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Methane emission from Indonesian rice fields with special references to the effects of yearly and seasonal variations, rice variety, soil type and water management

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Abstract:

Total amounts of CH_4 emission from a Sumatra rice field were in the ranges 29·5–48·2 and 43·0–64·6 g CH_4 m^{-2} $season^{-1}$ for the plots with chemical fertilizer (CF-plot) and those with rice straw application (RS-plot), respectively. Nearly the same amounts of CH_4 were emitted in the first and second half of the growth period, irrespective of rice straw application. The increase in the amounts of CH_4 emission by rice straw application were from 1·3 to 1·6 times. There was no significant difference in the mean CH_4 emission rates between rainy and dry seasons. Rain-fed conditions decreased the CH_4 emission by 27–37% compared with continuously flooded conditions. Total amounts of CH_4 emission from a rice field growing eight popular modern rice varieties in Indonesia were in the ranges 32·6–41·7 and 51·3–64·6 g CH_4 m^{-2} $season^{-1}$ for CF- and RS-plots, respectively. Total amounts of CH_4 emission from four Sumatra rice fields with different soil types (a Typic Paleudult, a Typic Sulfaquent, a Typic Tropohumult and a Typic Tropopsament) were in the range 22·1 (a Typic Sulfaquent) to 53·4 (a Typic Tropohumult) g CH_4 m^{-2} $season^{-1}$ for CF-plots and from 26·7 (a Typic Sulfaquent) to 72·2 (a Typic Tropohumult) g CH_4 m^{-2} $season^{-1}$ for RS-plots. CH_4 emission rates from Bali rice fields with soils of volcanic ash origin were very low; 3·5–7·7 and 5·3–14·3 g CH_4 m^{-2} $season^{-1}$ for CF- and RS-plots, respectively.

Respective rice fields showed the specific productivity of grain production, and CH_4 emission rates for 1 kg grain production were scattered widely from 8–11 and 11·24 g CH_4 kg^{-1} grain for rice fields of volcanic ash origin to 83 and 121 g CH_4 kg^{-1} grain for a Sumatra rice field for CF- and RS-plots, respectively. Water management was also an important factor in decreasing the CH_4 emission rate. © 1998 John Wiley & Sons, Ltd.

KEY WORDS grain production; CH_4 emission; rain-fed; rice field; rice straw; rice variety; soil type; water management

INTRODUCTION

The contribution of methane (CH_4) emitted from rice fields is now estimated to be about 11% of the total CH_4 emission (Prather *et al.*, 1995). Many studies have been conducted on estimation of the amounts of CH_4 fluxes under different growth conditions, in terms of the effects of cultivation (Cicerone and Shetter, 1981; Seiler

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et al., 1984; Holzapfel-Pschorn *et al.*, 1986; Sass *et al.*, 1990, 1991; Kimura *et al.*, 1991; Jermsawatdipong *et al.*, 1994; Yagi *et al.*, 1994), soil type (Sass *et al.*, 1990, 1991; Yagi and Minami, 1990; Kimura *et al.*, 1991), fertilization (Cicerone and Shetter, 1981; Cicerone *et al.*, 1983, 1992; Holzapfel-Pschorn and Seiler, 1986; Schütz *et al.*, 1989; Yagi and Minami, 1990; Kimura *et al.*, 1991; Sass *et al.*, 1991; Delwiche and Cicerone, 1993; Lindau and Bollich, 1993; Murase *et al.*, 1993; Watanabe *et al.*, 1993a,b, 1995; Jermsawatdipong *et al.*, 1994), yearly and seasonal variation (Cicerone *et al.*, 1983; Holzapfel-Pschorn *et al.*, 1986; Holzapfel-Pschorn and Seiler, 1986; Schütz *et al.*, 1989; Sass *et al.*, 1990, 1991; Yagi and Minami, 1990), diurnal variation (Cicerone *et al.*, 1983; Seiler *et al.*, 1984; Holzapfel-Pschorn and Seiler, 1986; Schütz *et al.*, 1989; Yagi and Minami, 1990; Miura *et al.*, 1992), temperature (Holzapfel-Pschorn and Seiler, 1986; Schütz *et al.*, 1989, 1990; Sass *et al.*, 1990, 1991; Yagi and Minami, 1990; Miura *et al.*, 1992), water management (Yagi *et al.*, 1990; Sass *et al.*, 1992; Murase *et al.*, 1993) and rice variety (Watanabe *et al.*, 1995a). Although harvested areas of rough rice in South-east Asia were 373 000 km^2 in 1990, which covered 26% of the total area in the world, and Indonesia has the largest area for rice production among South-east Asian countries (7·2% of the total area in the world; International Rice Research Institute, 1991), information CH_4 emissions from Indonesian rice fields was zero when we started experiments for its evaluation.

In this paper, we report a summary of our experiments on CH_4 emission from Indonesian rice fields with special reference to the effects of yearly and seasonal (dry and wet seasons) variations, rice straw application, rice variety, soil type and water management, along with grain yield (Nugroho *et al.*, 1996, 1997; Lumbanraja *et al.*, 1997; Subadiyasa *et al.*, 1997). Thus, we paid attention to both CH_4 emissions from rice fields and grain yield to get fundamental information for mitigation strategies for CH_4 emissions from tropical rice fields facing urgent demands to increase rice production.

MATERIALS AND METHODS

Experimental fields and cultivation of rice plants

The experiments on the effects of yearly and seasonal variations (experiment 1), rice variety (experiment 2) and water management (experiment 3) on CH_4 emissions from rice paddies were conducted in the rice fields at Taman Bogo, Central Lampung, South Sumatra. The soil was classified as a Typic Paleudult (red yellow Podzolic soil). The Paleudults are the soils where upland rice is grown extensively in the intertropical zone (Moormann, 1978). But now in Indonesia, large areas of the Paleudults grow paddy rice after irrigation water has become available. The experiment on the effect of soil type (experiment 4) was done in the rice fields at Taman Bogo, Rawa Sragi, Gedong Tataan and Sidomylyo, Central Lampung, South Sumatra. These fields were located within 30–90 km of each other. The soils were classified as a Typic Paleudult, a Typic Sulfaquent, a Typic Tropohumult and a Typic Tropopsamment, respectively. CH_4 emission rates from two rice fields of volcanic ash origin (Gianyar: an Oxic Tropaquept, and Tabanan: a Hapludalf), Bali Island, were also measured (experiment 5). The paddy soils in Bali were not classified into Andisols because of the loss of several Andic properties after strong weathering (acid oxalate-extractable Al plus 1/2 acid oxalate-extractable iron less than 2%, bulk density more than 0·90 g cm^{-3}, phosphate retention less than 85%). The chemical properties of the soils are listed in Table I.

