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Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines

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[1] The Intergovernmental Panel on Climate Change (IPCC) regularly publishes guidelines for national greenhouse gas inventories and methane emission (CH_4) from rice paddies has been an important component of these guidelines. While there have been many estimates of global CH_4 emissions from rice fields, none of them have been obtained using the IPCC guidelines. Therefore, we used the Tier 1 method described in the 2006 IPCC guidelines to estimate the global CH_4 emissions from rice fields. To accomplish this, we used country-specific statistical data regarding rice harvest areas and expert estimates of relevant agricultural activities. The estimated global emission for 2000 was 25.6 Tg a^{-1}, which is at the lower end of earlier estimates and close to the total emission summarized by individual national communications. Monte Carlo simulation revealed a 95% uncertainty range of 14.8–41.7 Tg a^{-1}; however, the estimation uncertainty was found to depend on the reliability of the information available regarding the amount of organic amendments and the area of rice fields that were under continuous flooding. We estimated that if all of the continuously flooded rice fields were drained at least once during the growing season, the CH_4 emissions would be reduced by 4.1 Tg a^{-1}. Furthermore, we estimated that applying rice straw off season wherever and whenever possible would result in a further reduction in emissions of 4.1 Tg a^{-1} globally. Finally, if both of these mitigation options were adopted, the global CH_4 emission from rice paddies could be reduced by 7.6 Tg a^{-1}. Although draining continuously flooded rice fields may lead to an increase in nitrous oxide (N_2O) emission, the global warming potential resulting from this increase is negligible when compared to the reduction in global warming potential that would result from the CH_4 reduction associated with draining the fields.

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1. Introduction

[2] The concentration of atmospheric methane (CH_4), which plays an important role in both tropospheric and stratospheric chemistry, has almost tripled since the industrial period [*Lelieveld et al.*, 1998]. Although the total source strength of global atmospheric CH_4 is relatively certain, the strength of individual sources remains uncertain [*Lelieveld et al.*, 1998]. Using the global source strength and assuming that 80 Tg CH_4 a^{-1} are emitted from rice fields, *Houweling et al.* [2000] modeled the global distribution of atmospheric CH_4. *Frankenberg et al.* [2005] subsequently compared these modeled results to satellite observations and found discrepancies over India and the tropics, indicating that the rice emissions used in the model were probably overestimated. *Keppler et al.* [2006] reported that CH_4 is emitted from terrestrial plants under oxic conditions, which resulted in the addition of 62–236 Tg CH_4 a^{-1} to the CH_4 budget. Although later recalculations and modeling studies reduced the plant contribution to 52.7–85 Tg CH_4 a^{-1} [*Parsons et al.*, 2006; *Houweling et al.*, 2006], these findings still indicate that it is necessary to reevaluate the CH_4 emissions from other sources.

[3] Rice fields were first identified as sources of atmospheric CH_4 in laboratory experiments conducted in the 1960s [*Koyama*, 1963]. Early studies that scaled up the results of a limited number of field measurements estimated that the global emission of CH_4 from rice fields was greater than 100 Tg a^{-1} [e.g., *Blake*, 1984; *Cicerone and Oremland*, 1988]. However, later studies that included a greater number of field measurements covering various rice ecosystems and

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management practices estimated the CH_4 emissions from rice fields to be 20–100 Tg CH_4 a^{-1} [e.g., *Wang et al.*, 1994; *Intergovernmental Panel on Climate Change* (*IPCC*), 1994], and large uncertainties in the actual amount of CH_4 emitted from rice fields remain to date.

[4] Generally, methane emission from rice fields on a large scale is estimated by process-based modeling or by scaling up field measurements. However, detailed process-based models can rarely be applied on a global scale because of the requirement of a large number of parameters with high spatial variability, although several of these models have been applied at a regional or national level [e.g., *Matthews et al.*, 2000; *Li et al.*, 2002]. As a result, most global estimates that have been conducted to date have been derived from county-specific inventories or scaled up from the results of individual field measurements in an empirical manner [e.g., *Holzapfel-Pschorn and Seiler*, 1986; *Wang et al.*, 1994; *Neue and Sass*, 1998].

[5] The Intergovernmental Panel on Climate Change (IPCC) regularly publishes Guidelines for National Greenhouse Gas Inventories to provide countries with a guideline for determining their emission inventories of greenhouse gases [*Intergovernmental Panel on Climate Change* (*IPCC*), 1997, 2000, 2007a]. For CH_4 emission from rice fields, the 1996 IPCC guidelines outline one method that uses annual harvested areas and area-based seasonally integrated emission factors. In addition, these guidelines provide scaling factors to account for water regimes during the rice growing season and organic amendment [*IPCC*, 1997]. However, the scaling factor for organic amendment was revised from a single value to amount-dependent values in the Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (referred to as GPG2000 [*IPCC*, 2000]). In addition, the IPCC recently published new guidelines (*IPCC* [2007a] hereafter referred to as the 2006 IPCC guidelines) for computing CH_4 emissions from rice fields. These new guidelines incorporated the following changes to the 1996 guidelines and the GPG2000: (1) revised emission and scaling factors derived from an updated analysis of a large data set of field measurements, (2) the use of daily emission factors instead of seasonal factors to allow more flexibility in separating cropping seasons and fallow periods, and (3) new scaling factors for the water regime prior to the cultivation period and timing of the incorporation of straw.

[6] The United Nations Framework Convention on Climate Change requires all signatories to develop and periodically update national inventories of anthropogenic emissions by source. Most signatories have submitted their national communications using 1994 as the base year, and annex I countries have submitted their national inventory reports on annual basis. Although most countries used the 1996 guidelines to estimate the CH_4 emission from rice cultivation, some major rice-producing countries developed their own emission factors on the basis of local measurements or used models. The purpose of this study is to provide an updated estimate of CH_4 emission from global rice fields using the Tier 1 method described in the 2006 IPCC guidelines with the default emission factors and country- or region-specific agricultural activity data for individual rice producing countries. This estimate is then compared to the estimates provided in the individual national communications. We also include an uncertainty analysis and an evaluation of the effects of some potential mitigation options using the uncertainty ranges of the emission factor and scaling factors provided in the new guidelines.

2. Methods

2.1. IPCC Guidelines for 2006

[7] The 2006 IPCC guidelines outline three tiers of methods that can be used to estimate CH_4 emissions from rice fields in a country or region. The Tier 1 method, which provides a default emission factor and scaling factors, is meant to be applied to countries in which CH_4 emissions from rice cultivation are not a key category or for which country-specific emission factors do not exist. The Tier 2 method is the same as the Tier 1 method, but requires that country-specific emission factors (EFs) and/or scaling factors (SFs) be used. The Tier 3 method encourages the use of empirical or mechanistic models and monitoring networks tailored to address national circumstances of rice cultivation that have been repeated over time, driven by high-resolution activity data and disaggregated at a subnational level. Obviously, the Tier 1 method is the most plausible for application at a global scale.

