CH_4 EMISSIONS FROM RICE AGRICULTURE

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ABSTRACT

Atmospheric methane (CH_4) is recognized as one of the most important greenhouse gases and may account for 20 percent of anticipated global warming. Flooded rice fields are a significant source of atmospheric CH_4. The emission is the net result of opposing bacterial processes, production in anaerobic microenvironments, and consumption and oxidation in aerobic microenvironments, both of which can be found side by side in flooded rice soils. This paper outlines options and issues for good practice guidance in the national inventory management of methane emissions from rice fields. The issues are presented in three sections: methodological issues, reporting and documentation, and inventory quality.

There are two methodological tiers in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)*. Measurement of methane emission using a Tier 2 approach is accurate in that the data reflects conditions specific to the agronomic practices, soil properties, and climate of site-specific studies within a country. Where actual measurements are not available, Tier 1 default data must substitute for site-specific data. The accuracy and precision of Tier 2 methane emission estimates increase with both the number of sites tested and the frequency and number of measurements at each site. A standard measurement technique is recommended in the IPCC Guidelines and is reviewed in this paper. Other data such as area studies, soil maps, and climate information are necessary to the success of the reported data. Crop yield and other grain production data are also important in assessing the quality and accuracy of methane emission levels.

Currently, many countries have sponsored scientific studies of methane emission from rice fields. Unfortunately, most of these studies have been concerned with process level differences in methane emissions in small sites. Few studies have addressed the problem of scaling up to regional or country levels, mainly because of the large variation in methane emission due to the large number of factors that influence the process. Because China is the largest producer of irrigated rice, extensive studies have been conducted in that country to determine a countrywide emission value. Those studies are reviewed in this paper and may be of value to other countries in designing and carrying out similar studies. Various predictive models have been recently published that may also aid in reporting methane emission values.

Ensuring the quality of an inventory also requires that countries implement quality assurance (QA) and quality control (QC) programmes. The common thread throughout the quality assurance process is the need for thorough documentation and complete transparency. QA/QC activities will need to occur at several steps in the process. At the rice field level, key elements should include the accurate recording of measurements of climate, agronomic, and soil factors that accompany measured seasonal methane emissions. These records should be well documented and available to reviewers. The inventory agency must ensure the accuracy of submitted scientific reports as well as the compiled inventory. It will also be responsible for providing documentation and reporting sufficient information to the United Nations Framework Convention on Climate Change (UNFCCC). One or more different types of external reviews and audits may also be appropriate, and each will require complete documentation.

1 INTRODUCTION

1.1 Nature, magnitude, and distribution of source

Overview of methane emissions from rice fields

The processes involved in methane emission from flooded rice paddies to the atmosphere include methane production in the soil by methane-producing bacteria (methanogens), methane oxidation within oxic zones of the soil and flood water by methane-oxidizing bacteria (methanotrophs), and vertical transport of the gas from soil to the atmosphere. Methane is produced in the terminal step of several anaerobic microbial degradation chains. The amount of methane produced in flooded rice soils is primarily determined by the availability of methanogenic substrates and the influence of environmental factors. The sources of organic carbon for methanogenic substrates are primarily rice plants via root exudation, root senescence and plant litter (Holzapfel-Pschorn and Seiler, 1986; Schütz et al., 1991; Lu et al., 1999) or added organic matter for fertilization and remains from previous crop (Schütz et al., 1989a; Yagi and Minami, 1990; Sass et al., 1991a; Cicerone et al., 1992; Wassmann et al., 1993b, Denier van der Gon & Neue, 1995). The effect of added organic matter for fertilization depends on type and amount. Examples of types of organic amendments are green manure (fresh biomass), rice straw from previous crop, animal manure, or compost, each of which affects methane emissions differently. Environmental factors affecting methane production include soil texture (Neue et al., 1994; Sass et al., 1994), climate (Schütz et al., 1990; Sass et al., 1991b), and agricultural practices, such as water regime and management (Inubushi et al., 1990a and b; Sass et al., 1992; Wassmann et al.; 1995 Lewis, 1996; Yagi et al., 1996, Wassmann et al., 2000).

Plant-mediated transport is the primary mechanism for the emission of methane from rice paddies, with as much as 90% of CH_4 transported to the atmosphere through the aerenchymal system of the rice plants (Cicerone & Shetter, 1981; Holzapfel-Pschorn and Seiler, 1986; Schütz et al., 1989). The rice aerenchymal system not only transports methane from the flooded rice to the atmosphere but also promotes the movement of atmospheric oxygen into the rhizosphere supporting root respiration and methane oxidation (De Bont et al., 1978; Conrad & Rothfuss, 1991; Gerard and Chanton, 1993). More than 50% of the generated methane is oxidized during the early phase of the vegetation period, whereas up to 90% is consumed during the late season of rice maturation (Schütz *et al.,* 1989; Sass *et al.*, 1992). Consequently, the emitted fraction of the produced methane decreases with rice growth and development.

Rice is grown under a variety of climatic, soil and hydrological conditions in nearly 90 countries of the world and on all continents except Antarctica. Fields of rice are found from northern regions of China and Japan (50° North) to southern regions of Australia (40° South) and from sea level to altitudes of more than 2,500 meters. Rice is a unique crop in that it tolerates a broad range of soil water content. It grows well in flood prone areas of South and Southeast Asia (as much as 5 meters of floodwater) and in drought-prone upland areas of Asia, South America, and Africa (Neue and Sass, 1994). The ecosystems within which rice is grown are characterized by elevation, rainfall pattern, depth of flooding and drainage, and by the adaptation of rice to these agroecological factors.

The available data base indicates that the emission per m^2 and season follows the order: irrigated rice ≥ continuously flooded rice > flood prone rainfed rice ≥ deepwater rice > drought prone rainfed rice > tidal rice. However, this ranking only provides an initial assessment of the emission potentials that can locally be superseded by crop management favouring or lowering actual emission rates (Wassmann et al., 2000a,b). Upland rice is not a source of CH_4, since it is grown in aerated soils that never become flooded for a significant period of time. Irrigated rice has the highest CH_4 source strength. Differences in residue recycling, organic amendments, scheduled short aeration periods, soils, fertilisation, and rice cultivars are major causes for variations of CH_4 fluxes in irrigated rice. Highest CH_4 fluxes are observed in fields receiving organic amendments. Lowest CH_4 fluxes are recorded in fields with low residue recycling, multiple aeration periods, poor soils and low fertilisation with resulting poor rice growth and low yields. The source strength of rainfed rice is most uncertain because of its high variability in all factors controlling CH_4 emissions. Summary values of CH_4 emissions for different rice ecosystems located in different countries are shown in Table 1. These fluxes show reasonable consistency with respect to a particular ecosystem (Neue and Sass, 1998).

TABLE 1
MINIMUM, MAXIMUM AND MEDIAN OF REPORTED CH_4 FLUXES FROM RICE FIELDS
(FROM SEEDING OR TRANSPLANTING TO HARVEST)

Country	No. of observations	Mean emission rate (g CH_4 $m^{-2}day^{-1}$)			Seasonal emission (g CH_4 m^{-2})			Reference
		min.	median	max.	min.	median	max.	
China								
• irrigated	74	0.06	0.34	1.41	5	34	155	Wang M. X. et al. 1993
								Wang M.X. 1995; Lu et al. 1995
India								
• irrigated	7		0.02		0.06	0.74	2	Mitra 1992
• irrigated	25	0.09	0.24	0.41	6	20	3	Adhya et al. 1994, CRRC 1996
• rainfed	8				5	17	60	Mitra 1992
• deepwater	7				14	19	24	Mitra 1992
Indonesia								
• irrigated	10	0.16	0.52	0.78	14	31	47	Nugroho et al. 1994;
• rainfed	4	0.01	0.06	0.10	4	8	10	Makarim et al. 1995
Italy								
• irrigated	22	0.10	0.29	0.68	12		77	Holzapfel-Pschorn & Seiler 1986; Schütz et al. 1989
Japan								
• irrigated	28	0.01		0.39	1		45	Yagi& Minami 1990,1991;
								Kimura & Minami 1995
Korea (ROK) • irrigated	4	0.07	0.24	0.46	9	33	63	Shin Y. K. et al 1995
Philippines								
• irrigated	56	0.09	0.25	0.79	10	27	87	IRRI 1996; Metra-C.et al.1995
• rainfed	1	0.09			7			
Spain								
• irrigated	1	0.10			12			Seiler et al.1984
Thailand								
• irrigated	27	0.38	0.48	0.72	34	48	86	Jermsawatdipong et al. 1994 a, b,
• rainfed	4	0.02	0.15	0.45	1	15	68	Chairoj, 1994;
								Kimura&Minami 1995;
• deepwater	2	0.09		0.17	12		32	Charoensilp et al.1995;
								Siriratpiriya 1994
USA								
• irrigated	41	0.05	0.27	0.55	1	25	48	Lindau et al 1991;
								Cicerone et al, 1992;
								Sass & Fisher 1995

Source: Neue and Sass, 1998.