All the experimental fields consisted of two plots: one plot (CF-plot) with chemical fertilizer application (250, 100 and 100 kg ha^{-1} of urea, triple superphosphate and KC1, respectively) and the other plot (RS-plot) with application of both chemical fertilizer and rice straw (5 tons ha^{-1}) in experiments 1–4. Of the total amount of urea, one-third was applied as basal dressing and the rest as top dressing. In experiment 5, 250 kg urea, 100 kg triple superphosphate (TSP) and 50 kg KCl per ha were applied as the chemical fertilizer, and of the total amount of urea, 150 kg of urea was applied as basal dressing and the rest as top dressing. About 20-day-old rice seedlings were transplanted (seedlings hill^{-1}), at a spacing of 20 cm × 20 cm, to the experimental fields, which were submerged before transplanting and irrigated when needed to maintain waterlogged conditions until harvesting. The rice variety used in experiments 1, 3 and 4 was *Oryza sativa* L. cv. IR-64. In experiment 2, eight modern varieties popular in Indonesia (*Oryza sativa* L. cv. Bengawan

Table I. Properties of soil used

	Taman Bogo	Rawa Sragi	Gedong Tataan	Sidomulyo	Gianyar	Tabanan
Total-C(%)	0·99	1·63	1·48	0·48	1·5	1·2
Total-N(%)	0·11	0·26	0·18	0·08	2·2	1·9
CEC*	2·0	22·0	10·3	5·5	35·6	47·9
pH(H_2O)	4·6	7·6	5·2	4·8	6·4	6·7
pH(KCl)	3·7	6·6	4·3	3·7		
Texture						
sand(%)	45	39	39	60	28	32
silt(%)	23	20	29	21	45	35
clay(%)	32	41	32	18	26	33
Free-Fe†	13·9	5·9	38·7	5·6		
E.R. Mn‡	0·12	0·26	1·0	0·55		
W.S. Sulfate§	0·27	0·18	0·015	0·18		
Aval-P¶	3·6	30	3·7	3·9	19·2	12·3

* me per 100 g soil, † 10^{-3} kg Fe kg^{-1} soil (Asami and Kumada, 1959).
‡ Easily reducible Mn. 10^{-3} kg Mn kg^{-1} soil (Sherman *et al.* 1942).
§ Water-soluble sulfate, 10^{-3} $kg\ SO_4^{-2}\ kg^{-1}$ soil (soil: H_2O = 1:5).
¶ 10^{-6} kg P kg^{-1} soil (Bray I; Bray and Kurtz, 1945).

solo, IR-74, IR-64) Atomita-4, Cisanggarung, Way seputih, Kapuas and Walanai) were transplanted to respective CF- and RS-plots. All of these are improved Indica type varieties. Most of the varieties are related to the IR variety (originally from International Rice Research Institute), except for Atomita-4, which was originally from a local variety (the Cisadane) that had been irrigated. These varieties are widely planted in Indonesia (Nugroho *et al.*, 1997). In experiment 5, IR-64 or IR-74, and the local variety, Krueng Aceh, were transplanted. In the water management experiment, the plot left under rain-fed conditions was also prepared. The cultivation calendar is shown in Table II.

Measurement of CH_4 emissions

Methane emission rates were measured every week throughout the growing period. Four hills of rice plants were covered with an acrylic box chamber (40 cm × 40 cm × 100 cm³). Stakes were driven into the soil at the time of transplanting for the chambers to cover the same soil surface for the four hills. A Tedlar® bag (2 litre) was attached to the chamber to keep th inside pressure equal to the atmospheric pressure. A rubber stopper, which was pierced with a glass tube and plugged with a septum (Shimadzu Co., Japan), was attached on the ceiling of the chamber for collecting gas samples. Gas samples were taken three times at 20 min intervals by introducing the inside air into an evacuated 10 ml glass tube through the septum using a double-ended hypodermic needle. The measurement was replicated three times with three chambers in each plot (Nugroho *et al.*, 1994). Every time, we visited the site and conducted the sampling between 1000 and 1300 hours.

The sample tubes were brought back to the Laboratory of Soil Biology, Faculty of Agriculture, Lampung University for the experiments in Sumatra, or to the Analytical Laboratory of the University of Udayana for the experiment in Bali, and the CH_4 content in the tubes was determined on the same day with a gas chromatograph equipped with a flame ionization detector (GC-8A1F, Shimadzu Co. or Varian model 3300). Methane emission rates were calculated from the increase in CH_4 concentration in the chamber with time and its volume.

RESULTS AND DISCUSSION

Seasonal variation in CH_4 emission rates and total CH_4 emission

Experiment 1: effects of yearly and seasonal variations. Figure 1 shows five-day means of daily mean temperature and monthly rainfall at Taman Bogo from December 1992 to September 1995. Temperatures

Table II. Cultivation calendar

	Experiment 1*						Experiment 5			Experiment 4			
	RS 92/93	DS 1993	RS 93/94	DS 1994	RS 94/95	DS 1995	Gianyar (1st)	Gianyar (2nd)	Tabanan (2nd)	Taman Bogo	Rawa Sragi	Gedong Tataan	Sidomu Iyo
Plowing													
1st	28 Nov. 1992	1 Apr. 1993	23 Nov. 1993	25 Apr. 1994	28 Nov. 1994	12 Apr. 1995	21 Jan. 1994	9 Sept. 1994	24 Sept. 1994	23 Nov. 1993	21 Nov. 1993	19 Nov. 1993	20 Nov. 1993
2nd	13 Dec.	14 Apr.	3 Dec.	5 May	14 Dec.	22 Apr.				3 Dec.	2 Dec.	30 Nov.	1 Dec.
Flooding	21 Nov.	3 Apr.	16 Nov.	18 Apr.	30 Nov.	5 Apr.	28 Jan. 1994	16 Sept. 1994	1 Oct. 1994	16 Nov.	15 Nov.	16 Nov.	15 Nov.
Transplanting	17 Dec.	26 Apr.	14 Dec.	16 May	28 Dec.	2 May	18 Feb. 1994	7 Oct. 1994	22 Oct. 1994	14 Dec.	15 Dec.	14 Dec.	15 Dec.
Fertilization													
Rice Straw	10 Dec.	20 Apr.	4 Dec.	6 May	21 Dec.	25 Apr.	4 Feb. 1994	23 Sept. 1994	8 Oct. 1994	4 Dec.	5 Dec.	4 Dec.	5 Dec.
Chemical fertilizer													
Basal	17 Dec.	26 Apr.	14 Dec.	16 May	28 Dec.	2 May	17 Feb. 1994	6 Oct. 1994	21 Oct. 1994	4 Dec.	5 Dec.	4 Dec.	5 Dec.
Top dressing (1st)	6 Jan 1993	18 May	4 Jan. 1994	7 Jun.	16 Jan. 1995	23 May	18 Mar. 1994	4 Nov. 1994	19 Nov. 1994	4 Jan. 1994	5 Jan. 1994	4 Jan. 1994	5 Jan. 1994
Top dressing (2nd)	1 Feb	5 Jun.	27 Jan.	25 Jun.	11 Feb.	10 Jun.				27 Jan.	28 Jan.	27 Jan.	28 Jan.
Weeding													
1st	2 Jan.	14 May	28 Dec.	1 Jun.	11 Jan.	16 May				28 Dec.	28 Dec.	27 Dec.	27 Dec.
2nd	30 Jan.	3 Jun.	26 Jan.	27 Jun.	9 Feb.	3 Jun.				26 Jan.	27 Jan.	26 Jan.	27 Jan.
Heading	1 Feb.	5 Jun.	27 Jan.	25 Jun.	11 Feb.	10 Jun.				27 Jan.	28 Jan.	27 Jan.	28 Jan.
Drainage	4 Mar.	10 Jul.	6 Mar.	16 Aug.	18 Mar.	27 Jul.				8 Mar.	9 Mar.	8 Mar.	9 Mar.
Harvest	18 Mar.	20 Jul.	18 Mar.	28 Aug.	29 Mar.	7 Aug.	4 Jun. 1994	7 Jan. 1995	23 Jan. 1995	18 Mar.	19 Mar.	17 Mar.	20 Mar.