[8] In the Tier 1 method, the emission from a country is the sum of emissions from fields under each specific condition, as shown by

$$\mathrm{CH}_{4\mathrm{Rice}} = \sum_{i,j,k} \mathrm{EF}_{i,j,k} T_{i,j,k} A_{i,j,k} 10^{-6}, \quad (1)$$

where $\mathrm{CH}_{4\mathrm{Rice}}$ is the annual CH_4 emission from rice cultivation in a country or region in Gg CH_4 a^{-1}, $\mathrm{EF}_{i,j,k}$ is a daily emission factor specific for i, j, and k conditions in kg CH_4 ha^{-1} d^{-1}, $T_{i,j,k}$ is the cultivation period of rice for i, j, and k conditions in days, $A_{i,j,k}$ is the annual harvested area of rice for i, j, and k conditions in ha a^{-1}, and i, j, and k represent different ecosystems, water regimes, types and amounts of organic amendments, and other conditions under which CH_4 emissions from rice may vary.

[9] As shown in equation (2), the daily specific emission factor is estimated from a baseline EF and various SFs to account for the water status during and before the rice season, as well as the types and amounts of organic fertilizers used

$$\mathrm{EF}_i = \mathrm{EF}_c \mathrm{SF}_w \mathrm{SF}_p \mathrm{SF}_o \mathrm{SF}_{s,r}, \quad (2)$$

where EF_i is the adjusted daily emission factor for a particular harvested area, EF_c is the baseline emission factor for continuously flooded fields without organic amendments, SF_w is the scaling factor for differences in the water regime during the cultivation period, SF_p is the scaling factor for differences in the water regime in the season prior to the cultivation period, SF_o is the scaling factor for both the type and amount of organic amendment applied, and $\mathrm{SF}_{s,r}$ is the scaling factor for soil type, rice cultivar, etc., if available.

Table 1. Sources of Statistical Data on Rice Area

Country	Title of Source	Year	Publisher/Sponsor	Location of Publisher/Sponsor
Bangladesh	Yearbook of Agricultural Statistics of Bangladesh	2000	Bangladesh Bureau of Statistics	Dhaka, Bangladesh
Bhutan	Statistical Yearbook of Bhutan	2000	Central Statistical Organization	Thimphu, Bhutan
Cambodia	Agricultural Statistics	2000	Ministry of Agriculture, Forestry and Fisheries	Phnom Penh, Cambodia
China	China Agriculture Yearbook (in Chinese)	2000	Agricultural Publishing House	Beijing, China
India	Indian Agriculture in Brief (32nd Edition)	2000	Ministry of Agriculture	New Delhi, India
Indonesia	Agricultural Survey: Production of Paddy in Indonesia	2000	Biro Pusat Statistik	Jakarta, Indonesia
Japan	Crop Statistics: General Crop, Feed Crop, Horticulture Crop (in Japanese)	2000	Ministry of Agriculture, Forestry and Fishery	Tokyo, Japan
Laos	Basic Statistics of the Lao P.D.R.	2000	Committee for Planning and Cooperation	Vientiane, Laos
Malaysia	Paddy Statistics of Malaysia	2000	Department of Agriculture	Putrajaya, Malaysia
Myanmar	Agricultural Statistics 1989–1990 to 1999–2000	2000	Central Statistical Organization	Nay Pyi Taw,Myanmar
Nepal	Statistical Information on Nepalese Agriculture	2000	Ministry of Agriculture	Kathmandu, Nepal
Pakistan	Agricultural Statistics of Pakistan	2000	Ministry of Food, Agriculture and Livestock	Islamabad, Pakistan
South Korea	Statistical Yearbook of Agriculture, Forestry and Fisheries	2000	Ministry of Agriculture and Forestry	Gwacheon, South Korea
Sri Lanka	Agricultural Statistics of Sri Lanka	2000	Ministry of Finance and Planning	Colombo, Sri Lanka
Taiwan	Taiwan Agricultural Yearbook	2000	Department of Agriculture and Forestry	Taipei, Taiwan
Thailand	Agricultural Statistics of Thailand, Crop Year 1999/2000	2000	Ministry of Agriculture and Co-Operatives	Bangkok, Thailand
Vietnam	Statistical Data of Agriculture, Forestry and Fishery 1975–2000	2000	Statistical Publishing House	Ha Noi, Vietnam
United States	2002 Census of Agriculture: State Data	2002	National Agricultural Statistics Service	Washington, D. C.

[10] Default values and error ranges for EF_c, SF_w, SF_p, and SF_o are provided in the guidelines for two complex cases: an aggregated case and a disaggregated case. In the aggregated case, SF_w is distinguished for an irrigated rice field and rain-fed rice field, and a single SF_p is considered. In the disaggregated case, SF_w for an irrigated rice field is further distinguished for continuous flooding, single drainage, and multiple drainage. SF_w for a rain-fed rice field is further distinguished for regular rain-fed, drought rain-fed, and deepwater fields. SF_p is further distinguished as flooding, short drainage and long drainage. For our estimate, we used the method for the disaggregated case. $SF_{s,r}$ is not provided in the guidelines; therefore, it was not considered.

2.2. Agricultural Activity Data

[11] The data required for this methodology include the areas of irrigated, rain-fed, and deepwater rice paddies; the proportions of irrigated rice fields that are continuously flooded, intermittently flooded with single drainage, and intermittently flooded with multiple drainage; the proportions of rain-fed rice fields that experience regular rainfall and are drought prone; the proportions of rice that have a long, nonflooded season (drained for more than 180 days prior to the rice season, hereafter referred to as long drainage), a short, nonflooded season water status (drained for less than 180 days before the rice season, hereafter referred to as short drainage), and a flooded season water status (continuously flooded for more than 30 days before the rice season, hereafter referred to as flooding); the type and amount of organic fertilizers used; and the length of the rice growing season.

[12] Data for the lowland rice area for the year 2000 were collected at the subnational level for monsoon Asian countries and the United States using country-specific statistics (data sources for specific countries are shown in the Table 1). Data for other countries were collected from the Food and Agriculture Organization's statistical database (http://faostat.fao.org/). The areas of rice fields that were irrigated and rain fed were scaled according to *Huke and Huke* [1997] and another data source from International Rice Research Institute (http://www.irri.org/science/ricestat/pdfs/Table%2030.pdf). The estimated proportions of fields under continuous flooding, single drainage, and multiple drainage are shown in Table 2.

[13] The season water status is an essential parameter for calculation of the emission of CH_4 from rice fields; however, no statistical data or expert judgment is available for this parameter. Therefore, the following assumptions were made: All deepwater rice fields and 90% of the rain-fed rice fields were assumed to be flooded prior to planting. This assumption was made because it would be difficult to plant rice if the fields were not flooded since irrigation is not available for such rice fields. Irrigated rice can be planted once, twice, or three times a year. For irrigated rice planted once a year, we assumed that 95% had a season water status of long drainage and that the rest had a season water status of flooding because such rice fields are usually fallow or planted with upland crops during the nonrice season. For irrigated rice planted more than once a year, the first crop of rice is likely to be planted after a short fallow season or planting of an upland crop; therefore, 90% of it was assumed to have a season water status of short drainage and 10% were assumed to have a season water status of flooding. The second and third crops of rice are likely to be planted immediately after the first and second crops in the same field; therefore, 80% of these fields were assumed to

Table 2. Ratio of Irrigated Rice Fields Subject to Various Water Regimes

Country	Continuous Flooding	Single Drainage	Multiple Drainage	Source
India	0.3	0.44	0.36	ALGAS report[a]
Indonesia	0.43	0.22	0.35	ALGAS report
Vietnam	1	0	0	ALGAS report
China	0.2	0	0.8	*Li et al.* [2002]
Japan, Korea, and Bangladesh	0.2	0	0.8	Assumed to be the same as China
Other monsoon Asian countries	0.43	0.22	0.35	Assumed to be the same as Indonesia
Other countries	0.3	0.44	0.36	Assumed to be the same as India

[a] ALGAS, Asia Least Cost Greenhouse Gas Abatement Strategy. Reports were downloaded from the Website of the Asian Development Bank (http://ntweb03.asiandevbank.org/oes0019p.nsf/pages/sitemap).

have a season water status of flooding, while 20% were assumed to have a season water status of short drainage.

