Mitigation of Methane Emissions from Rice Cultivation

K. MINAMI[1] and K. YAGI[2]

[1] *National Institute of Agro-Environmental Sciences*
Kannondai 3-1-1 Tsukuba, Ibaraki 305-8604, Japan
[2] *Environmental Resources Division*
Japan International Research Center for Agricultural Sciences (JIRCAS),
Tsukuba 305-0856, Japan

ABSTRACT

Flooded rice fields are an important source of atmospheric methane (CH_4). This paper discusses the factors that influence CH_4 production and emission from the source, estimates of CH_4 from rice production and potential methods of mitigating CH_4 emissions. The use of the mitigation options suggested could potentially decrease CH_4 emissions from flooded rice fields by about 40% worldwide.

Key words : flooded rice fields, methane flux, organic matter management oxidation, water management

1. INTRODUCTION

The concentration of atmospheric CH_4 has been increasing since the Industrial Revolution (Khalil & Rasmussen, 1981 ; Steel *et al.*, 1987 ; Blake & Rowland, 1988). Methane has a strong influence on atmospheric chemistry (Thompson & Cicerone, 1986). Methane is also an important greenhouse gas for the climate system because of its infrared absorption spectrum (Wang *et al.*, 1976). A rapid increase, therefore, could have significant environmental consequences (Ramanathan *et al.*, 1985). Although a slowing down of the growth rate of atmospheric CH_4 has been reported recently (Dlugokencky *et al.*, 1994), there are large uncertainties in the global budget of CH_4 and its changes. Therefore, further research is needed to estimate accurately the strength of individual sources and sinks of atmospheric CH_4.

Of the wide variety of sources of atmospheric CH_4, rice paddy fields are considered to be an important source (IPCC, 1995) because of the recent increase in rice harvest area worldwide (IRRI, 1991). Field measurements indicate that a number of agro-environmental factors, including soil properties, plant activities, cultivation practices, and climatic factors combine to influence CH_4 emissions from rice paddy fields (Conrad, 1989 ; Yagi *et al.*, 1994 ; Minami, 1995).

2. FACTORS AFFECTING CH_4 PRODUCTION

Measurements performed at various locations in the world show that there are large temporal variations of CH_4 flux which differ with sites, seasons of planting and agricultural treatments (Minami, 1995). These variations indicate that CH_4 flux is critically dependent upon several factors including climate, soil and paddy characteristics, and agricultural practices. About 90% of the world's harvested area of rice fields is located in Asia with India and China accounting for 60% of the total. Therefore, we need more detailed information about CH_4 flux values in Asia.

The main chemical processes that occur in flooded soils consist of a series of successive oxidation and reduction reactions mediated by different types of microorganisms. Flooding alters the character of the microbial flora in soils by decreasing O_2 diffusion from the atmosphere. Fermentation is one of the major biochemical processes responsible for organic matter degradation in flooded soils. The main products of the fermentation process in flooded soil are ethanol, acetate, lactate, propionate, butyrate, H_2, N_2, CH_4 and CO_2. The latter three gases usually contribute to the largest proportion of the gas phase of flooded soils.

The major pathways of CH_4 production in flooded soil are the reduction of CO_2 by H_2, with fatty acids or alcohols as hydrogen donors, and the transmethylation of acetic acid or methyl alcohol by methane producing bacteria (Takai, 1970 ; Conrad, 1989). In paddy fields, the kinetics of the reduction processes are strongly affected by the composition and texture of soil and its content of inorganic electron acceptors. The period between flooding of soil and onset of methanogenesis varies with soils.

