

Crop management affecting methane emissions from irrigated and rainfed rice in Central Java (Indonesia)

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Abstract

Methane (CH₄) emissions were determined from 1993 to 1998 using an automated closed chamber technique in irrigated and rainfed rice. In Jakenan (Central Java), the two consecutive crops encompass a gradient from low to heavy rainfall (wet season crop) and from heavy to low rainfall (dry season crop), respectively. Rainfed rice was characterized by very low emission at the onset of the wet season and the end of the dry season. Persistent flooding in irrigated fields resulted in relatively high emission rates throughout the two seasons. Average emission in rainfed rice varied between 19 and 123 mg CH₄ m⁻² d⁻¹, whereas averages in irrigated rice ranged from 71 to 217 mg CH₄ m⁻² d⁻¹. The impact of organic manure was relatively small in rainfed rice. In the wet season, farmyard manure (FYM) was completely decomposed before CH₄ emission was initiated; rice straw resulted in 40% increase in emission rates during this cropping season. In the dry season, intensive flooding in the early stage promoted high emissions from organically fertilized plots; seasonal emissions of FYM and rice straw increased by 72% and 37%, respectively, as compared with mineral fertilizer. Four different rice cultivars were tested in irrigated rice. Average emission rates differed from season to season, but the total emissions showed a consistent ranking in wet and dry season, depending on season length. The early-maturing Dodokan had the lowest emissions (101 and 52 kg CH₄ ha⁻¹) and the late-maturing Cisadane had the highest emissions (142 and 116 kg CH₄ ha⁻¹). The high-yielding varieties IR64 and Memberamo had moderately high emission rates. These findings provide important clues for developing specific mitigation strategies for irrigated and rainfed rice.

Introduction

Rice is grown in Indonesia in a wide range of environments comprising 10.6 million ha of harvested area (IRRI, 1995). The highly productive land, which is primarily located in Java and Sumatra, is irrigated lowland (72% of total rice area). Smaller portions of the rice land are classified as rainfed (7%) lowland, flood-prone (10%), and upland (11%). Indonesia used to import rice previously but has attained self-sufficiency since 1984 (IRRI, 1995). This success was mainly attributed to an annual production increase of 4–5% in the 1970s and 1980s. Rice is the staple food of the Indonesian people and the major source of income in many rural areas.

However, rice production is a major source of greenhouse gases such as methane (CH₄) (Neue et al., 1990; Cicerone et al., 1992). The increase of CH₄ concentration in the atmosphere contributes to global warming (Ramanathan et al., 1985) and affects the chemistry of the atmosphere (Bolle et al., 1986; Rasmussen & Kahlil, 1986). Global annual CH₄ emissions from rice fields were estimated in very wide range—from 25 to 100 Tg (IPCC, 1996). One of the main reasons for these uncertainties is the lack of field investigations addressing the variety of cultivation techniques used. Only a few studies using manual sampling techniques are available for Indonesia (Kimura et al., 1994; Husin et al., 1995).

The modalities of rice cultivation have undergone pronounced changes in previous decades, notably in irrigation facilities, fertilizer application, and cultivar traits. Virtually all these agronomic practices affect the conditions for CH₄ production, oxidation, and transport (Neue & Roger, 1993), whereas the net result of these changes remains uncertain.

The study presented here was conducted within an international network of measuring stations for determining CH₄ emissions from rice fields (Wassmann et al., this issue, a). The station is located in an area with predominant rainfed systems while irrigation rice is scattered in the regions. The objectives of the studies at the Jakenan station were

- to quantify CH₄ fluxes from rice fields in Central Java, one of the important rice areas of Indonesia;
- to assess the impact of management practices common to this region;
- to evaluate processes that control CH₄ emission in an equatorial climate; and
- to develop mitigation strategies with low CH₄ emission in a sustainable rice system for this region.

Field site and methods

Field experiments were conducted from 1993 to 1998 at the Jakenan station located in Central Java (Indonesia). Experiments included irrigated and rainfed rice; a comparison between these two ecosystems is presented in Wassmann et al. (this issue, b). Soil properties listed in Table 1 indicate relatively high acidity, low CEC, and low content of organic material. The soil is classified as Acric Tropoqualf and has a silty loam texture.