RS: Rainy season. DS: Dry season. Cultivation calendar of Experiment 2 was the same with RS 94/95. Cultivation calendar of Experiment 3 was the same with RS 93/94 and RS 94/95.

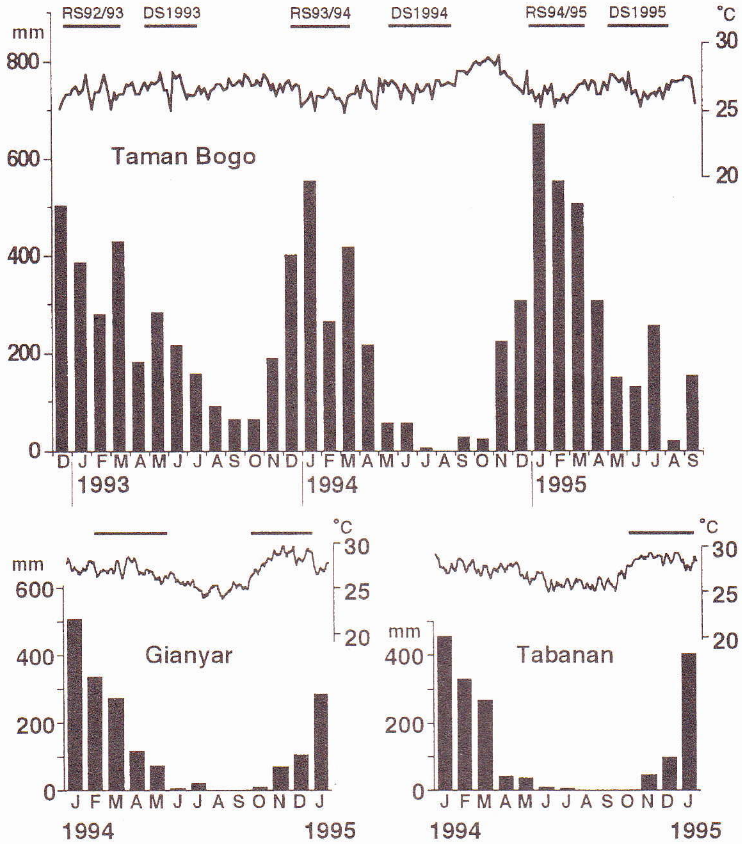

Figure 1. Five-day means of daily mean temperature and monthly rainfall at Taman Bogo, Gianyar and Tabanan. Bars show the growth periods. RS: Rainy season, DS: dry season

were uniform during cultivation periods in the rainy and dry seasons, and they were within the narrow range 25·1–28·0 °C in the rainy season and 25·1–27·9 °C in the dry season. The dry seasons in 1993 and 1995 had abnormal amounts of rain, while the rainy season in 1994 was short of rain.

Seasonal variations. As shown in Figure 2, methane emission rates increased from the first measurement onward and decreased near harvesting. Methane emission rates from CF-plots showed a broad peak around 7 weeks after transplanting in the rainy seasons in 1993–1994 and 1994–1995, while two sharp peaks were observed 3 and 6–7 weeks after transplanting in the dry seasons. The emission rates from RS-plots also showed broad peaks, one of which appeared in the early growth stage (by 6 weeks after transplanting). Two or three sharp peaks were observed in the dry seasons in 1993 and 1994.

The highest rates of CH_4 emission in the three-year measurements were in the ranges 27·9–35·4 and 36·5–51·8 mg CH_4 m^{-2} hr^{-1} in the rainy season and 30·1–47·5 and 49·5–63·5 mg CH_4 m^{-2} hr^{-1} in the dry season from CF- and RS-plots, respectively.

Mean emission rates. The mean CH_4 emission rates during the growth period were in the range 16·0–26·1 mg CH_4 m^{-2} hr^{-1} for CF-plots (28·2 ± 5·0 mg CH_4 m^{-2} hr^{-1}) and 23·3–34·9 mg CH_4 m^{-2} hr^{-1} for RS-plots (20·3 ± 4·1 mg CH_4 m^{-2} hr^{-1}) (Table III). They were significantly different between CF-plots and RS-plots (<0·001). The increase in the amounts of CH_4 emission by rice straw application were from 1·3 to 1·6 times. There was no significant difference in the mean CH_4 emission rates between rainy and dry seasons.

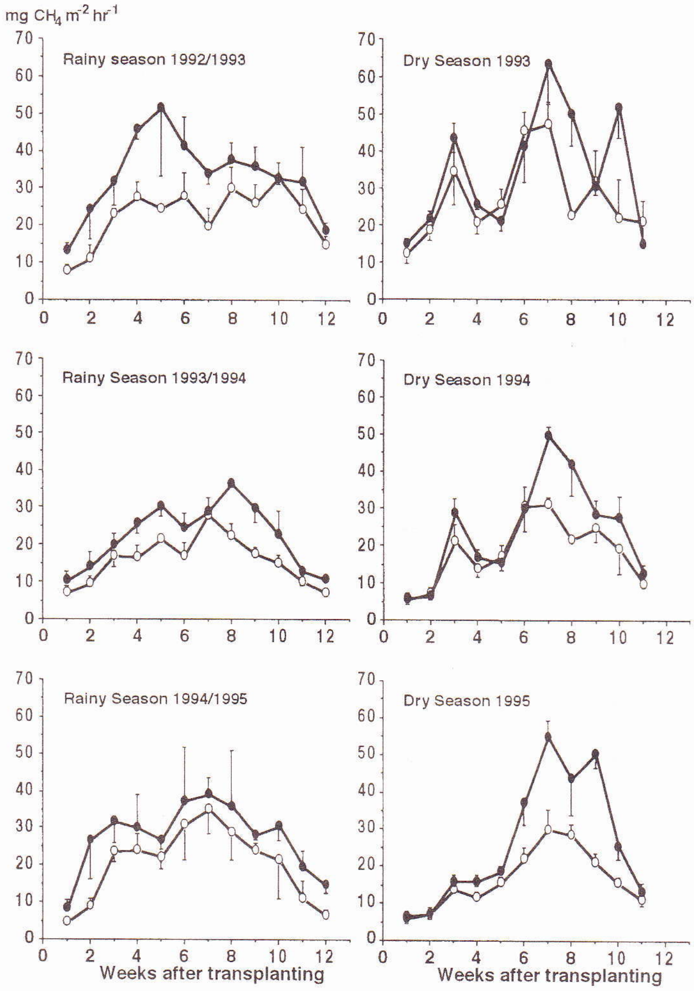

Figure 2. Experiment 1. Effects of yearly and seasonal variation on CH_4 emission rates. Bars indicate the standard deviation. (—○—) CF-plots; (—●—) RS-plots

Total CH_4 emission. Total amounts of CH_4 emitted during the period of rice growth are also shown in Table III. In the calculations, CH_4 emission during the period between transplanting and the first measurement and during the period between the last measurement and harvest were omitted. The amounts were in the ranges of 29·5–48·2 and 43·0–64·6 g CH_4 m^{-2} for CF-plots and for RS-plots, respectively. And the mean amounts of total CH_4 emission during the period of rice growth and their standard deviations in the six cropping seasons were 37·5 and 52·1 g CH_4 m^{-2}, and 18 and 16% for CF-plots and RS-plots, respectively.