The redox potential (Eh) directly controls the production of CH_4 in soils. The Eh of the soil gradually decreases after flooding. Takai *et al.* (1956) and Yamane and Sato (1964) showed that CH_4 was not emitted from flooded paddy soils until the Eh fell below -200mv. There is a negative correlation between the soil redox potential and CH_4 emission (Patrick *et al.*, 1981 ; Cicerone *et al.*, 1983 ; Yagi and Minami, 1990). Fig. 1 shows the seasonal variations in CH_4 emission, the daily mean soil and air temperature, and the soil Eh in Ryugasaki paddy fields (Yagi & Minami, 1990). The period of CH_4 emission from the paddy fields corresponded closely to the period of low redox potential in the paddy soil.

Substrate and nutrient availability is also an impor-

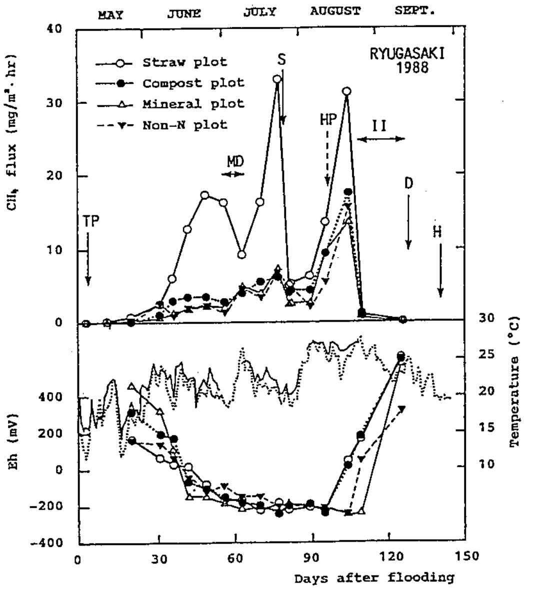

Fig.1 Seasonal variations of CH_4 flux, daily mean temperature of soil and air, and soil Eh at four depths in a Japanese paddy field (Yagi and Minami, 1990).

tant factor. Fig. 1 shows that the application of rice straw to paddy fields significantly increases CH_4 emission compared with the application of compost prepared from rice straw or chemical fertilizer.

Temperature is an important factor controlling the activity of soil microorganisms. Yamane and Sato (1961) found that CH_4 formation reached a maximum value at 40°C in waterlogged alluvial soils. At above 40°C, CH_4 formation decreased and stopped at 60°C. A negligible amount of CH_4 was produced below 20°C.

It is generally recognized that most CH_4 is formed in a very narrow pH range around neutrality (6.4 to 7.8). Following flooding, the pH of acid soils increases, and that of alkaline soils decreases. The pH increase in acid soils is mainly due to the reduction of acidic Fe^{3+} to Fe^{2+}.

The addition of sulfate as chemical fertilizer to flooded soils also influences the production of CH_4 because it increases the redox potential, and H_2S production is toxic to methanogens. Also, the addition of sulfate increases the activity of sulfate-reducing bacteria which outcompete methanogens for substrate. Sulfate must be reduced before CH_4 can be formed in paddy soils (Takai, 1980).

The addition of fertilizer nitrate to flooded soils may also suppress the production of CH_4. Since nitrate acts as a terminal electron acceptor for anaerobic respiration in the absence of molecular oxygen it fixes the redox potential of soils at certain values so that the activity of strict anaerobes is prevented (Minami, 1995).

3. METHANE EMISSION AND OXIDATION

There are three processes for the transfer of CH_4 from rice paddies to the atmosphere. Methane loss as bubbles from paddy soils should be a common and significant mechanism. Diffusion loss of CH_4 across the water surface is another process. The third and the most important pathway of CH_4 transport is through aerenchyma. Release to the atmosphere through the shoot nodes which are not subject to stomatal control is generally the most important emission mechanism accounting for more than 90% of total CH_4 emissions from rice paddies (Nouchi, 1994 ; Minami, 1994).

