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The effect of nitrogen fertilizer use and other practices on methane emission from flooded rice

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Abstract

Methane (CH_4) flux measurements from rice paddy fields in the world and its controlling factors, especially fertilizer effects are summarized. The measurements at rice paddy fields in various locations of the world showed that there were large temporal variations of CH_4 flux and that the flux differed markedly with climate, characteristics of soil and paddy, application of organic matter and mineral fertilizer, and agricultural practices. From the data, it appears that identifying and controlling CH_4 flux factors have a potential to reduce CH_4 emission from rice cultivation. Potential mitigation options include: the form and amount of nitrogen and other chemical fertilizers, the method of fertilizer applications, the application of other chemical amendments, water management and cultivation practices.

Introduction

Methane (CH_4) is one of the most abundant organic gases in the atmosphere. Recently the importance of CH_4 as a greenhouse gas has been recognized and studies have been carried out to assess its contribution to global warming.

More than thirteen years have passed since the first evidence for an increase in the concentration of atmospheric CH_4 was reported [39]. Several time-series measurements of the trend of atmospheric CH_4 have been carried out in various locations of the world up to present time. The results obtained show that the average increase of atmospheric CH_4 during last decade was about 1% per year [3,41]. Analysis of ancient air trapped in polar ice cores reveal that the concentration of atmospheric CH_4 remained almost constant at less than about half of the present concentration until 300 years ago, with an increase in the concentration starting in the 19th century [10,20,40]. Although the rate of increase has slowed down in the last decade [22,42,53], the above concerns still require research to construct an accurate budget relating sources and sinks of CH_4 to atmospheric concentrations.

Methane plays an important role in the photochemical reactions of the troposphere and the stratosphere, and the changes of its concentration exert a strong influence over the atmospheric chemistry [54]. In addition, CH_4 is a so-called greenhouse gas along with CO_2, CFCs and N_2O, which have strong absorption bands and trap part of the thermal radiation from the earth's surface [58]. Therefore, the increasing concentration of CH_4 may affect significantly the global heat balance and cause a possible elevation of the global surface temperature [11,38]. Methane accounts for almost 20% of the radiative forcing added to the atmosphere [14].

Atmospheric CH_4 is produced by a wide variety of natural and anthropogenic processes. Major sources of atmospheric CH_4 have been estimated by several investigators [2,8,12,14,15,52]. However, there are uncertainties in the estimated value of individual sources and sinks, and in the leading causes of the increasing concentration of atmospheric CH_4.

Rice paddy fields are considered as an important source for the observed changes in atmospheric CH_4 concentration because of the recent increase in world area. The Intergovernmental Panel on Climate Change [15] estimated the global emission rate from paddy fields to be from 20 to 150 Tg yr^{-1}, averaging 60 Tg yr^{-1} which accounts for about 5–30% of the total emissions from all sources. This figure is mainly based on the field measurement of CH_4 flux from paddy fields in the United States, Spain, Italy, China, India, Australia and Japan.

The measurements in rice paddy fields in various locations of the world show that there are large temporal variations of CH_4 flux and that the flux differs markedly with climate, characteristics of soil and paddy, application of organic matter and mineral fertilizer, and agricultural practices. In this paper, I summarize research on factors that affect CH_4 emissions and discuss the effects of fertilizer use on CH_4 emission from flooded rice. Table 1 shows the results of the CH_4 flux measurements from rice paddy fields in the world, including partial data, pot data and laboratory data. Additional information on CH_4 production and oxidation in soils and emission from rice paddy fields were discussed in previous paper [33].

Methane emissions

Diurnal, seasonal and annual variation in CH_4 emission

A very clear dependence on temperature is observed in the duel variation of CH_4 emission. The temperature dependence of seasonal emission patterns is not as obvious. Variations in CH_4 emission during the growing season have been correlated with soil temperature in some studies but not in others. Three seasonal maxima were found in Italy [49], the first shortly after flooding, the second during the vegetative stage of the rice plants, and the third during the grain filling and maturation stage. Although cultivation practice has a strong influence on CH_4 emission levels, three seasonal maxima were also observed in Japan [60]. In China, both two-maxima and three-maxima seasonal patterns have been observed [57]. In Texas, although different in absolute emission values, seasonal patterns in three soils over three years had similar characteristics [43,44,45,48]. Sass and Fisher [48] compared methane emissions over three years from two paddy fields. Methane emission rates differed each year. There was a 2 to 3 fold variation in CH_4 emission over three years. Table 2 shows the annual variations in CH_4 emission for two to four years in three studies [49,61,63]. It shows that CH_4 emission rates vary every year when agricultural management practice is under the same conditions.