Central Java has an equatorial climate with heavy rainfalls typically occurring from November to April. Annual precipitation varied from 950 mm to 2200 mm over the last four decades with a long-term average of 1588 mm. Farmers in this region plant two consecutive rainfed crops with a short intermediate fallow. These seasons are commonly denoted as wet season (*gogorancah*) and dry season (*walik jeramih*), although each of them encompasses a gradient from dry to wet and from wet to dry conditions, respectively. In rainfed systems, the wet season crop is dry-seeded, whereas the dry season crop is transplanted. Farmers with access to irrigation water plant two crops of irrigated rice; both crops are transplanted.

Table 1. Soil physical and chemical characteristics of Jakenan Experiment Station.

Parameters	Value
Soil texture (%)	
Sand	29
Silt	58
Clay	13
pH (H ₂ O)	4.7
Total N (%)	0.05
Total organic carbon (%)	0.48
Available P (ppm)	21
Exchangeable cations (meq/100 mg)	
Ca	2.13
Mg	0.44
K	0.04
Na	0.12
Al	1.45
CEC	6.14
Microelement (ppm)	
Fe	41
Mn	10
Cu	1
Zn	2

A closed chamber technique was used to determine CH₄ emission continuously through an automated system (Wassmann et al., this issue, a).

The standardized measuring systems had the following basic features: (i) three chambers per treatment distributed in the field according to a complete block design; (ii) a pneumatic system for alternate chamber closing (for 16 min to record emission) and opening (for 104 min to equilibrate with ambient air); (iii) a sampling system providing direct air transfer from the inner volume of the chambers to a sample loop and a direct injection of aliquots into the gas chromatograph (GC); and (iv) an analytical system (GC plus integrator) linked to a data acquisition device.

Results and discussion

Characterization of seasonal emissions

Figure 1 shows seasonal patterns of CH₄ emission rates for two consecutive seasons. The experiments in the 1996-97 wet season and the 1997 dry season were conducted with urea as N source in irrigated and rainfed rice (Table 2).

In irrigated rice, flooding started at 4 d before transplanting (for soaking of the soil) and ended a week

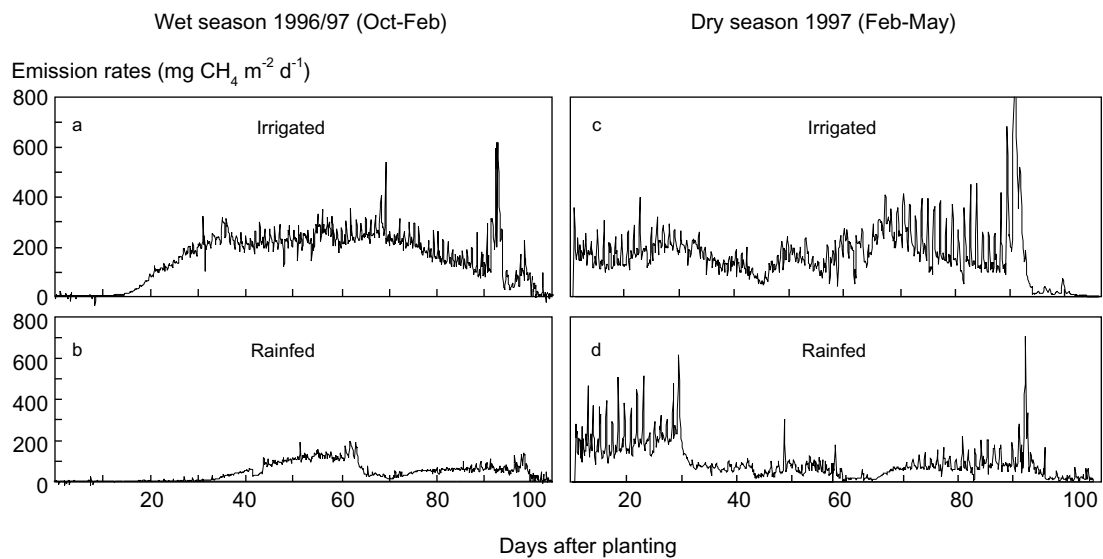


Figure 1. Seasonal patterns of CH_4 emissions in rainfed and irrigated rice during the 1996-97 wet season and 1997 dry season