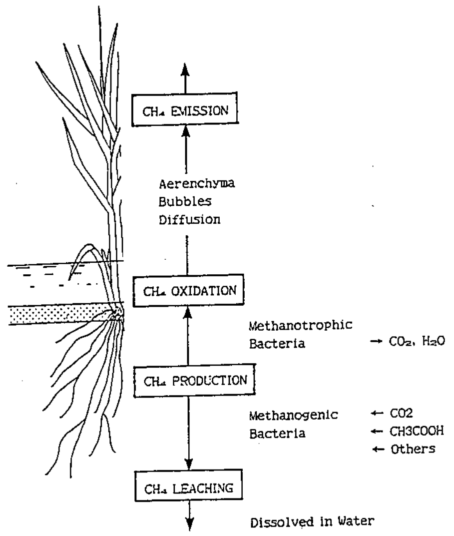

Fig.2 Diagram of CH_4 production, oxidation, emission and leaching (Minami, 1994).

During the course of the rice growing season a large portion of the CH_4 produced in the flooded soil is oxidized before being released to the atmosphere (Sass *et al.*, 1992). Although CH_4 flux rates are a function of the total amount of CH_4 in the soil, there is the possibility that the gas may be consumed in the thin oxidized layer close to the soil surface and in deep flood water. It is known that soil methanotrophic bacteria can grow with CH_4 as their sole energy source, and that other soil bacteria consume CH_4. As a small amount is dissolved in water CH_4 is also leached to ground water.

Fig. 2 illustrates the balance between emissions of CH_4 from flooded rice fields as the result of CH_4 production, oxidation, and leaching to ground water (Minami, 1994). The quantity of CH_4 emitted from a rice field depends upon the balance among these processes.

4. ESTIMATES OF CH_4 FROM RICE PRODUCTION

The harvested paddy rice area has increased from 86×10^6 ha in 1935 to 148×10^6 ha in 1985. However, in that decades, the rate of expansion of rice growing areas has decreased. About 90% of the world's harvested area of rice paddies is located in Asia. Of the total harvested area in Asia, about 60% is located in India and China.

IPCC (1992) estimated the global emission rate from paddy fields to range from 20 to 150 Tg/yr, averaging 60 Tg/yr, or about 5-30% of the total emission from all sources. These estimates were mainly based on the field measurements of CH_4 flux

Table 1 Estimates of CH_4 emissions from rice fields in different countries (Minami et al., 1994) and estimate of global CH_4 emission from rice (Sass, 1994)

Country	Total area of rice paddies (10^{10} m^2)	Total rice grain yield (Mg)	CH_4 emission (Tg/yr)
China	32.2	174.7	13–17
India	42.2	92.4	2.4–6
Japan	2.3	13.4	0.02–1.04
Thailand	9.8	19.2	0.5–8.8
Philippines	3.5	8.9	0.3– 0.7
USA	1.0	6.4	0.04–0.5
Total	91	315.1	16–34
World Total	147.5	473.5	25.4–54*

* World total emission rate obtained by area scaling of the total emission rates measured in the paper presented in Minami et al. (1994).

from paddy fields in United States, Spain, Italy, China, Australia and Japan. There were no detailed data available to estimate CH_4 flux from India and China in 1990, but recently some data have been published on Asian countries (e.g. Minami *et al.,* 1994).

Sass (1994) tightened the range of projected CH_4 emissions after a review of CH_4 studies in China, India, Japan, Thailand, the Philippines and the USA. He combined the data on total area of rice paddies with the flux estimates published in various chapters of the book of Minami *et al.* (1994) to produce Table 1. By extrapolating these data to the world rate Sass (1994) estimated that total CH_4 emissions from rice fields range between 25.4 and 54 Tg/yr. The greater value is consistent with an IPCC (1992) estimate of 60 $TgCH_4$/yr, but the range indicates that the actual rate may be lower.