Experiment 2: effects of rice variety. Seasonal variations The plots growing IR-64 were the same as those used in experiment 1. CH_4 emission rates from CF-plots showed a peak around 6 and 8 weeks after transplanting, irrespective of the variety (Figure 3). In addition, the emission rates from RS-plots showed peaks or shoulders in the early growth stage (by 4 weeks after transplanting) and in the late growth stage (after 8 weeks after transplanting). Higher CH_4 emission rates were generally recorded in RS-plots than in CF-plots throughout the growth period.

Table III. Total amounts of CH_4 emission, grain yield and CH_4 emission rate for 1 kg grain production

Plot	Mean rate of CH_4 emission (mg CH_4 m^{-2} hr^{-1})	Total emission amounts (g CH_4 m^{-2})	Emission % in the 1st half stage	Grain yield (kg ha^{-1})	CH_4 emission rate for 1 kg grain production (g CH_4 kg^{-1})
Experiment 1: effects of yearly and seasonal variations					
	Plots with chemical fertilizer application				
Rainy season 1992–1993	23·6 ± 2·7*	43·6 ± 4·9*	45·3	5530	78·8
Dry season 1993	26·1 ± 2·3	48·2 ± 4·2	47·6	5790	83·2
Rainy season 1993–194	16·6 ± 0·3	30·8 ± 0·6	47·7	5230	58·9
Dry season 1994	17·8 ± 1·7	33·0 ± 3·2	53·1	5040	65·5
Rainy season 1994–1995	21·5 ± 1·8	39·8 ± 3·3	47·6	5920	67·2
Dry season 1995	16·0 ± 0·6	29·5 ± 1·2	42·8	5030	58·6
	Plots with rice straw and chemical fertilizer application				
Rainy season 1992–1993	34·9 ± 2·7	64·6 ± 5·0	52·4	6380	101·3
Dry season 1993	33·2 ± 2·4	61·4 ± 4·4	47·1	5830	105·3
Rainy season 1993–1994	23·4 ± 1·3	43·2 ± 2·4	49·5	6370	67·8
Dry season 1994	23·3 ± 1·6	43·0 ± 3·0	44·9	5020	85·7
Rainy season 1994–1995	29·0 ± 1·3	53·6 ± 2·4	40·7	6030	88·9
Dry season 1995	25·5 ± 0·3	47·2 ± 0·5	36·1	5260	89·7
Experiment 2: effects of rice variety					
	Plots with chemical fertilizer application				
Bengawan solo	22·6 ± 3·3	41·7 ± 6·1	43·5	6200	67·3
IR-74	18·2 ± 2·7	36·8 ± 5·3	46·3	5650	65·1
IR-64	21·5 ± 1·8	39·8 ± 3·3	47·9	5920	67·2
Atomita-4	17·7 ± 0·6	32·6 ± 1·1	45·4	6200	52·6
Cisanggarung	19·8 ± 1·4	36·5 ± 2·6	47·2	5460	66·9
Way seputih	17·8 ± 1·2	32·7 ± 2·2	47·4	5580	58·6
Kapuas	20·5 ± 0·8	37·8 ± 1·6	46·7	5090	74·3
Walanai	20·2 ± 1·7	37·4 ± 3·1	53·7	5060	73·9
	Plots with rice straw and chemical fertilizer application				
Bengawan solo	27·7 ± 1·2	51·3 ± 2·3	40·8	5720	89·7
IR-74	31·6 ± 6·0	63·7 ± 12·1	53·3	6550	97·3
IR-64	29·0 ± 1·3	53·6 ± 2·4	49·6	6030	88·9
Atomita-4	31·3 ± 4·2	57·8 ± 7·8	49·5	6220	92·9
Cisanggarung	32·3 ± 5·2	59·7 ± 9·6	52·1	5520	108·2
Way seputih	35·0 ± 5·6	64·6 ± 10·4	50·0	5730	112·7
Kapuas	31·0 ± 2·2	57·3 ± 3·7	52·1	4750	120·6
Walanai	31·8 ± 4·1	58·8 ± 7·5	52·2	5490	107·1
Experiment 3: effects of water management					
	Plots with chemical fertilizer application				
Continuous flooding (93/94)	16·6 ± 0·3	30·8 ± 0·6	47·7	5230	58·9
Continuous flooding (94/95)	21·5 ± 1·8	39·8 ± 3·3	47·6	5920	67·2
Rain-fed (93/94)	11·7 ± 0·9	21·6 ± 1·6	44·0	5580	38·7
Rain-fed (94/95)	13·6 ± 0·9	22·9 ± 1·5	43·3	6030	38·0
	Plots with rice straw and chemical fertilizer application				
Continuous flooding (93/94)	23·4 ± 1·3	43·2 ± 2·4	49·5	6370	67·8
Continuous flooding (94/95)	29·0 ± 1·3	53·6 ± 2·4	40·7	6030	88·9
Rain-fed (93/94)	17·0 ± 0·4	31·4 ± 0·8	48·9	5980	52·5
Rain-fed (94/95)	18·4 ± 1·1	30·8 ± 1·8	45·0	6700	46·0

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Table III. Continued

Plot	Mean rate of CH_4 emission (mg CH_4 m^{-2} hr^{-1})	Total emission amounts (g CH_4 m^{-2})	Emission % in the 1st half stage	Grain yield (kg ha^{-1})	CH_4 emission rate for 1 kg grain production (g CH_4 kg^{-1})
Experiment 4: Effects of soil type					
	Plots with chemical fertilizer application				
Taman Bogo	16.6 ± 0.3	30.8 ± 0.6	47·7	5230	58·9
Rawa Sragi	11.9 ± 0.7	22.1 ± 1.2	36·7	5480	40·3
Gedong Tataan	28.9 ± 0.1	53.4 ± 0.2	52·5	7750	68·9
Sidomulyo	23.8 ± 0.6	44.1 ± 1.1	52·4	6760	65·2
	Plots with rice straw and chemical fertilizer application				
Taman Bogo	23.4 ± 1.3	43.2 ± 2.4	49·5	6370	67·8
Rawa Sragi	14.4 ± 0.8	26.7 ± 1.4	34·8	5590	47·8
Gedong Tataan	39.0 ± 0.7	72.2 ± 1.3	43·7	8040	89·8
Sidomulyo	33.4 ± 0.5	61.8 ± 0.9	53·4	7380	83·7
Experiment 5: CH_4 emission from paddy fields of volcanic ash origin					
	Plots with chemical fertilizer application				
IR-74 (Gianyar, 1st crop)	2.51 ± 0.58	4.22 ± 0.97	67·3	5350	7·9
IR-64 (Gianyar, 2nd crop)	1.87 ± 0.06	3.45 ± 0.12	44·9	3920	8·8
IR-64 (Tabanan, 2nd crop)	3.02 ± 0.12	5.57 ± 0.22	54·4	7100	7·8
K.Aceh (Gianyar, 1st crop)	2.65 ± 0.51	4.45 ± 0.85	66·0	5430	8·2
K.Aceh (Gianyar, 2nd crop)	2.14 ± 0.00	3.96 ± 0.01	48·6	4330	9·1
K.Aceh (Tabanan, 2nd crop)	4.18 ± 0.21	7.73 ± 0.38	61·0	7030	11·0
	Plots with rice straw and chemical fertilizer application				
IR-74 (Gianyar, 1st crop)	3.23 ± 0.34	6.87 ± 0.87	67·9	5480	12·5
IR-64 (Gianyar, 2nd crop)	2.85 ± 0.08	5.26 ± 0.15	61·7	4560	11·5
IR-64 (Tabanan, 2nd crop)	7.58 ± 0.14	14.00 ± 0.25	73·4	6960	24·1
K.Aceh (Gianyar, 1st crop)	3.76 ± 0.17	6.32 ± 0.29	64·6	5810	10·9
K.Aceh (Gianyar, 2nd crop)	3.86 ± 0.02	7.13 ± 0.04	68·2	4570	15·6
K.Aceh (Tabanan, 2nd crop)	7.71 ± 0.02	14.25 ± 0.04	66·0	7150	19·9