Default values for various water regimes and organic amendments

Based on reported observed methane emissions, proposed OECD/*IPCC* default values discriminate rice fields and respective CH_4 emissions according to rice ecology and introduce factors for organic amendments and water regimes (IPCC, 1997 a and b). These default guidelines are presented in Table 2. A default seasonally integrated methane emission of 20 g m^{-2} is recommended for continuously irrigated and continuously flooded lowland rice ecosystem without organic amendments with proportionately lower values for other ecosystems and a multiplier factor of 2 (range 2-5) for emissions for the corresponding rice ecosystems with organic amendments. A multiplier factor for added organic amendments is a simplification because in reality the effect of organic inputs on methane emission should be treated as an added factor dependent on the amount and type of organic material supplied.

TABLE 2

SCALING FACTORS FOR METHANE EMISSIONS FOR RICE ECOSYSTEMS RELATIVE TO CONTINUOUSLY FLOODED FIELDS WITHOUT ORGANIC AMENDMENTS

Category	Sub-Category[a]			Scaling Factors (Relative to Emission Factors for Continuously Flooded Fields)
Upland	None			0
Lowland	Irrigated	Continuously flooded		1
		Intermittently flooded[b]	Single aeration	0.5 (0.2-0.7)
			Multiple aeration	0.2 (0.1-0.3)
	Rainfed	Flood prone		0.8 (0.5-1.0)
		Drought prone		0.4 (0-0.5)
	Deep water	water depth > 50-100 cm		0.8 (0.6-1.0)
		water depth > 100 cm		0.6 (0.5-0.8)

[a] Other rice ecosystem categories, like swamps, inland, saline or tidal wetlands may be discriminated within each sub-category according to local emission measurements.

[b] Defined as > 3 days aeration during the vegetative period

Note: For irrigated and continuously flooded, lowland rice ecosystems, the default seasonally integrated methane emission is 20 g m-2 for soils 'without organic amendments'. For conversion to methane emissions from soils 'with organic amendments', apply a default correction factor of 2 (Range 2-5) to the corresponding rice ecosystem for the 'without organic amendment' category.

Source: IPCC Guidelines for National Greenhouse Gas Inventories, 1997.

Range of observed seasonal emissions

Observed seasonal methane emissions from rice fields reported from several countries around the world show large ranges, reflecting the effects of local as well as regional differences in agricultural, biological, and climatic factors. An average of the median country methane emission values from irrigated rice (Table 1) is 27.23 g m^{-2}, with a range from a minimum value of less than 1 g m^{-2} to a maximum value of 155 g m^{-2}. A comparable data set from five countries (China, India, Indonesia, Thailand and Philippines) obtained under a network co-ordinated by the International Rice Research Institute showed averages of less than 30 gCH_4 m^{-2} under mineral fertilisation (Wassmannm et al., 2000a). Emissions under organic amendments were generally higher than 20 gCH_4 m^{-2} except for the site in Northern India where average emissions remained as low as 2 gCH_4 m^{-2} (Wassmann et al., 2000a). Although a compilation of measurements indicates that the average median value from all countries is reasonably close to the IPCC default value of 20 g m^{-2} (Table 2), median values vary somewhat from country to country and the ranges from the several countries are quite large, as expected. Thus the default value of 20 g CH_4 m^{-2} is reasonable as a benchmark.

In Texas, between 1991 and 1995, 32 seasonal methane emission rates were measured under conditions of continuous flooding, no organic amendments, in three different soil types with 11 different rice cultivars. The measured values were compared with simulated values calculated using a semi-empirical process level model (Huang et al., 1998a). These studies show a measured mean (±standard deviation) CH_4 emission of 21.99 (±8.53) g m^{-2} and a median value of 19.84 g m^{-2}. The application of the model results in a calculated mean CH_4 emission of 21.63 (±7.18) g m^{-2} and a median value of 21.69 g m^{-2}. Both observed and calculated values are seen to be in close agreement with the proposed *IPCC* default base value of 20 g m^{-2}. However, within this data set, temporal climate variations, different soil textures, multiple rice varieties, and natural differences in growing conditions are reflected in a spread of observed seasonal methane values ranging from a minimum value of 6.31 g m^{-2} to a maximum value of 41.05 g m^{-2}. The model is able to account for most of these variations. This is reflected in a calculated minimum emission value of 7.40 g m^{-2} and a maximum value of 36.90 g m^{-2}.

The situation is similar for rainfed and deepwater rice. For rainfed rice, the average median observed value is 13.33 g m^{-2} and reported ranges are from 1 to 68 g m^{-2} (Table 1). The default value (Table 2) for rainfed rice ranges from 8 g m^{-2} (drought prone rice) to 16 g m^{-2} (flood prone rice), consistent with the observed values from Table 1. For deepwater rice, the average median observed value is 19 g m^{-2} with a range from 12 to 32 g m^{-} (Table 1). The default value for deepwater rice (Table 2) ranges from 12 g m^{-2} (50-100 cm water depth) to 16 g m^{-2} (>100 cm water depth).

2 METHODOLOGICAL ISSUES

Methane emission from rice fields is governed by a complex set of parameters linking the physical and biological characteristics of flooded soil environments with specific agricultural management practices. In various regions of the world where rice agriculture is important, the natural and cultural components of these systems vary widely. These variations are reflected in the different values of methane emission rates obtained throughout the world and make it extremely difficult to accurately calculate a total annual methane emission value for a particular country. Whether a Tier 1 or a Tier 2 approach is used to report country emissions from rice fields, these variations must be kept in mind and country specific measurements should be used when at all possible. Default values should be used only when actual data cannot be obtained and then only with caution.

2.1 Estimates of methane emission based on default guidelines

The OECD/*IPCC* default values for country methane emissions from rice fields (IPCC 1997) appearing in Table 2 have been used to estimate emissions using available data from the world rice statistics for 108 countries (Neue and Sass, 1998). These authors varied the assumed basic CH_4 flux from continuously irrigated rice fields without any organic amendment except recycling of roots and stubble from 20 to 30 g m^{-2} to account for possible underestimates due to factors such as soil properties and post drain emissions. Because of lack of data they used a stable fraction of farmers using organic amendments and a stable reduction-factor for rice grown under rainfed conditions (rainfed rice and deepwater rice). An abbreviated version of these calculations (48 countries with the highest calculated methane emissions from rice fields) is presented in Table 3 and includes annual emissions computed from field experiments reported by various countries (Sass, 1994). In general, the calculated emissions agree well with measured values reported by various countries, except for India. This discrepancy is addressed in a recent review by Neue and Sass (1998). Summing the various country values results in a calculated annual world total methane emission from rice paddies of 33-49 Tg.

TABLE 3
WORLD RICE FIELD METHANE EMISSIONS BY COUNTRY

Country Methane= (Fraction inorganic+2 ● fraction organic) ● (irrigated area+rainfed factor ● rainfed area) ● world methane constant

			Fraction of farmers using organic amendments						0.4	0.4	0.4	
			World methane g/m^2 100% irrigated,no organic ammends.						20	25	30	
			Factor for rainfed rice						0.7	0.7	0.7	
			Factor for upland rice						0	0	0	
Country	**1996 IPCC Guidelines Area 1000s ha**	**% of total world**	**% of irrigated**	**% of rainfed**	**% upland**	**Irrigated 1000s ha**	**Rainfed 1000s ha**	**Upland 1000s ha**	**Tg CH_4 see above for param.**	**Tg CH_4 see above for param.**	**Tg CH_4 see above for param.**	**Tg CH_4 reported data by country**
China	33,265	22.44	93	5	2	30,936	1,663	665	8.99	11.24	13.48	13-17
India	42,321	28.55	53	32	15	22,430	13,543	6,348	8.93	11.17	13.40	2.4-6
Indonesia	10,502	7.08	72	17	11	7,561	1,785	1,155	2.47	3.08	3.70	4.00
Bangladesh	10,435	7.04	22	70	8	2,296	7,305	835	2.07	2.59	3.11	
Thailand	9,650	6.51	7	92	1	676	8,878	97	1.93	2.41	2.89	0.47-8.77
Vietnam	6,028	4.07	53	39	8	3,195	2,351	482	1.36	1.69	2.03	
Myanmar	4,760	3.21	18	76	6	857	3,618	286	0.95	1.19	1.42	
Philippines	3,319	2.24	61	37	2	2,025	1,228	66	0.81	1.01	1.21	0.31-0.70
Pakistan	2,113	1.43	100	0	0	2,113	0	0	0.59	0.74	0.89	
Japan	2,074	1.40	99	0	1	2,053	0	21	0.57	0.72	0.86	.02-1.04
Kampuchea	1,800	1.21	8	90	2	144	1,620	36	0.36	0.45	0.54	
Korea, Republic	1,242	0.84	100	0	0	1,242	0	0	0.35	0.43	0.52	0.44
USA	1,114	0.75	100	0	0	1,114	0	0	0.31	0.39	0.47	0.04-0.47
Nepal	1,445	0.97	23	74	3	332	1,069	43	0.30	0.38	0.45	