[14] The rice straw application rate was estimated for each country on the basis of the rice straw yield and the ratio of rice straw being applied to the field. The rice straw yield was calculated from the rice yield using the following equation:

$$\mathrm{Straw} = 3.43\mathrm{Ln}(\mathrm{Yield}) + 1.36, \tag{3}$$

where Straw is the rice straw yield in t ha^{-1}, and Yield is the rice grain yield in t ha^{-1}. The equation was derived from data regarding straw and grain yields given by *Meena et al.* [2003], *Krishnaveni et al.* [2001], and *Sengar et al.* [2000].

[15] Data regarding the rice yields were obtained from the same sources from which data regarding the rice areas were obtained. It was assumed that 70% of the unburned rice straw was applied to the rice fields. The ratio of rice straw burned in the field and as fuel was obtained from *Yan et al.* [2006] for China and from *Yevich and Logan* [2003] for other developing countries. When the straw burning ratio for a country was unavailable for *Yevich and Logan* [2003] or *Yan et al.* [2006], we assumed that 45% of the rice straw was unburned, which is the average value for Asian countries given by *Yevich and Logan* [2003].

[16] The farmyard manure application rate was estimated on the basis of the nitrogen content of farmyard manure and the rate of application of animal nitrogen to cropland, which was calculated using the method described by *Mosier et al.* [1998].

[17] The length of the rice-growing season for Asian countries was obtained from the database of field reports given by *Yan et al.* [2005]. The length of the growing season varies with agroecological zones and rice season. For example, the length of the growing season for early rice, late rice and single rice in southern China is 77, 93 and 110 days, respectively; however, the length of the growing season for single rice in northern China, Japan, and North and South Korea ranges from 120 to 130 days. Moreover, the length of the rice season in South and Southeast Asian countries varies from 99 to 115 days and the length of the rice season in non-Asian countries is assumed to be 130 days.

2.3. Sensitivity Analysis

[18] The sensitivity of the estimated emission to variation in the input parameters was evaluated using the Risk Analysis Add-In for Microsoft Excel version 4.5 (Palisade Corporation). Input parameters included a baseline emission factor, various scaling factors, the amount of organic amendment, and the proportions of rice fields under different water regimes during the rice-growing season and season. The baseline emission factor and all of the scaling factors have a lognormal distribution [see *Yan et al.*, 2005] with a mean and range that are provided in the 2006 IPCC guidelines. The amount of organic amendment is country specific as estimated above; however, we assumed it was normally distributed with a coefficient variation (CV) of 30%. We have estimated the ratios of the water regimes of irrigated rice fields under continuous flooding, single drainage, and multiple drainage for each country on an individual basis, as described above. In addition, we assumed that the proportion of fields under continuous flooding had a CV of 30%, and that when this value varied it had a trade-off relationship with the ratio of irrigated rice fields under single and multiple drainage. The ratio of rice fields with different season water statuses defined in the previous section were all assumed to have an exponential distribution. The mean values, statistical distributions and 95% ranges of the input parameters are shown in Table 3.

3. Results and Discussion

3.1. Estimated Emission and Comparison to Earlier Global Estimations, National Communications, and Country-Specific Estimates

[19] Using the agricultural activity data for the year 2000 and the disaggregated case described in the Tier 1 method in the 2006 IPCC guidelines, we estimated a global emission of 25.6 Tg $\mathrm{CH_4}$ a^{-1}, of which 19.0 Tg was from irrigated rice fields and 6.5 Tg was from rain-fed and deepwater rice fields. As shown in Table 4, which presents the emission by individual countries, more than half of the global emission from rice fields occurred in China and India, while more than 90% of the global emission from rice fields was from monsoon Asian countries.

[20] A summary of published global estimates of $\mathrm{CH_4}$ emission from rice cultivation is shown in Figure 1. The first such estimate of 190 Tg $\mathrm{CH_4}$ a^{-1} is based on laboratory incubation of paddy soils in a study conducted by *Koyama* [1963]. The first field measurements of $\mathrm{CH_4}$ emissions from rice paddy fields were made by *Cicerone and Shetter* [1981] in California. In their study, an average daily flux of 0.18 g $\mathrm{CH_4}$ m^{-2} was observed, which gave an estimated global emission of 59 Tg a^{-1}. *Seiler et al.* [1983] observed an average flux of 4 mg $\mathrm{CH_4}$ m^{-2} h^{-1} in a rice field in Spain and used this value to derive a global estimation

Table 3. Statistical Properties of Input Parameters for Sensitivity Analysis[a]

Parameters	Mean Value	Distribution	95% Range
Baseline emission factor	1.3	Lognormal	0.8–2.2
Scaling factors for water regimes during rice growing season			
Continuous flooding	1	Lognormal	0.79–1.26
Single drainage	0.6	Lognormal	0.46–0.80
Multiple drainage	0.52	Lognormal	0.41–0.66
Regular	0.28	Lognormal	0.21–0.37
Drought	0.25	Lognormal	0.18–0.36
Scaling factors for water status in season			
Short drainage	1	Lognormal	0.88–1.14
Long drainage	0.68	Lognormal	0.58–0.80
Flooded	1.9	Lognormal	1.65–2.18
Parameters related to the effect of organic amendment			
Stimulating effect of rice straw	0.59	Normal	0.54–0.64
Conversion factor of farmyard manure	0.14	Normal	0.0694–0.2106
Agricultural activity data			
Amount of organic amendment	Country-specific (see text)	Normal	Country-specific, with a CV of 30%
Ratio of irrigated rice fields continuously flooded in rice growing season	Country-specific (see Table 2)	Normal	Country-specific, with a CV of 30%
Ratio of rain-fed rice fields drained in season	0.1	Exponential	0.0025–0.3689
Ratio of single rice flooded in season	0.05	Exponential	0.0013–0.1832
Ratio of first rice flooded in season	0.1	Exponential	0.0025–0.3689
Ratio of second or third rice drained in season	0.2	Exponential	0.005–0.738

[a] Mean values and ranges of the baseline emission factor and scaling factors are from the 2006 IPCC guidelines. Mean values and ranges of agricultural activity data are defined in the text.