CH_4 emission rates and soil characteristics

Methane emission from soil bacterial activity in agricultural wetlands is influenced by physical, chemical and biological properties of soil, organic residues in soil and water (including fertilizers and other chemical additives), water regime and management, temperature (including wet-dry season and planting date), root exudates and plant physiology.

Yagi and Minami [60] investigated the effect of different soils on CH_4 emission in the same areas. Emission rates differed markedly with the soil type as shown in Table 1. Peaty soil fields recorded the highest rates, followed by Gley soil and then Andosol. Other studies in Thailand [16,62] showed that CH_4 emission rates differed markedly with the soil textures (C, CL, SiC, HC and LFS) as shown in Table 1. Seasonal CH_4 emissions showed a clear inverse relation to clay content of soils as shown in Table 3 [48].

CH_4 emission rates and the form and amount of chemical fertilizers

Urea and ammonium sulfate account for 80–90% of total nitrogen fertilizer required in rice cultivation [13]. The effects of urea, ammonium sulfate and other N fertilizer have on methanogenesis are not clearly understood and are often contradictory.[59]. Methane fluxes appear to be strongly influenced by the type, rate and method of N fertilizer application to rice paddies.

Cicerone and Shetter [6] reported ammonium sulfate addition to California rice paddies increased CH_4 emissions 5-fold compared to control plots (unfertilized). Schutz *et al.* [49] evaluated fertilizer applications to rice paddy fields in Italy over a 3-year cropping period. Based on seasonal averages, fluxes measured from ammonium sulfate treated plots were lower by 5–60% depending upon method of application. Addition of urea to the Italian paddies reduced emissions by 18% compared to controls but fluxes were strongly influenced by the application method.

Lindau *et al.* [27,28] observed fluxes of CH_4 from ammonium sulfate and potassium nitrate treated fields. These were much lower than urea treated fields over the 21-day sampling period. Lindau *et al.* [29] reported emissions increased as urea-N rate increased in a Louisiana field experiment. Lindau [32] measured CH_4 emission rates as affected by the form of N fertilizer (urea, ammonium sulfate, and potassium nitrate)

Table 1. Methane flux measurements from rice fields

Study	Country	Soil	Rice Cultiver Grain ($g\ m^{-2}$)	Treatment N-fertilizer ($kg\ N\ ha^{-1}$)		Amendment ($t\ ha^{-1}$)		Days	Flux $mg\ m^{-2}\ hr^{-1}$
1	USA	C	M101	Compound+U	113			100	10.4
2	Spain			Urea+AN	200			125	4.0
3	Italy	SL	Roma	No				118	10.6
				$CaCN_2$(rake)	200			118	12.5
				Urea(rake)	100			118	9.6
				Urea(rake)	200			118	9.6
				Urea(inco)	200			113	7.9
				Urea(surf)	200			113	15.8
				AS(inco)	50			105	7.5
				AS(inco)	100			105	8.8
				AS(inco)	200			109	5.6
				AS(rake)	200			118	6.7
				AS(surf)	200			113	12.5
						RS(inco)	3	105	9.6
						RS(inco)	5	118	24.2
						RS(inco)	6	109	13.5
						RS(inco)	12	110	22.1
						RS(inco)	24	113	18.8
				$CaCN_2$	37.5	RS	2.5	118	11.7
				$CaCN_2$	75	RS	5	118	17.9
				AS	200	RS	12	109	20.6
				Urea	200	RS	6	113	20.0
				Urea	200	RS	12	113	25.0
						Comp	60	113	27.5
4	Japan	SCL	Koshi-	No				119	2.8
		(Gley soil)	hikari	Compound	90			118	2.9
				Compound	90	Compo	12	112	3.9
				Compound	90	RS	6	117	9.6
		CL		Compound	85	RS	6	115	16.3
		(Peaty soil)							
		L		No				122	1.4
		(Andosol)		Compound	80			125	1.2
				Compound	80	Compo	12	129	1.9
				Compound	80	RS	6	128	3.2
				Compound	80	RS	9	128	4.1
		L		Compound	100			125	0.2
		(Andosol)		Compound	100	RS	6	115	0.4
5	Japan	CL		AS 150 percolation 0 mm/day				148	2.6
		(Eutric Gleysols)		AS 150 percolation 5 mm/day				148	1.4
				AS 150 percolation 20 mm/day				148	0.1