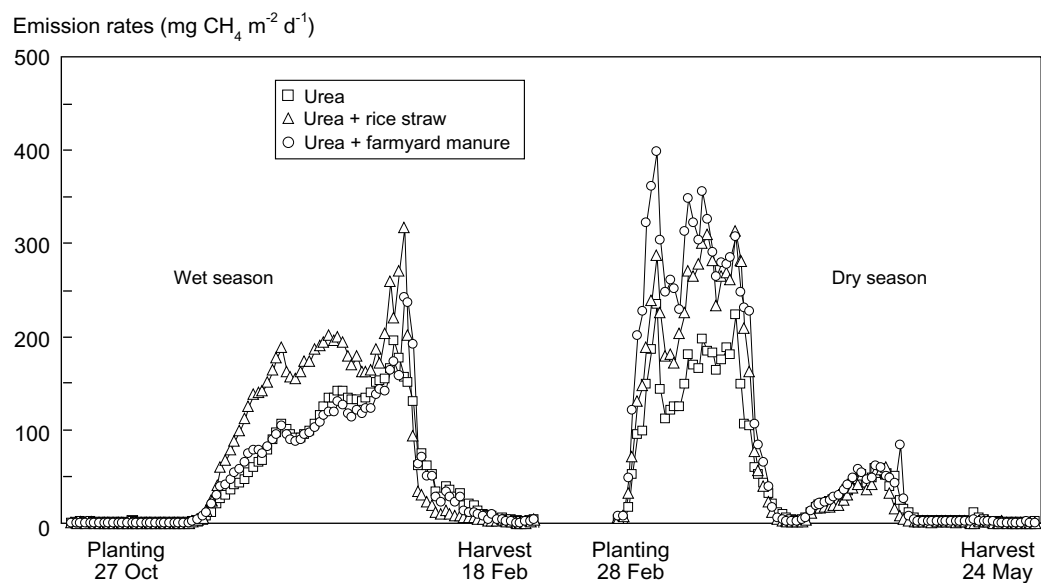


Figure 2. Methane emissions in rainfed rice as affected by amendments, 1995-96 wet season and 1996 dry season (tick marks on the x axis indicate 20-d intervals)

Table 2. Summary of treatments and management practices for the Jakenan experiments, 1993-98.

