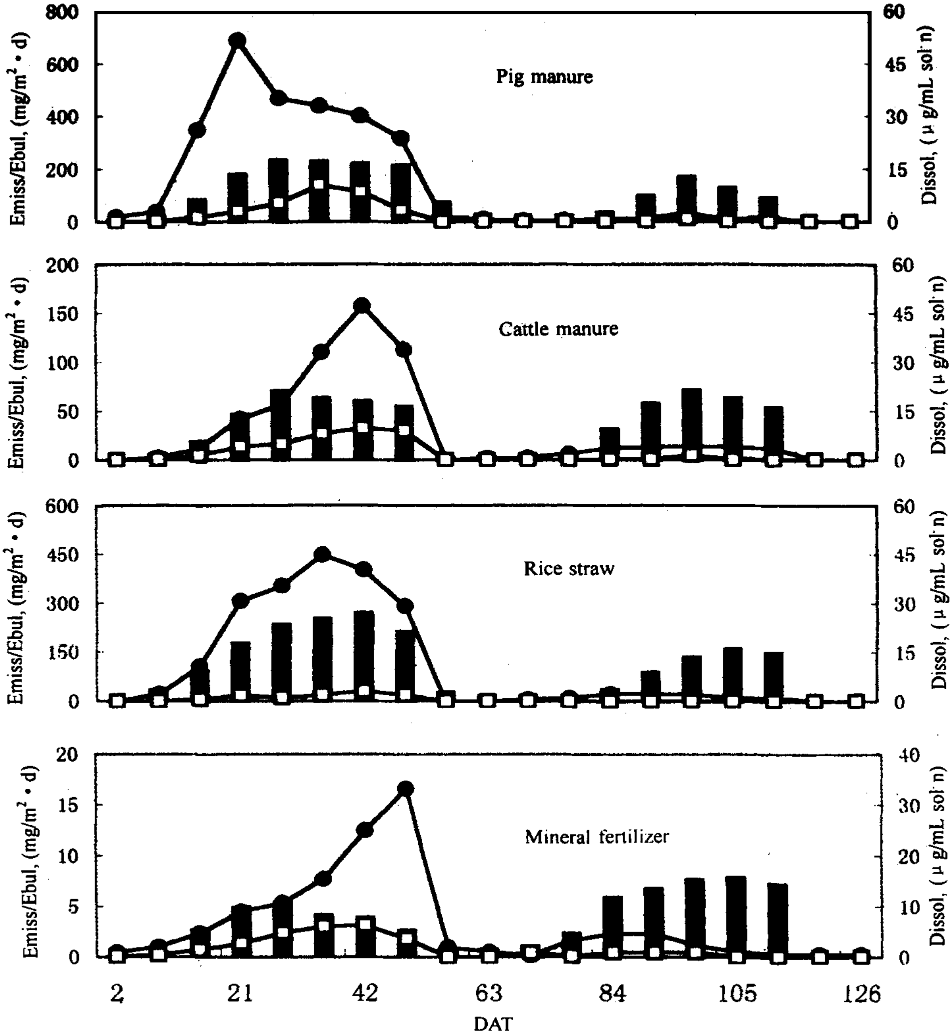

Fig. 6 Seasonal pattrens of methane emission, ebullation and dissolved methane in the 1997 rice season

Methane mitigation options used in rice fields must both reduce methane emission and sustain rice production. Water control is one of the most important factors in rice production. Alternative wetting and drying management reduced methane emissions by 23% ～ 59% while yield increased by 16%. Water management would be the most promising mitigation option in China where irrigation water is available and irrigation/drainage systems are established.

Application of organic manure is a common practice to maintain soil fertility but it increases methane emission from rice fields. This effect on methane emission may be reduced through choosing the organic amendment with low methane potential, e. g. composting manure instead of pig manure and fresh rice straw. An alternative way is rotation application of organic amendment and mineral fertilizer in the sequence years.