of 35–59 Tg a^{-1}. Subsequently, *Holzapfel-Pschorn and Seiler* [1986] completed the first full season measurement on an Italian rice field and reported a higher average flux (16 mg CH_4 m^{-2} h^{-1}), which resulted in a larger global CH_4 rate of 120 Tg CH_4 a^{-1}. Similarly, *Schütz et al.* [1989] observed an average flux of 12 mg CH_4 m^{-2} h^{-1} in an Italian rice field and used this to derive a global emission flux of 50–150 Tg a^{-1}, with an average value of 100 Tg a^{-1} based on an exponential relationship between methane flux and soil temperature. Each of these estimates were based on a limited number of hourly and daily fluxes and extrapolated to global annual emissions using the global rice area and temperature dependency observed in the laboratory or field. However, *Neue et al.* [1990] argued that only 80 of the 143 million ha of harvested wetland rice fields are a potential source of CH_4 and thus reduced the global emission totals to 25–60 Tg CH_4 a^{-1}. Because of these conflicting calculations and assumptions, *Intergovernmental Panel on Climate Change* (*IPCC*) [1990] reported that global CH_4 emissions from rice fields range from 25 to 170 Tg CH_4 a^{-1}, with an average of 110 Tg CH_4 a^{-1}.

[21] Approximately 90% of the world's rice fields are located in monsoon Asian countries. Accordingly, CH_4 emission from rice fields in such countries has been measured extensively since the 1990s. We previously conducted a statistical analysis of these data, which revealed that the primary factors that constrain CH_4 emission were organic amendment, rice ecology, water regimes during and before the rice-growing season and soil properties [*Yan et al.*, 2005]. The IPCC 2006 guidelines for CH_4 emission from rice cultivation attempt to account for these factors. By applying the current IPCC guidelines for CH_4 emission, we estimated the global CH_4 emission from rice fields for the year 2000 to be 25.6 Tg CH_4 a^{-1}, which is at the lower end of the early estimates.

[22] A major reason for the discrepancy between our estimate and previously published global totals may be that we distinguished rice ecologies and water management practices (i.e., continuously flooded, intermittently irrigated, rain-fed, or deepwater rice fields). Earlier emission estimates were primarily based on field measurements conducted on continuously flooded rice fields; however, it is well know that CH_4 production and emissions vary in response to water level. For example, *Yan et al.* [2005] estimated that the average fluxes in CH_4 from intermittently irrigated and rain-fed rice fields were only approximately 50% and 25% of those from continuously flooded rice fields, respectively. By distinguishing fluxes from irrigated and rain-fed rice fields, *Sass* [1994] estimated a global emission of 25–54 Tg CH_4 a^{-1}. A second reason for this discrepancy may be differences in the estimated lengths of

Table 4. Estimated Emissions From Global Rice Fields[a]

Region/Country	Irrigated Rice	Rain-Fed and Deepwater Rice	Total
China	7.41	0.00	7.41
India	3.99	2.09	6.08
Bangladesh	0.47	1.19	1.66
Indonesia	1.28	0.38	1.65
Vietnam	1.26	0.39	1.65
Myanmar	0.80	0.36	1.17
Thailand	0.18	0.91	1.09
Other monsoon Asian countries	2.32	0.67	2.99
Rest of the world	1.20	0.49	1.70
Total	18.90	6.49	25.39

[a] Values given in Tg CH_4 a^{-1}.

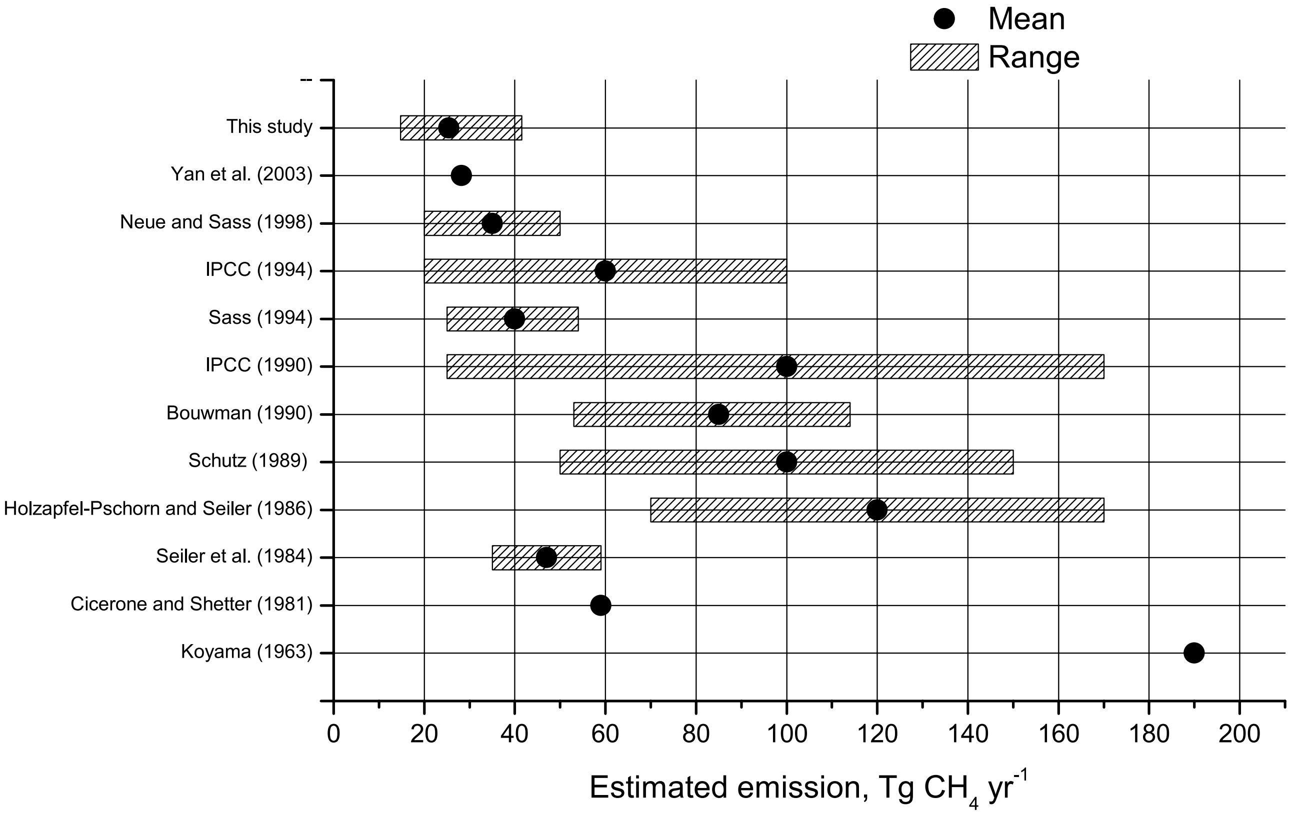

Figure 1. Various estimates on methane emission from global rice fields.

the rice-growing season. Early estimates on the basis of field measurements conducted in the United States and Europe generally used a rice-growing season of 140–150 days [*Cicerone and Shetter*, 1981; *Seiler et al.*, 1983; *Holzapfel-Pschorn and Seiler*, 1986]. However, in the present study, the length of the rice-growing season was derived from a large number of studies that were conducted in major rice-producing countries with growing seasons that ranged from 77 to 130 days.