Year	Season	Treatment No.	Treatment description		Inorganic input (kg ha ⁻¹)			Organic input (Org N)	Date transplanted	Date harvested
			Water management	Other management	Type	Basal	Topdressed			
1993-94	Wet	1	Irrigated	IR72/transplanted/20×20	Urea	0	120		10/23	02/19
		2	Irrigated	IR72/direct seeded/20×20	Urea	0	120		10/23	02/19
		3	Rainfed	IR64/transplanted/15×20	Urea	0	120		10/02	02/16
		4	Rainfed	IR64/direct seeded/20×20	Urea	0	120		10/02	02/16
1994	Dry	1	Irrigated	IR72	Urea	0	120		03/01	06/13
		2	Rainfed	IR64	Urea	0	120		03/01	05/26
		3	Rainfed	IR72	Urea	0	120		03/01	05/26
		4	Irrigated	IR64	Urea	0	120		03/01	05/26
1994-95	Wet	1	Rainfed	Urea	Urea	0	120		11/16	03/16
		2	Rainfed	Farm manure	Urea	0	109	11	11/16	03/16
		3	Rainfed	Farm manure	Urea	0	98	22	11/16	03/16
		4	Irrigated	Urea	Urea	0	120		01/06	04/07
1995	Dry	1	Rainfed	Urea	Urea	0	120		03/22	07/17
		2	Rainfed	Farm manure	Urea	0	120	11	03/22	06/08
		3	Rainfed	Farm manure	Urea	0	120	22	03/22	06/08
		4	Irrigated	Urea	Urea	0	120		04/11	06/29
1995-96	Wet	1	Rainfed	Urea	Urea	0	120		10/27	02/18
		2	Rainfed	Rice straw	Urea	0	78.4	42	10/27	02/18
		3	Rainfed	Farm manure	Urea	0	75.4	45	10/27	02/18
		4	Irrigated	Urea	Urea	0	120		11/21	02/10
1996	Dry	1	Rainfed	Urea	Urea	0	120		02/28	05/24
		2	Rainfed	Rice straw	Urea	0	120	41	02/28	05/24
		3	Rainfed	Farm manure	Urea	0	120	45	02/28	05/24
		4	Irrigated	Urea	Urea	0	120		02/28	05/24
1996-97	Wet	1	Irrigated	Prilled urea	Prilled urea	0	120		10/30	02/06
		2	Irrigated	Tablet urea	Urea tablet	0	120		10/30	02/06
		3	Rainfed	Prilled urea	Prilled urea	0	120		10/14	02/06
		4	Rainfed	Tablet urea	Urea tablet	0	120		10/14	02/06
1997	Dry	1	Irrigated	Prilled urea	Prilled urea	0	120		02/12	05/06
		2	Irrigated	Tablet urea	Urea tablet	0	120		02/12	05/06
		3	Rainfed	Prilled urea	Prilled urea	0	120		02/12	05/06
		4	Rainfed	Tablet urea	Urea tablet	0	120		02/12	05/06
1997-98	Wet	1	Irrigated	Dodokan	Urea	0	120		12/02	03/02
		2	Irrigated	IR64	Urea	0	120		12/02	03/08
		3	Irrigated	Menberamo	Urea	0	120		12/02	03/14
		4	Irrigated	Cisadane	Urea	0	120		12/02	04/06
1998	Dry	1	Irrigated	Dodokan	Urea	0	120		05/28	08/10
		2	Irrigated	IR64	Urea	0	120		05/28	08/17
		3	Irrigated	Menberamo	Urea	0	120		05/28	08/18
		4	Irrigated	Cisadane	Urea	0	120		05/28	09/01

before harvest in each season. Therefore, CH₄ emissions increased relatively fast after transplanting and remained on a relatively high level between 100 and 200 mg CH₄ m⁻² d⁻¹ throughout the seasons (Figure 1a, c). The emission peaks at the end of the season indicate the presence of soil-entrapped CH₄ gas that is released after drainage (Wassmann et al., 1994; Denier van der Gon et al., 1996).

For rainfed rice, CH₄ emission rates were virtually zero during the first month of the wet season when the soil is still very dry. Frequent rainfall in November and December gradually increased the flooding intensity and thus, CH₄ emission rates (Figure 1b). However, emission rates were generally below 100 mg CH₄ m⁻² d⁻¹ in the wet season. High flux rates at the onset of the dry season (Figure 1d) can be attributed to persistent flooding in combination with a substrate supply derived from organic residues, i.e. stubble and roots of the preceding crop. After 20 d, emission rates were suppressed in rainfed rice to values below 100 mg CH₄ m⁻² d⁻¹. Rainfed fields were also drained a week before harvest, but the emerging CH₄ pool from the soils was either negligible (wet season) (Figure 1b) or relatively small (dry season) (Figure 1d) as compared with irrigated rice (Figure 1a,c).

For irrigated rice, the cumulated emission computed for dry and wet seasons are in a similar range (Table 2). Rainfed rice generally had a lower emission in the wet season, although the differences varied broadly from year to year (Table 3). Apparently, dry periods at the early stage have a stronger impact on seasonal emissions than dry periods at later plant stages.

Impact of organic amendment

In the 1995-96 wet season and the ensuing 1996 dry season, the field experiments encompassed three different combinations of mineral and organic amendments in rainfed rice (Table 3). All field trials received urea; one field trial received an additional dose of rice straw and one trial an additional dose of farmyard manure (FYM) (Table 3). Organic amendment had only a minor impact at the onset of the wet season (Figure 2). Soils were still dry in this period, so that the bulk of the organic material was decomposed aerobically. Even when the fields were flooded, emissions were in an identical range in the plots without and those treated with FYM. Application of FYM had no detectable impact on CH₄ emission in the 1995-96 wet season while in the 1994-95 wet season, it even reduced CH₄ emission as compared to urea-applied plots ($P < 0.05$) (Table 3).