Table 1. continued

Study	Country	Soil	Rice Cultiver Grain ($g\ m^{-2}$)	Treatment N-fertilizer ($kg\ N\ ha^{-1}$)		Amendment ($t\ ha^{-1}$)		Days	Flux $mg\ m^{-2}\ hr^{-1}$
6		China		Late rice, average				62	26.4
				Early rice, average				70	6.6
7	China							120	36.6
8, 9	USA	C	Jasmine 85	(600g) Urea	190			85	2.2
	(Entic Pelludert)			(516g) Urea	102	RS	8	86	5.5
		C		(700g) Urea	149			85	7.8
	(Typic Pelludert)			(490g) Urea	102	RS	12	86	15.0
10	USA	SiC	Jasmine 85	(994g) Urea	190			85	18.3
		(Vertic Ochraqualf)		(850g) Urea	190			81	11.8
				(770g) Urea	190			76	12.0
				(846g) Urea	190	Pasp S	6	85	23.5
				(784g) Urea	190	Pasp S	6	81	18.3
				(668g) Urea	190	Pasp S	6	76	12.7
11	USA	SiL	Lemont	No				86	10.2
		(Typic Albaqualf)		Urea	100			86	14.5
				Urea	200			86	15.0
				Urea	300			86	17.9
12	USA	SiC		Compound+U	114			111	4.0
		C		No				128	0.5
				Urea	78			128	0.9
				Urea	78	RS	2.5	128	3.0
				Urea	78	RS	5	128	13.9
						RS	2.5	128	6.4
						RS	5	128	18.9
13	USA	SiCL (Vertic Ochraqualf)		Jasmine	85	Urea	165		
		Normal flood irr.		(825g)				87	4.4
		Mid-season aeration		(820g)				87	2.3
		Multiple aeration		(813g)				87	0.6
		Late season flood irr.		(640g)				99	6.3
14,15	Japan	SCL	Koshi-	1988 Compound	90			118	2.9
			hikari	1989 Compound	90			105	7.1
		(Eutric Gleysol)		1990 Compound	90			121	14.0
				1991 Compound	90			106	6.0
		Int.rrr		1988 Compound	90	RS	6	117	9.6
				1989 Compound	90	RS	6	105	7.9
				1990 Compound	90	RS	6	121	14.8
				1991 Compound	90	RS	6	106	8.1

Table 1. continued

Study	Country	Soil	Rice Cultiver Grain (g m^{-2})	Treatment N-fertilizer (kg N ha^{-1})		Amendment (t ha^{-1})		Days	Flux mg m^{-2} hr^{-1}
16	China	L	Huang j	(545g) $NH_4HCO_3^{\bullet}$	610	Horse dung	15	79	14.6
				(440g) $NH_4HCO_3^{\bullet}$	900			79	17.5
				(522g) $NH_4HCO_3^{\bullet}$	610	Horse dung	15	79	35.9
				(470g) $NH_4HCO_3^{\bullet}$	710	Horse dung	30	79	48.9
			Dry seeded	$NH_4HCO_3^{\bullet}$	610	Horse dung	15	79	0
		Yellow-	S63	(676g) Urea	190	Barn M	15	101	10.8
		brow earth		(676g)		Barn M	45	101	9.5
				(661g) AS*	600			101	2.6
				(706g) Urea	190	Rape S	3	101	14.3
				(661g) Urea	190	Barn M	15	101	6.6
17	USA	SiL	Texmont	No				77	13.0
	(Typic Albaqualf)			Urea	100	(no plant)		77	2.7
				Urea	100			77	18.4
		Ratoon plants		No			73	12.6	
		Ratoon plants		Urea	84			73	29.7
		Ratoon plants		Urea	84	RS	10	73	80.6
18	USA	SiL	Oryza s	Urea	128			70	43.3
	(Typic Albaqualf)			Urea	128	$CaSO_4$	1	70	30.7
				Urea	128	$CaSO_4$	2	70	23.5
19	Thailand		Oryza s						
		(Sulfic Tropaquept)	C DS	Compound	120			83	4.0
		(Veric Tropaquept)	C DS	Compound	85			109	19.5
			WS	Compound	90			97	32.2
		(Aeric Tropaquept)	CL WS	Compound	80			94	1.8
20	Japan	SCL	Koshihikari						
			Flooded	(538g) 1991 Compound	90			73	8.4
			Flooded	(570g) 1993 Compound	90			131	3.0
	Int. irr (4+6 days)			(504g) 1991 Compound	90			73	4.9
	(7-day + int.)			(589g) 1993 Compound	90			131	1.7
21	Thailand	Oryza s							
		SiC	Unhulled	(270g) No				77	3.2
	(Fulvic Tropaquent)			(450g) Compound	50			77	7.3
				(390g) Compound	50	Sesbania R	30	77	42.5
		HC	Unhulled	(230g) No				75	10
	(Thionic Tropaquest)			(350g) Compound	35			75	0.4
				(310g) Compound	35	RS	2	75	12.4
		LFS	Unhulled	(190g) No				79	21.9
	(Anthraqunic Palleaquult)			(280g) Compound	44			79	24.5
				(270g) Compound	44	Sesbania R	3.1	79	15.0