TABLE 3

WORLD RICE FIELD METHANE EMISSIONS BY COUNTRY

Country Methane= (Fraction inorganic+2 ● fraction organic) ● (irrigated area+rainfed factor ● rainfed area) ● world methane constant

Fraction of farmers using organic amendments	0.4	0.4	0.4	
World methane g/m^2 100% irrigated,no organic ammends.	20	25	30	
Factor for rainfed rice	0.7	0.7	0.7	
Factor for upland rice	0	0	0	

Country	1996 IPCC Guidelines Area 1000s ha	% of total world	% of irrigated	% of rainfed	% upland	Irrigated 1000s ha	Rainfed 1000s ha	Upland 1000s ha	Tg CH_4 see above for param.	Tg CH_4 see above for param.	Tg CH_4 see above for param.	Tg CH_4 reported data by country
Brazil	3,945	2.66	19	6	75	750	237	2,959	0.26	0.32	0.38	
Madagascar	1,160	0.78	10	76	14	116	882	162	0.21	0.26	0.31	
Taiwan	700	0.47	97	0	3	679	0	21	0.19	0.24	0.29	
Sri Lanka	828	0.56	37	56	7	306	464	58	0.18	0.22	0.26	
Former USSR	624	0.42	100	0	0	624	0	0	0.17	0.22	0.26	
Nigeria	1,567	1.06	16	33	51	251	517	799	0.17	0.21	0.26	
Iran	570	0.38	100	0	0	570	0	0	0.16	0.20	0.24	
Korea, DPR	670	0.45	67	20	13	449	134	87	0.15	0.19	0.23	
Malaysia	639	0.43	66	22	12	422	141	77	0.15	0.18	0.22	
Egypt	436	0.29	100	0	0	436	0	0	0.12	0.15	0.18	
Columbia	435	0.29	67	10	23	291	44	100	0.09	0.11	0.14	
Laos	638	0.43	2	61	37	13	389	236	0.08	0.10	0.12	
Guinea	608	0.41	8	45	47	49	274	286	0.07	0.08	0.10	
Tanzania	375	0.25	3	75	22	11	281	83	0.06	0.07	0.09	
Italy	208	0.14	100	0	0	208	0	0	0.06	0.07	0.09	
Ecuador	266	0.18	40	50	10	106	133	27	0.06	0.07	0.08	
Afghanistan	173	0.12	100	0	0	173	0	0	0.05	0.06	0.07	
Peru	185	0.12	84	0	16	155	0	30	0.04	0.05	0.07	
Cuba	150	0.10	100	0	0	150	0	0	0.04	0.05	0.06	
Uruguay	108	0.07	100	0	0	108	0	0	0.03	0.04	0.05	
Venezuela	119	0.08	90	0	10	107	0	12	0.03	0.04	0.04	
Argentina	103	0.07	100	0	0	103	0	0	0.03	0.04	0.04	
Australia	102	0.07	100	0	0	102	0	0	0.03	0.04	0.04	
Dominican Rep	93	0.06	98	0	2	91	0	2	0.03	0.03	0.04	
Spain	81	0.05	100	0	0	81	0	0	0.02	0.03	0.03	
Sierra Leone	339	0.23	1	32	67	3	108	227	0.02	0.03	0.03	
Iraq	78	0.05	100	0	0	78	0	0	0.02	0.03	0.03	
Guyana	68	0.05	95	0	5	65	0	3	0.02	0.02	0.03	
Ivory Coast	583	0.39	6	7	87	35	41	507	0.02	0.02	0.03	
Surinam	58	0.04	100	0	0	58	0	0	0.02	0.02	0.02	
Mali	222	0.15	25	0	75	56	0	167	0.02	0.02	0.02	
Turkey	52	0.04	100	0	0	52	0	0	0.01	0.02	0.02	
Mexico	123	0.08	41	0	59	50	0	73	0.01	0.02	0.02	

TABLE 3 (CONTINUED)
WORLD RICE FIELD METHANE EMISSIONS BY COUNTRY

Country Methane= (Fraction inorganic+2 ● fraction organic) ● (irrigated area+rainfed factor ● rainfed area) ● world methane constant

			Fraction of farmers using organic amendments						0.4	0.4	0.4	
			World methane g/m^2 100% irrigated,no organic ammends.						20	25	30	
			Factor for rainfed rice						0.7	0.7	0.7	
			Factor for upland rice						0	0	0	
Country	**1996 IPCC Guidelines Area 1000s ha**	**% of total world**	**% of irrigated**	**% of rainfed**	**% upland**	**Irrigated 1000s ha**	**Rainfed 1000s ha**	**Upland 1000s ha**	**Tg CH_4 see above for param.**	**Tg CH_4 see above for param.**	**Tg CH_4 see above for param.**	**Tg CH_4 reported data by country**
Romania	37	0.02	100	0	0	37	0	0	0.01	0.01	0.02	
Zaire	393	0.27	5	5	90	20	20	354	0.01	0.01	0.01	
Total (n=48)	146,804	99	57	32	11	83,779	46,723	16,302	32.62	40.77	48.92	
Rest of World (n=58)	1,435	1	32	2	67	456	22	958	0.00	0.16	0.20	
Total (n=106)	148,239	100	57	32	12	84,235	46,744	17,260	33	41	49	

2.2 Statistical framework for country emission reporting

Background of the problem

Several options exist for reporting country estimates of methane emissions from rice fields as a component of national greenhouse gas inventories. Scientists in many rice growing countries have and are gathering local seasonal emission data as part of process level studies. The high spatial and temporal variability of such measurements, even within small scales, severely limits one's ability to define source strengths of large regions or countries. The problem is primarily a statistical one. Merely increasing the number of sites of CH_4 flux measurements may not reduce uncertainties.

Regional or country emissions from microsite emission factors

The annual methane emission, F_T, for a region or country may be represented by the sum of contributions from identifiable homogeneous areas:

$$F_T = \Sigma_i \Sigma_j \Sigma_k E_{ijk} \bullet A_{ijk} \qquad (1)$$

Where:

E_{ijk}: the methane flux measured under a specific set of different biological, chemical and physical factors (i,j,k) that control methane emission and

A_{ijk}: the corresponding areal extent.

If A_T is the total area under consideration, then

$$\begin{aligned} A_T &= \Sigma_i \Sigma_j \Sigma_k A_{ijk} \\ &= \Sigma_i \Sigma_j \Sigma_k X_{ijk} A_T \qquad (2) \end{aligned}$$

Where:

X_{ijk} is the fraction of the total area represented by specific values for the parameters i, j, and k.

Thus, we can represent F_T as

$$
\begin{aligned}
F_T &= \Sigma_i \Sigma_j \Sigma_k E_{ijk} \bullet A_{ijk} \\
&= \Sigma_i \Sigma_j \Sigma_k E_{ijk} \bullet X_{ijk} A_T \\
&= A_T \Sigma_i \Sigma_j \Sigma_k E_{ijk} \bullet X_{ijk} \\
&= A_T \langle E_{ijk} \rangle \qquad (3)
\end{aligned}
$$

and, if the total area, AT is known, FT can be calculated from a knowledge of the average emission value $\langle E_{ijk} \rangle$. The average emission value, $\langle E_{ijk} \rangle$, can be arrived at in practice by simply averaging all of the existing emission data for the area AT. As more and more data are collected, more terms are used to calculate an ever-changing average value.

2.3 Country emission values from simulation and process level models

Several process level models exist for calculating country level methane emissions from rice fields. These have primarily been applied to China. Employing a simplified version of a process-based methane emission model described by Cao et al. (1995a) and a geo-referenced database, methane emission rates from 329 defined agricultural zones in China were estimated (Cao et al., 1995b). The model was based on the influences of climate, soil texture, agricultural management and rice growth on flux rates. Calculated annual methane emissions ranged from 25 to 80 g m^{-2}. On average across the rice growing area of China, 59.9 g m^{-2} methane was released annually. The total calculated methane emission of the rice paddies of China was estimated as 16.2 Tg CH_4 yr^{-1}.

China has developed, since 1990, a national inventory “Report on Greenhouse Gas Inventory Studies from Non-energy Sources” based on estimations performed at the Chinese Academy of Science, Institute of Atmospheric Physics, the Chinese Academy of Agricultural Sciences, Agrometeorology Institute and Beijing Forest University (Wang, M. X. et al., unpublished). Based on the results of 14 measurement sites and employing a simplified version of the simulation model (Ding and Wang, 1996) utilizing data on weather, soil texture and pH, organic matter inputs, cropping systems, irrigation and fertilizer use, daily emission coefficients and harvest areas were established for each individual province. Daily emission rates ranged from 0.028-0.200 g m^{-2} for early rice and single cropped rice, from 0.076-0.526 g m^{-2} for late rice and 0.069-1.352 g m^{-2} for single cropped late rice, waterlogged and wheat-rice cropping systems. A total emission of 9.6-12.7 Tg CH_4 yr^{-1} was estimated for the year 1990.