Application of rice straw, however, resulted in enhanced emission rates during the middle season (Figure 3). The seasonal emissions are 40% higher than the urea- and FYM-applied plots ($P < 0.05$) (Table 3). This increment in CH₄ emission can be attributed to a relatively high resilience of rice straw to aerobic decomposition. Rice straw is only partially decomposed during the first month of aerobic conditions in the soil.

The different decomposition rates of FYM and rice straw were also discernable during the dry season. Both types of amendments increased emission rates within the first month after planting, but FYM produced consistently higher emissions than rice straw during this period. Again, this difference can be attributed to a faster decomposition of FYM. In contrast to the preceding season, however, anaerobic conditions prevailed in the soil and led to a relatively faster CH₄ production at the start of the experiment.

Methane emission rates converged for all treatments after the initial stage. The overall impact of FYM in the dry season corresponded to a 72% increase in CH₄ emission. The increment triggered by rice straw (37%) roughly corresponded to the relative impact during the preceding wet season (Table 3).

Impact of rice cultivars

Four different cultivars were tested in the 1997-98 wet season and 1998 dry season (Table 2); this comparison was conducted in irrigated rice. The most distinctive feature among these cultivars was the length of cropping season (Figure 3). Dodokan was an early maturing cultivar and was harvested after 90 d in the wet season and 75 d in the dry season. The cultivars IR64 and Memberamo had similar season lengths with 98 d (wet season) and 82 d (dry season). Cisadane required the longest time for maturing with 125 d and 75 d, respectively. IR64 produced the highest yield followed by Memberamo, Dodokan, and Cisadane ($P \leq 0.05$) (Table 3).

Methane emission rates are shown in Figure 3 for Dodokan, IR64, and Cisadane; emission rates for Memberamo and IR64 were almost identical. Emissions of all cultivars were in a similar range and showed similar patterns. Preharvest drainage triggered the emergence of entrapped CH₄ from the soil, resulting in an emission peak shortly before harvest. Then, CH₄ emission rates subsided rapidly after harvest. Due to different harvesting dates, the emission peaks were staggered for the different cultivars (Figure 3).

Table 3. Summary of methane fluxes, biomass, and grain yield from the Jakenan experiments, 1993-98^a

Year	Season	Treatment no.	Treatment description		Mean emission (mg m ⁻² d ⁻¹)	Seasonal emission (kg ha ⁻¹)	Biomass (t ha ⁻¹)	Yield (t ha ⁻¹)
			Water management	Other management				
1993-94	Wet	1	Irrigated	IR72/transplanted/20×20	166 a [†]	229	5.0 b	4.7 b
		2	Irrigated	IR72/direct seeded/20×20	152 a	256	14.3 a	7.1 a
		3	Rainfed	IR64/transplanted/15×20	28 b	59	13.2 a	6.5 a
		4	Rainfed	IR64/direct seeded/20×20	19 b	26	4.9 b	4.4 b
1994	Dry	1	Irrigated	IR72	134 a	141	6.9 b	2.6 b
		2	Rainfed	IR64	90 b	77	9.5 a	3.8 a
		3	Rainfed	IR72	66 c	69	8.7 a	3.6 a
		4	Irrigated	IR64	163 a	115	6.7 b	2.9 b
1994-95	Wet	1	Rainfed	Urea	63 b	75	11.0 a	4.9 a
		2	Rainfed	Farm manure	55 d	65	9.7 a	4.1 a
		3	Rainfed	Farm manure	58 c	69	11.9 a	5.1 a
		4	Irrigated	Urea	124 a	105	11.9 a	4.7 a
1995	Dry	1	Rainfed	Urea	- ^b	-	8.6 b	3.4 a
		2	Rainfed	Farm manure	-	-	8.2 b	3.3 a
		3	Rainfed	Farm manure	-	-	7.6 b	2.9 a
		4	Irrigated	Urea	-	-	9.5 a	3.7 a
1995-96	Wet	1	Rainfed	Urea	52 b	56	10.9 a	4.8 a
		2	Rainfed	Rice straw	73 a	78	12.2 a	5.3 a
		3	Rainfed	Farm manure	52 b	56	11.4 a	4.9 a
		4	Irrigated	Urea	81 a	87	10.5 a	4.4 a
1996	Dry	1	Rainfed	Urea	59 c	53	10.6 a	4.4 a
		2	Rainfed	Rice straw	81 c	73	11.9 a	4.6 a
		3	Rainfed	Farm manure	102 b	92	10.6 a	4.5 a
		4	Irrigated	Urea	184 a	166	10.4 a	4.6 a
1996-97	Wet	1	Irrigated	Prilled urea	171 a	170	14.9 b	7.4 a
		2	Irrigated	Urea tablet	105 b	104	14.9 b	7.4 a
		3	Rainfed	Prilled urea	32 d	37	16.3 a	6.9 b
		4	Rainfed	Urea tablet	39 c	45	15.9 a	6.8 b
1997	Dry	1	Irrigated	Prilled urea	217 a	181	-	4.6 a
		2	Irrigated	Urea tablet	197 a	163	-	5.0 a
		3	Rainfed	Prilled urea	106 c	88	-	4.2 a
		4	Rainfed	Urea tablet	123 b	102	-	4.8 a
1997-98	Wet	1	Irrigated	Dodokan	110 d	101	-	4.5 c
		2	Irrigated	IR64	132 b	128	-	7.0 a
		3	Irrigated	Memberamo	133 ac	137	-	6.0 b
		4	Irrigated	Cisadane	113 cd	142	-	4.2 c
1998	Dry	1	Irrigated	Dodokan	71 c	52	-	-
		2	Irrigated	IR64	100 b	81	-	-
		3	Irrigated	Memberamo	118 b	97	-	-
		4	Irrigated	Cisadane	121 a	116	-	-

