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Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines)

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Abstract

Methane (CH_4) emissions were measured with an automated system in Central Luzon, the major rice producing area of the Philippines. Emission records covered nine consecutive seasons from 1994 to 1998 and showed a distinct seasonal pattern: an early flush of CH_4 before transplanting, an increasing trend in emission rates reaching maximum toward grain ripening, and a second flush after water is withdrawn prior to harvesting. The local practice of crop management, which consists of continuous flooding and urea application, resulted in 79-184 mg CH_4 m^{-2} d^{-1} in the dry season (DS) and 269-503 mg CH_4 m^{-2} d^{-1} in the wet season (WS). The higher emissions in the WS may be attributed to more labile carbon accumulation during the dry fallow period before the WS cropping as shown by higher % organic C. Incorporation of sulfate into the soil reduced CH_4 emission rates. The use of ammonium sulfate as N fertilizer in place of urea resulted in a 25-36% reduction in CH_4 emissions. Phosphogypsum reduced CH_4 emissions by 72% when applied in combination with urea fertilizer. Midseason drainage reduced CH_4 emission by 43%, which can be explained by the influx of oxygen into the soil. The practice of direct seeding instead of transplanting resulted in a 16-54% reduction in CH_4 emission, but the mechanisms for the reducing effect are not clear. Addition of rice straw compost increased CH_4 emission by only 23-30% as compared with the 162-250% increase in emissions with the use of fresh rice straw. Chicken manure combined with urea did not increase CH_4 emission. Fresh rice straw has wider C/N (25 to 45) while rice straw compost has C/N = 6 to 10 and chicken manure has C/N = 5 to 8. Modifications in inorganic and organic fertilizer management and water regime did not adversely affect grain yield and are therefore potential mitigation options. Direct seeding has a lower yield potential than transplanting but is getting increasingly popular among farmers due to labor savings. Combined with a package of technologies, CH_4 emission can best be reduced by (1) the practice of midseason drainage instead of continuous flooding, (2) the use of sulfate-containing fertilizers such as ammonium sulfate and phosphogypsum combined with urea; (3) direct seeding crop establishment; and (4) use of low C/N organic fertilizer such as chicken manure and rice straw compost.

Introduction

There is an urgent need to increase rice production in the Philippines to feed a population that is growing to 70 million. Per capita consumption of rice in the Philippines is currently 103 kg. The development of reliable, efficient irrigation systems is the remaining best option as rice areas continue to decrease. Rice production in the coming years is expected to lean toward more intensification in terms of increased cropping per year and the use of high-input technologies. Expansion and intensification of the irrigated rice area could increase CH_4 emission from rice fields.

Irrigated rice fields have high potential to produce CH_4 because continuous flooding favors CH_4 production and emission. However, irrigated rice cultivation is one of the few anthropogenic sources where the management of CH_4 is possible. Thus, it becomes a critical focus of mitigation efforts. Mitigation technologies, however, must be formulated parallel to the need to increase and sustain high productivity. One major step is to identify mitigation options by investigating the influence of various factors on the processes of CH_4 production and consumption. The field experiment presented here was part of an interregional network on CH_4 emissions from rice fields (Wassmann et al., this issue). The objectives of our research were (1) to measure CH_4 fluxes in irrigated rice fields under different cultivation practices in a major rice-growing area of the Philippines; (2) to evaluate processes that control CH_4 formation; and (3) to identify mitigation options to reduce CH_4 emission from irrigated rice fields while sustaining high yield.

Materials and methods

Field site

The experimental site at PhilRice Central Experiment Station in Maligaya, Muñoz, Nueva Ecija, is located at 15° 40' 21" N latitude and 120° 53' 26" E longitude. The province of Nueva Ecija is situated in the central plain of Luzon, the top rice-producing region in the Philippines with a total irrigated land area of 300,341 ha. The central plain is a terrace in a river valley with a slope of <1% and elevation of 35 m above sea level. Annual mean precipitation is 1780 mm with distinct 4-5 mo dry season (DS) and 4-6 mo wet season (WS). The project site is fully irrigated and cropped twice in a year, one in the WS and another in the DS. The soil at PhilRice Maligaya site is derived from alluvium parent material and is poorly drained. It is classified as fine, montmorillonitic, isohyperthermic Ustic Epiaquerts (Maligaya clay). Some of its physicochemical properties are listed in Table 1.

Table 1. Some characteristics of Maligaya soil at PhilRice Central Experiment Station at Muñoz, Nueva Ecija, Philippines

pH (H_2O)	6.88
pH ($CaCl_2$)	6.36
Organic carbon (%)	1.32
Total nitrogen (%)	0.09
Ammonium nitrogen (cmol kg^{-1})	0.72
CEC (cmol kg^{-1})	34.28
Active iron (µg g^{-1})	75.02
Olsen phosphorus (mg kg^{-1})	3.10
Exchangeable potassium (cmol kg^{-1})	0.10
Available zinc (mg kg^{-1})	1.48
Available sulfate (mg kg^{-1})	13.54
% clay	43.00
% silt	51.40
% sand	5.60

Duration of experiment

Field experiments measuring CH_4 emission from irrigated Maligaya clay were conducted for nine consecutive seasons (five dry + four wet) from 1994 to 1998.

Crop management practices

The DS cropping usually starts in the second week of January and ends in late April or early May. The WS cropping starts in late June to mid-July and ends in mid- to late October. The crop was harvested leaving a 28-38 cm stubble for the next crop, except in 1996 when the crop was harvested close to the ground leaving only the roots. The amount of stubble left in the field after harvest is equivalent to 2.4-4.0 t ha^{-1} dry matter. In all experiments, the roots were incorporated to decay. The crop residues were incorporated during land preparation, which is usually 15-30 d before planting. The field was flooded 2-3 d before the start of land preparation. In 1997, the differences in date of residue incorporation between T1/T3 and T2/T4 were due to the reference dates which was the date before transplanting for T1/T3 and days before sowing for T2/T4. The use of organic amendments, using either fresh rice straw, rice straw compost, chicken manure, or commercial bio-organic fertilizers commenced in 1996. After transplanting, the field was kept moist without standing water for 7-10 d after which a 5-cm water level was kept in continuously flooded treatments. About 14 d before harvest, water was withdrawn from the plots so that the soil was dry during harvest. In 1997 and 1998, water regime treatments such as midseason drainage and intermittent irrigation treatments were imposed. Midseason drainage was done by withdrawing water for 7-10 d before the panicle initiation stage. The soil, however, was not allowed to crack. In the intermittent irrigation treatment, floodwater was left to dry out and water was introduced again when the soil started to crack. This was done continuously throughout the cropping season. Nitrogen was supplied as either urea or ammonium sulfate at 90-180 kg N ha^{-1}. The rate was 120 kg N ha^{-1} in the reference treatment (T1) both in the DS and WS of 1994-96 cropping. Rice variety IR72 was used from 1994 to 1996; IR64 in 1997; and PSBRc 28 in 1998. Fourteen-day-old seedlings were transplanted at 20- × 20-cm spacing giving a population of 25 hills m^{-2}. Seeding rates in direct-seeded rice were 140 kg ha^{-1} in 1997 and 40 kg ha^{-1} in 1998, giving a tiller density of 1,104-1,745 m^{-2}.

Experiment layout and treatments

Treatments in each cropping season are shown in Table 2. Four treatments in each season were arranged in twelve 5- × 11.6-m plots using randomized complete block design with three replications. The treatments imposed were designed to investigate CH_4 emission as influenced by 1) the amount of N application, 2) the use of sulfate (SO_4^{-2})-containing fertilizers such as phosphogypsum and ammonium sulfate, 3) the use of fresh or rice straw compost, 4) crop establishment method, 5) water management, and 6) combinations of treatments 1-5. In 1994 DS, the fertilizer rates and variety in T3 reflected the prevailing practice of farmers in Nueva Ecija. This practice was modified in T4 by balancing the amount of N, P, and K. T1 was the reference treatment across seasons and years, while T2 was the amount of fertilizer targeting high rice yield in the Maligaya site. The aim was to compare CH_4 emission under current fertilizer application practice for high yield with those under farmers' practice.

The effect of inorganic amendments on CH_4 fluxes was tested in the 1994 and 1995 experiments. The rate of N was varied from 120 to 180 kg ha^{-1}, supplied either as urea or as ammonium sulfate. Phosphogypsum, a sulfur-containing byproduct of phosphate fertilizer manufacture, was tested at the rate of 0.5-1.0 t ha^{-1} in 1994 WS, at 6.0 t ha^{-1} in 1995 WS, and at 3.0 t ha^{-1} in 1996 DS and WS. Finally, in 1998 DS, the combination of cultural practices for high yield with the least CH_4 emission—use of low C/N organic fertilizer, ammonium sulfate as N fertilizer, direct-seeding crop establishment, midseason drainage, and intermittent irrigation—were tested.