A model developed by Huang et al. (1998a) was further validated against field measurements from various regions of the world and calibrated to estimate methane emission from irrigated rice cultivation of China (Huang et al., 1998b). On the basis of available information on rice-cultivated area, growth duration, grain yield, soil texture and temperature, methane emission from Chinese rice paddies was estimated for each rice-growing province in the mainland. The calculated daily methane emission rates, on a provincial scale, ranged from 0.15 to 0.86 g m^{-2} with an average of 0.32 g m^{-2}. Comparisons of the estimated with the observed emission rates show that the estimates were in general close to the measurements obtained at most locations. A total amount of 9.66 Tg CH_4 $year^{-1}$, ranging from 7.19 to 13.62 Tg CH_4 $year^{-1}$, was estimated to be released from Chinese rice paddy soils.

A simulation model describing the main processes involved in methane emissions from flooded rice fields was recently developed by linking an existing crop simulation model (CERES-Rice) to a model describing the steady-state concentrations of methane and oxygen in a soil profile (Matthews et al., 2000). The model was linked to a spatial database in a Geographical Information System (GIS) environment (Knox et al., 2000) for upscaling of emissions for China, India, Indonesia, Thailand and the Philippines. Annual combined emissions were calculated under different crop management scenarios and ranged from 31 Tg CH_4 (field drainage, no organic manure) to 63 Tg CH_4 (continuous flooding, with organic manure) for these five countries that comprise approximately 70% of the global rice area (Matthews and Wassmann, 2000)

2.4 Activity data

For Tier 1 reporting, only the area extent of rice cropping is required and should be divided by ecosystem type (upland, irrigated, rainfed, etc.). For more detailed reporting, a Tier 2 approach may divide the country into specific regions using soil characterisation among other agronomic and climate variables.

Activity data include data on the area extent of rice agriculture, climate, soil characterisation, and crop yields. Some data on inorganic fertiliser usage may also be available. Data on area extent and crop yield is generally collected on the local level and transmitted to a national data bank. These data are normally used to determine national policy; particularly where rice is an important component of the country diet. Soil characterisation differs from country to country, but generally includes texture and carbon content.

2.5 Uncertainty

Methane emission from most agricultural systems is the result of several biological processes, which, by nature, are highly variable both spatially and temporally. As a result, emission factors are highly uncertain, even when measured very carefully. This uncertainty drops with the addition of more carefully chosen experimental measurements, which consider the several parameters characterising the emission factors.

An example of the natural variation in emission factors can be found in the three-year data set shown in Table 4 from a report monitoring greenhouse gas emissions from the Japan Soil Society (1996). It illustrates temporal variation (annual variability in methane emissions) and spatial variation (soil type variability in methane emissions). Upper rows of each year show average seasonal methane emission factors (g m^{-2}), and lower rows standard deviation. Numbers in parentheses are the number of experimental observations. All data are for rice straw applied plots (incorporated immediately after harvest) and normal Japanese cropping treatment.

TABLE 4
METHANE EMISSION FACTORS (G M-2) WITH STANDARD DEVIATIONS
DATA AREA COMPARISON FROM VARIOUS SOILS IN JAPAN

Year data collected	Volcanic Ash soil	Yellow soil	Glay lowland soil	Gley soil	Peat soil	Average
1992	9.98 (2)	17.8(3)	19.9(21)	16.3(4)	16.3(2)	18.4(32)
St. Dev.	4.12	3.56	10.2	7.93	3.25	9.25
1993	5.93(2)	29.5(4)	19.3(17)1	20.4(6)	22.6(2)	20.2(31)
St. Dev.	0.53	12.8	12.7	9.36	0.40	12.3
1994	9.60(2)	15.9(4)	18.0(20)	15.5(4)	41.5(2)	18.3(32)
St. Dev.	4.40	1.16	13.9	10.1	29.3	15.5
3 year ave.	8.50(6)	21.4(11)	19.1(58)	17.8(14)	26.8(6)	19.0(95)
St. Dev.	3.94	10.1	12.3	9.47	20.1	12.5

2.6 General emission calculation procedure

Module 4 (Agriculture) of the *IPCC Guidelines*: Workbook, contains instructions (Section 4.3 Rice Cultivation) and a worksheet (Worksheet 4-2) for country reporting of methane emissions from rice fields. Chapter 4 (Agriculture) of the Reference Manual (1997b) contains additional information related to reporting in section 4.3 Methane Emissions from Rice Cultivation: Flooded Rice Fields. Table 5 of this paper is a reproduction of the Worksheet 4-2. E_{ijk}, the methane flux associated with a specific set of agronomic, climatic, biological, chemical and physical factors (i,j,k), is the product of entries in columns B, C and D and A_{ijk} is the corresponding harvested area (m^2) in column A of Table 5. The factor 10^{-9} in column A converts the resulting calculation (column E) from grams to Gigagrams (Gg).

Determination and categorization of harvest area (Table 5, Column A)

This methodology recognizes that rice grown under different water management regimes must be treated differently and divides the total harvested area into upland and lowland rice. Upland fields are never flooded for a significant period of time. Upland rice is not a source of CH_4, since it is grown in aerated soils and is thus not reported. Lowland fields are flooded for a significant period of time and are divided into irrigated, rainfed and deep water rice agriculture. Irrigated systems are subdivided into continuously flooded and intermittently flooded with a further division of intermittently flooded rice into a single aeration or multiple aeration water management. Continuously flooded fields have standing water throughout the rice growing season and may only dry in preparation for harvest. Rainfed rice, in which water regime depends solely on precipitation, is subdivided into flood prone and drought prone. In flood prone rice, the water level may rise up to 50 cm during the cropping season. Drought prone rice is such that drought periods occur during every cropping season. Deep-water rice is subdivided into fields inundated with water depths between 50 and 100 cm and fields with water depths exceeding 100 cm. Some countries may also grow tidal wetland rice, which can be added to the table as a separate category. The listed water management area categories may require additional subdivisions when experimental data for regional differences in such factors as agronomic practice, cultivar choice, type of organic amendment, or different soil properties are available and show differences in relevant emission factors.

TABLE 5
COUNTRY WORKSHEET FOR METHANE EMISSIONS FROM FLOODED RICE FIELDS

Module	Agriculture
Submodule	Methane Emissions from Flood Rice Fields
Worksheet	4-2
Sheet	1 of 1

Water Management Regime			A Harvested area ($m^2 \bullet 10^{-9}$)	B Scaling Factor	C Correction Factor for Organic Amendment	D Seasonally Integrated Emission Factor for Continuously Flooded Rice without Organic Amendment (g/m^2)	E CH_4 Emissions (Gg) E=(A ● B ● C ● D)
Irrigated	Continuously Flooded						
	Intermittently Flooded	Single Aeration					
		Multiple Aeration					
Rainfed	Flood Prone						
	Drought Prone						
Deep Water	Water Depth >50-100 cm						
	Water Depth > 100 cm						
Totals							

Source: IPCC Guidelines for National Greenhouse Gas Inventories: Workbook, 1997.

General methane emission factors

E_{ijk}(Equation 1), the methane flux emission factor associated with a specific set of agronomic, climatic, biological, chemical and physical factors ($_{i,j,k}$), is the product of entries in columns B, C and D of the Greenhouse Gas Inventories Worksheet reproduced in Table 5. The worksheet considers the methane flux to be the product of three components: a scaling factor (Column B), a factor for the inclusion of organic amendments (Column C) and a country-specific seasonally integrated basic methane emission factor for continuously irrigated rice systems without organic fertilizer. The primary division of reported data specifies major rice ecosystems: irrigated, rainfed, and deepwater. Table 1 presents a summary of experimentally measured minimum, median and maximum daily and seasonal methane emission values. In general,, the emissions from irrigated rice > flood prone rainfed rice ≥ deepwater rice > drought prone rainfed rice. These measurements were obtained under a variety of conditions and demonstrate a wide range of emission values dependent on these conditions. It should be observed that the median values and ranges vary from country to country and reflect the range of climatic, soil, and agronomic practices of a particular country.

Scaling factors (Worksheet Column B)

Scaling factors for various categories of water treatment are reported in column B of Table 5. Default values are suggested in Table 2. These scaling factors are relative to a unit value for emissions from continuously flooded fields without organic amendments and are based on best estimates derived from experimental values reported throughout the world's rice growing countries. The default value for each scaling factor is accompanied by a range that may show as much as a 50% deviation from the default value. In the case of intermittently flooded fields, the scaling factor will depend on the rice growth stage and the duration and frequency of aeration. The default value of 0.5 associated with a single aeration may range from 0.2 to 0.7 (Sass et al., 1992; Yagi, et al., 1996). This range accounts for differences in methane emission due to the timing of the aeration such as at heading or during tiller formation and the length of the aeration. A short period of water removal may not allow for the complete reestablishment of the pre-flooded soil redox potential and thus may not be as effective in ceasing methane production and emission as a longer period. Multiple aeration suppresses methane emissions even further; resulting in a scaling factor which may range as low as 0.1 to 0.3.