* Mean ± standard error.

Mean emission rates. As shown in Table III, the mean CH_4 emission rates during the growth period were in the range 17·7–22·6 mg CH_4 m^{-2} hr^{-1} for CF-plots (19.8 ± 2.4 mg CH_4 m^{-2} hr^{-1}) and 27·7–35·0 mg CH_4 m^{-2} hr^{-1} for RS-plots (31.2 ± 4.0 mg CH_4 m^{-2} hr^{-1}), respectively. And they were significantly different between CF-plots and RS-plots ($p < 0.01$).

The mean CH_4 emission rate was highest in the plot with the variety Bengawan solo and lowest in the plots with the varieties Atomita-4 and Way seputih amongst CF-plots, while they were highest in the plot with Way seputih and lowest in the plot with Bengawan solo amongst RS-plots. The increase in the mean CH_4 emission rates with rice straw application was higher for the plots planted with Way seputih (1·98 times) and Atomita-4 (1·77 times) than for the plots of Bengawan solo (1·23 times) and IR-64 (1·35 times). It was noteworthy that Way seputih and Atomita-4 were derived from the variety Cisadane, and Bengawan solo and IR-64 from the variety IR-54, and Walanai and Cisanggarung from the varieties IR-36 and Pelita 1-1, respectively.

Total CH_4 emission. Total amounts of CH_4 emitted during the period of rice growth were in the ranges 32·6–41·7 and 51·3–64·6 g CH_4 m^{-2} for CF-plots and RS-plots, respectively (Table III). The increase in the amounts of CH_4 emission by rice straw application were in the range 9·6 g CH_4 m^{-2}, for the plot with Bengawan solo, to 31·9 g CH_4 m^{-2}, for the plot with Way seputih.

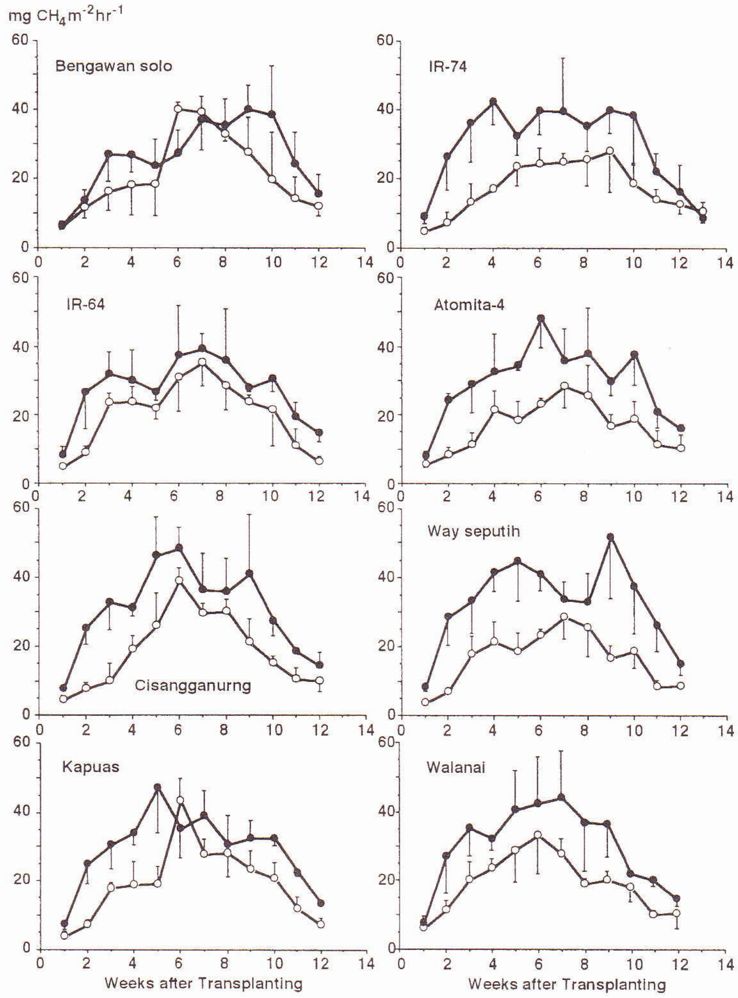

Figure 3. Experiment 2. Effects of rice variety on seasonal variation of CH_4 emission rates. Bars indicate the standard deviation. (—○—) CF-plots; (—●—) RS-plots

Experiment 3: effects of water management. Seasonal variations. The plots of continuous flooding were the same as those used in experiment 1. As shown in Figure 4, the CH_4 emission rates from CF-plots showed a broad peak around 7 weeks after transplanting, irrespective of water management. The emission rates from the continuously flooded RS-plot showed two broad peaks, one of which appeared in the early growth stage (by 6 weeks after transplanting), while only a shoulder appeared in the early growth stage in the rain-fed RS-plots.

Mean emission rates. Mean CH_4 emission rates were in the range 16·6–21·5 and 11·7–13·6 mg CH_4 m^{-2} hr^{-1} for CF-plots and 23·4–29·0 and 17·0–18·4 mg CH_4 m^{-2} hr^{-1} for RS-plots under continuously flooded and rain-fed conditions, respectively (Table III). Mean CH_4 emission rates from continuously flooded plots were significantly higher than those from rain-fed plots ($p < 0{\cdot}01$). A significant difference between CF-plots and RS-plots was also found in this experiment ($p < 0{\cdot}01$).