5. METHANE OXIDATION IN SOIL

Ojima *et al.* (1993) estimated that land-use changes during the past 200 years have decreased the global temperate soil sink for CH_4 by 20-30%. Reeburgh *et al.* (1993) estimated that the global aerobic soil sink was about 40 $TgCH_4$/yr. From a review of available CH_4 uptake data, Minami *et al.* (1993) limited the total terrestrial CH_4 consumption to between 7 and 78 Tg/yr. Thurlow *et al.* (1995) showed that unflooded paddy soils, after drainage practices, are able to act as a sink of CH_4 and vary in their ability to consume CH_4 depending on soil temperature and atmospheric CH_4 concentrations.

6. OPTIONS FOR MITIGATING CH_4 EMISSION

(1) Strategies

Based on the processes involved in the control of CH_4 emissions from rice paddy fields, it is concluded that the possible strategies for mitigating CH_4 emissions from rice cultivation include control of either production, oxidation, or transport processes. Since methanogens require highly reducing conditions for their activity, arresting the development of soil reduction is one of the most effective methods of decreasing the CH_4 production rate in soils. This can be accomplished by aerating soils during the flooding period by altering water management, or by inhibiting the progression of sequential redox reactions by adding chemicals. Changing tillage may lead to the same effect on soil reduction. These options may simultaneously enhance CH_4 oxidation rates in soils. Reducing the amount of labile organic matter in soils by composting organic fertilizer or promoting aerobic decomposition of biomass is another effective way of controlling CH_4 production in soils. Since rice plants also contribute significantly to the production/oxidation of CH_4 in the rhizosphere and its transport to the atmosphere, selection of rice varieties that emit smaller amounts of CH_4 may also be an effective way to mitigate CH_4 emissions from rice paddy fields (Yagi, *et al.,* 1997).

(2) Water management

Methane emission is influenced by the type of water regime used on a rice field, especially by the duration of the flooding period and the drainage schedule. Draining the rice field during the growing season seems to decrease CH_4 production by increasing the state of oxidation of the paddy soil (Sass *et al.,* 1992).

Short-term drainage had a strong effect on CH_4 emissions as shown in Fig. 3 (Yagi *et al.,* 1997). A large flush of CH_4 emissions was observed in the intermittently drained plots immediately after each drainage. Total emission rates of CH_4 during the cultivation period were 14.8 and 8.63 g/m^2 for 1991 and 9.49 and 5.18 g/m^2 for 1993 in the continuously flooded and intermittently drained plots, respectively.

The rate of water percolation in rice paddy fields also exerts an influence on CH_4 production and emission, because water percolation influences chemical conditions in flooded soils. A lysimeter experiment showed that CH_4 emission rates significantly decreased with the increase in the percolation rates (Yagi *et al.,* 1990). Total emission during the cultivation period ranged from 5.7 to 13.8, from 0.6 to 4.8, and from 0.1 to 0.3g/m_2 in the no, moderate (about 5mm/day), and high (about 20mm/day) percolation plots, respectively.

(3) Soil amendments and mineral fertilizers

Sulfate is one of the most promising candidates for this strategy because it is commonly used as a component of mineral fertilizers and soil amendments. The addition of sulfate to soil activates sulfate-reducing bacteria which decrease the activity of methanogens by restricting the availability of substrates in submerged soils.

Lindau *et al.* (1993) reported that CH_4 emissions can be decreased by adding sodium sulfate (28-35%) or coated calcium carbide (36%) with urea compared to urea alone, and by using ammonium sulfate (20%) instead of urea.