Measurements

Methane flux. CH_4 fluxes were measured continuously every 2 h from transplanting until 7 d after harvest. Continuous measurement was facilitated by chamber method — automatic sampling technique (IAEA 1993). The system used was designed by the Fraunhofer Institute for Atmospheric Environmental Research (Germany) and installed at PhilRice in September 1993. The measuring system was composed of gas-collecting plexiglas boxes installed in 12 plots connected by stainless steel and copper tubing to a field laboratory equipped with datalogger, gas chromatograph (GC), and computer for a fully automated gas sampling and analysis. Air samples trapped in plexiglas boxes were immediately pumped and flushed through the stainless steel tubing to the GC. One measurement cycle lasting 2 h started with sampling of a CH_4 gas standard followed by a series of sampling of air trapped in the boxes and ended with the CH_4 standard. During the 2-h cycle, six pairs of boxes closed successively; each pair of boxes closed for 16 min and sampled four times alternately. A datalogger program automatically controlled the closing and opening of the boxes and the timing of gas sampling and analysis. Methane concentration data were transmitted from the GC integrator to the computer after each measurement cycle. Each treatment was measured from three boxes representing three replications.

Analysis of CH_4 concentration. The concentration of CH_4 in the gas samples was analyzed in a GC (Shimadzu GC-8A) equipped with flame ionization detector and porous polymer beads Porapak N 80/100 mesh column. Analysis was performed at 60 °C column temperature and 100 °C detector temperature with N_2 as carrier gas.

Statistical analysis. The statistical analysis of mean CH_4 emission was done using the STATISTICA software. For each experiment, the daily data per treatment were evaluated as to type of distribution (i.e., normal or skewed). If the distribution is normal, t-test

Table 2. Summary treatments from 1994 dry season to 1998 dry season in PhilRice Central Experiment Station

Year/season	Treatment	T1	T2	T3	T4
1994/DS	Cultivar	IR72	IR72	IR64	IR64
	Crop establishment	Transplanted	Transplanted	Transplanted	Transplanted
	Water regime	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm
	NPK	120-30-30	180-60-30	171-25-25	117-34-31
1994/WS	Cultivar	IR72	IR72	IR72	IR72
	Crop establishment	Transplanted	Transplanted	Transplanted	Transplanted
	Water regime	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm
	NPK	120-30-30	120-30-30	120-30-30	120-30-30
	N source	Urea	Ammosul[a]	Urea	Urea
	Phosphogypsum	-	-	0.5 t ha^{-1}	1.0 t ha^{-1}
1995/DS	Cultivar	IR72	IR72	IR72	IR72
	Crop establishment	Transplanted	Transplanted	Transplanted	Transplanted
	Water regime	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm
	NPK	120-40-40	120-40-40	180-40-40	180-40-40
	N source	Urea	Ammosul	Urea	Ammosul
1995/WS	Cultivar	IR72	IR72	IR72	IR72
	Crop establishment	Transplanted	Transplanted	Transplanted	Transplanted
	Water regime	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm
	NPK	120-40-40	120-40-40	180-40-40	120-40-40
	N source	Urea	Ammosul	Urea	Urea
	Phosphogypsum	-	-	-	6.0 t ha^{-1}
1996/DS	Cultivar	IR72	IR72	IR72	IR72
	Crop establishment	Transplanted	Transplanted	Transplanted	Transplanted
	Water regime	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm
	NPK	120-40-40	90-40-40	90-40-40	90-40-40
	Organic material	-	4 t ha^{-1} FSR[b]	2.5 t ha^{-1} RSC[c]	4 t ha^{-1} FSR[1]
	Phosphogypsum	-	-	-	3.0 t ha^{-1}
1996/WS	Cultivar	IR72	IR72	IR72	IR72
	Crop establishment	Transplanted	Transplanted	Transplanted	Transplanted
	Water regime	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm	Flooded, 5 cm
	NPK	120-40-40	90-40-40	90-40-40	90-40-40
	Organic material	-	4 t ha^{-1} FSR	2.5 t ha^{-1} RSC	4 t ha^{-1} FSR
	Phosphogypsum	-	-	-	3.0 t ha^{-1}
1997/DS	Cultivar	IR64	IR64	IR64	IR64
	Crop establishment	Transplanted	Direct-seeded	Transplanted	Direct-seeded
	Water regime	Continuously flooded, 5 cm	Continuously flooded, 5 cm	Midseason drained	Midseason drained
	NPK	150-60-60	150-60-60	150-60-60	150-60-60
	Organic material	300 kg ha^{-1} Commercial bio-organic fertilizer	300 kg ha^{-1} Commercial bio-organic fertilizer	300 kg ha^{-1} Commercial bio-organic fertilizer	300 kg ha^{-1} Commercial bio-organic fertilizer
1997/WS	Cultivar	IR64	IR64	IR64	IR64
	Crop establishment	Transplanted	Direct-seeded	Transplanted	Direct-seeded
	Water regime	Continuously flooded, 5 cm	Continuously flooded, 5 cm	Midseason drained	Midseason drained
	NPK	90-30-60	90-30-60	90-30-60	90-30-60
	Organic material	300 kg ha^{-1} Commercial bio-organic fertilizer	300 kg ha^{-1} Commercial bio-organic fertilizer	300 kg ha^{-1} Commercial bio-organic fertilizer	300 kg ha^{-1} Commercial bio-organic fertilizer

Table 2 continued

Year/season	Treatment	T1	T2	T3	T4
1998/DS	Cultivar	PSBRc 28	PSBRc 28	PSBRc 28	PSBRc 28
	Crop establishment	Transplanted	Transplanted	Direct-seeded	Direct-seeded
	Water regime	Continuously flooded, 5 cm	Continuously flooded, 5 cm	Midseason drained	Intermittent irrigation
	NPK	150-60-60	150-60-60	150-60-60	150-60-60
	N source	Urea	Urea	Ammosul	Ammosul
	Organic material	-	1.5 t ha^{-1} Chicken manure	2.5 t ha^{-1} Rice straw compost	2.5 t ha^{-1} Rice straw compost

[a]Ammonium sulfate. [b]Fresh rice straw. [c]Rice straw compost.

was used (parametric analysis). If the distribution is not normal, sign test was used (nonparametric analysis). The T value for t-test and the Z value for sign test were determined. Then the significance was determined from the value of probability (Table 4).

Results

The results of the 5-yr experiment were summarized by season in Table 3. In 1994 DS, flux measurement was discontinuous during the first 58 d owing to measurement system problems. Many data points during this period were actually interpolated between two actual measurements (Figure 1). IR64 with 117 kg N ha^{-1} gave slightly higher CH_4 fluxes for the period 38-83 DAT (Figure 1). This resulted in a mean emission of 114 mg CH_4 m^{-2} d^{-1} that was highest (z values = 3.2**, 7.5**, 8.2**) among the treatments. The reference treatment, IR72 with 120 kg N ha^{-1}, gave a mean emission of 90 mg CH_4 m^{-2} d^{-1}. The mean emission was lower than the reference treatment (64 mg CH_4 m^{-2} d^{-1}, z value = 8.6**) in IR72 with 180-60-30 fertilizer and in IR64 with 171-25-25 fertilizer applied (74 mg CH_4 m^{-2} d^{-1}, z value = 8.0**). An increasing trend in mean CH_4 emission was observed as rice growth progresses. The maximum was reached toward grain ripening. Two weeks before harvest, when irrigation was withdrawn, a flush of CH_4 emission occurred which was reduced to a negligible amount after 5-7 d. IR72 (T1) and (T2) treatments gave higher yields of 8.36 t ha^{-1} and 9.26 t ha^{-1}, respectively, than IR64 (T3) and (T4) with yields of 6.79 t ha^{-1} and 7.36 t ha^{-1}. Accordingly, the amount of CH_4 produced per ton of grain yield was lower in IR72. But the total aboveground biomass production did not differ among treatments.

In the 1994 WS, a distinct seasonal pattern which is an early flush of CH_4 before transplanting, followed by an increasing rate of emission reaching maximum toward grain ripening, and a second flush CH_4 after water was withdrawn before harvest was established (Figure 2). T1 (urea, 120 N) gave slightly higher fluxes starting at 30 DAT through 90 DAT, resulting in a mean emission of 266 mg CH_4 m^{-2} d^{-1}. Ammonium sulfate (T2) and (T3) urea + 0.5 t phosphogypsum (PG) ha^{-1} gave slightly lower mean emission of 232 mg CH_4 m^{-2} d^{-1}(z value = 6.6**) and 227 mg CH_4 m^{-2} d^{-1}(z value = 7.2**), respectively. The observed reduction in total seasonal CH_4 emission was about 14% in the ammonium sulfate (230 kg CH_4 ha^{-1}) compared with the urea treatment (266 kg CH_4 ha^{-1}). A 9-15% reduction of total seasonal emission was observed with application of 0.5 to 1.0 t PG ha^{-1}. The mean emission and the amount of CH_4 emitted per ton yield were the same in treatments with SO_4^{-2} (from ammonium sulfate as N fertilizer and urea plus PG). The grain yield as well as total aboveground biomass produced did not differ among the treatments.