Total CH_4 emission. Total amounts of CH_4 emitted during the period of rice growth were in the ranges 30·8–39·8 and 21·6–22·9 g CH_4 m^{-2} for CF-plots and 43·2–53·6 and 30·8–31·4 g CH_4 m^{-2} for RS-plots under

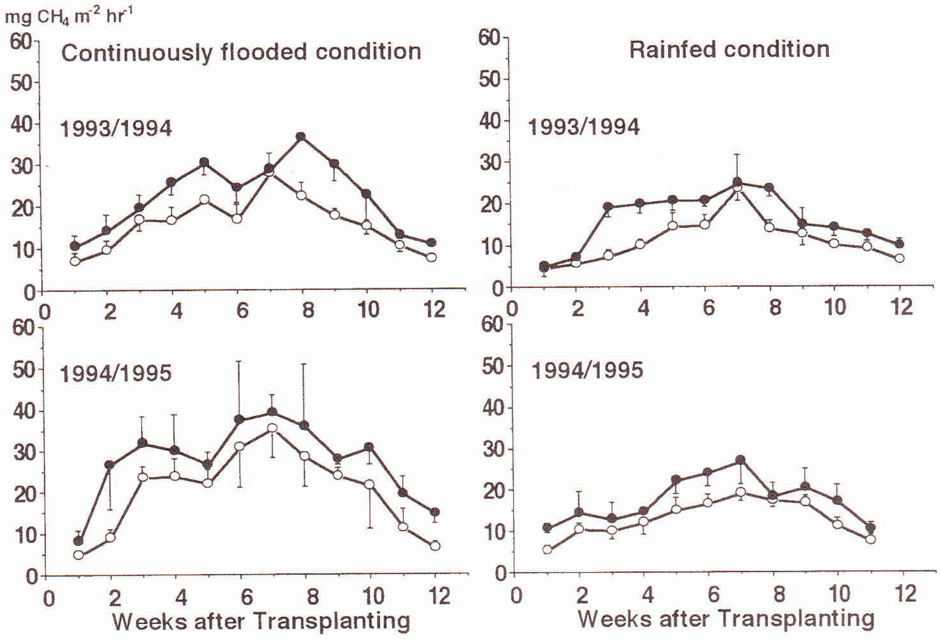

Figure 4. Experiment 3. Effects of water management on seasonal variation of CH_4 emission rates. Bars indicate the standard deviation. (—○—) CF-plots; (—●—) RS-plots

continuously flooded and rain-fed conditions, respectively (Table III). The increase in the amounts of CH_4 emission by rice straw application was 1·3–1·4 times for the continuously flooded plots and 1·3–1·5 times for the rain-fed plots. The rain-fed rice field emitted 27–30% less CH_4 in 1993–1994 and 37% less CH_4 in 1994–1995 than the continuously flooded rice field.

Experiment 4: effects of soil type. Seasonal variations. The plots at Taman Bogo were the same plots as used in experiment 1. As shown in Figure 5, CH_4 emission rates from CF-plots were, in general, highest in the Gedong Tataan rice field, followed by the Sidomulyo, Taman Bogo and Rawa Sragi rice fields, in that order. The seasonal variation in CH_4 emission rates from the Taman Bogo, Gedong Tataan and Sidomulyo rice fields showed broad peaks, with a maximum 7–9, 6 and 5 weeks after transplanting, respectively. CH_4 emission rates from the Rawa Sragi rice field increased over time until 10 weeks after transplanting.

Relatively high CH_4 emissions from the Gedong Tataan and Sidomulyo rice fields may be because the Gedong Tataan soil contained a large amount of soil organic matter, and the Sidomulyo soil contained a very small amount of free iron, although its soil organic matter content was relatively low, resulting in the fast soil reduction with time in these rice fields (Table I). The soil organic matter content in the Taman Bogo soil was low, which might retard the soil reduction in this soil. The Rawa Sragi soil was classified as a Typic Sulfaquent (Table I). It was reported from Thai rice fields that CH_4 emission from acid sulfate rice fields was very low (Jermsawatdipong *et al.*, 1994; Yagi *et al.*, 1994). As the soil sample from the Rawa Sragi rice field contained a small amount of $SO_4^{2-} - S$ and its pH was neutral (Table I), direct effects of sulfate and soil pH on low CH_4 emission rates were not expected in the Rawa Sragi rice field. Rather, several soil properties inherent to the acid sulfate rice field may have brought about the low CH_4 emission rates in this soil (a Typic Sulfaquent).

The increase in CH_4 emission rates with rice straw application was observed in every rice field surveyed. In general, patterns of CH_4 emission rates for RS-plots were similar to those for CF-plots in each rice field with an additional shoulder 5 weeks after transplanting in the Taman Bogo rice field, the shoulder in the late

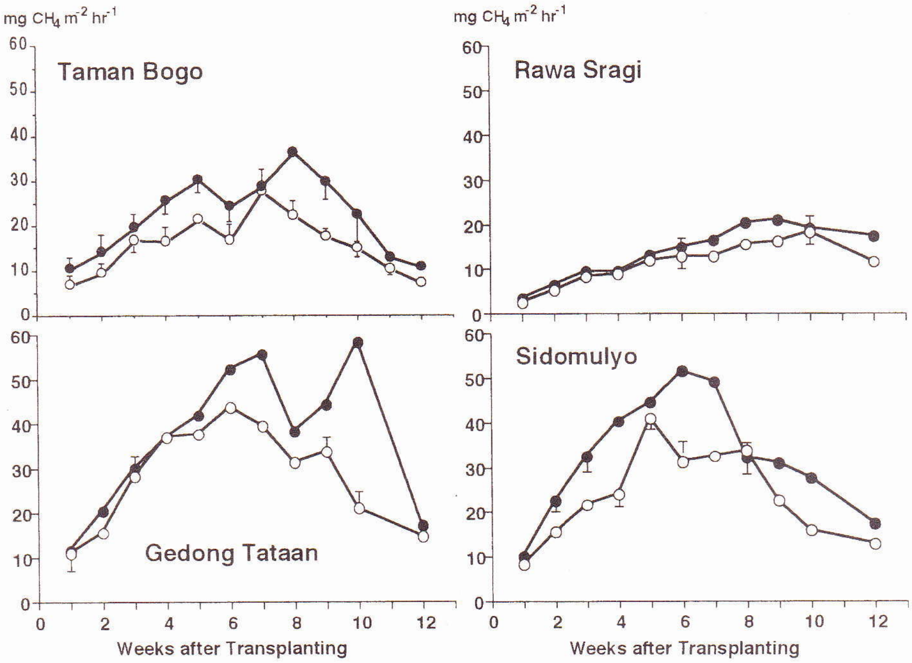

Figure 5. Experiment 4. Effects on soil type on seasonal variation of CH_4 emission rates. Bars indicate the standard deviation. (—○—) CF-plots; (—●—) RS-plots

growth stage in the Sidomulyo rice field and an additional sharp peak 10 weeks after transplanting in the Gedong Tataan rice field, respectively.

Mean emission rates. Mean CH_4 emission rates were in the range 16·6–23·4, 11·9–14·4, 28·9–39·0 and 23·8–33·4 mg CH_4 m^{-2} hr^{-1} in the Taman Bogo, Rawa Sragi, Gedong Tataan and Sidomulyo rice fields, respectively (Table III). Thus, they were very low in the Rawa Sragi rice field compared with the other rice fields and they were significantly different between CF-plots and RS-plots ($p < 0{\cdot}05$).