Addition of other oxidants, iron containing materials such as bauxite, iron ore and residues of iron

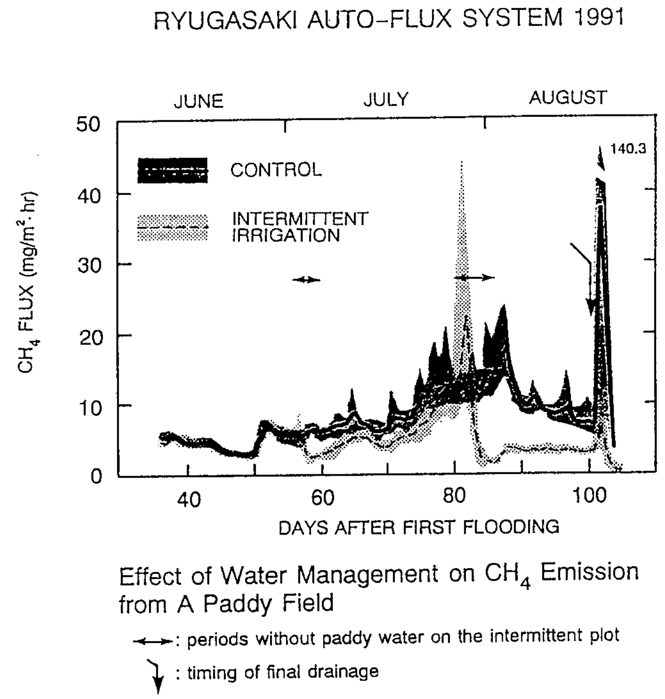

Fig.3 Effect of water management on CH_4 emissions from a rice paddy field. The arrows indicate the duration of the period of midseason drainage in the intermittent irrigation plot and the timing of final drainage in both plots (Yagi *et al.*, in press).

manufacture probably reduce CH_4 emissions.

(4) Organic matter management

In world's rice cultivation, fresh organic matter is often applied solely or after being mixed with rice straw. In the fields, a part of the biomass of previous crops and weeds remains in soils at the start of rice cultivation. Such organic matter is decomposed in soils and acts as an electron donor and a substrate of fermentation reactions. Therefore, organic matter management has a significant effect on CH_4 production in soils. The management of organic matter in rice cultivation is also important from the viewpoint of sustaining soil fertility. This organic matter management option for mitigating CH_4 emission is deeply related to sustainable agriculture afterwards.

Many researchers demonstrated that the incorporation of rice straw and green manure into rice paddy soils dramatically increases CH_4 emission. A field study showed that the incorporation of rice straw in soil at rates of 600-900 g/m_2 after previous harvest increased CH_4 emission rates by 1.1- to 3.5-fold in Japanese rice paddy fields, while application of rice straw compost slightly increased CH_4 emission (Yagi, *et al.*, 1997). These results clearly indicate that composting of fresh organic matter significantly mitigates CH_4 emission from rice paddy fields.

(5) Others

Methane emissions vary greatly with rice varieties (Sass & Fisher, 1994). Selection for CH_4 emission potential as well as productivity and taste may be a useful strategy for mitigating CH_4 (Neue, 1992). Sass and Fisher (1994) surveyed 10 rice cultivars that were adapted for temperate and subtropical irrigated fields and found that seasonal CH_4 emission rates varied from 18 to 41g/m^2.

Certain methods of tillage, seeding and weeding used to minimize water use and mechanical soil disturbance may also offer some CH_4 mitigation potential (Neue, 1992). Choice of rice cultivar and types of chemicals and the placement of fertilizer can affect the activity of CH_4 producing bacteria and hence the emission of CH_4. For example, the substitution of wet tillage and transplanting of rice seedlings with dryland tillage and dry seeding seems to reduce CH_4 emissions. Minimum tillage should have similar effects. Avoidance of mechanical soil disturbance during weeding may also reduce CH_4 emissions.

(6) Estimates of CH_4 emissions reduction in rice production

The three major management options that have been suggested for limiting CH_4 emissions from rice are (1) water management, (2) nutrient management and (3) cultivation practices and use of new cultivars. Combination of these practices for global rice production could lead to large decreases in CH_4 production in

Table 2 Estimated effect of management practices on CH_4 production in flooded rice (Mosier *et al.*, in press)

Mitigation practice	Production amenable for mitigation	Potential decrease	Range
	TgCH$_4$		
Irrigation management	50	5	3.3–9.9
Nutrient management	50	10	2.5–15
New cultivars and other cultural practices	50	5	2.5–10
Emissions amenable to mitigation	50	20	8–35

rice. In Table 2, potential CH_4 reduction ascribed to specific management practices is outlined (Mosier *et al.*, 1998).