The results of the 1995 DS also showed the distinct seasonal pattern of CH_4 emission. Measurement was discontinued after 80 DAT owing to a problem in the system. Thus, the second flush upon withdrawal of water before harvest was not observed. All treatments gave similar magnitude of CH_4 flux during the first 15 DAT (Figure 3). Starting from 25 DAT until 70 DAT, CH_4 fluxes in urea treatments were higher than those in ammonium sulfate treatments. Using ammonium sulfate in place of urea reduced mean emission from 184 mg CH_4 m^{-2} d^{-1} to 166 mg CH_4 m^{-2} d^{-1} (z value = 3.8**) at lower N level (120 kg N ha^{-1}) and from 205 mg CH_4 m^{-2} d^{-1} to 131 mg CH_4 m^{-2} d^{-1} (z value = 6.7**) at higher N level (180 kg N ha^{-1}). Increasing the amount of N applied from 120 to 180 kg ha^{-1} using urea slightly increased (z value = 3.4**) mean CH_4 emission. However, with ammonium sulfate, the higher N rate reduced

Table 3. Methane emissions from 1994 dry season to 1998 dry season in the PhilRice Central Experiment Station[a]

Year/season	Measurement	T1	T2	T3	T4
1994/DS	Mean emission (mg m^{-2} d^{-1})	90	64	74	114
	Season length (d)	105	105	91	91
	Seasonal flux (kg CH_4 ha^{-1})	95	67	67	104
	Biomass (t ha^{-1})	12.63a	13.32a	13.36a	12.79a
	Grain yield (t ha^{-1})	8.36ab	9.26a	6.79c	7.36bc
	kg CH_4 per ton yield	11.36	7.24	9.87	14.13
1994/WS	Mean emission (mg m^{-2} d^{-1})	269	232	227	243
	Season length (d)	99	99	99	99
	Seasonal flux (kg CH_4 ha^{-1})	266	230	225	241
	Biomass (t ha^{-1})	11.46a	12.54a	11.82a	11.50a
	Grain yield (t ha^{-1})	5.22a	5.10a	4.90a	5.27a
	Kg CH_4 per ton yield	50.96	45.10	45.92	45.73
1995/DS	Mean emission (mg m^{-2} d^{-1})	184	166	205	131
	Season length (d)	111	111	111	111
	Seasonal flux (kg CH_4 ha^{-1})	204	184	228	145
	Biomass (t ha^{-1})	13.79a	13.07a	14.44a	15.00a
	Grain yield (t ha^{-1})	6.54a	6.40a	6.45a	6.34a
	Kg CH_4 per ton yield	31.19	28.75	35.35	22.87
1995/WS	Mean emission (mg m^{-2} d^{-1})	503	317	516	139
	Season length (d)	103	103	103	103
	Seasonal flux (kg CH_4 ha^{-1})	518	327	531	143
	Biomass (t ha^{-1})	13.92a	13.90a	12.75a	14.33a
	Grain yield (t ha^{-1})	3.30a	3.72a	3.36a	3.78a
	Kg CH_4 per ton yield	156.97	87.90	158.04	37.83
1996/DS	Mean emission (mg m^{-2} day^{-1})	165	433	184	318
	Season length (d)	97	97	97	97
	Seasonal flux (kg CH_4 ha^{-1})	160	420	178	308
	Biomass (t ha^{-1})	15.35a	13.29ab	12.18b	10.08bc
	Grain yield (t ha^{-1})	7.30a	7.13a	7.41a	7.20a
	Kg CH_4 per ton yield	21.92	58.91	24.02	42.78
1996/WS	Mean emission (mg m^{-2} d^{-1})	272	952	353	599
	Season length (d)	100	100	100	100
	Seasonal flux (kg CH_4 ha^{-1})	272	952	353	599
	Biomass (t ha^{-1})	14.60a	14.05a	13.37a	13.05a
	Grain yield (t ha^{-1})	5.17a	5.22a	5.35a	5.27a
	Kg CH_4 per ton yield	52.61	182.38	65.98	113.66
1997/DS	Mean emission (mg m^{-2} d^{-1})	91	73	52	46
	Season length (d)	98	91	98	91
	Seasonal flux (kg CH_4 ha^{-1})	89	75	51	48
	Biomass (t ha^{-1})	12.5a	11.2a	13.5a	10.2a
	Grain yield (t ha^{-1})	7.91b	6.71a	7.74b	6.42a
	Kg CH_4 per ton yield	11.25	11.18	6.59	7.48
1997/WS	Mean emission (mg m^{-2} d^{-1})	375	323	347	178
	Season length (d)	93	84	93	84
	Seasonal flux (kg CH_4 ha^{-1})	348	272	323	150
	Biomass (t ha^{-1})	12.4a	13.4a	14.1a	11.7a
	Grain yield (t ha^{-1})	5.36b	3.84a	5.45b	3.41a
	Kg CH_4 per ton yield	64.92	70.83	59.27	43.99

Table 3 continued.

Year/season	Measurement	T1	T2	T3	T4
1998/DS	Mean emission (mg m^{-2} d^{-1})	79	80	14	6
	Season length (d)	114	114	114	114
	Seasonal flux (kg CH_4 ha^{-1})	90	91	16	7
	Biomass (t ha^{-1})	16.4b	14.7b	24.2a	23.2a
	Grain yield (t ha^{-1})	8.0ab	8.5a	7.7b	7.1c
	Kg CH_4 per ton yield	11.25	10.71	2.08	0.98

[a]In a row, numbers followed by the same letter are not significantly different at the 5% level by DMRT.

mean emission by 21% (z value = 2.9**). Grain yield and total aboveground biomass produced did not differ among treatments. The lowest amount of CH_4 (22.87 kg CH_4 t^{-1} grain yield) was observed with ammonium sulfate applied at 180 kg N ha^{-1}. In the 1995 WS, urea + PG treatment gave consistently lower CH_4 fluxes from 15 DAT until harvest as compared with the other treatments (Figure 4). No measurement was done before transplanting because of some problem in the system that started during the DS cropping. The same seasonal pattern of emission with a previous cropping was observed. Ammonium sulfate treatment also gave fluxes consistently lower than those in the urea treatments throughout the growing season. Seasonal flux in urea treatments at 180 kg N ha^{-1} (daily average of 516 mg CH_4 m^{-2}) was the same as that at 120 kg N ha^{-1} treatment (daily average of 503 mg CH_4 m^{-2}). The higher amount of N applied from urea slightly increased CH_4 emission during the 1995 DS but this was not significant during the 1995 WS. Ammonium sulfate treatment gave a mean emission of 317 mg CH_4 m^{-2} d^{-1} while urea + PG treatment gave only 139 mg CH_4 m^{-2} d^{-1}. The use of ammonium sulfate reduced seasonal CH_4 flux by 37% (z value = 8.5**), while the combination of urea + PG reduced CH_4 emission by 72% (z value = 10.0**). The lowest amount of CH_4 (37.83 kg CH_4 t^{-1} grain yield) was observed with PG addition to urea. Grain yield and total aboveground biomass produced did not differ among treatments.

In the 1996 DS, a similar distinct seasonal pattern of CH_4 emission was observed (Figure 5). Methane fluxes in the 4 t ha^{-1} fresh rice straw treatment were consistently highest among the treatments throughout the growing period. The magnitude of CH_4 fluxes was about twice as high as in the urea treatment starting at 22 DAT until 70 DAT. The CH_4 fluxes from urea-treated plots were parallel with those of fresh rice straw-treated plots starting at 70 DAT. Mean emission increased from 165 to 433 mg CH_4 m^{-2} d^{-1} (z value = 9.8**) with the addition of 4 t ha^{-1} fresh rice straw. The addition of 3 t ha^{-1} PG in rice straw-treated plots increased the mean emission to only 318 mg CH_4 m^{-2} d^{-1} (z value = 9.8**). The addition of PG in T4 with 4 t ha^{-1} fresh rice straw did not fully counteract the high CH_4 fluxes (Table 3). Methane fluxes in the rice straw compost treatment (T3) were similar to the urea treatment throughout the season. Mean CH_4 emission in compost-treated plots (184 mg CH_4 m^{-2} d^{-1}) was only slightly higher than the reference treatment (165 mg CH_4 m^{-2} d^{-1}, z value = 2.3**) where no organic amendment was added. The amount of CH_4 produced (22 kg CH_4 t^{-1} grain yield) was lowest in the urea treatment and followed by the rice straw compost treatment (24 kg CH_4 t^{-1} grain yield). The total aboveground biomass was lower when 30 kg inorganic N was replaced with organic N from fresh rice straw and rice straw compost. The grain yield, however, did not differ among treatments. In the 1996 WS, there were very high CH_4 fluxes in the fresh rice straw treatment from 15 d before transplanting until 25 DAT (Figure 6). Within 40 d from the application of fresh rice straw, CH_4 flux was high in the fresh rice straw-treated plots. Starting from 25 DAT until 100 DAT, the CH_4 fluxes in the fresh rice straw plots were parallel with those of urea and rice straw compost plots. However, the application of 4 t ha^{-1} fresh rice straw consistently gave the highest CH_4 fluxes throughout the growing season. The addition of fresh rice straw increased seasonal CH_4 flux by 250% (from 272 to 952 kg CH_4 ha^{-1}), considerably higher than the 30% increase (from 272 to 353 kg CH_4 ha^{-1}) with addition of 2.5 t ha^{-1} rice straw compost. The addition of 3 t ha^{-1} PG to fresh rice straw-treated plots decreased the seasonal CH_4 flux to almost one-half of the amount (from 952 to 599 kg CH_4 ha^{-1}) where fresh rice straw alone was added. On the other hand, CH_4 fluxes in the rice straw compost treatment were only slightly higher than those in the urea