Total CH_4 emission. The total amount of CH_4 emitted during the period of rice growth was largest for the Gedong Tataan rice field (53·4–72·2 g CH_4 m^{-2}), followed by the Sidomulyo rice field (44·1–61·8 g CH_4 m^{-2}), the Taman Bogo rice field (30·8–43·2 g CH_4 m^{-2}) and the Rawa Sragi rice field (22·1–26·7 g CH_4 m^{-2}), in that order (Table III). Thus, the Gedong Tataan rice field (a Typic Tropohumult) emitted 2·4–2·7 times more CH_4 than the Rawa Sragi rice field (a Typic Sulfaquent).

The effect of rice straw application on the increase in CH_4 emission was relatively small in these rice paddies as was observed by Nugroho *et al.* (1994, 1996) in the Taman Bogo rice field. The Sidomulyo rice field recorded the largest emission increase (1·40 times) with rice straw application, followed by the Gedong Tataan rice field (1·35 times), the Taman Bogo rice field (1·42 times) and the Rawa Sragi rice field (1·21 times).

Experiment 5: CH_4 emission from rice fields of volcanic ash origin. Figure 1 also shows five-day means of daily mean temperature and monthly rainfall at Giayar and Tabanan, Bali, from January 1994 to January 1995. Temperatures were uniform during cultivation periods in the first and second crop seasons, and they were within the narrow range 25·0–30·1 °C at Gianyar and 24·4–29·4 °C at Tabanan, respectively.

Seasonal variations. The general pattern of CH_4 emission rates from plots planted with two varieties, IR-74 and Krueng Aceh, was the same (Figure 6). The highest rates of CH_4 emission occurred 1–2 weeks after

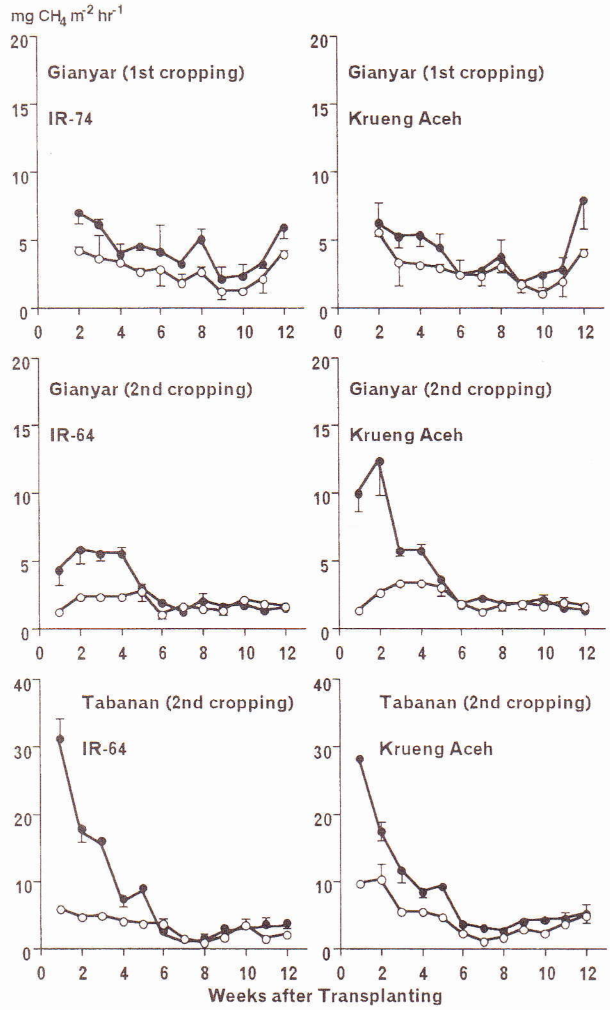

Figure 6. Experiment 5. Seasonal variation of CH_4 emission rates from rice fields of volcanic ash origins. Bars indicate the standard deviation. (—○—) CF-plots; (—●—) RS-plots

transplanting and decreased thereafter until the late stage of plant growth. The emission rates of CH_4 from the Gianyar rice field were significantly lower than those from the Tabanan rice field ($p < 0{\cdot}05$), especially for RS-plots. The highest rates of CH_4 emission two weeks after transplanting were probably a result of the breakdown of straw and stubble derived from the previous rice cultivation, in addition to the rice straw applied two weeks prior to transplanting.

The effect of variety was only significant in the Gianyar rice field in the second cropping season, where RS-plots planted with Krueng Aceh emitted a larger amount of CH_4 than the respective plots planted with IR-64.

Mean emission rates. The mean rates of CH_4 emission in the Gianyar rice field were 1·87–2·65 mg CH_4 m^{-2} hr^{-1} for CF-plots and 2·85–3·86 mg CH_4 m^{-2} hr^{-1} for RS-plots, and 3·02–4·18 mg CH_4 m^{-2} hr^{-1} for CF-plots and 7·58–7·71 mg CH_4 m^{-2} hr^{-1} for RS-plots in the Tabanan rice field, respectively. They were significantly different between CF-plots and RS-plots ($p < 0{\cdot}025$).

Total CH_4 emission. The total CH_4 emissions for CF-plots and RS-plots were 3·45–4·45 g CH_4 m^{-2} and 5·26–7·13 g CH_4 m^{-2} in the Gianyar rice field, and 5·57–7·73 g CH_4 m^{-2} and 14·00–14·25 g CH_4 m^{-2} in the Tabanan rice field, respectively. Thus, the application of rice straw significantly increased CH_4 emission from these rice fields, irrespective of the soil type, the cropping season and the rice variety. The effect of rice straw application on CH_4 emission was mainly observed in the early stage of rice growth, as reported by Watanabe *et al.* (1993a).

Thus, it was known that the total amounts of CH_4 emission from these rice fields were much lower than those observed in the Sumatra rice fields. Similar low emission rates from Andosol rice fields were reported from Japanese rice fields (Yagi and Minami, 1990).

Main stage of CH_4 emission from Indonesian rice fields

As shown in Figure 1, the temperature is high from the beginning of rice cultivation in the tropics, which may bring about the active decomposition of soil organic matter and applied rice straw with resultant CH_4 production from the very beginning of rice growth. Therefore, the amounts of CH_4 emission in the early stage of rice cultivation compared with the total CH_4 emission were considered to be relatively higher in the tropical rice fields than in the temperate rice fields. Nearly the same amounts of CH_4 were emitted in the first half stage of rice cultivation in the Taman Bogo, Gedong Tataan and Sidomulyo rice fields, irrespective of yearly variations, rice varieties cultivated, rice straw application and water management (Table III). Rice fields of volcanic ash origin generally emitted more than half of the total in the first half stage. The exception was the Rawa Sragi rice field, a rice field with acid sulfate soil properties, where only about 35% of the total CH_4 emission was emitted in the first half stage. The contribution of the first half stage in the total CH_4 emission in the Indonesian rice fields examined was very high compared with Japanese rice fields (Watanabe *et al.*, 1993a).

CH_4 emission rates for production of unit weight of grain

Although the increase in rice production is the first priority because of the dramatic population increase in Indonesia, rice production in the future should also pay special attention to the environment. Therefore, relationships between grain yields and CH_4 emissions from the respective rice fields are discussed for each experiment below. Grain yields and CH_4 emission rates for the production of a unit weight of grain are also shown in Table III.