Table 1. continued

Study	Country	Soil	Rice Cultiver Grain (g m^{-2})	Treatment N-fertilizer (kg N ha^{-1})		Amendment (t ha^{-1})		Days	Flux mg m^{-2} hr^{-1}
22	Indonesia	LiC	IR64	(580g) Urea+AS	300			60	27.5
				(550g) Urea	250			60	22.5
				(570g) AS	500			60	21.8
				(640g) Urea	250	RS	5	60	32.8
				(610g) Urea	250	Sesba R	5	60	27.1
				(630g) Urea	250	Cow DM	5	60	23.7
23	USA (Typic Albaqualf)	SiL	Lacussine	No				93	2.6
				AS	60			93	3.1
				AS	120			93	4.5
				KNO3	60			93	3.6
				KNO3	120			93	4.0
				Urea	60			93	4.9
				Urea	120			93	9.9
24	Japan	SCL	Koshihikari						
	Int. irr (7-day + int.)			Compound	90			122	3.2
25	India	34	sites					44–113	0–2.8
26	Philippines (Aquandic Epiaqualt)	C	IR72	(582g) DS Urea	117			82	8.0
				(520g) WS Urea	60			105	3.6
				(560g) WS Urea	60	RS	5	105	7.3
Partial data									
27	USA			•					1.3–7.8
28	China								1–50
29	India SL, SiCL, CL, SL, SCL								0.07–80
30	USA (Typic Albaqualf)	SiL	Lemont	No				21	0–1041
				Urea	120			21	0–1375
				KNO_3	120			21	0–342
31	USA (Typic Albaqualf)	SiL	Oryza s	No				21	96–1850
				Urea	120			21	0–3141
				$(NH_4)_2SO_4$	120			21	0–354
				KNO_3	120			21	62–746
32	China			No					7.4–47.0
				K_2SO_4/KCl	694				7.7–35.4
				K_2SO_4/KCl	694	RSC	1		7.9–44.0
						RSC	1		6.0–50.6
Pot data									
33	Japan	LiC	(Typic Haploaquept) Oriza s 1/50m^2 pot						
	Broadcasting		(27.5g/pot)	AS	150			109	25.8
	Broadcasting		(24.9g/pot)	NH_4Cl	150			109	29.0
	Broadcasting		(23.9g/pot)	Urea	150			109	33.6
	Foliar spray		(21.0g/pot)	AS	150			109	14.2
	Foliar spray		(15.8g/pot)	NH_4Cl	150			109	11.5
	Foliar spray		(21.4g/pot)	Urea	150			109	26.9

Table 1. continued

Study	Country	Soil	Rice Cultiver Grain ($g\ m^{-2}$)	Treatment N-fertilizer ($kg\ N\ ha^{-1}$)	Amendment ($t\ ha^{-1}$)	Days	Flux mg m^{-2} hr^{-1}
34	USA	(Glossoboric Hapludalf)			RS	105	17.8
					GM	105	62.6
					GM+RS	105	58.7
		(Aeric Hapluaquept)			RS	105	28.2
					GM	105	40.9
					GM+RS	105	46.5
Laboratory data							
35	Philippines	CH_4 production during incubation (CH_4 mg kg^{-1} soil, 20°C)					
	Pila:	LiC		No		56	71
					Compo	56	41
					RS	56	371
					GM	56	459
	Maahas:	HC		No		56	1.2
					Compo	56	1.6
					RS	56	57
					GM	56	117
	Luisiana:	HC		No		56	5.7
					Compo	56	5.9
					RS	56	79
					GM	56	160
Inhibited data							
36	Australia	C	Urea 80 decreased from 12.4 g to 3 g CH_4 ha^{-1} day^{-1} decreased Nitrapyrin and CCC decreased from 15.4 g to .5.8, 2.8 g CH_4 ha^{-1} day^{-1}				