Table 4. Results of statistical analysis of mean CH_4 emission (mg CH_4 m^{-2} d^{-1})[a]

Year/ season	Treatment no.	Treatment	Mean emission (mg CH_4 m^{-2} d^{-1})	z values[b] T2	T3	T4
1994/DS	T1	120 kg N ha^{-1}: IR72	90	8.6**	8.0**	3.2**
1994/DS	T2	180 kg N ha^{-1}: IR72	64	-	3.5**	7.5**
1994/DS	T3	171 kg N ha^{-1}: IR64	74	-	-	8.2**
1994/DS	T4	117 kg N ha^{-1}: IR64	114	-	-	-
1994/WS	T1	120 kg N ha^{-1} urea	269	6.6**	7.2**	4.8**
1994/WS	T2	120 kg N ha^{-1} ammosul	232	-	0.4 ns	1.9 ns
1994/WS	T3	120 kg N ha^{-1} + 0.5 t ha^{-1} PG	227	-	-	6.6**
1994/WS	T4	120 kg N ha^{-1} + 1.0 t ha^{-1} PG	243	-	-	-
1995/DS	T1	120 kg N ha^{-1} urea	184	3.8**	3.4**	3.4**
1995/DS	T2	120 kg N ha^{-1} ammosul	166	-	4.5**	2.9**
1995/DS	T3	180 kg N ha^{-1} urea	205	-	-	6.7**
1995/DS	T4	180 kg N ha^{-1} ammosul	131	-	-	-
1995/WS	T1	120 kg N ha^{-1} urea	503	8.5**	0.8 ns	10.0**
1995/WS	T2	120 kg N ha^{-1} ammosul	317	-	8.5**	5.3**
1995/WS	T3	180 kg N ha^{-1} urea	516	-	-	10.0**
1995/WS	T4	120 kg N ha^{-1} urea + 6 t ha^{-1} PG	139	-	-	-
1996/DS	T1	120 kg N ha^{-1} urea	165	9.8**	2.3**	9.8**
1996/DS	T2	Urea + 4 t ha^{-1} rice straw	433	-	9.8**	7.9**
1996/DS	T3	Urea + 2.5 t ha^{-1} compost	184	-	-	8.9**
1996/DS	T4	Urea + 4 t ha^{-1} rice straw + 3 t ha^{-1} PG	318	-	-	-
1996/WS	T1	120 kg N ha^{-1} urea	272	9.9**	7.9**	9.9**
1996/WS	T2	Urea + 4 t ha^{-1} rice straw	952	-	9.9**	9.9**
1996/WS	T3	Urea + 2.5 t ha^{-1} compost	353	-	-	9.5**
1996/WS	T4	Urea + 4 t ha^{-1} rice straw + 3 t ha^{-1} PG	599	-	-	-
1997/DS	T1	Transplanted, continuous flooding	91	3.0**	3.2**	4.7**
1997/DS	T2	Direct-seeded, continuous flooding	73	-	4.9**	8.4**
1997/DS	T3	Transplanted, midseason drained	52	-	-	0.1 ns
1997/DS	T4	Direct-seeded, midseason drained	46	-	-	-
1997/WS	T1	Transplanted, continuous flooding	375	4.0**	0.5 ns	8.0**
1997/WS	T2	Direct-seeded, continuous flooding	323	-	1.5 ns	8.2**
1997/WS	T3	Transplanted, midseason drained	347	-	-	7.3**
1997/WS	T4	Direct-seeded, midseason drained	178	-	-	-

[a]The analysis was done using STATISTICA software. For each experiment, daily data per treatment were evaluated as to the type of distribution (i.e., normal or skewed). If distribution is normal, t-test is used (parametric analysis). If distribution is not normal, sign test is used (nonparametric analysis). T value (t-test) and Z value (sign test) were determined. The significance was determined from the value of probability. [b]Comparison is between treatment no. vs T2 or T3 or T4. Level of significance: ** = highly significant (1% level); * = significant (5% level); ns = not significant.

treatment during the period 15 d before transplanting to 25 DAT. Mean CH_4 emission amounted to 272 mg CH_4 m^{-2} d^{-1} in the urea treatment and 353 mg CH_4 m^{-2} d^{-1} (z value = 7.9**) in the rice straw compost treatment. The lowest amount of CH_4 emitted was observed in the reference treatment where no straw was added, both in the DS (22 kg CH_4 t^{-1} yield) and WS (53 kg CH_4 t^{-1} yield). In both seasons, grain yield did not differ among treatments.

In the 1997 DS, the distinct seasonal pattern of CH_4 emission was also observed (Figure 7). The first flush of CH_4 flux was observed during the early growth stage. More CH_4 flux was observed in direct-seeded rice than in transplanted rice during the early stage because there was no standing water in transplanted rice until 7-10 DAT. When irrigation water was introduced, all the treatments had the same CH_4 emission from 20 DAT until midseason drainage was introduced. After the midseason drainage, CH_4 flux was significantly reduced. The CH_4 flux increased again upon reflooding, but did not reach the same level as that in continuously flooded treatment. The second flush of CH_4 flux was observed after water was withdrawn before harvest. The magnitude of CH_4 flux during this second flush was higher in the continuously flooded treatment for both transplanted and direct-seeded rice. Direct-seeded rice

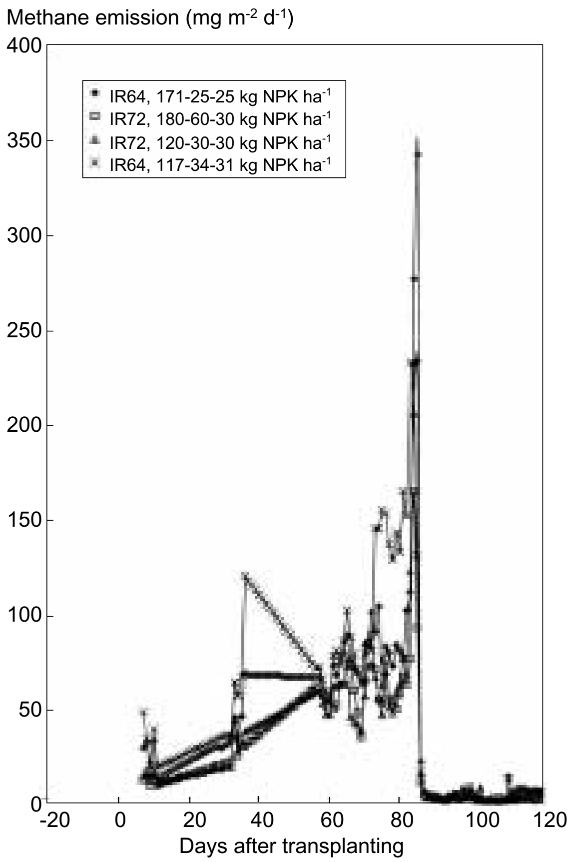

Figure 1. Effect of inorganic amendment on CH_4 emission from rice field grown to IR72 at PhilRice, Maligaya, Philippines, 1994 DS.