Scaling factors for rainfed rice depend on the amount and duration of precipitation that may vary from country to country and from region to region within a country. This could result in scaling factors ranging from 0 to 0.5 in drought prone areas and from 0.5 to 1.0 in more flood prone areas. Scaling factors for deep-water rice will also vary with respect to depth and duration of the floodwater.

Scaling factors for each major category, derived from either experimental data or from a consideration of the default values, can either be applied by establishing a finer division of the worksheet, or may be arrived at through an averaging process developed from a consideration of area weighted subcategories such as suggested in equation 9 in section 5.2 of this paper.

Inclusion of organic amendments (Worksheet Column C)

The effect of organic amendments for various categories of emission factors is reported in column C of Table 5. For the conversion of methane emissions from soils 'with organic amendments' the default value suggested in Table 2 is a factor of 2, but a range of from 2 to 5 is indicated.

Many studies agree that the application of organic matter to rice paddies strongly increases methane emission rates over that from mineral fertilization (Yagi and Minami, 1990; Chen et al., 1993; Lindau and Bollich, 1993; Wassmann et al., 1993a; Neue et al., 1994). Emission rates are dependent on amount, kind, and prior treatment of the organic components. In addition, an increase in methane emission with additional straw amendments depended on the method of incorporation. A comprehensive review of methane flux measurements over the past decade, from a variety of countries and with different organic amendments and inorganic fertilizer treatments, is presented by Minami (1995). The amount of methane that is emitted as a result of organic soil amendments depends greatly on the amount and condition of readily available decomposable carbon contained in the treatment. Methane emission with incorporated rice straw was found to be higher than that from either compost or mineral fertilized plots (Yagi and Minami, 1990). The effect of incorporating green manure is even more dramatic than rice straw as shown from a study in the Philippines (Denier van der Gon et al., 1993). Schütz et al. (1989b) observed increases from a control value of 28.6 g CH_4 m^{-2} yr^{-1} to 68.4 g CH_4 m^{-2} yr^{-1} with added rice straw, a factor of 2.4. Cicerone et al. (1992) observed increases from a control value of 1.4 g CH_4 m^{-2} yr^{-1} to up to 58.18 g CH_4 m^{-2} yr^{-1} with added straw, a factor of over 40 times. In field studies in the Philippines, Denier van der Gon and Neue (1995) found that fields treated with green manure applied at a rate of 22 t ha-1 emitted over twice as much methane as fields in which the application rate was 11 t ha^{-1}. Also, residue recycling and organic amendments are also generally less in rainfed rice compared to irrigated rice, leading to a smaller effect on methane emission from these fields.

Seasonally integrated methane emission factor for continuously flooded rice without organic fertilizers (Worksheet Column D)

A seasonally integrated methane emission factor for continuously flooded rice without organic fertilizers (g/m^2) is entered in column D of the worksheet. Existing data which are specific to some countries along with the arithmetic mean of the dataset are listed in Table 6 which is a reproduction of Table 4-11 of the *IPCC Guidelines*: Workbook (1997a). This dataset may be used to establish a default value if no other information is available. If data are lacking, values could be established by applying calculations based on one of the existing models (Cao et al., 1995a; Ding and Wang, 1996; Huang et al., 1998a). A different value for this factor could be required for each row of the worksheet because of differences in climate, soil characteristics and rice cultivar used in areas employing different water regimes and organic amendments.

Total methane emission in gigagrams (Worksheet Column E)

The total methane emission for each category of the worksheet (Table 5 column E), is obtained by multiplying the Harvested Area (column A) by the Scaling Factor for Methane Emissions (column B), the Correction Factor for Organic Amendment (column C), and the Seasonally Integrated Methane Emission Factor for Continuously Flooded Rice without Organic Fertilizers (column D).

TABLE 6 SEASONALLY INTEGRATED METHANE EMISSION FACTORS FOR CONTINUOUSLY FLOODED RICE WITHOUT FERTILIZER IN VARIOUS LOCATIONS OF THE WORLD		
Country	**Seasonally Integrated Emission factor and (range) (g/m^2)**	**Literature Source**
Australia	22.5	NGGIC, 1996
China	13 (10-22)	Wassmann et al. 1993a,b
India	10 (5-15)	Mitra et al., 1996; Parashar et al., 1997
Indonesia	18 (5-44)	Nugroho et al, 1994 a,b
Italy	36 (17-54)	Schutz et al., 1989a
Japan	15	Minami, 1995
Republic of Korea	15	Shin et al., 1995
Philippines	(25-30)	Neue et al., 1994; Wassmann et al., 1994
Thailand	16 (4-40)	Towpryaoon et al., 1993
USA (Texas)	25 (15-35)	Sass and Fisher, 1995
Arithmetic Mean	20 (12-28)	
Source: IPCC Guidelines for National Greenhouse Gas Inventories: Workbook, 1997.		

2.7 Regional and site-specific factors affecting emissions

Relationships between methane emission factors and rice plant growth

Variations in seasonal methane emission from rice paddies are complex and differ among several reported studies. A correlation with soil temperature has been reported in some studies (Schütz et al., 1989a,b), but not in others (Cicerone et al. 1983; Neue and Sass, 1994). Growth-seasonal methane fluxes observed in temperate rice fields show a general correlation with temperature, but respond primarily to seasonal trends in plant development. From negligible values at the beginning of the season, methane emissions show a gradual rise during the vegetative phase correlating with increasing plant biomass, peaking near panicle differentiation, a period of rapid root development. Emission is then relatively constant during the reproductive stage, but may decrease during late grain filling because of root degradation. Prior to the end of the season, a second emission peak may be observed. This late season increase in emission can be attributed to an increase in soil carbon substrate due to accelerating leaf and root senescence (Neue and Sass, 1994). The general effect of soil temperature is quantified in the model by Huang et al. (1998a).

Relationships between methane emission factors and multiple cropping

In irrigated tropical rice paddies with double cropping, both methane emission and rice grain yields are consistently higher in the dry season than in the wet season (Neue et al., 1994). One interpretation of these results is that higher photosynthetic rates during the sunnier days of the dry season lead to larger amounts of carbon available to methanogenic bacteria and consequently greater production and emission rates of methane. Seasonal emission rates of methane and amount of rice grain yield have been positively correlated with accumulated solar radiation (Sass, et al., 1991b).

Relationships between methane emission and soils

Conditions for methane production in wetland rice soils have been categorized into six crucial parameters: water regime, Eh/pH buffer, carbon supply, temperature, texture and mineralogy, and salinity (Neue et al., 1990; Neue, 1997). It was suggested that Oxisols, most of the Ultisols, and some of the Aridisols, Entisols, and Inceptisols are less favorable to methane production when flooded. Rice soils that are prone to methane production mainly belong to the orders of Entisols, Inceptisols, Alfisols, Vertisols, and Mollisols. Methane production in incubation samples of 10 wetland rice soils from the Philippines was influenced both by the reduction characteristics of the soils and the presence of labile organic substrates (Gaunt et al., 1997).

Significant variations in methane emission have been observed in soils of different percolation rates. Yagi et al. (1990) showed that increased percolation rates in lysimeter experiments resulted in decreased seasonal methane emission. In soils of high methane production, Inubushi et al., (1992) found methane emission to be reduced by up to 58% by increasing percolation rates from essentially zero to approximately 4 mm d-1.

A comparison of methane emissions from rice paddy soils in Beijing and Nanjing, China, using a variety of organic and inorganic fertilizer additions and water management, has been reported by Chen et al. (1993). In general, they observed methane emissions about 3.3 times higher in Beijing, even though the average temperature is higher in Nanjing. The Beijing soil is sandy loam with an organic matter content of 1.33%, whereas the Nanjing soil is yellow-brown clayey earth with an organic matter content of 2.29%.

Methane emissions from different paddy soils located in approximately the same climate region show annual emission rates of 44.8, 27.0, 9.8, and 1.1 g/m^2 from Peat soil, Gley soil, Humic Andosol, and Light-colored Andosol, respectively (Yagi and Minami, 1990). The higher emission rates from the Peat and Gley soils may be due to the lower percolation rates observed in these soils. There appears to be no correlation with total carbon content, but a good correlation was found with readily mineralizable carbon, indicating that the quality of available carbon is an important factor. In another Japanese study (Inubushi et al., 1990a), methane production from incubation samples under flooded conditions of 13 Japanese soil samples showed positive correlation with water soluble organic carbon and mineralizable N. Negative correlation with free iron (Fe) oxide was also observed. There was no indication of other soil parameters that may have been considered.