Study: 1) Cicerone *et al.*, 1983; 2) Seiler *et al.*, 1984; 3) Schutz *et al.*, 1989; 4) Yagi and Minami, 1990; 5) Minami, 1994; 6) Schutz *et al.*, 1990; 7) Khalil and Rasmussen, 1991; 8) Sass *et al.*, 1990; 9) Sass *et al.*, 1991a; 10) Sass *et al.*, 1991b; 11) Lindau *et al.*, 1991; 12) Cicerone *et al.*, 1992; 13) Sass *et al.*, 1992; 14) Yagi and Minami, 1993; 15) Kumagai *et al.*, 1993; 16) Chen *et al.*, 1993; 17) Lindau and Billich, 1993; 18) Lindau, *et al.*, 1993; 19) Yagi *et al.*, 1993; 20) Yagi *et al.*, 1994a; 21) Jermsawatdipong *et al.*, 1994; 22) Nugroho *et al.*, 1994; 23) Lindau, 1994; 24) Tsuruta *et al.*, 1994; 25) Parashar *et al.*, 1994; 26) Neue *et al.*, 1994; 27) Cicerone and Shatter, 1981; 28) Khalil *et al.*, 1990; 29) Parashar *et al.*, 1991; 30) Lindau *et al.*, 1990b; 31) Lindau *et al.*, 1990a; 32) Wassmann *et al.*, 1993; 33) Kimura *et al.*, 1992; 34) Lauren and Duxbury, 1993; 35) Tsutsuki and Ponnamperuma, 1987; 36) Keerthisinghe *et al.*, 1993

Grain: Grain yield ($g\ m^{-2}$), Days: Number of days that CH_4 actually was measured from the rice paddied.
Compound: compound muneral fertilizer, AP: ammonium phosphate, U: urea
AS: ammonium sulfate
HC : heavy clay, C : clay, LiC : light clay, SiC : silty clay, SCL : sandy clay loam, CL : clay loam, SiCL : silty clay loam, SL : sandy loam, L : loam, SiL : silt loam, LFS : loamy fine sand
RS: rice straw, GM: green manure, Comp: compost, Pasp S: paspalum straw, Barn M: barnyard manure, Rape S: rape straw, Sesba R: Sesbania rostrata, Cow DM: cow dung manure, RSC: rape seed cake
inco: incorporated, rake: raked into the soil, surf: surface applied Int. irr: Intermittently irrigated, irr: irrigated
DS : dry season, WS : wet swason
Huang j: Huang jinguang, S63: Sanyou 63
*: not N, total

and the rate of application (0, 60 or 120 Kg N ha^{-1}). High ammonium sulfate and potassium nitrate usage reduced CH_4 emissions by 55 and 59%, respectively, compared to fluxes measured from the high urea application. Urea application recorded the highest emission rates, followed by potassium nitrate and then ammonium sulfate in low N rate, and followed by ammonium sulfate and then potassium nitrate in high N rate.

Kimura *et al.* [24] measured CH_4 emission rates as affected by the application methods of broadcast-

Table 2. Annual variations in CH_4 emission

Study	Country	Soil	Year	Treatment				Days	Flux
				N-fertilizer ($kg\ N\ ha^{-1}$)		Amendment ($t\ ha^{-1}$)			($mg\ m^{-2}\ h^{-1}$)
3	Italy	SL	1985	AS (inco)	200			109	6.3
			1986	AS (inco)	200			109	5.6
			1985			RS (inco)	6	109	12.9
			1986			RS (inco)	6	109	14.2
			1985			RS (inco)	12	110	15.8
			1986			RS (inco)	12	110	28.3
20	Japan	SCL	1991	Compound	90			73	8.4
			1993	Compound	90			131	3.0
14,15	Japan	SCL	1988	Compound	90			118	2.9
			1989	Compound	90			105	7.1
			1990	Compound	90			121	14.0
			1991	Compound	90			106	6.0
			1988	Compound	90	RS	6	117	9.6
			1989	Compound	90	RS	6	105	7.9
			1990	Compound	90	RS	6	121	14.8
			1991	Compound	90	RS	6	106	8.1

Study: See footnotes in Table 1.

Table 3. Methane flux measurements from Texas, USA [48]

Average seasonal CH_4 emission ($g\ m^{-2}$)	Soil clay (%)	Soil type
14	65	Entic Pelludent (Beaumont)
26	35	Typic Pelludent (Lake Charles)
31	25	Vertic Ochraqualf (Bernard-Morey)

ing and foliar spray with a pot experiment. Among the broadcasting treatments, the emission rate for the ammonium sulfate treatment was the lowest, followed by ammonium chloride and then urea. Foliar spray reduced CH_4 emission in each fertilizer treatment compared to broadcasting method, with a reduction of 45, 60, and 20% in ammonium sulfate, ammonium chloride and urea, respectively.