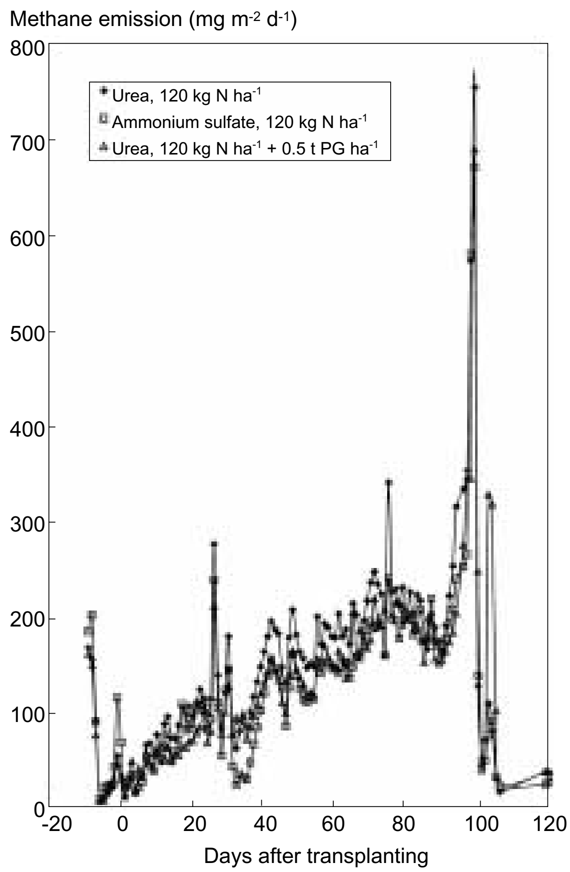

Figure 2. Effect of inorganic amendment on CH_4 emission from rice field grown to IR72 at PhilRice, Maligaya, Philippines, 1994 WS.

produced the same biomass as transplanted rice. However, grain yield of transplanted IR64 (7.7 and 7.9 t ha^{-1}) was significantly higher than that of direct seeded rice (6.4 and 6.7 t ha^{-1}). Midseason drainage significantly reduced CH_4 emission but not grain yield, hence reducing the amount of CH_4 produced from 11.3 and 11.2 kg CH_4 t^{-1} to 6.6 and 7.5 kg CH_4 t^{-1} grain yield, respectively. In 1997 WS, the CH_4 flux was high during the early vegetative growth and greater in transplanted than in direct-seeded rice (Figure 8). The reduction in CH_4 flux after midseason drainage was not distinct during the WS unlike in the DS. Water is difficult to control during the WS. The second flush of CH_4 flux before harvest was also observed. CH_4 flux was higher in continuously flooded plots than in midseason-drained plots. The final aboveground biomass in direct-seeded rice was again the same in all treatments. Also, as in the DS, the grain yield of transplanted IR64 (5.36 and 5.45 t ha^{-1}) was significantly higher than that in direct-seeded rice (3.41 and 3.84 t ha^{-1}). Midseason drainage did not reduce the mean CH_4 emission in transplanted rice (375 vs 347 mg CH_4 m^{-2} d^{-1} (z value = 0.5 ns). In direct-seeded rice, however, the mean CH_4 emission in midseason-drained plot was reduced by 45% (z value = 8.2**). The significant reduction in CH_4 emission in midseason-drained, direct-seeded rice resulted in the lowest amount (44 kg CH_4 t^{-1} grain yield) compared with the 64.9 - 70.8 kg CH_4 t^{-1} grain yield in continuously flooded rice.

In 1998 DS, the increasing trend in CH_4 emission as rice growth progresses and the flush of CH_4 before harvest were again observed, particularly in continuously flooded plots (Figure 9). Grain yield in transplanted rice was higher (8.0-8.5 t ha^{-1}) than in direct-seeded rice (7.1-7.7 t ha^{-1}), although biomass production in direct-seeded rice was much higher than that in transplanted rice. There was significant reduction in CH_4 emission of direct-seeded rice with intermittent irriga-

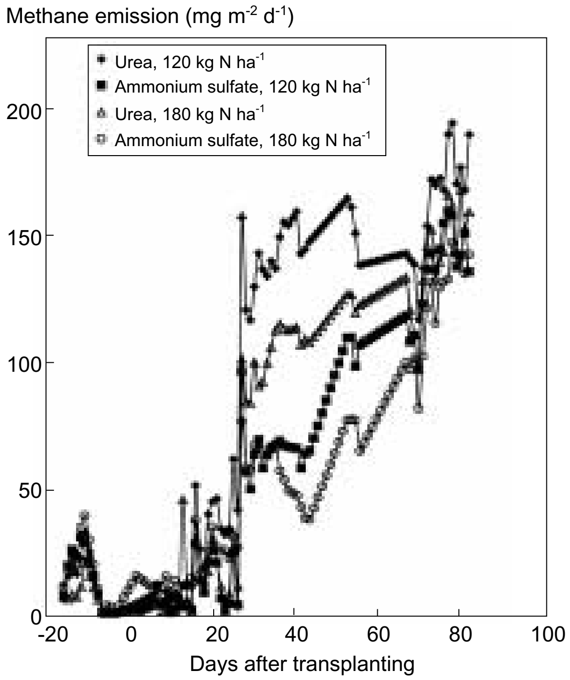

Figure 3. Effect of inorganic amendment on CH_4 emission from rice field grown to IR72 at PhilRice, Maligaya, Philippines, 1995 DS.

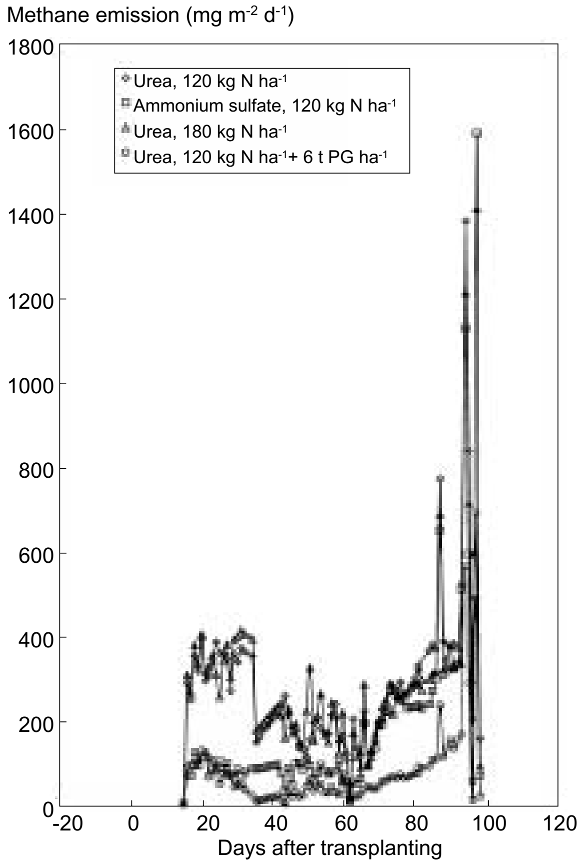

Figure 4. Effect of inorganic amendment on CH_4 emission from rice field grown to IR72 at PhilRice, Maligaya, Philippines, 1995 WS.

tion treatment (from 90 kg CH_4 ha^{-1} to 7 kg CH_4 ha^{-1}) and midseason drainage treatment (from 90 kg CH_4 ha^{-1} to 16 kg CH_4 ha^{-1}). These two treatments gave only 1 and 2.1 kg CH_4 t^{-1} grain yield as compared with 11.3 and 10.7 kg CH_4 t^{-1} grain yield in continuously flooded transplanted rice. Although intermittent irrigation resulted in negligible CH_4 emission, the yield was slightly lower.

Discussion

Effect of cropping season. The CH_4 emission at a given treatment was higher during the WS by 2 to 3 times the emission during the DS. Dry season CH_4 emissions in the reference treatment, i.e., 120 kg N ha^{-1} (urea N) were 95, 204, and 160 kg CH_4 ha^{-1} in 1994, 1995, and 1996, respectively. Wet season emissions amounted to 266, 518, and 272 kg CH_4 ha^{-1} in 1994, 1995, and 1996, respectively. Not only was there a variation between cropping season but there was also an annual variation in CH_4 emission. The T1 (reference treatment) showed wide differences in seasonal flux from year to year. This will pose problems in monitoring mitigation measures in farmers' fields. Table 5 shows that the DS months (December to April) had an average daily temperature

Table 5. Seasonal mean and range of air temperature during the 5-yr CH_4 measurement in PhilRice, Maligaya, Muñoz, Nueva Ecija, Philippines

Year	Temperature (°C)					
	Seasonal mean		Minimum		Maximum	
	DS	WS	DS	WS	DS	WS
1994	27.1	27.1	23.1	23.4	32.3	36.4
1995	26.4	27.3	22.4	25.2	29.2	29.2
1996	26.3	29.6	22.2	24.2	31.6	40.8
1997	26.7	28.4	20.9	24.9	30.3	30.8
1998	26.6	-	23.8	-	28.9	-
Mean of 5 seasons	26.62	28.10	22.48	24.42	30.46	34.30

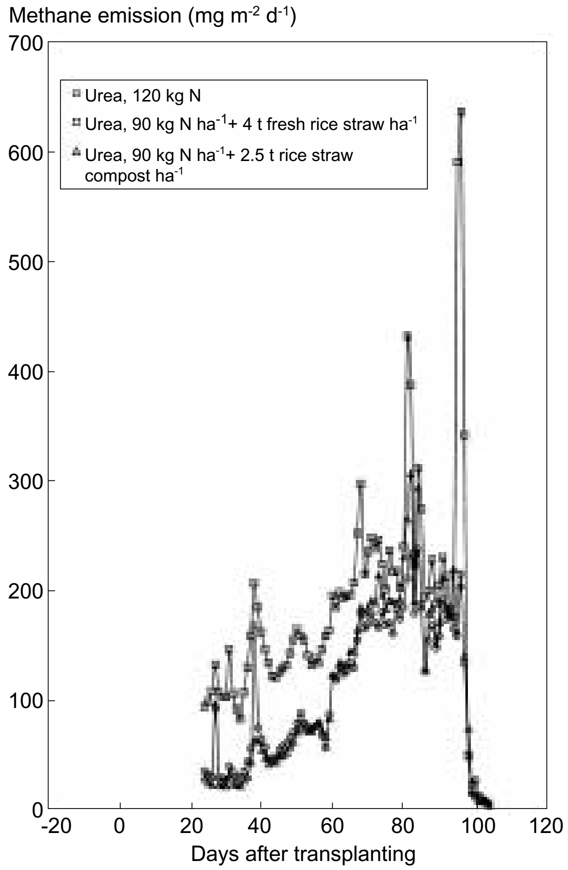

Figure 5. Effect of organic amendment on CH_4 emission from rice field grown to IR72 at PhilRice, Maligaya, Philippines, 1996 DS.