^aData at the same season of the same year following the same letter are not significantly different at $P < 0.05$. ^bMissing data.

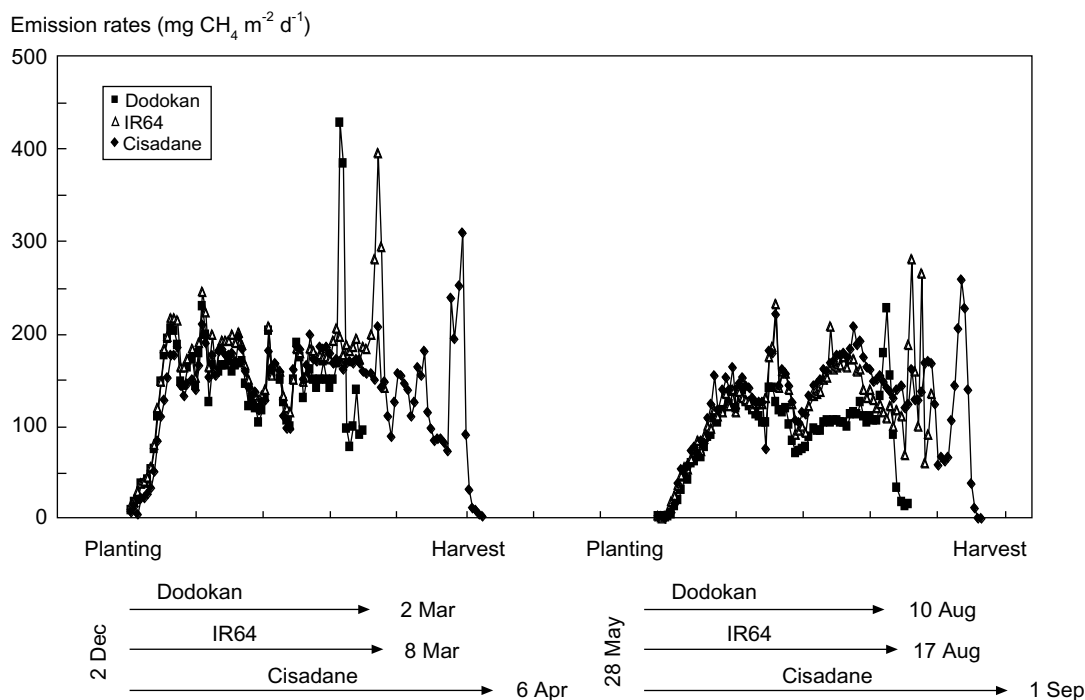


Figure 3. Methane emissions in irrigated rice as affected by cultivars, 1997-98 wet season and 1998 dry season (tick marks on x axis indicate 20-d intervals, arrows indicate length of growing season for each cultivar)

These seasonal patterns resulted in significantly different cumulative values of emission rates ($P \leq 0.05$) (Table 3). In the case of cultivars tested in this experiment, the differences in CH_4 emissions were greatly related to season length. Based on this finding, progress in breeding short-maturing cultivars should be beneficial for an environmentally sound rice production.