Experiment 1: effects of yearly and seasonal variations. Grain yields were in the range 5230–5920 kg ha^{-1} and 6030–6380 kg ha^{-1} in the rainy seasons, and 5030–5790 kg ha^{-1} and 5020–5830 kg ha^{-1} in the dry seasons for CF-plots and RS-plots, respectively. Thus, the increase in grain yield with rice straw application was only observed in the rainy season cultivation. Grain yield tended to be higher in the rainy seasons than in the dry seasons, for both CF- and RS-plots.

The CH_4 emission rates for the production of a unit weight of grain were in the range 59–79 g CH_4 (kg grain)$^{-1}$ and 68–101 g CH_4 (kg grain)$^{-1}$ in the rainy seasons, and 59–83 g CH_4 (kg grain)$^{-1}$ and 86–105 g CH_4 (kg grain)$^{-1}$ in th dry seasons, for CF-plots and RS-plots, respectively (Table III), They were significantly different between CF-plots and RS-plots ($p < 0.001$). There was a significant correlation between mean rate of CH_4 emission and grain yield for CF-plots ($p < 0.05$) but not for RS-plots.

Experiment 2: effects of rice variety. Grain yields were in the range 5060–6200 kg ha^{-1} for CF-plots, and 4750–6550 kg ha^{-1} for RS-plots, respectively. The effect of rice straw application on the grain yield was not recognized in this experiment. Varieties tested in the present experiment were improved for the lowland rice cultivation, like ours, except for Cisanggarung, which was improved for areas with high elevation (500–900 m). But Cisanggarung recorded intermediate yields for both plots with and without rice straw application in this experiment (Table III).

The amounts of CH_4 emitted for 1 kg grain production were in the ranges 53–74 and 89–121 g CH_4 (kg grain)$^{-1}$ for CF-plots and RS-plots, respectively. Thus, they were significantly different between CF-plots and RS-plots ($p < 0{\cdot}001$). CH_4 emission was lowest (53 g CH_4 kg^{-1} of grain) in the plot growing variety Atomita-4 and highest in the plots with Kapuas and Walanai varieties (74 g CH_4 kg^{-1} of grain) and highest in the plot with Kapuas (121 g CH_4 kg^{-1} of grain) amongst the RS-plots. There was no significant correlation between mean rate of CH_4 emission and grain yield, either for CF-plots or RS-plots.

Experiment 3: effects of water management. Grain yields were in the ranges of 5230–5920 and 6030–6370 kg ha^{-1} for continuously flooded plots, and 5580–6030 and 5980–6700 kg ha^{-1} for the rain-fed plots, with chemical fertilizer application and with both chemical fertilizer and rice straw application, respectively. The amounts of CH_4 emission per 1 kg of grain production were in the range 59–67 g CH_4 (kg grain)$^{-1}$ and of 68–89 g CH_4 (kg grain)$^{-1}$ for CF-plots and RS-plots in continuously flooded conditions, and 38–39 CH_4 (kg grain)$^{-1}$ for the respective plots under rain-fed conditions. Thus, the rates were significantly larger under continuously flooded conditions than under rain-fed conditions ($p < 0{\cdot}01$).

Experiment 4: effects of soil type. Grain yields were in the range 5230–7750 kg ha^{-1} for CF plots and 5590–8040 kg ha^{-1} for RS-plots. The amounts of CH_4 emitted for 1 kg grain production were in the range 40–69 g CH_4 (kg grain)$^{-1}$ for CF-plots and 48–90 g CH_4 (kg grain)$^{-1}$ for RS-plots. The lowest was in Rawa Sragi rice field (a Typic Sulfaquent) and the highest was in Gedong Tataan rice field (a Typic Tropohumult), irrespective of the application of rice straw. The yields were significantly different between CF-plots and RS-plots ($p < 0{\cdot}05$), and there was significant correlation between the mean rate of CH_4 emission and grain yield for RS-plots ($p < 0{\cdot}01$) but not for CF-plots.

Experiment 5: CH_4 emission from rice fields of volcanic ash origin. Grain yields were in the range 4330–5430 kg ha^{-1} for CF-plots and 4560–5810 ka ha^{-1} for RS-plots in the Gianyar rice field, and 7030–7100 ka ha^{-1} for CF-plots and 6960–7150 kg ha^{-1} for RS-plots in the Tabanan rice field. The amounts of CH_4 emission per 1 kg of grain production ranged from 8–9 g CH_4 (kg grain)$^{-1}$ and 12–16 g CH_4 (kg grain)$^{-1}$ for CF-plots and RS-plots in the Gianyar rice field and from 8–11 g CH_4 (kg grain)$^{-1}$ and 20–24 g CH_4 (kg grain)$^{-1}$ for the respective plots in the Tabanan rice field. Thus, the rates were significantly higher for RS-plots than for CF-plots ($p < 0{\cdot}025$). The rates in these rice fields with soils of volcanic ash origin were significantly lower than those observed in the Sumatra rice fields ($p < 0{\cdot}001$). There was significant correlation between the mean rate of CH_4 emission and grain yield both for CF-plots ($p < 0{\cdot}05$) and for RS-plots ($p < 0{\cdot}05$).

Figure 7 shows the total CH_4 emission against grain yield. Lines on the figure show the respective levels of the amount of CH_4 emission per 1 kg grain production. Grain yield in the Taman Bogo rice field fell into a

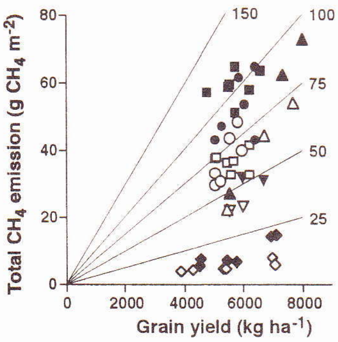

Figure 7. Relationships between grain yield and amounts of total CH_4 emission. Lines within the figure indicate the respective levels of the amount of CH_4 emission (g) for 1 kg grain production. (○, ●) experiment 1; (□, ■) experiment 2; (▽, ▼) experiment 3; (△, ▲) experiment 4; (◆, ◇) experiment 5. Open and closed symbols indicate CF-plots and RS-plots, respectively

rather narrow range, 5000–6500 kg ha^{-1}, with one exception, irrespective of yearly variation, rice variety planted and water management. The Gedong Tataan, Sidomulyo and Tabanan rice fields produced more than 6500 kg ha^{-1} of grain (Table II). While grain yield in the Gianyar rice field was less than 5000 kg ha^{-1}. Thus, each rice field may have a specific productivity of grain production.

Total amounts of CH_4 emission during the rice cultivation period were scattered widely, and many of the rice fields examined emitted 50–120 g kg^{-1} grain production. Generally, rice straw application, shown with closed symbols, increased CH_4 emission per 1 kg grain production in comparison with sole application of chemical fertilizers. Exceptions were for rice fields of volcanic ash origin (lozenge symbols), where only less than 25 g CH_4 were emitted for 1 kg grain production. It was noteworthy that the Rawa Sragi rice field, a rice field of acid sulfate soil properties, emitted only 40–48 g CH_4 for 1 kg grain production. Water management was also a very important factor in decreasing CH_4 emissions, and CH_4 rates for 1 kg grain production were in the range 38–53 g.

These findings suggest that we have several options in choosing the areas, rice variety and field management, for increasing rice production in tropical countries while keeping CH_4 emission from rice fields low.

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