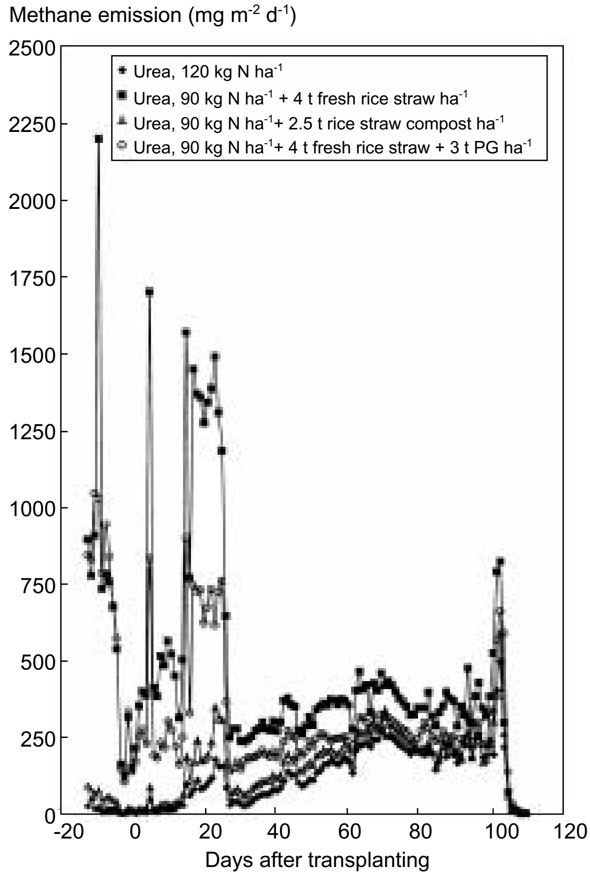

Figure 6. Effect of organic amendment on CH_4 emission from rice field grown to IR72 at PhilRice, Maligaya, Philippines,1996 WS.

of 26.6 °C, while the WS months (June to November) had 28.1 °C. Maximum air temperature was lower in DS months by 4 and 9 °C during 1994 and 1996, respectively. But in 1995 and 1997, the maximum temperature for DS and WS were the same. Holzapfel-Pschorn and Seiler (1986) reported a marked influence of soil temperature on the CH_4 flux. Most isolates of methanogenic bacteria are mesophilic with temperature optimum of 30 °C to 40 °C (Vogel et al., 1988). The difference in daily mean temperature between the DS and the WS cropping period was, however, too small (1.6 °C) to explain the higher CH_4 emission during the WS. Temperature, theoretically, would deter or enhance the rate, not the magnitude, of emission. Contributing to this difference may be differences in labile organic carbon (OC) between the two seasons. Analysis of the OC before the 1998 DS and 1998 WS cropping showed an average of 1.15% OC before the DS cropping and 1.27% OC before the WS cropping at 0-25 cm depth. The difference was the same at the 25-50 cm depth (i.e., 0.52% OC before the DS cropping and 0.65% OC before the WS cropping). Furthermore, the field was still wet during the fallow period between WS and DS cropping. Bronson et al. (1997b) reported that CH_4 emitted from wet fallow periods is significant and should be considered when monitoring CH_4 emission from rice soils. Methane emissions during the wet fallow period during October and November before the DS crop could have resulted from decaying roots and stubble. Methane is not emitted during the April - May dry fallow period before the WS crop and accumulation of labile carbon shown by higher % OC may have resulted.

Effect of inorganic fertilizer. Most likely the SO_4^{-2} was responsible for the reduced CH_4 emission from ammonium sulfate- than from urea-treated plots. Saenjan and Wada (1990) reported that the presence of sulfate suppressed CH_4 formation. The CH_4 formation, both in flooded rice fields and in submerged soil under

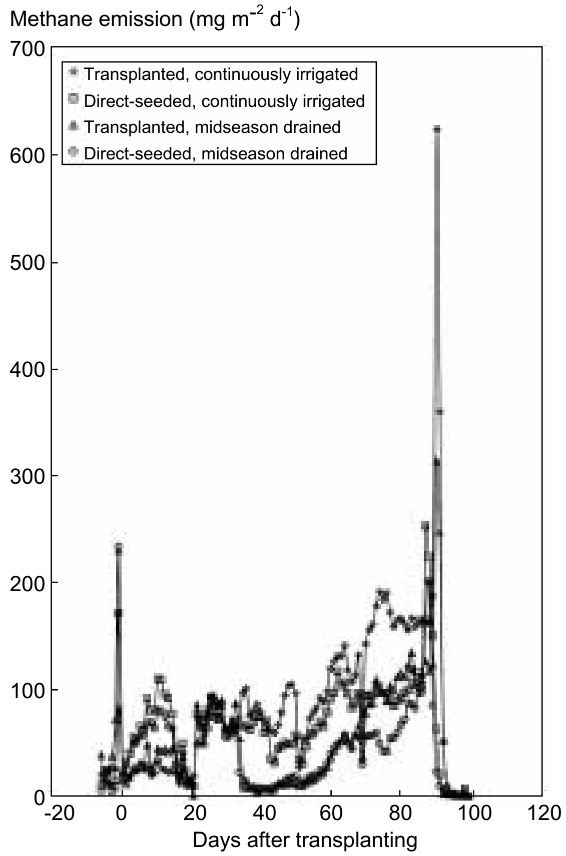

Figure 7. Effect of crop establishment and water regime on CH_4 emission from rice field grown to IR64 at PhilRice, Maligaya, Philippines, 1997 DS.

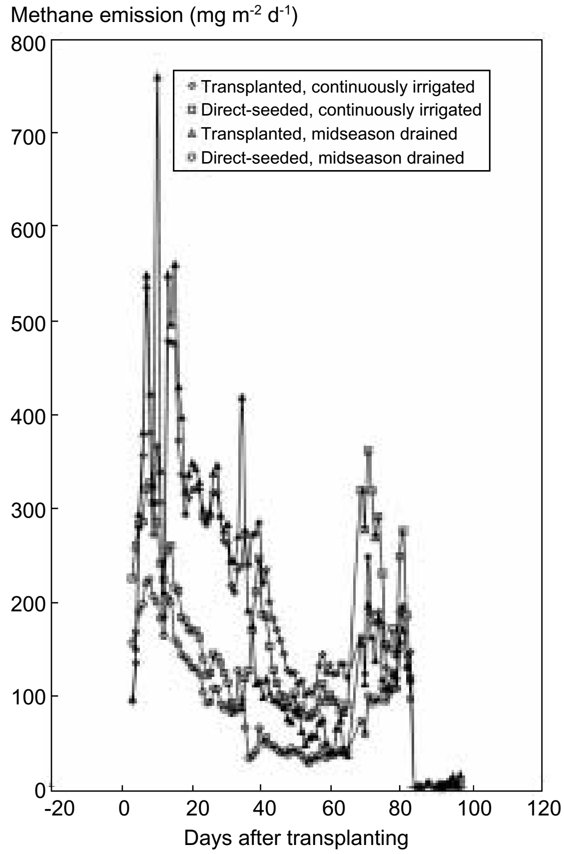

Figure 8. Effect of crop establishment and water regime on CH_4 emission from rice field grown to IR64 at PhilRice, Maligaya, Philippines, 1997 WS.

laboratory condition, is carried out largely by the transmethylation of acetic acid and by CO_2 reduction, utilizing H_2, butyric acid, etc. as hydrogen donors (Takai, 1970). Sulfate ions serve as an alternative to CO_2 as electron acceptors for the oxidation of organic matter (Delwiche & Cicerone, 1993). Differences on the effect of ammonium sulfate and urea fertilizer on CH_4 formation was reported by Wang et al. (1993) to be related to the effect on soil pH. Ammonium sulfate-treated plots had 25% to 56% less CH_4 emission averaged over the years and seasons compared with the urea-treated plots. Since addition of SO_4^{-2}-containing N fertilizers hardly changes the measured soil Eh and soil pH, the competition of SO_4^{-2}-reducing and CH_4-producing bacteria for substrates hydrogen and acetic acid, and possibly toxicity to the CH_4-producing bacteria from H_2S produced after SO_4^{-2} reduction, are likely mechanisms for the decreased CH_4 production in ammonium sulfate-treated plots. Hori et al. (1993) confirmed the possibility of competition for the usage of hydrogen between CH_4 formation and SO_4^{-2} reduction in strongly reduced rice soil. Competition for hydrogen, however, is less likely than that for acetic acid because the degree of competition for hydrogen is controlled by many factors. The added SO_4^{-2} from the ammonium sulfate fertilizer must have stimulated the SO_4^{-2}-reducing bacteria.