[23] Table 5 compares the CH_4 emissions from rice paddies in the top 20 rice-producing countries (in terms of the rice harvest area given by FAOSTAT (The FAO Statistical Database, 2008, available at http://faostat.fao.org/) for the year 2000) to those estimated in the national communications (NCs) to the United Nations Framework Convention on Climate Change as well as to some other country-specific estimates. Table 5 identifies discrepancies between our estimates and those provided in the NCs that may be explained by three primary sources, which were as follows: First, the base year of most of the NCs was 1994 (for the Unites States and Japan, the base year was 2000), while our estimates were for the year 2000; therefore, the rice cultivation area that the estimates were based on may have changed. Second, we used the 2006 IPCC guidelines, while some NCs were determined using the 1996 IPCC guidelines (with either local or default EFs), or other local methods. Third, our estimated water regimes and organic amendments may have differed from those used to determine the values reported in the NCs.

[24] For China, which was found to emit the most CH_4 during the production of rice, our estimate exceeds the value reported in the NC by approximately 20%. Although the base year differed, the rice harvest areas used to generate the two estimates were similar. Therefore, the difference in results were likely due to methodological differences. The estimate in the Chinese NC was generated using the same model that was used to estimate an emission of 9.7–12.6 Tg CH_4 from Chinese rice fields in 1990, which the authors stated may have been an overestimation (ALGAS report, see Table 5 for source). In another study, we estimated an emission of 7.67 Tg CH_4 for China in 1995 using a large data set of local field measurements and detailed regionalization [*Yan et al.*, 2003], which is very close to the current estimate. In addition, using a process model coupled with GIS soil property data generated at the provincial level, *Matthews et al.* [2000] estimated that the CH_4 emission from Chinese rice fields ranged from 3.35 to 8.64 Tg a^{-1}, with a more realistic value of 7.22–8.64 Tg a^{-1}. However, the DNDC model revealed that the CH_4 emission from Chinese rice fields can range from 1.71 to 12.02 Tg a^{-1} depending on water regimes [*Li et al.*, 2004]. On the basis of these findings, it will be difficult to determine which estimate is more accurate before reliable information regarding water management and organic amendment becomes available.

[25] Our estimate of 6.08 Tg CH_4 for India is 50% higher than that of their NC. This discrepancy may have occurred for two reasons. First, the rice area used to generate our estimate was 10% higher than that used to generate their NC

Table 5. Comparisons of Estimated Emission With National Communications and Other Country-Specific Estimations for Major Rice-Producing Countries[a]

		National Communication[c]		*Yan et al.* [2003][d]		ALGAS Report[e]	
Country	This Study[b]	Value	Method	Value	Method	Value	Method
China	7405	6147	Distinguished four rice types, double-harvest early rice, double-harvest late rice, single-harvest rice and winter flooding fields; EFs for the first three types were modeled using CH4MOD, and EF for the last type was measured locally	7668	Distinguished 5 climate zones, 3 rice seasons and 2 water regimes; assumed half of the rice fields received organic amendment; zone-specific EFs derived from 204 local field measurements	9660–12650	Modeling (for 1990)
India	6078	4090	1996 IPCC guidelines, with local EF	5876	Distinguished 4 climate zones, 2 water regimes, assumed half of the rice fields received organic amendment; zone-specific EFs derived from local measurements	4110	1996 IPCC guidelines with local EF (for 1990)
Bangladesh	1663	/		1548	Used average EFs for irrigated and rain-fed rice fields of Indonesia and Philippines	767	1996 IPCC guidelines, assuming no organic amendment (for 1990)
Indonesia	1653	2281	1996 IPCC guidelines; details not mentioned	2909	Rice fields classified into 3 regions according to soil pH; distinguished 4 water regimes; assumed half of the rice fields received organic amendment; EFs derived from local measurements.	2600	1995 IPCC guidelines, with EFs for different water regimes derived From local measurements and with temperature adjustment (for 1993)
Vietnam	1651	1560	1996 IPCC guidelines; default EF used for south Vietnam, local measured EF for north Vietnam	1246	Used average EFs for irrigated and rain-fed rice fields of Indonesia and the Philippines	1755	1996 IPCC guidelines (for 1993)
Myanmar	1166	/		1299	Used average emission factor of east Thailand and east India as the default	1328	1996 IPCC guidelines (for 1990)
Thailand	1089	2110	1996 IPCC guidelines with local EF	1748	Distinguished 5 regions and 3 water regimes; EFs for continuously flooded and deepwater rice fields derived from local measurements, other EFs derived using IPCC 1996 scaling factors; assumed half of the rice fields received organic amendment	1765	On the basis of local measurement and distinguished water regimes, soil types and organic amendments (for 1994)
Philippines	744	636	Distinguished between irrigated and rain-fed rice fields, organic amendment not considered; used local EF	532	EFs for irrigated rice fields with and without organic amendment derived from local measurements, EFs for rain-fed rice estimated using the IPCC 1996 scaling factor	566	1995 IPCC guidelines with EF derived from local measurements (mean of 1983–1993)
Brazil	138	283		/		/	
Pakistan	453	222.6	Assumed an EF of 10 g CH_4 m^{-2} for all rice fields	430	EFs derived for India were used as the default	526	1995 IPCC guidelines, with EF adjusted to local temperature and rice season length (for 1990)
Nigeria	156	1086	IPCC 1996 guidelines	/		/	
Cambodia	331	150	IPCC 1996 guidelines	298	Used average EFs for irrigated and rain-fed rice fields of Indonesia and the Philippines	/	

Table 5. (continued)

Country	This Study[b]	National Communication[c]		*Yan et al.* [2003][d]		ALGAS Report[e]	
		Value	Method	Value	Method	Value	Method
Japan	407	284	Distinguished five soil types, with local EF and scaling factors for organic amendment	416		/	
Nepal	251	306	IPCC guidelines and default EFs. Organic amendment correction factor applied to all rice fields	194	EFs derived for India were used as the default	/	
United States	348	362	*IPCC* [2000] employs United States-specific emission factors derived from local measurements	/		/	
Madagascar	137	29	/	/		/	
North Korea	146	/		/		/	
South Korea	316	414	1996 IPCC guidelines, with local EFs	337	EFs of irrigated rice fields with and without organic amendment derived from local measurements; EFs of rain-fed rice estimated using 1996 IPCC scaling factor	414	1996 IPCC, with local EFs (for 1994)
Sri Lanka	152	42	1996 IPCC guidelines; assumed that all rice cultivation is done using a single aeration method; EF from India	157	Used average EFs for irrigated and rain-fed rice fields of Indonesia and the Philippines	/	
Malaysia	126	252	1996 IPCC guidelines, but EF adopted from Thailand	127	Used average EFs for irrigated and rain-fed rice fields of Indonesia and the Philippines	/	
Globe	25552	24561[f]		28200[g]		/	

[a] The emission unit is Gg CH_4 a^{-1}. Here "/" means that there is no information available.

[b] Base year of this study is 2000.

[c] National communications were downloaded from http://unfccc.int/national_reports/non-annex_i_natcom/items/2716.php. Emission base year is 1994 for all countries except the U.S. and Japan, for which the emissions are for the year 2000.

