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S.-S. Yang · H.-L. Chang

Methane emission from paddy fields in Taiwan

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Abstract In order to investigate the effect of environmental conditions on CH_4 emission from paddy fields in Taiwan, four locations, two cropping seasons and two irrigation systems were studied. CH_4 emission was high at the active tillering and the booting stages in the first cropping season, whereas it was low at the transplanting and the ripening stages with an intermittent irrigation system. CH_4 emission was high at the transplanting stage in the second cropping season, and decreased gradually during rice cultivation. Daily temperature and light intensity increased gradually during rice growth in the first cropping season (February–June), while it was reversed in the second cropping season (August–December). The seasonal CH_4 emission from paddy fields ranged from 1.73 to 11.70 g m^{-2}, and from 10.54 to 39.50 g m^{-2} in the first and second cropping seasons, respectively. The seasonal CH_4 emission in the second cropping season was higher than that in the first cropping season in all test fields. The seasonal CH_4 emission was 32.65 mg m^{-2} in the first cropping season of the National Taiwan University paddy field with continuous flooding, and it was 28.85 mg m^{-2} in the second cropping season. The annual CH_4 emission ranged from 12.3 to 49.3 g m^{-2} with an intermittent irrigation system, and the value was 61.5 g m^{-2} with a continuous flooding treatment. The annual CH_4 emission from paddy fields was estimated to be 0.034 Tg in 1997 from 364,212 ha of paddy fields with an intermittent irrigation system, which was less than the 0.241 Tg calculated by the IPCC method with a continuous flooding treatment

Keywords Methane emission · Paddy field · Cropping season · Intermittent irrigation · Continuous flooding

Introduction

The quantification of CH_4 emissions from rice fields has attracted increasing attention in recent years (Schutz et al. 1989; Khalil and Rasmussen 1990; Chanton et al. 1997; Watanabe et al. 1997; Yang and Chang 1998, 1999). CH_4 emission from rice paddy is the net effect of a series of complex processes involving plant-microbe interactions (Banker et al. 1995; Wassmann and Aulakh 2000). Heavy precipitation leads to flooding and creates conditions conducive to soil reduction, promoting methanogenesis. On the other hand, during dry cycles, the return of aerobic conditions inhibits methanogenesis and favours CH_4 oxidation. Mid-season drainage, a common agronomic practice in Japan used to alleviate soil-related toxicity to rice plants in anaerobic soils, also reduces CH_4 emissions (Yagi and Minami 1990). However, frequent flooding and drying cycles in a cropping season under a rain ecosystem may adversely affect crop growth and yield in addition to influencing CH_4 emissions (Nugroho et al. 1994; Yang and Chang 1998).

Fertilizer and organic matter amendments have been found to be crucial factors in determining the magnitude of CH_4 emissions from rice fields (Wassmann et al. 1993, 1996; Neue et al. 1994; Yang and Chang 1998, 2000). As such information is not available from rice fields in Taiwan, the present study was undertaken to measure CH_4 emission from paddy fields in four locations with different soils, two cropping seasons and two irrigation systems (continuous and intermittent). There are two rice cropping seasons in Taiwan. The first crop of rice is transplanted in February and harvested in June, while the second crop is transplanted in August and harvested in December.

S.-S. Yang (✉) · H.-L. Chang
Department of Agricultural Chemistry,
National Taiwan University, Taipei 10617, Taiwan
e-mail: ssyang@ccms.ntu.edu.tw
Tel.: +886-2-23621519
Fax: +886-2-23679827

Materials and methods

Site description and agricultural practices

Paddy fields of the Agricultural Experimental Station of National Taiwan University (NTU) (Taipei City), Taoyuan District Agricultural Improvement Station (Taoyuan County), Langyang Branch Station of Hualien District Agricultural Improvement Station (Ilan County), and Tzawchyau farmer's paddy field (Miaoli County) were selected. Properties and agricultural practices of the test fields are listed in Tables 1 and 2, respectively. All agriculture practices were performed in quadruplicate.

Gas sampling chamber

For gas samples, acrylic chambers were constructed. Each chamber (40 cm long, 40 cm wide, 65 cm high, about 96 l volume) was equipped with an electric fan, a thermometer and a sampling hole covered with a rubber septum. In the later growth stage of rice, two-layer chambers were used (height 130 cm, volume about 192 l). Four hills per chamber (spacing between hills was 24 × 27 cm) were measured and four chambers were used in each measurement (Chang and Yang 1997). Each chamber was placed on the soil surface with 2–3 cm inserted into the soil 10 min prior to each sampling for equilibration to reduce the disturbance to the sampling site.