CH_4 emission rates and the method of chemical fertilizer applications

Mineral nitrogen fertilizers are commonly used in rice cultivation to increase yields. Schutz *et al.* [49] compared CH_4 emission rates associated with the method of nitrogen fertilizer application, including raked into the soil, incorporated into the soil and applied to the surface, using urea and ammonium sulfate. The influence of fertilization with urea and ammonium sulfate on CH_4 emission is heavily dependent on the mode of fertilizer application. In general, CH_4 emission rate were much higher in the fields with surface application than in raked and incorporated applications as shown in Table 4.

In the pot experiments, Kimura *et al.* [24] compared CH_4 emission rates of various topdressing of nitrogen fertilizer applications, such as broadcasting and foliar spray, using with ammonium sulfate, ammonium chloride and urea. Although foliar spraying decreased CH_4 emission compared with broadcasting on the soil, grain yield of the former also decreased. The emission

Table 4. CH_4 emission rates on the methods of chemical fertilizer application [49]

Application Mode	Fertilizer	Application Rates (kg N ha^{-1})	Days	Flux (mg m^{-2} yr^{-1})
raked into the soil	Urea	200	118	9.6
incorpotated	Urea	200	113	7.9
surface applied	Urea	200	113	15.8
raked into the soil	$(NH_4)_2SO_4$	200	109	5.6
incorporated	$(NH_4)_2SO_4$	200	118	6.7
surface applied	$(NH_4)_2SO_4$	200	113	12.5

rate was lowest with ammonium sulfate, followed by ammonium chloride and urea fertilization plots by both broadcasting and foliar spray as shown in Table 1.

CH_4 emission rates and mineral fertilizer and amendment applications

The production and emission of CH_4 from rice fields to the atmosphere is the result of a complex array of soil processes involving plant-microbe interactions. Major substrates for the methanogenic bacteria are derived from root exudates, lysates, litter, and to a lesser extent, dead organic material such as derived from incorporated vegetation [43,45]. The substrates from organic matter in the soil are characterized by Yagi and Minami [60] as readily mineralizable carbon (RMC) and are the main factors affecting CH_4 emission from flooded soils. RMC is defined as the total amount of CO_2 carbon and CH_4 carbon produced after 28 days of fresh soil incubation. Carbon dioxide and CH_4 are produced by microorganisms present in the anaerobic paddy soil by the degradation of plant-derived material. A small content of specific low molecular weight organic substrates are produced in the process of mineralization that are in turn converted to CH_4 by methanogenic bacteria. Thus variations in the rate of CH_4 production ultimately may be dependent on the kind and rate of organic matter applied to rice paddy fields.

Additions of rice straw to flooded rice paddy fields has been shown to greatly increase CH_4 emissions. Rice straw applied to Italian and Japanese rice fields increased CH_4 emission rates by factors of 2 to 4 times compared with control plots [49,60]. Although applications of rice straw to Japanese rice fields strongly increased CH_4 emission, application of compost slightly increased the CH_4 emission [47,60]. Grass straw applied to Texas rice fields also increased CH_4 emission, but decreased grain yield [45]. Added organic matter to California paddy fields was the major factor affecting methane emissions, showing that the total methane emission over the growing season varied from 1.2 g CH_4 m^{-2} (with no added organic matter) to 58.2 g CH_4 m^{-2} (with largest organic matter treatments) [9].

Many other experiments [5,16,31,34,35,59,61] also showed that the application of organic matters strongly increased CH_4 emission from rice paddy fields. The emission rates depend on the amount and kind of organic materials.

Tsutsuki and Ponnamperuma [56] measured CH_4 and CO_2 formed from three added organic materials, compost, rice straw, and green manure, in 8 weeks of submergence at 20 and 30°C under laboratory experiments. The amount of CH_4 produced from green manure is the highest, followed by rice straw and then compost. Methane production may depend on the content of RMC in the organic matter.

CH_4 emission rates and wet-dry season

Neue *et al.* [34] measured methane fluxes in wetland rice fields of Philippines and observed that methane emission fluxes are higher in the dry than in the wet season. The elevated methane production and emission in the dry season was related to higher solar radiation and produced better rice growth. Yagi *et al.* [62,64] reported that there were differences in the emission rates of CH_4 between dry and wet seasons. For example, the estimated emission rates for one cultivation period were 19.5 and 32.2 mg m^{-2} h^{-1} in dry and wet season, respectively at Suphan Buri, Thailand.