In general, reduced sandy soils high in organic carbon produce more methane than clay soils with similar carbon content (Neue and Sass, 1994). Sass et al. (1994), showed that a strong linear correlation exists between seasonal methane emission and the percent sand in a sand:clay:silt gradient among three Vertisols in Texas. However, methane production may be limited in all soils if water percolation and the resultant redox potential are high. Sandy soils show lower entrapped methane while clayey soils may have reduced methane fluxes because entrapped methane may be oxidized before escaping to the atmosphere.

3 REPORTING AND DOCUMENTATION

Determination of harvest area

The reported harvest area may be larger than the cultivated area because of double or triple rice cropping. The harvested area should be determined for each single rice crop. If an area is double or triple cropped during the year, it should be counted two or three times, respectively. Each of the multiple rice crops on the same area may fall into a different category depending on specific treatments and then should be treated under a different management category. For example, in China, such would normally be the case in early and late season rice crops where methane emissions from the late crop are affected by organic residues from the early crop.

Harvested area estimates corresponding to different conditions may be obtained on a countrywide basis through accepted methods of reporting. The use of locally verified areas would be most valuable when they are correlated with available data for emission factors under differing conditions such as climate, agronomic practices, and soil properties. Table 4-9 of the *IPCC Guidelines*: Workbook (1997a) contains country default values for total harvested rice area and the percentage of this area which is irrigated, upland, and rainfed rice. In some cases the irrigated area is subdivided into continuously flood and intermittently flooded and the rain-fed area is subdivided into flood-prone and drought-prone. These areas may be used if data are not locally available and/or no additional subdivision of the table is contemplated.

Emission factors

When reporting methane emissions from rice fields, it is recommended that actual emission measurements be performed by the reporting country. If the default values recommended by the *IPCC Guidelines* are used, they should be critically examined for country specific effects and used with great care. To aid in this process, the general emission factors are considered in three parts; a scaling factor to account for different water management regimes, a factor accounting for the incorporation of specific organic amendments, and a country standard or control factor for the specific conditions of continuous flooding in the absence of any organic amendments.

Organic amendments

Type and quantity of added organic amendments vary from country to country and even within a country. The common organic amendments are green manure (fresh biomass), rice straw from previous crop, animal manure, or compost, each of which affects methane emissions differently. Thus, scaling factors for organic amendments that are applied to report country methane emissions should be experimentally measured under amendment conditions common to particular regions and countries whenever possible. It may be necessary to either extend the number of reporting rows in the worksheet for methane emissions (Table 5) or to establish an area weighted average in reporting a correction factor for organic amendments which reflects the relative usage. It should be remembered that, even when using the default value of 2, one needs to area average that factor with a value of 1 for fields that have no organic amendment unless the two categories are entered in separate rows of Table 5.

4 INVENTORY QUALITY

4.1 Introduction

Inventory QA/QC involves a complete range of activities and intermediate steps in creating an inventory. A well-developed and well-implemented quality assurance programme fosters confidence in the final inventory results regardless of the purpose and goal of the inventory. The common thread throughout the quality assurance process is the need for thorough documentation and complete transparency. The government agency responsible for compiling the national methane inventory needs to receive full documentation of existing data, model results and available data sets in order to perform its own QA. It also needs to document the national compilation process and the QC performed so that it is transparent to external reviewers and the UNFCCC.

4.2 Internal inventory QA/QC systems

Global measurements of standard methane emissions

The inventory QC procedures used at the rice field level will be determined largely by country scientists. There are, however, certain internationally determined procedures to obtain 'standard emission factors' that should be common to all monitoring programmes. Instructions for obtaining standard emission factors are contained in "Global Measurements Standards of Methane Emissions for Irrigated Rice Cultivation (IGAC, 1994). It is desirable for each laboratory in every reporting country to obtain this 'standard' emission factor to ensure the intercomparibility and intercalibration of extended data sets used to establish country-specific emission factors.

Field-level activities

It is recommended that a standardized control rice plot shall be used to obtain these emission factors. Each measurement site should consist of at least three replicate fields. Plots are to be kept flooded (5 cm minimum depth) from shortly before transplanting until maturity. A five-year history of the plots should be known and the plots should have been under cultivation during this time in order to have reached equilibrium. The experimental plots should not have a recent history (five years) of added organic amendments to the soil other than recycled roots and perhaps short stubble.

Methane flux measurements should be recorded at least twice per week over an entire flooded season. In areas where double or triple rice cropping is practiced, data should be collected for all growing seasons. A minimum data set should accompany the flux measurements that should include the following:

- Geographic data including site country and province, latitude and longitude, average elevation, and a short description of the location;
- A data log of all agricultural events including a record of the date of important plant events such as transplant date, panicle initiation, heading, anthesis, harvest, etc. as well as water management schedule, weeding schedule, herbicide and pesticide treatments, and all other activities where the fields are affected;
- Air temperature, flood water temperature, and the soil temperature at 5 cm depth taken at the time of each flux measurement;
- Fertilization amount, type and schedule. Urea should be the nitrogen source of choice for all fields. If that is impossible, the fertilizer type (ammonium nitrate, ammonium sulfate, etc.) should be reported. The application rate as kg N ha-1 and number and timing of splits should be reported. Phosphorus, potassium and any chemical amendment such as zinc sulfate, if added, should be stated together with rates;
- Soils should be classified according to Soil Taxonomy, at least on subgroup levels. General soil characteristics, including texture, pH, organic C%, total N%, and cation exchange capacity (CEC) should be measured;
- The rice cultivar used should be given;
- At the time of heading, the aboveground biomass (cut at the soil surface), plant height (soil surface to the tip of the extended highest leaf), tiller number and leaf area index should be determined, and

- At harvest time the yield (rough rice corrected to 14% moisture), harvest index, and number of total tillers and productive tillers should be reported.

4.2.1 Inventory agency level activities

Inventory agency review (QA/QC) of field level information

Before accepting emissions data, the inventory agency should carry out an assessment of data quality and sampling procedures. This type of review requires close cooperation with national laboratories to obtain enough information to verify the reported emissions, as discussed above. The assessment should include sample recalculations, an examination of the representativeness of the data and agronomic and climate conditions, and an identification of potential bias in the methodology, and recommendations for improvement.

Inventory agency QC on compiling national emissions

In addition to a thorough quality of assessment of field-level data discussed above, the inventory agency should ensure that the process of aggregating these data and existing government sponsored data sets with various models to develop the national inventory undergoes quality control. This should include, among other things:

- Cross-referencing aggregated crop yield and reported field area statistics with national totals;
- Back-calculating national emissions factors from aggregated emissions and other data, and
- Cross-referencing reported national totals with default values and data from other countries.

Inventory agency documentation on compiling national emissions

For rice field methane inventories, a QA/QC management plan should address the specific items needed to perform audits and reviews. When estimates are provided by laboratories, details should be documented at the field level to account for differences in local agronomic practices.

When simple default emission factors are used to estimate methane emissions, uncertainty can increase dramatically. Countries using the emission factor approach should provide information on the origin and basis of the factor, compare it to other published emission factors and explain any significant differences, and attempt to place bounds on the uncertainty.

The sum of individual emissions is reported as the total country emission. Each individual entry may result from experimental data, model considerations, tabulated databases, or a default value. Each type of data has an associated range or standard error. These ranges should be considered when reporting the data and, when possible, data consistency should be investigated by utilizing more than one data source or type.

4.4 External inventory QA/QC systems

External QA activities include a system of review and audit conducted by persons not directly involved in the initial inventory process. The point is to obtain an independent and objective review to assess the quality of the inventory and to eliminate any question of bias. A third party audit by an accredited organization or expert should assure that the documentation and calculations are traceable to their origins. Expert review is appropriate when a procedure for estimating methane emissions is first used or significantly modified. A review by organizations and governmental agencies associated with the rice growing effort can provide a review of the methods used and may be helpful in assessing the activity data used such as crop yields and/or area extent of country rice ecosystems.

5 CONCLUSIONS

Although methane emissions from rice fields are sometimes subject to substantial natural variations in both time and space, an accurate emission inventory at the country level is both possible and obtainable. A substantial amount of experimental and theoretical data have been collected and are available in the literature to help the practitioner establish reliable estimates and ranges in these estimates for methane emissions from rice fields, particularly if sufficient metadata are available. The processes leading to the emission of methane from rice agriculture are largely understood. The range in emissions that have been observed from rice fields may be very large, but to a large extent, the cause of these ranges is understood and can reasonably be taken into account in determining emission inventories. The most important factors controlling the methane emission can be enumerated and their effects accurately estimated. For each factor, the range in emissions caused by variations of the factor is known. If data for these factors and thus the effect on net emission are unavailable or unknown for a particular region, the scientific tools, including process level models, are currently available to specify what data needs to be collected and how to use these data to estimate regional methane emissions. The current level of understanding of the factors affecting methane emissions from rice fields is sufficient to specify what information is necessary to make reasonable estimates of their country levels. Our current understanding is also sufficient to specify what additional data needs to be collected so that one can use models that are now available or will be available in the near future to understand and predict the variability in emissions and to soon significantly reduce the uncertainty in these estimates.