Gas sampling

Following the methodology of previous studies (Holzapfel-Pschorn and Seiler 1986; Schutz et al. 1989; Yang et al. 1994; Buendia et al. 1998; Yang and Chang 1998, 1999), five sampling stages: flooding to transplanting, active tillering, booting, flowering and ripening, were chosen in each cropping season for CH_4 flux measurements. Gas samples were collected at 0, 30 and 60 min (cumulative time) using the gas dilution method. CH_4 flux was measured twice a day, first in the early morning (5–7 a.m.) and secondly in the afternoon (2–4 p.m.). The air temperature increased 2–3 °C during 1 h closure in the afternoon and it increased 0–0.5 °C in the early morning. Using a 10-ml disposal plastic syringe, 5 ml headspace air was withdrawn from a 12-ml serum bottle that had been sealed with a butyl rubber stopper and flushed with O_2-free N_2 gas. Then another 5 ml of the gas sample from the sampling chamber was injected into a serum bottle (Chang and Yang 1997). The recovery of the gas sample with this dilution method was $<95\%$.

CH_4 emission

CH_4 emission was determined at 30-min intervals for 1 h by measuring the changes of CH_4 concentration in the chamber. CH_4 concentration was determined with a Shimadzu 14A gas chromatograph (Shimadzu, Japan) using a glass column (2.6 mm × 2.0 m) which was packed with Porapak Q (80/100 mesh). The column temperature was set at 100 °C, and the injection and the detector temperatures were set at 130 °C. The CH_4 concentration was calculated from a standard curve from 0.1 to 1,000 mg kg^{-1} (volume) (Chang and Yang 1997).

Estimation of CH_4 emission

CH_4 emission from paddy fields was calculated from the experimental data using the following equation (Rolston 1986): $f=(V/A)\,(\Delta C/\Delta t)$, where $f=CH_4$ emission rate (mg m^{-2} h^{-1}), V = volume of the chamber above soil (m^3), A = cross-section of chamber (m^2), ΔC = concentration difference between 0 and time t (mg m^{-3}), and Δt = duration between two sampling periods (hours). The total CH_4 emission from paddy fields was the summation of CH_4 emissions at five growth stages of rice plants (Yang and Chang 1999).

Analytical methods

Redox potential was measured directly with a Hanna 081-854 potential meter (HI 8424) at 5–20 cm soil depth using a Pt electrode after 20–25 min equilibration with the soil (Yang and Chang 1997). Soil pH was determined on 1:1 (w/w) soil:water suspension with a pH meter (Mode Sentron 2001). Light intensity was measured with a Toshiba SPI-5 photometer. Soil and air temperatures were determined by a thermometer. Experiments were carried out to obtain four measurements and flux data were subjected to ANOVA and Duncan's multiple range test ($P=0.05$) using SAS (SAS Institute 1988).

Results and discussion

CH_4 emission in the first cropping season

At the transplanting stage of the first cropping season, CH_4 emission rates were <0.78 mg m^{-2} h^{-1}, except in the Taoyuan paddy field (7.12 mg m^{-2} h^{-1}) which had been amended in 1995 with *Sesbania roxburghii* due to its low temperature and low light intensity (Tables 3 and 4). CH_4 emission increased during the active tillering and the booting stages. However, it decreased at the flowering and the ripening stages because of the practice of drainage and intermittent irrigation and the high soil redox potential. The CH_4 emission rate was

Table 1 Location, climatic conditions and properties of paddy fields

Site	Latitude and longitude	Soil characteristics							Annual mean temperature (°C)	Annual precipitation (mm)	Rainy days (days $year^{-1}$)	Sunshine duration (h $year^{-1}$)
		pH	Soil type	Sand (%)	Clay (%)	Silt (%)	Organic C (g kg^{-1})	Total N (g kg^{-1})				
NTU	25°02′N, 120°31′E	5.6 ± 0.1	Haplanthrept (sandy loam)	45.3	20.1	34.6	28.4 ± 0.4	1.73 ± 0.20	22.43	1,886	157	1,427
Taoyuan	25°01′N, 121°02′E	5.7 ± 0.1	Puto (clay loam)	23.9	45.7	30.4	28.4 ± 0.5	1.74 ± 0.50	22.15	1,466	112	1,994
Langyang	24°42′N, 121°44′E	6.0 ± 0.1	Malintso (sandy loam)	50.6	7.1	41.6	29.6 ± 0.8	1.86 ± 0.30	22.25	2,653	189	1,319
Tzawchyau	24°39′N, 120°52′E	5.4 ± 0.1	Hapludults (sandy loam)	60.2	2.6	37.7	32.4 ± 1.2	1.68 ± 0.20	22.15	1,466	112	1,994

Table 2 Agricultural practices used. *NTU* National Taiwan University, *T.P.* transplanting, *T.I.* tillering, *A.T.* active tillering, *B.T.* booting, *F.I.* flowering