REFERENCES

Blake, D.R. and F.S. Rowland (1988) Continuing worldwide increase in tropospheric methane, 1978 to 1987. *Science,* 239 : 1129-1131.

Cicerone, R.J., J.D. Shetter and C.C. Delwiche (1983) Seasonal variation of methane flux from a California rice paddy. *J. Geophys. Res.,* 88 : 11,002-11,024.

Conrad, R. (1989) Control of methane production in terrestrial ecosystems, In : *Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere* (eds M.O. Andreae & D.S.Schimel) John Wiley, Chichester. pp. 35-58.

Dlugokencky, E.J., L.P. Steel, P.M. Lang and K.A. Masarie (1994) The growth rate and distribution of atmospheric methane. *J. Geophys. Res.,* 99 : 17,021-17,043.

Intergovernmental Panel on Climate Change (1992) *Climate Change 1992, The Supplementary Report to the IPCC Scientific Assessment (1992)* (eds J.R. Houghton, B.A. Callander & S.K. Varnet) Cambridge University Press, Cambridge. pp. 1-46.

Intergovernmental Panel on Climate Change (1996) *Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change : Scientific-Technical Analyses* (eds R.T. Watson, M.C. Zinyowera, R.H. Moss & D.J. Dokken, Cambridge University Press, Cambridge. pp. 745-771.

International Rice Research Institute (1991) *World Rice Statistics 1990* Los Banos, Philippines.

Khalil, M.A.K. and R.A. Rasmussen (1981) Atmospheric methane (CH_4) ; Trends and seasonal cycles. *J. Geophys. Res.,* 86 : 9826-9832.

Lindau, C.W., P.K. Bollich, R.D. DeLaune, A.R. Mosier and K.F. Bronson (1993) Methane mitigation in flooded Louisiana rice fields. *Biol. Fertil. Soils,* 15 : 174-178.

Minami, K., J.Goodriun, J.Lantinga and T. Kimura (1993) The significance of grasslands in emission and absorption of greenhouse gases. Proc. 17th Grassland Cong. : 1231-1237.

Minami, K. (1994) Methane from rice production. *Fert. Res.,* 37 : 167-180.

Minami, K., A.Mosier and R.Sass (eds) (1994) CH_4 and N_2O Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources. *NIAES Series 2.* YOKENDO Publishers, Tokyo. 234p.

Minami, K.(1995) The effect of nitrogen fertilizer use and other practices on methane emission from flooded rice. *Fert. Res.,* 40 : 71-84.

Mosier, A.R., J.M. Daxbury, J.R. Freney, O.Heinemeyer, K. Minami and D.E. Johnson, (1998) Mitigating agricultural emissions of methane. *Climate Change,* in press.

Neue, H.U. (1992) Agronomic practices affecting methane fluxes from rice cultivation. In : Trace Gas Exchange in a Global Perspective (eds D.S.Ojima & B.H. Svensson) *Ecol. Bull.,* 42 : 174-182.

Nouchi, I. (1994) Mechanism of methane transport through rice plant. In : *CH_4 and N_2O Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources* (eds. K. Minami, A. Mosier & R. Sass) NIAES, Yokendo Publishers, Tokyo, pp.87-104.

Ojima, D.S., D.W.Valentine, A.R.Mosier, W.J.Parton and D.S.Schimel (1993) Effect of land use change on methane oxidation in temperate forest and grassland soils. *Chemosphere,* 26 : 675-685.

Patrick, W.H.Jr. (1981) *The role of inorganic redox systems in controlling reduction in paddy soils.* Proc. Symp. Paddy Soil, Science Press, Beijing, Springer Verlag. pp. 107-117.