REFERENCES

Adhya, T.K., A.K. Rath, , P.K. Gupta, V.R. Rao, S.N. Das, K.M. Parida, D.C. Parashar and N. Sethunathan (1994). Methane emission from flooded rice fields under irrigated conditions. *Biology and Fertility of Soils* 18: 243-248.

Cao, M., J.B. Dent and O.W. Heal (1995a) Modeling methane emission from rice paddies. *Global Biogeochemical Cycles*, 9:183-195.

Cao, M., J.B. Dent and O.W. Heal (1995b) Methane emissions from China's paddyland. *Agriculture, Ecosystems and Environment,* 55:129-137.

Charoensilp, N., B. Buddhaboon, P. Charoendham (1995*). Methane emission from deepwater rice fields.* Prachinburi Rice Research Center, RRI, Department of Agriculture, Bangkok, Thailand.

Chairoj, P. (1994). Research Report: *A Cooperative project on methane emission from rice paddy fields*, Department of Agriculture, Ministry of Agriculture and Cooperatives, Thailand and Department of Environmental Science, Japan.

Chen Z, Li D, Shao K and Wang B (1993*) Features of CH_4 emission from rice paddy fields in Beijing and Nanjing*. Chemosphere 26:239-245.

Cicerone, R.J. and J.D. Shetter (1981) Sources of atmospheric methane: Measurements in rice paddies and a discussion. *Journal of Geophysical Research*, 86:7203-7209.

Cicerone, R.J., Shetter, J.D. and Delwiche, C.C. (1983) Seasonal variation of methane flux from a California rice paddy. *Journal of Geophysical Research*, 88:11022-11024

Cicerone, R.J., C.C.Delwiche, T.C., Tyler, and P. R. Zimmermann (1992). Methane emission from Californian rice paddies with varied treatment. *Global Biogeochemical Cycles* 6: 233-248.

Conrad, R. and F. Rothfuss (1991) Methane oxidation in the soilk surface layer of a flooded rice field and the effect of ammonium, *Biol. Fert. Soiols*, 12:28-32.

CRRC (1996). Central Rice Research Institute, Cuttack, India. Annual Report 1994-95.

De Bont, J.A.M., K. Lee, and D.F. Bouldin (1978) Bacterial oxidation of methane in a rice paddy. *Ecological Bulletin,* 26:91-96.

Denier van der Gon, H. A. C., H. U. Neue, R. S. Lantin, R. Wassmann, M. C. R. Alberto, J. B. Aduna, and M. J. P, Tan, (1993) *Controlling factors of methane emission from rice fields, In WISE* Workshop, , August 24-27, 1992, Wageningen.

Denier van der Gon, H.A.C. and H.U. Neue (1995) Influence of organic matter incorporation on the methane emission from a wetland rice field. *Global Biogeochemical Cycles*, 9:11-22.

Ding, A. and Wang, M.X. (1996) Model for Methane Emission from Rice Fields and Its Application in Southern China, *Advances in Atmospheric Science*, 13:159-168.

Gaunt, J.L., Neue, H.U., Bragais, J., Grant, I.F. and Giller, K.E. (1997) Soil characteristics that regulate soil reduction and methane production in wetland rice soils. Soil *Science Society of America Journal*, 61:1526-1531.

Gerard, G and J. Chanton (1993) Quantification of methane oxidation in the rhizosphere of emergent aquatic macrophytes: defining upper limits. *Biogeochemistry,* 23:79-97.

Holzapfel-Pschorn, A. and W. Seiler (1986). Methane emission during a cultivation period from an Italian rice paddy. *Journal of Geophysical Research* 91: 11803-11814.

Huang, Y., R.L. Sass and F.M. Fisher, Jr. (1998a). A Semi-Empirical Model of Methane Emission from Flooded Rice Paddy Soils, *Global Change Biology*, 4:247-268.

Huang, Y., R.L. Sass, and F. M. Fisher, Jr. (1998b) Model Estimates of Methane Emission from Irrigated Rice Cultivation of China, *Global Change Biology*, 4, 809-822.

Inubushi, K., Umebayashi, and H. Wada (1990a*) Control of methane emission from paddy soil.* Paper presented at 14th International Congress of Soil Science, Kyoto, August 1990.

Inubushi, K., Umebayashi, and H. Wada (1990b*) Methane emission from paddy fields*. Paper presented at 14th International Congress of Soil Science, Kyoto, August 1990.

Inubushi, K., Muramatsu, Y. and Umebayashi, M. (1992) Influence of percolation on methane emission from flooded paddy soil. *Japan Journal of Soil Science and Plant Nutrition*, 63:184-189.

IGAC (1994). *Global Measurement Standardisation of Methane Emissions from Irrigated Rice Cultivation*, A Report of the Rice Cultivation and Trace Gas Exchange Activity (RICE) of the International Global Atmospheric Chemistry (IGAC) Project (Convenors, R. Sass and H. U. Neue), IGAC Core Office, Cambridge, MA.

IPCC-Intergovernmental Panel on Climate Change. (1997a). *Guidelines for National Greenhouse Gas Inventories*: Workbook, Chapter 4.3, Agriculture: Rice Cultivation. OECD, Paris, France.

IPCC-Intergovernmental Panel on Climate Change. (1997b). Guidelines for National Greenhouse Gas Inventories: Reference Manual, Chapter 4.3, *Agriculture: Methane emission from rice cultivation*. OECD, Paris, France.

IRRI (1996). Program Report 1995. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Japan Soil Association (1996) *A report of inventory monitoring of greenhouse gas emissions from Japanese crop fields, Japan Soil Association,* Tokyo, Japan [in Japanese].

Jermsawatdipong, P., P. Prabuddham, Y. Hasathon, N. Khomthong, K. Naklang and M. Chinda (1994a). *Methane emission paddy fields in Thailand. In: Thailand's present and projected future contribution to global emissions of GHG*. Report to Asian Development Bank, pp. 3-35.

Jermsawatdipong, P., P. Murase, P. Prabuddham, Y. Hasathon, M. Chinda , B. Chaiwatana, N. Khomthong, S. Sattawatananon, K. Naklang, A. Watanabe, H. Haraguchi and M. Kimura (1994b). Methane emission from plots with differences in fertilizer application in Thai paddy. *Soil Science and Plant Nutrition* 40: 63-71.

Kimura, M. and K. Minami (1995). *Dynamics of methane in rice fields: Emissions to the atmosphere in Japan and Thailand.* In: Peng, S., Ingram K.T., Neue, H.U., Ziska, L.H. (eds.) Climate Change and Rice. Springer-Verlag Berlin, pp. 30-45.

Kludze, H. K. and R. D. DeLaune. (1995). Straw application effects on methane and oxygen exchange and growth in rice. *Soil Sci,. Soc., Am.* J. 59, 824-830.

Knox, J., R. B. Matthews, R. Wassmann (2000) *Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia: III*. Databases . Nutrient Cycling in Agroecosystems 58: 179-199, 2000, ©2000 Kluwer Academic Publishers, The Netherlands.

Lewis, S.T. (1996) *The use of redox measurements to study methane mitigation options in Texas rice paddies*. PhD thesis, Rice University, Houston, Texas, USA

Lindau, C.W., P.K. Bollich, R.D. DeLaune, W.H. Patrick and V.J. Law (1991). Effect of urea fertilizer and environmental factors on methane emissions from a Louisiana, USA rice field. *Plant and Soil* 136: 195-203.

Lindau CW and Bollich PK (1993) Methane emissions from Louisiana first and ratoon crop rice. *Soil Sci.* 156:42-48.

Lu, W., W. Chen W. Guo and B. Duan (1995*). Emission of methane from the rice field affected by irrigation. Paper presented at the Planning Meeting of Methane Emission from Rice Fields*, Chonburi, Thailand 19-26.Nov. 1995. China National Rice Reserach Institute, Hangzhou 3100056, Zheijiang, China.

Lu, Y., R. Wassmann, H.U. Neue and C. Huang (1999) Impact of Phosphorus Supply on root Exudation, Aerenchyma Formation and Metheane Emission of Rice Plants. : Biogeochemistry, 1999, V47, N2 (Nov), p203-218, ISSN: 0168-2563; Kluwer Academic Publ, Spuiboulevard 50, PO BOX 17, 3300 AA, Dordrecht, Netherlands

Makarim, A. K., A. Bey, R. Boer and P. Setyanto (1995). Methane *gas from lowland rice fields in Indonesia:* Development and research directions (in Indonesian). Central Research Institute for Food Crops, Bogor, Indonesia.

Matthews, R. B., R. Wassmann and J. Arah (1999) *Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia:* I. Model development. Nutrient Cycling in Agroecosystems 58: 141-159, 2000, ©2000 Kluwer Academic Publishers, The Netherlands.Matthews, R. B.,

R. Wassmann, J.W. Knox, and L.V. Buendia (2000) Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia: IV. Upscaling to national levels. *Nutrient Cycling in Agroecosystems* 58: 201-217, 2000, ©2000 Kluwer Academic Publishers, The Netherlands.