Increasing the rate of N from urea slightly increased CH_4 emission. Lindau et al. (1990, 1991) also reported increasing CH_4 fluxes with increasing rates of urea application. The increase in CH_4 emission with addition of higher N rate from urea could be due to the inhibitory effect of NH_4^+ on CH_4 oxidation (Conrad & Rothfuss, 1991).

Impact of phosphogypsum. Phosphogypsum (85-90% gypsum) is a waste product from the production of phosphoric acid by the wet process. The overall SO_3 content of PG is 44-46% (Alcordo & Rechcigl, 1993).

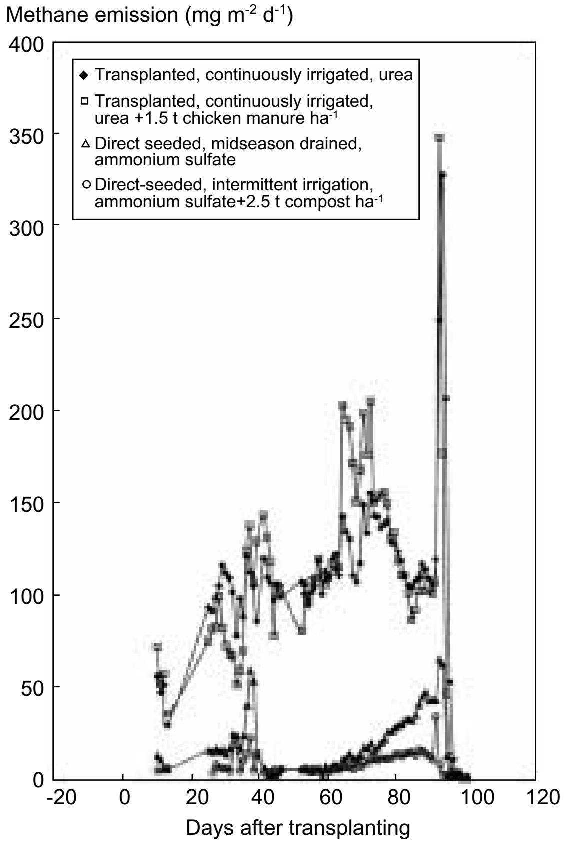

Figure 9. Combined effect of crop establishment, water regime, and inorganic and organic amendments on CH_4 emission from rice field grown to PSBRc28 at PhilRice, Maligaya, Philippines, 1998 DS.

When applied to the soil, PG solubilizes, producing Ca^{+2} and SO_4^{-2} ions. When PG was combined with urea, there was a significant reduction (z value = 10.0**) in mean CH_4 emission because of the SO_4^{-2} effect on CH_4 production. The effect of high amounts of ammonium sulfate and PG on CH_4 emission was similar. This confirms that it was the SO_4^{-2} and not the NH_4^+ that had affected the reduction in CH_4 emission. Denier van der Gon and Neue (1994) also reported a 55-70% reduction in CH_4 emission in an Aquandic Epiqualfs with amendment of 6.66 t ha^{-1} gypsum. Even with addition of green manure, the gypsum significantly decreased CH_4 emission (Denier van der Gon & Neue 1994). Addition of 3 t ha^{-1} of PG to fresh rice straw resulted in a 27% reduction in CH_4 emission compared with that from plots amended with fresh rice straw alone. The amount of carbon in fresh rice straw could be so high that the SO_4^{-2} from PG was not enough for sulfate-reducing bacteria to compete with the CH_4-producing bacteria to fully counteract the high CH_4 fluxes. However, another application of PG in succeeding cropping increased the cumulative effect of SO_4^{-2}. The succeeding cropping with same rate of PG and fresh rice straw resulted in a 37% reduction in CH_4 emission. PG is a cheaper source of SO_4^{-2} than ammonium sulfate and urea is a less expensive source of N fertilizer. Thus, the combination of urea as N fertilizer and PG as SO_4^{-2} source could be a management option to reduce CH_4 emission especially in sulfur-deficient irrigated lowland rice. Sulfate is normally reduced after the depletion of nitrate and other more energetically favorable reactions in anaerobic rice soils (Connel & Patrick, 1968, 1969; Ponnamperuma, 1972). Sulfate is reduced to H_2S which is toxic to rice at a concentration of approximately 0.07 ppm (Mitsui et al., 1951; Freney et al., 1982). However, H_2S seldom accumulates at toxic concentrations in most rice soils, since H_2S is either immediately precipitated as metallic sulfide, chiefly FeS, or is oxidized to sulfate or elemental sulfur in the rice rhizosphere by chemosynthetic microorganisms (Huang, 1991). The reoxidation of S^{-2} to SO_4^{-2} in the rhizosphere may also suppress CH_4 emission over long periods of time (Freney et al., 1982). This is the reason why addition of up to 6 t ha^{-1} PG in Maligaya clay with 75.02 µg g^{-1} active iron (Fe) did not manifest sulfide toxicity in the rice plant. In addition, PG was reported to have soil-conditioning effect in saline soils (Alcordo & Rechcigl, 1993). The annual world production of PG was estimated at 125 million Mg, and only 4% (5 million Mg) of it is used in agriculture and in gypsum board and cement industries. The remaining 120 million Mg PG accumulates annually as waste (Alcordo & Rechcigl, 1995). These could be used as soil ameliorant to decrease CH_4 emission in lowland rice.

Effect of organic amendment. Seasonal CH_4 fluxes from fresh rice straw-treated plots were 2.5 to 3.5 times greater than that from urea plots. Even the addition of PG in fresh rice straw treatment did not fully counteract these high CH_4 fluxes (Table 3). On the other hand, CH_4 fluxes in the rice straw compost treatment were similar to those in the urea treatment throughout the season.

Yagi and Minami (1990) reported that annual emission rates from plots receiving 6 t ha^{-1} of rice straw in addition to mineral fertilizer increased approximately 2 to 3 fold as compared with the mineral fertilizer plots, irrespective of soil type. Compost was also reported by Yagi and Minami (1990) to have only slightly increased emission compared with control plots. The readily mineralizable carbon (RMC) in the organic amendment was one of the principal factors affecting CH_4 emission from flooded soils (Yagi & Minami, 1990). Even without organic amendment, the readily mineralizable soil organic matter in rice soil is the main source for the fermentation products that finally drive CH_4 formation in wetland rice soils (Neue, 1993). Composting of the rice straw aerobically decreased the C/N from a range of 25-45 in fresh rice straw to a range of 6-10 in rice straw compost. This resulted in lesser carbon substrates, which in turn reduced CH_4 emission. The incorporation of rice straw during land preparation stage increased CH_4 emissions during the early vegetative stage until 30 DAT. Methane must have been produced from volatile fatty acids that were intermediate products of rice straw decomposition. In Texas, rice straw (8-12 t ha^{-1}) increased CH_4 emissions but rice yields dropped (Sass et al., 1991a,b).

Rice straw applications increased emissions 2-2.5 times but did not affect yield. Alberto et al. (1996) reported that straw incorporation increased dissolved CH_4 tenfold. Similar to the observation of Alberto et al. (1996), CH_4 emission was low in urea-and rice straw compost-treated plots 15 d before transplanting until 45 DAT and then paralleled those plots having straw treatment at later stages of rice growth (Figure 6). The early flush in CH_4 emission must have come from the decomposition of soil organic matter and added organic substrates such as rice straw. At the later stages, it is the root exudates and the decaying roots that become the major carbon source for CH_4 production (Alberto et al., 1996). Methane fluxes were slightly higher in the chicken manure treatment compared with the urea treatment at 35-45 DAT and 65-75 DAT (Figure 9). The seasonal emission, however, was the same in urea-treated plot and in chicken manure plus urea treatment. Chicken manure has a narrow C/N that is between 5 and 8. The CH_4 emission per unit of carbon from chicken manure was comparable with that of the rice straw compost that had a C/N of 6-10.