Site	Year	Cropping season	Season length (days)	Rice variety	Basal fertilizer		Top fertilizer		*Sesbania* amendment (t ha^{-1})	Water regime
					Type	(kg ha^{-1})	Type	(kg ha^{-1})		
NTU	1994	Second crop	147	Tainung no. 67 Japonica	Taifei no. 1	400	Urea $(NH_4)_2SO_4$	500 (A.T)[a] 100 (B.T.)	–[c]	Intermittent
	1995	First crop	129	Tainung no. 67 Japonica	Taifei no. 1	400	Urea Urea	100 (T.I.) 50 (B.T.)	–	Intermittent
		Second crop	136	Tainung no. 67 Japonica	Taifei no. 1	400	$(NH_4)_2SO_4$ $(NH_4)_2SO_4$	100 (T.P.) 100 (A.T.)	– –	Continuous flooding
	1996	First crop	152	Tainung no. 67 Japonica	Taifei no. 1	400	$(NH_4)_2SO_4$	100 (T.P.)	–	Intermittent
		First crop	152	Tainung no. 67 Japonica	Taifei no. 1	400	$(NH_4)_2SO_4$	100 (T.P.)	–	Continuous flooding
Taoyuan	1994	Second crop	122	Tainung no. 67 Japonica	Taifei no. 39	400	Paohsiao no. 2	200 (T.P.) 200 (A.T.) 80 (B.T.)	–	Intermittent
		Second crop	122	Hsinchu no. 64 Japonica	Taifei no. 39	200	$(NH_4)_2SO_4$	100 (T.P.)	37	Intermittent
	1995	First crop	126	Taikeng no. 2 Japonica	Taifei no. 39	400	Paohsiao no. 2	400 (T.I.) 400 (A.T.) 200 (B.T.)	–	Intermittent
	1995	First crop	133	Hsinchu no. 64 Japonica	Taifei no. 39	400	$(NH_4)_2SO_4$ Taifei no. 1 Taifei no. 1	200 (T.I.) 200 (A.T.) 100 (B.I.)	–[d]	Intermittent
		Second crop	117	Hsinchu no. 64 Japonica	Taifei no. 39	400	Taifei no. 1 Taifei no. 1 Taifei no. 1	200 (T.P.) 150 (T.I.) 100 (A.T.)	–	Intermittent
		Second crop	117	Hsinchu no. 64 Japonica	Taifei no. 39	400	Taifei no. 1	200 (T.P.) 100 (T.I.)	25	Intermittent
	1996	First crop	152	Tainung no. 67 Japonica	Taifei no. 39	400	Taifei no. 1	300 (A.T.) 100 (B.T.)	–	Intermittent
Langyang	1994	Second crop	136	Taikeng no. 10 Japonica	Taifei no. 5	560	Taifei no. 5 $(NH_4)_2SO_4$ $(NH_4)_2SO_4$	220 (T.P.) 180 (A.T.) 45 (B.T.) 34 (F.I.)	–	Intermittent
	1995	First crop	134	Taikeng no. 10 Japonica	Taifei no. 5 Silicates	1450	$(NH_4)_2SO_4$ $(NH_4)_2SO_4$ $(NH_4)_2SO_4$ Urea	40 (T.I.) 40 (A.T.) 40 (B.T.) 20 (B.T.)	–	Intermittent
Tzawchyau	1994	Second crop	123	Tainung no. 67 Japonica	Taifei no. 1	200	$(NH_4)_2SO_4$ $(NH_4)_2SO_4$ $(NH_4)_2SO_4$	250 (T.P.) 250 (B.T.) 50 (F.I.)	–	Intermittent
	1995	First crop	130	Tainung no. 9 Japonica	Taifei no. 1	200	KCl mixed[b] KCl mixed KCl mixed	250 (T.I.) 250 (A.T.) 50 (B.T.)	–	Intermittent

[a] The $N:P_2O_5:K_2O$ ratio for Taifei no. 1 is 20:5:10, 16:8:12 for Taifei no. 5, 12:18:12 for Taifei no. 39, and 21:0:14 for Paohsiao no. 2

[b] $KCl:urea:Ca(ClO_4)_2:(NH_4)SO_4=1:2:1:2$

[c] Not added

[d] Previous cropping season had 37 t ha^{-1} *Sesbania* amendment

Table 3 Environmental conditions of paddy fields from August 1994 to July 1996. *Taoyuan* Taoyuan District Agricultural Improvement Station, *Langyang* Langyang Branch Station of Hualien District Agricultural Improvement Station, *Tzawchyau* Farmer's paddy field