CH_4 emission rates and rice planting date

Sass and Fisher [48] showed CH_4 emission rates are dependent on rice planting date as shown in Table 5. Rice fields were planted on three separate dates: April

Table 5. Solar radiation, seasonal methane flux, and rice yield for three different planting dates, without and with incorporated straw [48]

Planting data, straw addition	Average solar radiation (Ei m^{-2} d^{-1})	Seasonal CH_4 emission (g m^{-2})	Rice grain yield (g m^{-2})
April 13, 1990			
No straw	49.3	37.3	994
Straw	49.3	47.9	846
May 18, 1990			
No straw	44.2	22.8	850
Straw	44.2	35.6	784
June 18,1990			
No straw	39.2	22.0	770
Straw	39.2	23.5	668

13, May 18 and June 18 of 1990 to create a range in plant and soil temperatures, solar radiation and microbial substrates. Experiments were performed on a Verland silty clay loam in Texas. They pointed out that CH_4 emission rates, measured through the cultivation period, varied markedly with planting date and straw addition. The highest emission rate originated from the earliest planted straw-supplemented field. In general, CH_4 emission decreased with later plantings that received less solar radiation. Annual emission rates of CH_4 and rice grain yields from individual fields were positively correlated with accumulated solar radiation for both straw-incorporated and control plots.

CH_4 emission rates on water treatment

Sass *et al.* [46,48] investigated the effects of different water management programs on CH_4 and rice grain yield using four treatments: normal permanent flood (49 days post planting), normal flood with mid-season drainage aeration, normal flood with multiple drainage aeration, and late food (76 days post planting). Methane emission rates varied markedly with water regime, showing the lowest seasonal total emission (1.2 g m^{-2} d^{-1}, 0.6 mg m^{-2} h^{-1}) with the multiple-aeration treatment and the highest (14.9 g m^{-2} d^{-1}, 6.3 mg m^{-2} h^{-1}) with the late flood as shown in Table 1. These results indicate that, with sufficient water to allow for draining and reflooding the rice fields at intervals of 2–3 weeks, CH_4 emissions from flooded rice fields can be essentially eliminated without seriously effecting rice grain yield.

Minami [33] summarized the results of water percolation effect on methane emission in Japan. The CH_4 flux from the lysimeter without water percolation plot (0 mm per day) increased with progressive reduction of soil and the increase of soil temperature. Compared with the case of 0 mm per day per plot, the fluxes from the lysimeters with water percolation, even at the rate of 5 mm per day per plot, were significantly reduced. In the plot of 20 mm per day percolation, the flux was maintained at quite a low level throughout the flooding period. During the 1989 cultivation period, emission rates of CH_4 from the lysimeter paddy fields percolated at the rates of 0, 5 and 20 mm per day were 2.6, 1.4 and 0.1 mg per m^2 per h, respectively.

Yagi *et al.* [63] also investigated the effects of different water management programs on CH_4 emission and rice grain yield under field experiments using an automated chamber method. Compared with the case of continuously flooded plots, the fluxes from the intermittently drained plots (1991: 4 and 6 days, 1993: 7 days and interval irrigation) were significantly reduced. During the cultivation periods, CH_4 emission rates from the continuously flooded plot and intermittently irrigated plot were 8.4 and 4.9 mg m^{-2} h^{-1} in 1991, and 3.0 and 1.7 mg m^{-2} h^{-1} in 1993, respectively.

The results of these experiments suggest that CH_4 emission from paddy fields is able to be controlled with water management.

CH_4 emission rates and other chemical amendments

One of our continuing goals is to characterize all factors that influence the emission of CH_4 from rice fields. To attain the goal there is one way to use the chemical amendments application to rice fields.

Lindau *et al.* [30] measured CH_4 fluxes associated with the application of a common soil amendment, calcium sulfate, at rates of 0, 1 and 2 t ha^{-1} to flooded rice fields treated with urea (128 kg ha^{-1}). They found that the low and high rate of $CaSO_4$ reduced CH_4 emission 29 and 46%, respectively, compared to control fields as shown in Table 1.

The effectiveness of wax-coated carbide (as a slow-release source of acetylene) and nitrapyrin in inhibiting emission of CH_4 was evaluated in a microplot study with dry-seeded, flooded rice grown on a grey clay in Australia [17]. Their results showed that the application of nitrapyrin and wax-coated calcium carbide significantly reduced CH_4 emission by the flooded soil from 15.4 g ha^{-1} day^{-1} in the control treatment to 5.8 and 2.8 g CH_4 ha^{-1} day^{-1}, respectively.