Rice cultivars differ in methane emissions. Variety selection is feasible and effective to find cultivar like Zhongzhuo 93 with low methane emission efficiency and high harvest index. Using rice cultivar as a mitigation strategy is an easily adopted option because farmers may use it without any expensive input.

Reference

1 Bolle H J, W Seiler, B Bollin. In: *Climate Change and Ecosystems*, John Wiley & Sons, NY, 1986. 157～198
2 Rasmussen R A, M A K Khalil. *Science*, 1986. 32: 1623～1624
3 Thompson, A M, R J Cicerone. *J Geophys Res*, 1986. 91(D): 10858～10864
4 IPCC. *Climate Change*, Cambridge University Press, UK, 1992
5 Neue H U. *Bioscience*, 1993. 43(7): 466～474
6 Sass R L. *Global Change Newsletter*, 1995. 22: 4～5
7 Editoral Office of the Agricultural Year Book of China. *The agricultural Year Book of China*, Agricultural Press, Beijing, China. 1995
8 Wang M X, A Dai, R X Shen et al. *Acta Meteorologica Sinica*, 1990. 4(3): 265～275
9 Chen D Z, M X Wang, X J Shangguan et al. *Adv. Earth Sci.* 1993a. 8(5): 47～54
10 Chen Z L, D B Li, K S Shao et al. *Chemosphere*, 1993b. 26(1～4): 239～245
11 Min H. *Rural Eco-Environment Sup*, 1993. 28～32
12 Wassmann R, H Schutz, H Papen et al. *Biogeochemistry*, 1993. 20: 83～101
13 Wassmann R, X J Shangguan, M Tolg et al. *Biol Fertil Soil*, 1996. 22: 191～195
14 Cai Z C, X Y Yan, H Xu et al. *Acta Pedol Sin*, 1995. 32(supp.): 136～143
15 Shao, K S, Z Li *Acta Scientiarum Naturalium*, Universitatis Pekinesis, 1996. 32(4): 505～512
16 Tao Z, D D Du. *Agri. Environ. Prot.* 1998. 17(1): 1～7
17 Wang Z Y, Y C Xu, Z Li et al. *Acta Agro Sin* 1998. 24(2): 134～138
18 Wassmann R. *Nutrient Cycling in Agroecosystems*, Special Issue, 2000. 1～12

稻田CH$_4$排放及控制技术的研究

王增远[1] **徐雨昌**[1] **李震**[1] **过益先**[1] R Wassmann[2] H U Neue[2] R S Lantin[2] L V Buendia[2]

(**[1]中国农业科学院作物育种栽培研究所，北京** 100081；[2]**菲律宾国际水稻研究所**)

提　要　为了探索北方稻田水管理、施肥和水稻品种对稻田甲烷排放的影响，于1995年至1998年应用全自动甲烷采样-测定系统，测定了水稻田甲烷排放通量。实验探明：北方稻田甲烷排放通量为4～364 mg/m^2. d，平均值为82 mg/m^2. d；稻田甲烷的季节排放只有一个高峰，发生在水稻分蘖期，该期的甲烷排放量占年排放总量的85%以上，水稻生长中、后期的稻田甲烷非常有限。水管理对稻田甲烷的生成、排放有显著的影响，稻田采用间歇灌溉代替常规灌溉和淹灌，可减排稻田甲烷46%～59%；稻田施用有机肥，甲烷排放量则剧增。但在同等有机碳含量情况下，不同有机肥的产甲烷潜势存在明显差异，猪粪和稻草较高，堆肥和牛粪较低，稻田施用堆肥和牛粪，可比施用猪粪和稻草的稻田减排稻田甲烷72%～90%；试验中选用的水稻品种，以中作93的甲烷排放效率为最低，其甲烷排放通量比杂交稻京优和高秆品种中花94-1017减少50%～55%。实验揭示，水稻分蘖期是控制北方稻田甲烷排放的关键时期，该试验结果为制定稻田甲烷控制策略提供了重要参考。

关键词　甲烷排放通量；水稻田；水管理；水稻品种；有机肥