Cropping season	Temperature (°C)			Light intensity (lux)	pH		Eh (mV)	Total cultivation period (days)
	Air	Water	Soil		Water	Soil		
Second cropping season of 1994								
NTU[a]	32–23	32–21	28–20	1.2×10^{5}–2.0×10^{4}	6.7–6.2	6.6–5.7	–180 to 220	133
Taoyuan	32–22	32–21	31–20	1.2×10^{5}–2.3×10^{4}	7.0–6.8	6.7–6.5	–160 to 310	122
Langyang	32–20	32–20	31–20	1.1×10^{5}–1.1×10^{4}	6.8–6.3	6.8–6.3	–230 to 170	136
Tzawchyau	32–24	32–21	31–21	1.5×10^{5}–6.2×10^{4}	7.1–6.3	7.1–6.0	–140 to 205	123
First cropping season of 1995								
NTU	20–31	19–28	18–27	5.6×10^{4}–8.2×10^{4}	6.4–6.8	6.5–6.8	–100 to –160	139
Taoyuan	21–31	20–28	19–27	3.0×10^{4}–8.4×10^{4}	7.2–6.5	6.9–6.4	–165 to –100	137
Langyang	19–28	19–27	17–27	2.0×10^{4}–6.5×10^{4}	7.1–7.0	7.0–6.9	–270 to –120	134
Tzawchyau	19–31	19–29	18–28	1.6×10^{4}–9.6×10^{4}	6.3–6.9	6.4–6.8	–190 to 40	130
Second cropping season of 1995								
NTU	29–18	29–20	28–20	3.0×10^{4}–1.7×10^{4}	7.0–7.2	6.4–7.0	–190 to –200	135
Taoyuan	30–22	29–21	28–21	4.2×10^{4}–2.2×10^{4}	7.2–6.8	7.1–6.9	–230 to 150	112
First cropping season of 1996								
NTU	20–31	20–29	20–28	1.1×10^{5}–8.4×10^{4}	6.2–6.7	6.3–6.5	–180 to 40	143
Taoyuan	21–32	20–30	19–29	3.1×10^{4}–7.3×10^{4}	6.3–7.2	6.3–7.1	–180 to 70	149

[a] NTU paddy field was continuously flooded in the second cropping season of 1995 and the first cropping season of 1996, while the others were under intermittent irrigation

Table 4 CH_4 emission rate from paddy fields during rice cultivation in the first cropping season (mean ± SD, $n=4$). Means in the same row *followed by different letters* were significantly different at the 5% level according to Duncan's multiple range test. For abbreviations, see Tables 2 and 3

CH_4 emission rate (mg m^{-2} h^{-1})						
Growth stage	NTU		Taoyuan		Langyang	Tzawchyau
	Intermittent irrigation	Continuous flooding	Industrial fertilizer	Manure[a]		
First cropping season of 1995						
T.I.	0.50±0.20 c		0.30±0.20 c	7.12±4.38 b	0.27±0.15 c	0.78±0.04 c
A.T.	0.69±0.15 c		0.10±0.08 c	1.42±0.35 c	1.63±0.21 c	3.91±0.10 c
B.T.	1.01±0.16 c		0.59±0.11 c	0.69±0.34 c	0.35±0.18 c	7.14±3.92 c
F.I.	1.46±0.20 c		0.37±0.25 c	0.50±0.21 c	0.30±0.16 c	1.80±0.48 c
Ripening	0.34±0.14c		0.15±0.06 c	0.32±0.11 c	0.21±0.10 c	0.32±0.09 c
Seasonal CH_4 emission (g m^{-2})	2.55±0.16 c		1.73±0.25 c	5.55±1.05 b	2.92±0.30 c	9.82±2.80 a
Average CH_4 emission rate (mg m^{-2} h^{-1})	0.76±0.05 c		0.52±0.06 c	1.65±0.51 b	0.87±0.11 c	2.92±0.83 a
First cropping season of 1996						
T.I.	0.38±0.16 c	0.44±0.20 c	0.28±0.16 c			
A.T.	3.94±1.19 bc	4.81±1.69 bc	3.87±1.21 bc			
B.T.	7.43±1.06 b	20.71±3.19 a	0.26±0.06 c			
F.I.	1.13±0.78 c	15.75±4.10 a	0.11±0.05 c			
Ripening	0.16±0.08 c	6.93±2.19 bc	0.04±0.02 c			
Seasonal CH_4 emission (g m^{-2})	11.70±2.76 b	32.65±4.17 a	5.23±1.93 c			
Average CH_4 emission rate (mg m^{-2} h^{-1})	3.48±1.12 b	9.72±1.23 a	1.56±0.57 c			

[a] Green manure amendment and industrial fertilizer application. *Sesbania* (37 t ha^{-1}) amendment was applied before the second cropping season of 1994

high between 12 a.m. and 3 p.m. and low in the early morning (Yang and Chang 1999). CH_4 emission rates in the NTU paddy fields were between 0.21 ± 0.05 and 0.83 ± 0.20 mg m^{-2} h^{-1} at the transplanting stage, between 0.31 ± 0.06 and 0.88 ± 0.08 mg m^{-2} h^{-1} at the active tillering stage, between 0.85 ± 0.13 and 1.49 ± 0.20 mg m^{-2} h^{-1} at the booting stage, between 1.02 ± 0.19 and 2.83 ± 0.77 mg m^{-2} h^{-1} at the flowering stage, and between 0.21 ± 0.05 and 0.54 ± 0.19 mg m^{-2} h^{-1} at the ripening stage (Yang and Chang 1999). These results were somewhat different from those of Watanabe et al. (1997) who found high CH_4 emission rates at the panicle differentiation/flowering stage due to root exudations or decaying root tissue. The seasonal CH_4 emission and the average CH_4 emission rate in the first cropping season of 1995 were high in the Tzawchyau paddy field as a result of the high organic matter content. The rank order was as follows: Taoyuan paddy field with *Sesbania* amendment>NTU paddy field>Langyang paddy field>Taoyuan paddy field treated with industrial fertilizer.