CH_4 emission rates and plant growth

Sass and Fisher [48] summarized the relationship between CH_4 emission and biomass production of rice for different soils over a period of three years, for three different planting dates without and with incorporated straw (Table 5), for various straw residue treatments (Table 6), and for various water management procedures (Table 7) [44,45,46]. Annual emission rates of CH_4 and the amount of rice grain yield from individual fields were positively correlated with accumulated solar radiation for both straw-incorporated and control plots. Straw incorporation resulted in decreased grain yield and increased CH_4 emission in all three fields. They postulate that solar radiation and hence photosynthetic activity of the rice plant correlates with CH_4 production and grain yield through partitioning of nonstructural carbohydrates to the root system and grain panicle [48].

Four water management schedules were investigated as described before [48]: normal permanent flood with a mid-season drainage aeration, normal flood drainage aeration of 2–3 days each, and late flood as shown in Table 7. Methane emission rates varied markedly with water regime showing the lowest seasonal total emission with multiple aeration. The multiple-aeration treatment, relative to conventional floodwater treatment, reduced CH_4 emission by almost 90% with no decrease in grain yield in return for a fourfold increase in water usage.

Although there are some field experiments that investigated the relationship between CH_4 emission and grain yield in China, Japan, Thailand and Indonesia [5,16,24,35,63], the results are not necessarily in agreement. In general, when organic matter was applied to the fields, CH_4 emission rates strongly increased, but the rice yield was not higher compared to chemical fertilizer application.

Mitigation of methane flux from rice paddy fields

Human requirements for food and fiber have led to widespread conversion of natural ecosystems to agricultural use. This extensive land use change, coupled with agricultural production practices and other anthropogenic effects, has had a substantial impact on the biogeochemical cycles that determine atmospheric concentrations of CO_2, CH_4 and N_2O [14]. Among the activities contributing to current anthropogenic emissions of CH_4, IPCC [15] estimated the global emission rate from paddy fields ranged from 20 to 150 Tg yr^{-1}, averaging 60 Tg yr^{-1}, and accounts for about 5–30% of total emission from all sources.

The IGAC CH_4 from rice paddy working group evaluated possibilities for reducing CH_4 emissions in the National Inventories of CH_4 and N_2O Workshop [23]. They concluded that four principles must be followed in recommending or testing any proposal to reduce CH_4 emissions from rice agriculture:

1) The yield should not be decreased, and probably increased, by a mitigation practice.
2) There should be some additional benefit to the farmer, such as better water utilization or reducing of labor.
3) The rice varieties used should be desired by local consumers.
4) The mitigation practice should not increase emissions of other greenhouse gases, particularly N_2O

The factors of CH_4 emission control also form the basis for development of practices to decrease CH_4 emissions. Currently available technology includes floodwater control and type of N fertilizers. It seems that different rice cultivers have different capacities for CH_4 emissions as shown in Table 1. Experiments using ammonium sulfate and coated calcium carbide decrease CH_4 emissions [30]. Fertilizing with ammonium sulfate supplies is to supply N and sulfate which maintains the soil Eh above -200mV because CH_4 is produced at less than -200mV of soil Eh. Coated calcium carbide is used to slowly produce small quantities of acetylene over time [1,4,17] to limit nitrification and CH_4 production.

Table 6. Seasonal CH_4 flux, rice yield and aboveground biomass production for various straw residue treatments [48]

Resident treatment	Seasonal CH_4 emission (g m^{-2})	Rice grain yield (g m^{-2})	Total aboveground biomass (g m^{-2})
Fallow (Control)	13.11	832	2344
Late tillage	15.81	803	2290
Not tillage	16.51	853	2412
Burned straw	18.01	859	2244
Early tillage	14.22	874	2240

Table 7. Seasonal CH_4 flux, rice yield and aboveground biomass production for various water management procedures [48]

Water treatment	Seasonal CH_4 emission (g m^{-2})	Rice grain yield (g m^{-2})	Total aboveground biomass (g m^{-2})
Late flood	14.98	640	1610
Normal flood	9.27	825	2410
Mid season aeration	4.86	820	2346
Multiple aeration	1.15	813	2428

Conclusion

Recent research has begun to identify various agricultural management practices that could reduce CH_4 emission from rice paddy fields. Table 1 shows that identifying and controlling the effects described above has the potential to reduce CH_4 emission from rice cultivation: the form and amount of nitrogen and other chemical fertilizers, the method of fertilizer applications, the application of another chemical amendments, water management, cultivar selection and cultivation practices. However, we need much additional research to establish and demonstrate practices that will maintain or increase rice productivity using nitrogen fertilizer while reducing CH_4 emissions from rice cultivation.

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