Metra-Corton, T., J. B. Bajita, C. A. Asisk, R. R. Pamplona, and Salamanca (1995*) Methane emission from an irrigated rice field.* Philippine Rice Research Institute, Munoz, Nueva Ecija, Philippines.

Minami, K. (1995) The effect of nitrogen fertilizer use and other practices on methane emission from flooded rice. *Fertilizer Res*. 40:71-84.

Mitra, A.P. (1992). *Greenhouse gas emission in India*: 1991 Methane Campaign. Science Report No 2. Council of Scientific and Industrial Research and Ministry of Environment and Forests, New Delhi, India.

Mitra, A. P. (1996) (ed.) *Greenhouse gas inventory for India*; 1995 Update, Global Change Series, Council of Scientific and Industrial research, and Ministry of Environment and Forest, NPL, New Delhi, India

Neue, H.U. (1997) Fluxes of methane from rice fields and potential for mitigation. *Soil Use and Management*, 13:258-267.

Neue, H.U. and R. Sass (1994). *Trace gas emissions from rice fields. In: Prinn R.G.* (ed.) Global Atmospheric-Biospheric Chemistry. Environmental Science Res. 48. Plenum Press, New York, pp. 119-148.

Neue, H.-U., P. Becker-Heidmann and H. W. Scharpenseel (1990) *Organic matter dynamics, soil properties, and cultural practices in rice lands and their relationship to methane production. In: Soils and the Greenhouse Effect.* A. F. Bouwman, ed. John Wiley, New York. pp. 457-466.

Neue H. U., Latin, R. S., Wassmann, R., Aduna, J. B., Alberto, C. R. and Andales M. J. F. (1994) Methane emission from rice soils of the Philippines. In: CH_4 and N_2O*: Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources (eds* Minami K, Mosier A, Sass R), pp. 55-63, Yokendo Publishers, Tokyo.

Neue, H.U. and R.L. Sass. (1998). The Budget of Methane from Rice Fields. *IGACtivities NewsLetter*, 12, 3-11.

Nugroho, S.G., L. Lumbanraja, H. Suprapto, Sunyoto, W.S. Ardjasa, H. Haraguchi and M. Kimura (1994a). Methane emission from Indonesian paddy field subjected to several fertilizer treatments. *Soil Science and Plant Nutrition* 40: 275-281.

Nugroho, S.G., L. Lumbanraja, H. Suprapto, Sunyoto, W.S. Ardjasa, H. Haraguchi and M. Kimura (1994b). Effect of intermittent irrigation on methane emission from an Indonesian paddy field, *Soil Science Plant Nutrition* 40:609-615

Parashar, D. C., K. P. Gupta and S. Bhataachaya (1997) Methane emissions from paddy fields in India-An update, *J. Radio and Space Physics*, 26, 237.

Sass, R.L. (1994) Short summary chapter for methane. In: CH_4 and N_2O: *Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources*. K. Minami, A. Mosier and R. L. Sass, eds. NAIES. Yokendo Publishers, Tokyo. p. 1-7.

Sass, R.L., Fisher, F.M., Harcombe, P.A. and Turner, F.T. (1991a) Mitigation of methane emissions from rice fields: Possible adverse effects of incorporated rice straw. *Global Biogeochemical Cycles*, 5:275-287.

Sass, R.L., Fisher, F.M., Turner, F.T. and Jund, M.F. (1991b) Methane emission from rice fields as influenced by solar radiation, temperature, and straw incorporation. *Global Biogeochemical Cycles* 5, 335-350.

Sass, R.L., F.M. Fisher, Y.B. Wang, F.T. Turner, and M.F. Jund (1992) Methane emission from rice fields: The effect of floodwater management. Global Biogeochem. Cycles, 6:249-262.

Sass, R.L., F.M. Fisher, S.T. Lewis, M.F. Jund, and F.T. Turner (1994) Methane emission from rice fields: effect of soil properties. *Global Biogeochemical Cycles*, 8:135-140.

Sass, R. L. and F.M. Fisher (1995*). Methane emissions from Texax rice fields: a five year study*. In: Peng, S., Ingram K.T., Neue, H.U., Ziska, L.H. (eds.) *Climate Change and Rice*. Springer-Verlag Berlin, pp. 46-59.

Schütz H., A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg and W. Seiler (1989). A three-year continuous record on the influence of daytime season and fertilizer treatment on methane emission rates from an Italian rice paddy field. *Journal of Geophysical Research 94: 16405-16416.*

Schütz, H., W. Seiler, and R. Conrad (1990) Influence of soil temperature on methane emission from rice paddy fields. *Biogeochemistry*, 11:77-95, 1990.

Schütz, H., P. Schroder, and R. Rennenberg (1991) *Role of plants in regulating the methane flux to the atmosphere.* In: Trace Gas Emissions by Plants (eds Sharkey TD, Holland EA, Mooney HA), pp. 29-63, Academic Press, Inc., NY.

Seiler, W., A. Holzapfel-Pschorn, R. Conrad and D. Scharfe (1984). Methane emission from rice paddies. *Journal of Atmospheric Chemistry* 1: 241-268.

Shin, Y.K., S.H. Yun and M.E. Park (1995). Estimation of methane emission by water management and rice straw application in paddy soil in Korea. *Journal of Korean Society of Soil Science and Fertility* 28(3): 261-265.

Siriratpiriya, O. (1994). *Methane emission from rice fields in Thailand.* Institute of Environmental Research, Chulalongkorn University, Bangkok, Thailand.

Wang, M.X., A.G. Dai, J. Huang L.X. Ren, R.X. Shen, H. Schütz, W. Seiler, R.A. Rasmussen and M.A.K. Khalil (1993). Methane source from China. *Scientia Atmospherica Sinica* 17(2): 52-64.

Wang, M.X., A.G. Dai, X. Shangguan, L.X. Ren, R.H. Shen, H. Schutz, W. Seiler, R.A. Rasmussen, and M.A.K. Khalil (1994*) Sources of methane in China*. In K. Minami, A. Mosier, and R. Sass (eds.) CH_4 and N_2O: *Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources*. National Institute of Agro-Environmental Sciences, Tsukuba, Japan, 1994. pp. 9-26.

Wang, M.X. (1995*) Methane emission rates from various rice fields in China. In: China Contribution to global change studies*, Ye Du Zheng and Lin Hai, eds. China global Change Report No. 2. Science Press, Beijing, p. 154-160

Wassmann, R., Papen, H. and Rennenberg, H. (1993a) Methane emission from rice paddies and possible mitigation strategies. *Chemosphere* 26:201-217.

Wassmann, R., M. X. Wang, X. J. Shangguan, X. L. Xie, R. X. Shen, H. Papen, H. rennenberg, W. Seiler (1993b) First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan Province (PR China). *Geophysical Research Letters* 20:2071-2074.

Wassmann, R. H. U. Neue, R. S. Lantin. M. J. Javellana, R. Diego, V. E. Lignes, H. Hoffmann, H. Papen and H. Rennenberg (1995) Methane *emissions from rainfed* rice. In: IRRI-International Rice Research Institute, Fragile lives in fragile ecosystems. Pp. 217-225, Los Baños, Philippines.

Wassmann, R. H. U. Neue, R. S. Lantin, L. V. Buendia and H. Rennenberg (2000a) Characterization of methane emissions from rice fields in Asia. I. Comparison among field sites in five countries*. Nutrient Cycling in* Agroecosystems 58: 1-12, 2000, ©2000 Kluwer Academic Publishers, The Netherlands.

Wassmann, R., H. U. Neue, R. S. Lantin, K. Makarim, N. Chareonsilp, L.V. Buendia, and H. Rennenberg (2000b) Characterization of methane emissions from rice fields in Asia. II. Differences among irrigated, rainfed and deepwater rice. *Nutrient Cycling in Agroecosystems 58: 13-22*, 2000, ©2000 Kluwer Academic Publishers, The Netherlands.s

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, T.M. Corton and Y. Lu (2000) Characterization of methane emissions in Asia III: Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems 58: 23-36, 2000,* ©2000 Kluwer Academic Publishers, The Netherlands.

Yagi, K. and K. Minami (1990) Effects of organic matter application on methane emission from some Japanese paddy fields*. Soil Science and Plant Nutrition* 36: 599-610.

Yagi, K., Minami, K. and Ogawa, Y. (1990) Effects of water percolation on methane emission from paddy fields. Research Report, Division of Environmental Planning. *National Institute of Agro-Environmental Science,* 6:105-112.

Yagi, K. and K. Minami (1991) Emission and production of methane in the paddy fields of Japan. *Japan Agricultural Research Quarter (JARQ*) 25: 165-171.

Yagi, K., H. Tsuruta, K. Kanda, and K. Minami (1996) Effect of water management on methane emission from a Japanese rice paddy field: Automated methane monitoring. *Global Biogeochemical Cycles*, 10:255-267.