Green manure amendment in the Taoyuan paddy field enhanced CH_4 emissions. *Sesbania* amendment of the soil increased the soil organic matter content and stimulated CH_4 emission from the paddy fields (Yang and Chang 1998, 2000). Denier van der Gon and Neue (1995) found that CH_4 emission in the wet season (June–November) in the Philippines increased with the amount of fresh *Sesbania* added to the soil. In another study, the application of sugar beet leaves caused an instantaneous 20% inhibition of CH_4 oxidation, while the addition of biowaste compost to the soil increased CH_4 oxidation by 28% (Hütsch 1998).

In the first cropping season of 1996, the CH_4 emission rate and the average CH_4 emission rate with intermittent irrigation were similar to those in the first cropping season of 1995 (Table 4). However, the CH_4 emission rate was high at the booting and the flowering stages with continuous flooding. The seasonal CH_4 emission was 32.65 ± 4.17 mg m^{-2} in the NTU paddy field with continuous flooding, 11.70 ± 2.76 mg m^{-2} in the NTU paddy field with intermittent irrigation, and 5.23 ± 1.93 mg m^{-2} in the Taoyuan paddy field treated with industrial fertilizer and subjected to intermittent irrigation. The results showed significant differences among these three test paddy fields.

CH_4 emission in the second cropping season

At the transplanting stage of the second cropping season, the CH_4 emission rate was between 10.98 and 38.14 mg m^{-2} h^{-1} in 1994 because of high temperatures and high microbial activity (Table 5). CH_4 emission decreased gradually during rice growth due to the decreasing temperature and the increasing soil redox potential with intermittent irrigation. Organic matter degradation, due to high temperatures and low redox potentials, favoured CH_4 production at the flooding and the transplanting stages. The same phenomenon was also observed in Japan (Tsutsuki and Ponnamperuma 1987). After the active tillering stage, both light intensity and temperature decreased gradually, and intermittent irrigation was used in the paddy fields (Table 3). The soil redox potential was high and CH_4 emission was low at the active tillering, booting, flowering and ripening stages. Kimura et al. (1977), and Tsutauki and Ponnamperuma (1987) reported that the growth of paddy rice was very active at these stages and many metabolites secreted into soil were probably responsible for CH_4 production. During rice growth stages, the positive effect on CH_4 emission is also due to the increase in the rate of transport of CH_4 from the soil to the atmosphere (Wassmann and Aulakh 2000). In addition, the soil redox potential significantly increased at these stages because the drainage exposed soil to air and thus led to an increase in the O_2 concentration in the soil. These oxidative conditions stimulate the oxidation of CH_4 and repress the emission of CH_4 from paddy soil (Wang et al. 1993). CH_4 emission was low at the later growth stage of rice, presumably due to low temperatures (Wahlen and Reeburgh 1990) and a high soil redox potential with intermittent irrigation (Yang and Chang 1997). The cumulative CH_4 emission was high in the Tzawchyau paddy field, followed by the Taoyuan paddy field amended with *Sesbania*, the Langyang paddy field, the NTU paddy field and the Taoyuan paddy field treated with industrial fertilizer. The same tendency was observed for the average CH_4 emission rate in these five test paddy fields with significant differences among seasonal CH_4 emission and the average CH_4 emission rate (Table 5).

At the transplanting stage of the second cropping season of 1995, the temperature was high and the soil redox potential was low due to water flooding. The CH_4 emission rates were 15.44 ± 5.44, 12.82 ± 1.41 and 11.41 ± 3.68 mg m^{-2} h^{-1} in the Taoyuan paddy field amended with *Sesbania*, the NTU paddy field and the Taoyuan paddy field treated with industrial fertilizer, respectively. The CH_4 emission rate decreased with rice cultivation due to a decrease in temperature and increase in the soil redox potential with the intermittent irrigation system. Thus, CH_4 emission from the NTU paddy field with continuous flooding was high (Table 5). Cumulative CH_4 emissions were high in the NTU paddy field with continuous flooding, lower in the Taoyuan paddy field amended with *Sesbania*, and lower still in the Taoyuan paddy field treated with industrial fertilizer. The results showed significant differences between the intermittent irrigation system and continuous flooding treatment.

Effect of environmental conditions on CH_4 emission from paddy fields

The effect of cropping season, irrigation system and *Sesbania* amendment on seasonal CH_4 emission from

Table 5 CH_4 emission rate from paddy fields during rice cultivation in the second cropping season (mean ± SD, $n = 4$). Means in the same row *followed by different letters* were significantly different at 5% level according to Duncan's multiple range test. For abbreviations, see Tables 2 and 3