Effect of water regime and crop establishment. Methane fluxes under two water regimes (continuously flooded and midseason-drained) and two crop establishment methods (direct seeded and transplanted) were compared. The first flush of CH_4 fluxes during the early vegetative stage (Figures 7&8) could be due to decomposing stubble incorporated during land preparation and from the commercial bioorganic fertilizer applied during the final harrowing. Methane flux was reduced after midseason drainage due to aeration. This midseason drainage could be beneficial to the rice plant. The draining of rice fields for short-term periods in China at the end of tillering and before heading improved yields and reduced CH_4 emission (Wang, 1986). In Japan, the intermittent irrigation of rice fields resulted in lower CH_4 emission than those reported from western countries (Yagi & Minami, 1990). Bronson et al. (1997a) reported that midseason drainage (2-wk duration) at either maximum tillering or panicle initiation suppressed CH_4 flux. However, N_2O flux increased sharply during the drainage period, until reflooding, when it dropped back to zero. Midseason drainage as a strategy to reduce CH_4 emission should be on a short duration (7-10 d) and timed when the rice plants have used up the fertilizer N applied at basal and vegetative stages. Reflooding should be done before the application of N fertilizer at the panicle initiation stage. Intermittent irrigation, though it significantly reduced (92%) CH_4 emission, must be carefully evaluated as a mitigation strategy. Bronson (1994) reported that urea or ammonium sulfate fertilizer from irrigated rice fields have N_2O losses to a maximum of 0.1% of the applied fertilizer. With intermittent irrigation, where water regime is variable, more N_2O could be emitted as a result of higher rates of nitrification and denitrification that occur than in continuously flooded conditions. Multiple-aeration water management treatment emitted 88% less CH_4 and did not reduce yield (Sass et al., 1992). However, this intermittent drainage must be managed carefully to prevent losses of N and corresponding emission of N_2O through increased nitrification and denitrification (Neue, 1993; Bronson et al., 1997a).

Direct-seeded rice reduced CH_4 emission by 16-54% compared with transplanted rice. The mechanism explaining this difference is not yet clear. The root system of direct-seeded rice is expected to differ from that of transplanted rice. It is probable that the roots of direct-seeded rice are shallower than that of transplanted rice. With more roots present at the 0-10 cm depth, there could be more CH_4 oxidized to CO_2, thus reducing the CH_4 emission. Unfortunately, rooting characteristics of direct-seeded rice (as compared with transplanted rice) were not investigated in this experiment.

Mitigation strategies

The management practices tested in this 5-yr experiment have been primarily designed to look for mitigation strategies that are workable under Philippine conditions. It was postulated that some aspects of crop management, including the management of inorganic fertilizers, organic fertilizers, water regime, and crop establishment, could be effectively modified to mitigate CH_4 emissions from irrigated rice fields. Mitigation of CH_4 emissions, while targeting high yields, has been the prime target in using sulfur-containing inorganic amendments, in increasing N fertilizer application, in using rice straw compost, in practicing midseason drainage, and in practicing direct seeding. Whatever mitigation measure to reduce CH_4 emission has to ensure that it will not decrease grain yield. This is the most important consideration if these mitigation strategies are to be adapted by farmers. Results show significant reduction (25-36%) in CH_4 emissions with the use of ammonium sulfate as N fertilizer source instead of urea. The addition of 6 t ha^{-1} PG to urea has resulted in 72% reduction in emissions. Midseason drainage reduced CH_4 emission by 43%, while intermittent irrigation resulted in 92% reduction. Direct seeding, instead of transplanting, reduced CH_4 emission by 16-54%. Expectedly, the application of rice straw compost did not reduce emissions but rather increased it by 23-30%. But this is very small compared with the increase of 162-250% in emissions due to fresh rice straw application. Also, the use of chicken manure did not enhance CH_4 emissions in one experiment. The use of organic fertilizer and nutrient cycling from crop residues is presently being encouraged in view of soil fertility in the long term. In the last experiment (1998 DS) , the different management strategies (ammonium sulfate fertilizer, rice straw compost, direct seeding, midseason drainage, and intermittent irrigation) were combined in two treatments and the result was a dramatic reduction of CH_4 emission (83-93%). This, however, needs to be verified in WS and in another DS experiment. It is important to note that these modifying treatments that successfully reduced emissions did not adversely affect grain yield. The practice of direct seeding is an exception, where grain yield was lower by 0.8-1.3 t ha^{-1} in the DS and 1.8 t ha^{-1} in the WS. Direct seeding is already widely practiced in major rice-growing areas during the DS; in central Philippines (Panay Island), 90% of the farmers are practicing direct seeding both during DS and WS cropping. Development of high yield technology for direct-seeded rice cultivation is one of the current research thrusts of PhilRice.

The workability of the above mitigation strategies under the Philippine situation needs evaluation. Results of a survey conducted in October-November 1998 showed that rice farmers in Nueva Ecija commonly use urea and complete (14-14-14) fertilizer, not ammonium sulfate because urea N is cheaper than ammonium sulfate. Ammonium sulfate is used mostly in seedbed preparation. However, 14-14-14 fertilizer also contains sulfur. Thus, the use of this fertilizer may also contribute to reduced CH_4 emissions. Farmers in the Philippines are not deliberately practicing midseason drainage or intermittent irrigation. Drainage of soils within the season is determined by the availability of rain or irrigation water. Since water is becoming scarce in many instances, farmers normally would not deliberately remove water at definite periods of the season because of the uncertainty of water availability. On the other hand, because of water becoming a limiting resource, especially during the DS, the midseason drainage practiced by farmers in China and Japan will be favorable to the Filipino farmers' management of their scarce resources. The use of organic amendments, particularly rice straw, is presently being encouraged in an effort to recycle nutrients and improve the fertility of rice soils. As a mitigation strategy, composting the rice straw aerobically must be promoted rather than fresh rice straw incorporation. A rapid rice straw composting technology is available. Most farmers, however, found composting and spreading of straw laborious. Farmers burn their rice straw instead of incorporating it into the soil so as not to encourage pests such as rats. The adoption of mitigation strategies by farmers may not be as hard as it is assumed because of the following reasons. First, our results showed that there was no real adverse effect on yield. Second, mitigation measures proposed are compatible with building soil fertility (use of rice straw compost), proper management of water (midseason drainage vs continuous flooding), and savings on labor (direct seeding vs transplanting). Third, farmers are beginning to observe the effect of global warming from longer drought (El Niño) and flood (La Niña) periods.

Conclusion

The 5-yr CH_4 measurements have established a pattern of emission common to DS and WS. The emissions, however, are magnified in the WS, and seasonal emission was found to be 2-3 times as much as that in the DS. This was partly explained by the 1.6 °C higher daily mean temperature in the WS. However, temperature theoretically would deter or enhance the rate of emission, not its magnitude. One obvious contributor to CH_4 emissions is the carbon input (Neue et al., 1994). Dry matter production and also the stubble left for the next season did not significantly differ between the two seasons. The difference in decomposable carbon between the two seasons could possibly explain this difference in WS and DS emissions. There was 0.12%

more % OC in the soil before the WS cropping than before the DS cropping. Furthermore, CH_4 from the decaying roots and stubble during the wet fallow period during October and November before the DS crop could have been emitted but was not measured. Increasing the rate of urea N from 120 to 180 kg ha^{-1} increased seasonal CH_4 emission by only ~15% in the WS. Using ammonium sulfate in place of urea at 120 kg N ha^{-1} resulted in 25% reduction in annual average of CH_4 emission. Increasing ammonium sulfate rate to 180 kg N ha^{-1} increased the reduction in annual average CH_4 emission by 36%. The effect of 0.5-1.0 t ha^{-1} PG was similar to that of ammonium sulfate at 120 kg N ha^{-1}. A significant effect of PG on CH_4 emission (72% reduction) was obtained at 6 t ha^{-1}. The residual effect of the 857 kg ammonium sulfate (180 kg N ha^{-1} yr^{-1}) and 6 t ha^{-1} yr^{-1} PG application was not clear. It is possible that one time application in a year or every 2 yr or continuous application is required to obtain the desired effect. Organic amendment such as fresh rice straw with wider C/N increased CH_4 emission to twice that of mineral fertilizer alone. Rice straw compost and chicken manure, which have narrower C/N, had little effect on CH_4 emission. Even the addition of PG with fresh rice straw could not fully counteract the high CH_4 emission.

Introduction of midseason drainage water management is one cultural practice that could be used to reduce CH_4 emission by as much as 90% compared with continuously flooded rice. This, however, has to be timed to obtain the highest N fertilizer use efficiency and minimize N_2O emissions. Another interesting result obtained was the lower mean CH_4 emission in direct-seeded than in transplanted rice. Also, direct-seeded rice had a shorter season length than transplanted rice, which could further contribute to lower seasonal CH_4 flux. This was despite the higher number of tillers per m^2 in direct-seeded rice. It would be interesting to investigate the root development, root distribution, and root characteristics of direct-seeded rice, which contributed to this lower emission.

Several management options to mitigate CH_4 emissions from irrigated rice field were identified. In terms of their effectiveness in reducing CH_4 emissions compared with the control treatment (urea fertilizer, transplanted rice, and continuously flooded), these are ranked as follows: (1) 6 t ha^{-1} PG combined with urea fertilizer, (2) midseason drainage 7-10 d before panicle initiation, (3) use of ammonium sulfate fertilizer as N source, and (4) direct seeding crop establishment. If organic fertilizer is combined with inorganic fertilizer in integrated plant nutrient management, low C/N organic fertilizers such as chicken manure and rice straw compost will not significantly increase CH_4 emission. The measurements reported here were carried out in a heavy clay soil. Whether the same results will be obtained using a different soil in a different environment remains a consideration for future measurements.

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