[d] Activity data used by *Yan et al.* [2003] were for the year 1995.

[e] ALGAS, Asia Least Cost Greenhouse Gas Abatement Strategy. Reports were downloaded from http://www.adb.org/reach/algas.asp. Base year of this estimation varies with country, as indicated.

[f] Global emission was extrapolated from the total emission of the 17 available national communications listed in the table using FAOSTAT (database, 2008) rice harvest area for the year 2000.

[g] Global emission was extrapolated from the total emission of 20 rice-producing countries in the portion of Asia in the monsoon region.

because of the difference in the base years used. Second, and more importantly, organic amendment was not considered in their NC. In the estimate generated in this study, organic amendment contributed 1.7 Tg of CH_4 to the emission from rice fields in India. In a previous study [*Yan et al.*, 2003], we developed region-specific emission factors for India that were based on local measurements under the assumption that 50% of the rice fields received organic amendment. The estimate for India generated by that study was 5.88 Tg CH_4 for 1995. Using remote sensing data regarding rice area obtained from May 2001 to May 2002 and rice calendar and emission factors for different types of rice grown in India, *Manjunath et al.* [2006] obtained a mean emission estimate of 5.74 Tg per year for India. It is interesting to note that these two recent studies yielded results very similar to the results of the present study, even though they each used different methods and parameters.

[26] For Indonesia and Thailand, our estimates were 27–48% lower than the values reported in their NCs and other earlier estimates that used local EFs (e.g., *Yan et al.* [2005], ALGAS report, see Table 5). This likely occurred because of the method we used to calculate the effect of organic amendment on CH_4 emission. In previous studies, organic amendment was considered to be a category factor. However, in the 2006 IPCC guidelines, organic amendment is considered to be a continuous factor; therefore, its effect is dependant on the rate of organic input. In the present study, the rate of rice straw application was estimated from the rice yield as well as the ratio of rice straw burned as fuel and in the field. The average rice yield of Thailand is only 2.6 ton ha^{-1} (FAOSTAT, database, 2008), and it has been estimated that 67% of the rice straw is burned as fuel or in the field [*Yevich and Logan*, 2003]. The rice yield of Indonesia is 4.4 ton ha^{-1} (FAOSTAT, database, 2008), and it is estimated that 87% of the rice straw is burned as fuel and in field [*Yevich and Logan*, 2003]. These facts resulted in lower estimated CH_4 emissions from rice fields in Indonesia and Thailand in the present study than in their NCs. Our estimate for Indonesia was well within the modeled range of 1.0–2.87 Tg a^{-1} and in close agreement with the modeled baseline emission of 1.65 Tg a^{-1} that was reported by *Matthews et al.* [2000]. However, our estimate for Thailand was significantly higher than the modeled value of 0.14–0.32 Tg a^{-1} reported by *Matthews et al.* [2000], which indicates that further work should be conducted to reduce the uncertainty associated with the estimate for Thailand.

[27] NCs and estimates based on direct measurements were not available for Bangladesh and Myanmar. However, the values estimated in the current study agree well with those of previous studies that were calculated using measurements obtained from neighboring countries [*Yan et al.*, 2003]. For Myanmar, our estimate was also similar to that of their ALGAS report. However, for Bangladesh, our estimate was more than double that of their ALGAS report. This discrepancy likely occurred because the method used to estimate the emission in the Bangladesh ALGAS report assumed that there was no organic amendment. The first field measurement of emissions from rice fields in Bangladesh, which recently became available, showed high fluxes in emissions [*Frei et al.*, 2007].

[28] Our estimates for Vietnam, the Philippines, South Korea and Nepal all agree reasonably well with the values reported in their NCs. For the United States, the base year and rice harvest area used in our study and their NC were the same, and the resulting estimates were almost identical. The largest difference between our estimate and that of an NC occurred for Nigeria. However, we believe there is a calculation error in their NC because the calculated average emission flux from their NC is approximately 98 g CH_4 m^{-2} $season^{-1}$, which is far higher than any of the reported field measurements.

[29] With the exception of Bangladesh, Myanmar, and North Korea, for which NCs were not available, the rice harvest area of the other 17 countries listed in Table 5 accounted for 82.5% of the worldwide rice harvest for the year 2000 (FAOSTAT, database, 2008). In addition, the total CH_4 emission from rice cultivation reported in the NCs of these 17 countries was 20.3 Tg a^{-1}. Extrapolating this value gives a global emission of approximately 24.6 Tg CH_4 a^{-1}, which is very close to our estimate of 25.6 Tg CH_4 a^{-1} and also agrees well with our previous estimate of 28.2 Tg CH_4 a^{-1} [*Yan et al.*, 2003]. These findings indicate that the methodologies that distinguish rice ecologies tend to give low estimates for CH_4 emissions from rice fields.

3.2. Spatial Distribution of the Estimated Emissions

[30] The emissions were estimated at the subnational level for monsoon Asian countries and the United States and at the national level for other rice producing countries. With the exception of Russia and France, a rice distribution map with a resolution of 5 min [*Leff et al.*, 2004] was used to allocate the estimated emission data within each estimation unit. The Global Land Cover Characteristics Database (available at http://edcftp.cr.usgs.gov/pub/data/glcc/globdoc2_0.html#down) was used to estimate the distribution of emissions in Russia and France because of the unusual rice distribution for these two countries in the data set produced by *Leff et al.* [2004]. The resulting map (Figure 2) indicated that the areas with the greatest emissions were the delta regions of large rivers in Bangladesh, Myanmar, and Vietnam. In addition, the generated map revealed that other areas with high emissions were found on the island of Java in Indonesia, central Thailand, southern China and the southwestern portion of the Korean peninsula. The emissions were summarized at a resolution of 0.5 degrees and distributed monthly using the seasonality reported by *Matthews et al.* [1991]. The resulting data set is available at http://www.jamstec.go.jp/frcgc/research/p3/emission.htm.

[31] Although many studies have estimated the CH_4 emission from global rice fields, only a few have provided a spatial distribution. Most atmospheric models have used the data set produced by *Matthews et al.* [1991], who presented a monthly emission map at a spatial resolution of 1° using a prescribed total emission of 100 Tg a^{-1}. However, in that study, they stated that the CH_4 emission from rice paddies may have been considerably lower than their estimate. Furthermore, their online database currently shows a total source strength of 79.7 Tg a^{-1} (http://data.