CH_4 emission rate (mg m^{-2} h^{-1})						
Growth stage	NTU		Taoyuan		Langyang	Tzawchyau
	Intermittent irrigation	Continuous flooding	Industrial fertilizer	Manure[a]		
Second cropping season of 1994						
T.I.	28.27 ± 6.37 b		10.98 ± 2.25 c	33.71 ± 8.92 ab	36.10 ± 9.37 a	38.14 ± 9.39 a
A.T.	1.98 ± 0.65 d		1.20 ± 0.02 d	2.41 ± 0.25 d	11.69 ± 2.44 c	0.18 ± 0.09 d
B.T.	0.56 ± 0.14 d		0.14 ± 0.04 d	1.03 ± 0.23 d	0.29 ± 0.05 d	0.07 ± 0.03 d
F.I.	0.09 ± 0.01 d		0.04 ± 0.05 d	0.04 ± 0.04 d	0.07 ± 0.01 d	0.03 ± 0.01 d
Ripening	0.02 ± 0.01 d		0.04 ± 0.03 d	0.02 ± 0.01 d	0.04 ± 0.01 d	0.01 ± 0.01 d
Seasonal CH_4 emission (g m^{-2})	13.73 ± 1.70 c		10.56 ± 2.31 c	30.12 ± 3.53 b	24.64 ± 3.43 b	39.50 ± 5.63 a
Average CH_4 emission rate (mg m^{-2} h^{-1})	4.85 ± 0.59 c		4.00 ± 0.96 c	10.46 ± 1.22 b	8.93 ± 2.33 b	13.72 ± 1.96 a
Second cropping season of 1995						
T.I.		12.82 ± 1.41 a	11.41 ± 3.68 a	15.44 ± 5.44 a		
A.T.		15.58 ± 5.63 a	0.18 ± 0.06 c	0.19 ± 0.10 c		
B.T.		6.26 ± 0.72 b	0.05 ± 0.03 c	0.11 ± 0.08 c		
F.I.		4.96 ± 0.16 bc	0.03 ± 0.01 c	0.08 ± 0.02 c		
Ripening		0.02 ± 0.01 c	0.01 ± 0.01 c	0.05 ± 0.03 c		
Seasonal CH_4 emission (g m^{-2})		28.85 ± 3.25 a	10.54 ± 3.53 b	14.43 ± 3.15 b		
Average CH_4 emission rate (mg m^{-2} h^{-1})		9.54 ± 1.07 a	4.16 ± 1.32 b	5.68 ± 1.24 b		

[a] *Sesbania* (37 t ha^{-1}) amendment was applied before the second cropping season of 1994, and another 25 t of *Sesbania* ha^{-1} was applied before the second cropping season of 1995

the paddy fields is summarized in Table 6. It was found that seasonal CH_4 emissions in the second cropping season were higher than those in the first cropping season with the intermittent irrigation system in all test fields, while it was reversed with continuous flooding treatment. From the statistical analysis, it is observed that the seasonal CH_4 emission had significant difference between the first and the second cropping seasons with the intermittent irrigation system, whereas no significant difference was observed with continuous flooding. Seasonal CH_4 emissions in the second cropping season were about 2.8- to 11.3-fold higher than those in the first cropping season.

The seasonal CH_4 emission from paddy field showed significant differences between the intermittent irrigation system and the continuous flooding treatment in the NTU test paddy field. In addition, the seasonal CH_4 emission from the paddy field amended with *Sesbania* was significantly higher than those treated with industrial fertilizer in the Taoyuan paddy field. However, the effect decreased gradually in the successive cultivation. CH_4 emission was high in the NTU paddy field in the second cropping season of 1995 and in the first cropping season of 1996 due to continuous flooding during rice cultivation. The total CH_4 emission in these cropping seasons was the same as that from paddy rice fields in California from June to September (Cicerone et al. 1983). On the other hand, the inhibition of CH_4 emission due to intermittent irrigation of paddy fields has also been reported in Louisiana paddy fields (Delwiche and Cicerone 1993; Lindau et al. 1993).

In the four test paddy fields in the 2-year study, the seasonal CH_4 emission ranged from 1.73 ± 0.25 (Taoyuan) to 39.50 ± 5.63 g m^{-2} (Tzawchyau). CH_4 emissions from the paddy fields with intermittent irrigation in Taiwan were substantially lower than those with continuous flooding in other countries, such as Italy, Spain, USA, Japan, Korea, and the Philippines (Cicerone et al. 1983; Seiler et al. 1984; Holzapfel-Pschorn and Seiler 1986; Schutz et al. 1989; Sass et al. 1990; Yagi and Minami 1990; Lindau et al. 1991; Neue et al. 1994).