Ramanathan, V., R.J. Cicerone, H.B. Singh and J.T. Kienl (1985) Trace gas trends and their potential role in climate change. *J. Geophys. Res.,* 90 : 5547-5566.

Reeburgh, W.S., S.C. Whalen and M.J. Alpern (1993) The role of methylotrophy in the global methane budget. Microb. Growth on C1 Coump., pp. 1-4.

Sass, R.L., F.M. Fisher, Y.B. Wang, F.T. Turner and M.F. Jund (1992) Methane emission from rice fields ; the effect of floodwater management. *Global Biogeochem. Cycles.,* 6 : 249-262.

Sass, R.L. (1994) Short summary chapter for methane. In : *CH_4 and N_2O Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources* (eds K.Minami, A. Mosier & R. Sass) NIAES, YOKENDO Publishers, Tokyo, pp.1-7.

Sass, R.L. and F.M. Fisher (1994) CH_4 emission from paddy fields in the United States gulf coast area. In : *CH_4 and N_2O Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources* (eds K.Minami, A. Mosier & R.Sass) NIAES, Yokendo Publishers, Tokyo, pp.65-77.

Steel, L.P., P.J.Fraser, R.A.Rasmussen, M.A.K.Khalil, T.J. Conway, A.J. Crawford, R.H.Gammon, K.A.Msaarie and K.W.Thoning (1987) The global distribution of methane in the troposphere. *J. Atmos. Chem.,* 5 : 125-171.

Takai, Y., T.Koyama and T.Kamura (1956) Microbial metabolism in reduction process of paddy soils (Part 1). *Soil and Plant Food,* 2 : 63-66.

Takai, Y. (1970) The mechanism of methane fermentation in flooded paddy soil. *Soil Sci. Plant Nutr.,* 16 : 238-244.

Takai, Y. (1980) Microbial study on the behavior of the paddy soils. *Fert. Sci.* 3 : 17-55 (in Japanese).

Thompson, A.M. and R.J. Cicerone (1986) Possible perturbations to atmospheric CO, CH_4, and OH. *J. Geophys. Res.,* 91 : 10853-10864.

Thurlow, M., K.Kanda, H.Tsuruta and K.Minami (1995) Methane uptake by unflooded paddy soils ; The influence of soil temperature and atmospheric methane concentration. *Soil Sci. Plant Nutr.,* 41 : 371-374.

Wang, W.C., Y.L.Yung, A.A.Lacis, J.E.Mo and J.E.Hansen (1976) Greenhouse effects due to man-made perturbations of trace gases. *Science,* 194 : 685-690.

Yagi, K. and K.Minami (1990) Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Sci. Plant Nutr.,* 36 : 599-610.

Yagi, K., P.Chairoj, H.Tsuruta, W.Cholitkul and K.Minami (1994) Methane emission from rice paddy fields in the central plain of Thailand. *Soil Sci. Plant Nutr.,* 40 : 29-37.

Yagi, K., H.Tsuruta, K.Kanda and K.Minami (1995) Effect of water management of methane emission from a Japanese rice paddy field : Automated methane monotoring. *Global Biogeochem. Cycles,* 10 : 255-267.

Yagi, K., H.Tsuruta and K.Minami (1997) Possible options for mitigating methane emission from rice cultivation. Nutr. *Cycling in Agroecosystems,* in press.

Yamane, I. and K.Sato (1961) Effect of temperature on the formation of gases and ammonium nitrogen in the waterlogged soils. *Sci. Rep. Res. Inst.* Tohoku Univ. D (Agr.), 12 : 31-46.

Yamane, I. and K.Sato (1964) Decomposition of glucose and formation in flooded *Soil. Soil Sci. Plant Nutr.,* 10 : 127-133.

(Received Sep. 10, 1997, Accepted Nov. 15, 1997)