However, the results of the 1994 dry season indicate that cultivars with identical season length can also show significant differences in CH_4 emissions (Table 3). IR72 had a lower emission in irrigated rice (18%) and rainfed rice (17%) than another high-yielding variety IR64 ($P < 0.05$). The reasons for this difference are not clear, but low yields of IR72 (Table 3) indicate the suboptimum growth of IR72 that may have affected emissions.

Impact of other management practices

The first season of the experiment in Jakenan (1993/94 wet season) was conceived to explore promising parameters for future field studies. The individual rice hills were spaced in one field trial in 15-cm \times 20-cm dis-

tance, whereas all other trials during the entire Jakenan experiment had 20-cm \times 20-cm spacing. The different spacing was conducted in rainfed rice, and CH_4 emissions in this season was on an extremely low level (average $< 30 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) for both field trials in this season (Table 3). The observed differences between these field trials therefore can not be generalized.

In the same season, direct seeding was compared with transplanting. These modes of crop establishment were tested for irrigated rice and emission rates were relatively higher (Table 3). Direct seeding resulted in 8% reduction in CH_4 emission as compared with transplanting, but the difference was not significant. Therefore, this singular experiment also cannot be used to conclude ubiquitously valid statements on the impact of direct seeding vs transplanting.

The application mode of urea affected CH_4 emission rates in the 1996/97 wet season and 1997 dry season. In irrigated rice, deep placement of urea tablets decreased CH_4 emission rates by 39% in wet season (significant at $P < 0.05$) and 10% in the dry season as compared with broadcasting of prilled urea (Table 3). In rainfed rice, however, tablet urea caused an increase

of 21% ($P < 0.05$) and 16% ($P < 0.05$) in wet season and dry season, respectively (Table 3). Yields were similar for prilled and urea tablet, so that the reasons for this diverging effect in irrigated and rainfed rice remain unclear at this point.

Conclusion

The results of this study represent the most comprehensive data set on CH_4 emission from equatorial rice systems. The range of CH_4 emission rates from Indonesian rice fields were previously reported using manual sampling techniques (Kimura et al., 1994; Husin et al., 1995). The field experiment in Jakenan allows a profound assessment of CH_4 emissions through continuous measurements over an observation period of 5 yr. The field layout encompassed virtually all agronomic parameters affecting CH_4 emissions from irrigated and rainfed rice. This article focuses on crop management while preliminary results on temporal patterns and possible mitigation strategies were presented by Buendia et al. (1997). The difference between irrigated and rainfed rice is discussed by Wassmann et al. (this issue, b).

Based on data presented in this study, organic amendments had a much lower impact on CH_4 emissions in rainfed rice than in irrigated systems (Yagi & Minami, 1990; Sass et al., 1991; Wassmann et al., 1995). Easily decomposable material such as FYM is predominantly decomposed aerobically when applied in the wet season. In the dry season, the impact is also substantially smaller than in the irrigated stations of this interregional network. Therefore, the application of organic manure can be regarded as an integral part of sustainable crop management in rainfed rice, even by considering greenhouse gas budget of rice fields as one criterion.

The results for irrigated rice provided an important clue for the selection of cultivars. Previously, different emission potentials have been related to CH_4 transport capacity of the aerenchyma and root exudation (Butterbach-Bahl et al., 1997; Wang et al., 1997). For the set of cultivars tested in Jakenan, these differences appear to be minor and emission potentials are determined by season length. This finding can be used for a preselection of cultivars to identify those with low emission potentials. Breeding attempts to shorten the season length are also beneficial for an environment-friendly rice production with less emissions of greenhouse gases.

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