Wassmann et al. (1993) reported that the average CH_4 emission rate in Hunan paddy soil with 3–5 cm flooding was between 6.5 and 38.6 mg m^{-2} h^{-1} from April to July (total CH_4 emission ranging from 11.7 to 65.5 g m^{-2} for 75 days' cultivation) and between 14.30 and 56.20 mg m^{-2} h^{-1} from July to October (total CH_4 emission ranging from 29.17 to 114.65 g m^{-2} for 85 days' cultivation). Due to intermittent irrigation the values were lower in Taiwan than in Hunan paddy soil. The estimated average CH_4 emission rate was between 0.52

Table 6 Effect of agricultural practices on CH_4 emission from paddy fields (mean ± SD, $n = 4$). Means in the same column *followed by different letters* were significantly different at the 5% level according to Duncan's multiple range test

Location	Irrigation system	Fertilizer application	Cropping season	Period of time (days)	Seasonal CH_4 emission (g m^{-2})
NTU	Intermittent irrigation	Industrial fertilizer	First crop (1995)	129	2.55 ± 0.16 c
			First crop (1996)	152	11.70 ± 2.76 b
			Second crop (1994)	147	13.73 ± 1.70 b
	Continuous flooding		First crop (1996)	152	32.65 ± 4.17 a
			Second crop (1995)	136	28.85 ± 3.25 a
Taoyuan	Intermittent irrigation		First crop (1995)	126	1.73 ± 0.25 c
			First crop (1996)	152	5.23 ± 1.93 c
			Second crop (1994)	122	10.56 ± 2.31 b
			Second crop (1995)	117	10.54 ± 3.35 b
		Previous *Sesbania* application[a]	First crop (1995)	133	5.55 ± 1.05 c
		Sesbania (37 tons ha^{-1})	Second crop (1994)	122	30.12 ± 3.53 a
		Sesbania (25 tons ha^{-1})	Second crop (1995)	117	14.43 ± 3.15 b
Langyang		Industrial fertilizer	First crop (1995)	134	2.92 ± 0.30 c
			Second crop (1994)	136	24.64 ± 3.43 a
Tzawchyau			First crop (1995)	130	9.82 ± 2.80 b
			Second crop (1994)	123	39.50 ± 5.63 a

[a] *Sesbania*: *Sesbania* amendment before the second cropping season

and 2.92 mg m^{-2} h^{-1} in the first cropping season from February to June (the cultivation period ranging from 122 to 152 days) with the intermittent irrigation system in Taiwan; these values ranged from 4.00 to 13.72 mg m^{-2} h^{-1} in the second cropping season from August to December (the cultivation period ranging from 117 to 147 days).

Seasonal CH_4 emission depended on location. All the data showed significant differences among the different test paddy fields, with the highest emission in the Tzawchyau paddy field whose soil was characterized by the highest organic matter content. The pH of the test paddy fields showed weakly acidic soil, except in the Tzawchyau paddy field, which had moderately acidic soil. All of the test paddy fields contained organic matter ranging from 28.4 to 32.9 g kg^{-1} and the fertility of the soils was in the medium range (Huang 1991).

The seasonal variation of CH_4 emission rates in the paddy fields was very large, i.e. from 0.01 to 38.14 mg m^{-2} h^{-1}. Similar results were reported by Holzapfel-Pschorn and Seiler (1986) for Italian paddy fields. However, the average CH_4 emission was lower in Taiwan (between 4.00 and 13.72 mg m^{-2} h^{-1}), than in Italian paddy fields (16.0 mg m^{-2} h^{-1}). This difference can be attributed to different cultivation practices, as intermittent irrigation was used in Taiwan, whereas continuous flooding was used in Italy.

Estimation of total CH_4 emission from paddy fields in Taiwan

Seasonal and total CH_4 emissions calculated from the different paddy fields in Taiwan are shown in Table 7. CH_4 emissions from paddy fields in the second cropping season were higher than those in the first cropping season. Hsinchu-Miaoli area had the highest CH_4 emission among the studied areas. The CH_4 flux was 0.012 Tg and 0.021 Tg in the first crop and the second cropping seasons of 1996, respectively. From 1985 to 1997, the CH_4 emission from paddy fields in Taiwan was estimated by considering the seasonal emission rate and rice cultivation area (Table 8). The annual CH_4 emission from paddy fields in Taiwan was 0.062 Tg in 1985, and the value gradually decreased to 0.034 Tg in 1997 due to the decrease in the area of cultivated paddy fields. The average CH_4 emission from paddy fields was 66.6 and 125.0 kg ha^{-1} in the first and in the second cropping seasons of 1996, respectively. Each tonne of rice grain produced 5.1–23.5, 4.1, 1.6–11.4 and 17.2 kg CH_4 in the first cropping season in Taipei, Ilan, Taoyuan and Hsinchu-Miaoli areas, respectively. In the second cropping season the values were 44.7–93.9, 89.6, 27.8–65.6 and 83.1 kg CH_4. The average CH_4 production was 10.88 and 25.39 kg for each tonne of rice produced in the first and in the second cropping seasons of 1996, respectively.

Reported annual CH_4 emissions ranged from 5 to 86 g m^{-2} in USA (Cicerone et al. 1983; Saas et al. 1990), from 12 to 77 g m^{-2} in Italy (Schutz et al. 1989), from 1 to 45 g m^{-2} in Japan (Yagi and Minami 1990), from 41 to 150 g m^{-2} in China (Wassman et al. 1993), from 25 to 131 g m^{-2} in the Philippines (Neue et al. 1994), from 62 to 135 g m^{-2} in Taiwan with continuous flooding (Yang et al. 1994; Yang and Chang 1997) and from 12 to 49 g m^{-2} in Taiwan with intermittent irrigation. An annual CH_4 emission of 12 g m^{-2} was reported in Spain (Seiler 1984).