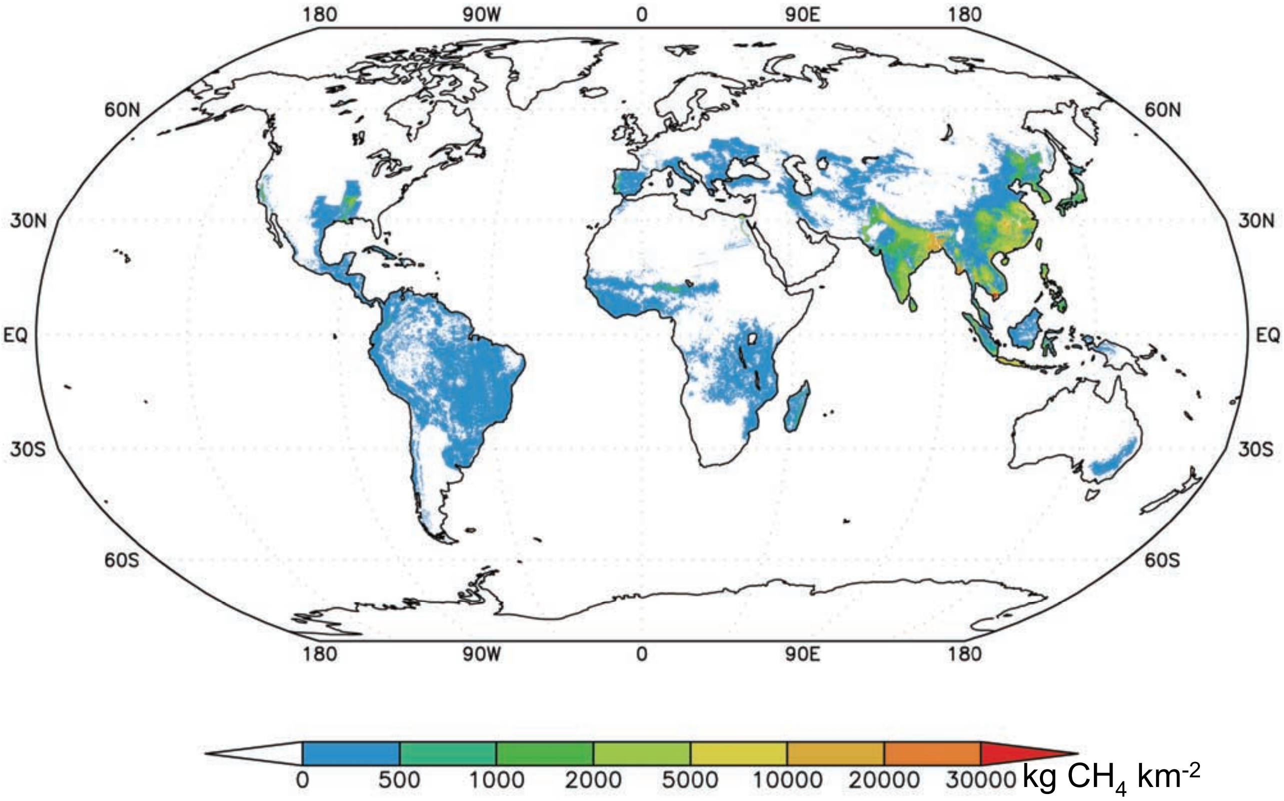

Figure 2. Estimated annual methane emission from global rice paddies at a spatial resolution of 5 min.

giss.nasa.gov/ch4_fung/). *Lelieveld et al.* [1998] and *Houweling et al.* [1999, 2000] used an a priori strength of 80 Tg a^{-1} in their atmospheric models; however, there was a large discrepancy between their results and satellite observations of the CH_4 column over the tropics. This discrepancy indicates that the estimated CH_4 emissions were larger than the actual emissions [*Frankenberg et al.*, 2005]. Accordingly, subsequent inversion studies used lower a priori rice emissions of 60 Tg a^{-1} [*Frankenberg et al.*, 2006; *Bergamaschi et al.*, 2007], which resulted in the estimated CH_4 emission being reduced to 48.7 Tg a^{-1}.

[32] The emission distribution generated in this study, which includes a fine spatial resolution, provides another option for inverse modeling. Our estimates are at the lower end of earlier estimates; however, given the large database that the current calculations are based on and the country-specific data we obtained, we feel that this approach may be more justifiable.

3.3. Uncertainty of the Estimated Emission

[33] We ran 10,000 Monte Carlo simulations using the error ranges of the baseline emission factor and scaling factors provided in the 2006 IPCC guidelines and the assumed error ranges of the activity data to test the sensitivity of the estimated emissions to the controlling factors. The 95% variation range for the estimated emissions was 14.8 to 41.7 Tg a^{-1} and the estimated emissions were most sensitive to variation in the baseline EF (Figure 3). This is primarily due to the large variability in the baseline EF, which includes the contribution of many influencing factors that are not considered in the guidelines. For example, the soil pH has a strong effect on CH_4 emission, and our database of field measurements revealed that the pH of paddy soils varies greatly. However, it is difficult to obtain a spatially explicit map of the pH value of global rice paddies. Although *Knox et al.* [2000] developed a soil database for five rice-producing counties at the provincial level using the global data set produced by *Batjes* [1997], they used a median value to represent each province (or state). Because the relationship between CH_4 emission and soil pH is not monotonic [*Yan et al.*, 2005], using a median value is likely to result in an artifact. For this reason, soil properties are not accounted for in the current IPCC guidelines. Therefore, until a very fine spatially explicit data set of soil properties becomes available, it will remain difficult to reduce the high variability in the estimated emissions.

[34] The estimated emissions were also highly sensitive to the amount of organic amendment and the fraction of rice fields under continuous flooding (Figure 3), indicating that reliable information regarding agricultural activities is crucial to improving the accuracy of emission inventories. This finding is in good agreement with the modeled results of *Li et al.* [2004].

[35] Although CH_4 emission from rice cultivation is not only affected by management (water regime, organic amendment), but also by soil properties (texture, organic carbon content, soil pH), rice cultivars and climate, the Tier 1 method of the 2006 IPCC guidelines only considers

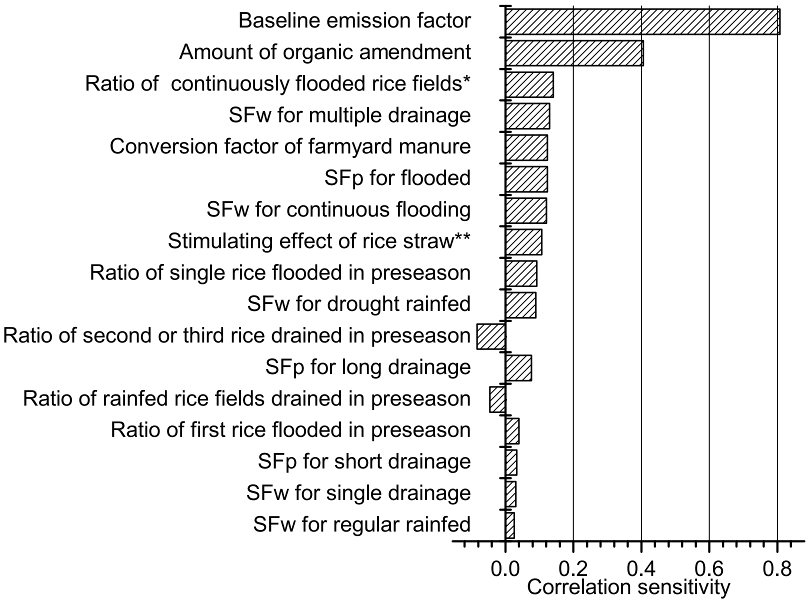

Figure 3. Correlation sensitivity of the estimated methane emission to input parameters calculated using the Risk Analysis Add-In for Microsoft Excel version 4.5 (Palisade Corporation). The asterisks indicate that a fraction of irrigated rice fields are continuously flooded during the rice growing season.

the effect of management practices. This is either because reliable information regarding the factors themselves is not easily available or because a clear relationship between influencing factors and emission flux cannot be drawn from limited observations [*Yan et al.*, 2005]. For example, *Cheng et al.* [2007] found that methane production was well correlated to easily decomposable carbon and reducible iron. However, spatial information regarding these soil properties is currently very difficult to obtain. Furthermore, methane emission from side by side plots of the same field may differ by factors of 2–4 [*Khalil and Butenhoff*, 2008]. The effects of some of the factors used to estimate CH_4 emissions in the present study are partly reflected by the effects of water regimes and organic amendment. For example, water regimes are dependant on rainfall to some extent. Similarly, the rice straw application rate is calculated from the rice yield, which is affected by the rice cultivar and climatic factors such as solar radiation. As mentioned above, the low rice yield may have resulted in the low estimated emissions from Thailand.