By considering the average CH_4 emission of the four locations of this study, the four locations reported by Wang and Shieh (1997) and the two locations reported by Perng and Huang (1998), the overall emissions from the paddy fields of Taiwan amounted to 0.033 Tg in

Table 7 Seasonal CH_4 emission from paddy fields in Taiwan

Location	Latitude, longitude	Annual mean temperature (°C)	Annual precipitation (mm)	Rainy days (days $year^{-1}$)	Sunshine duration (h $year^{-1}$)	Seasonal CH_4 emission (g m^{-2})		Total CH_4 emission (t)	
						First cropping season	Second cropping season	First cropping season	Second cropping season
Taipei and Keelung	121°27′–122°6′N, 24°41′–25°38′E	22.5	4,296	196	1,383	2.6–11.7	13.7–28.9	28.1–128.9	68.7–144.3
Taoyuan	120°58′–121°29′N, 24°35′–25°7′E	22.3	3,188	165	1,555	1.7–5.2	10.5–10.6	241.3–729.3	1,708.9–1,712.1
Ilan	121°18′–124°34′N, 24°19′–25°56′E	22.5	4,880	188	1,387	2.9	24.6	348.1	246.4
Hsinchu and Miaoli	120°38′–121°23′N, 24°18′–24°57′E	22.1	2,079	133	1,727	9.8	39.5	1,839.8	7,486.4
Taichung and Nantou[a]	120°29′–121°27′N, 23°28′–24°26′E	23.4	2,157	131	2,006	6.6	6.9	1,450.7	1,484.6
Changhua[a]	120°16′–120°38′N, 23°50′–24°11′E	23.3	2,284	123	1,974	6.6	7.3	1,971.9	2,060.2
Chiayi and Yunlin[a]	120°0′–120°57′N, 23°13′–23°50′E	23.2	2,411	114	1,942	6.5	7.7	2,824.5	3,117.1
Kaoshiung, Tainan and Pingtung[a]	120°1′–120°57′N, 21°42′–23°28′E	24.7	2,293	111	2,031	8.0	8.3	2,062.3	2,036.2
Hualian and Taitung[b]	120°44′–121°46◇N, 21°56′–24°22′E	23.9	2,984	144	1,496	8.8	18.1	1,114.8	2,372.5
Total	119°18′–124°34′N, 21°42′–25°56′E	23.6	2,867	138	1,753			11,881.5–12,470.3	20,581.0–20,659.8

[a] From Wang and Shieh (1997)
[b] from Perng and Huang (1998)

Table 8 Cultivation area and CH_4 flux of rice fields in Taiwan

Year	First cropping season		Second cropping season		Total	
	Cultivation area (ha)	CH_4 flux (t)[a]	Cultivation area (ha)	CH_4 flux (t)	Cultivation area (ha)	CH_4 flux (t)
1985	277,498	19,443	286,180	42,125	563,678	61,568
1986	268,769	18,831	262,792	38,683	531,561	57,514
1987	255,329	17,890	246,163	36,235	501,492	54,125
1988	240,698	16,864	230,367	33,910	471,065	50,774
1989	243,074	17,031	232,380	34,206	475,454	51,237
1990	242,298	16,977	211,968	31,201	454,266	48,178
1991	227,417	15,934	201,385	29,644	428,802	45,578
1992	209,474	14,677	187,676	27,626	397,150	42,303
1993	211,790	14,839	179,137	26,369	390,927	41,208
1994	196,317	13,755	169,520	24,953	365,837	38,708
1995	197,571	13,163	165,908	20,980	363,479	34,143
1996	182,807	12,176	164,955	20,624	347,762	32,800
1997	202,010	13,455	162,202	20,280	364,212	33,735

[a] Estimated from the average CH_4 emission of ten locations in Taiwan

1996 and 0.034 Tg in 1997. By considering the CH_4 emission factors of 4.804 and 5.584 kg ha^{-1} day^{-1} for the first and the second cropping seasons of 1996 in Taiwan, respectively, total seasonal CH_4 emission estimated by the IPCC method (1995) amounted to 0.126 and 0.115 Tg with an annual CH_4 emission of 0.241 Tg. The difference between these two estimates is due to the fact that our calculation was based on values of CH_4 emissions from paddy soils with intermittent irrigation, whereas the IPCC quantification was based on emissions from paddy fields with continuous flooding.

In conclusion, organic fertilizer applications and flooding have been shown to enhance CH_4 emissions from paddy fields, while inorganic fertilizer applications and intermittent irrigation have been shown to significantly reduce CH_4 emissions (Yang and Chang 1997, 1998). The rice variety had some effect on CH_4 emissions, but it was not the major factor (Yang et al. 1994). In essence, application of an appropriate fertilizer to the soil, and management of water irrigation during rice cultivation can lead to a considerable decrease in CH_4 emissions from paddy fields.

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