3.4. Mitigating Effects of Management Practices

[36] The Monte Carlo simulation demonstrated that emissions are sensitive to agricultural management activities. Therefore, there is the potential to reduce emissions by implementing appropriate management practices. An effective practice would be to stop the application of rice straw. This is because, with the exception of the baseline emission factor, rice straw application is the most sensitive factor influencing the estimated emission (Figure 3). However, if rice straw is not applied to rice fields it will most likely be burned, which causes air pollution and is prohibited in many areas. In addition, the application of rice straw is beneficial to maintaining the soil carbon content and soil fertility, which helps maintain crop yield. Therefore, an alternative method of disposing of rice straw would be to apply it off season. To accomplish this, rice straw from a previous season is incorporated into the soil long before cultivation (>30 days) so that it decomposes under aerobic conditions. According to the 2006 IPCC guidelines, rice straw applied off-season stimulates much less CH_4 emission than rice straw that is applied on season. However, this practice is not applicable to all rice seasons. For example, in double rice areas such as southern China, late rice is planted immediately after the early rice harvest, which necessitates that the rice straw be applied on season. However, if applying rice straw off season was adopted in all single rice areas and for early rice in double rice areas, the estimated global CH_4 emissions would be reduced by 4.1 Tg a^{-1}.

[37] Because continuous flooding increases the amount of CH_4 emitted from rice fields, another mitigation option is to drain continuously flooded fields once or more during the rice-growing season. Indeed, adoption of this practice would result in a reduction of 4.1 Tg a^{-1}. Furthermore, if the two mitigation options described above were adopted simultaneously, the net reduction in CH_4 emissions would be 7.6 Tg a^{-1}, or 30%, which would result in a global emission of 17.8 Tg a^{-1}. The geographical distribution of the mitigating effects are shown in Figure 4, which reveals that the effects primarily stem from northern India, Bangladesh, the delta regions of the Mekong River and Red River in Vietnam, the delta region of Irrawaddy River in Myanmar, West Java in Indonesia, and southwest Korea.

[38] Table 6 shows the mitigating potential of the top 20 rice-producing countries. For the four largest emitters (India, China, Bangladesh and Indonesia), the mitigating effect is relatively small (25.9–28.6%). Rice is produced more than once a year in many areas of these countries;

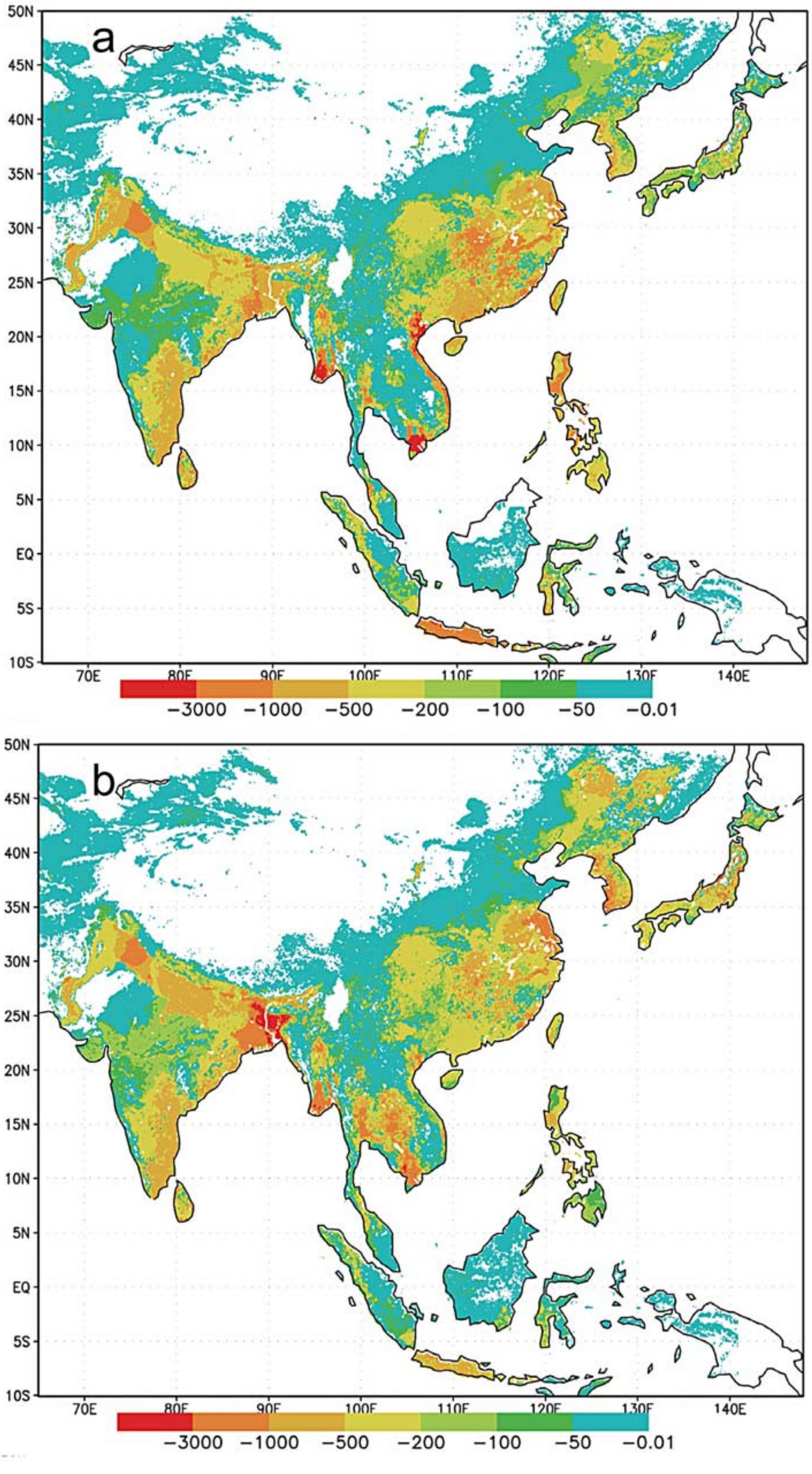

Figure 4. Distribution of potential mitigating effects by (a) applying rice straw off season where possible, (b) draining all continuously flooded rice fields, and (c) adopting both options. Negative values indicate an emission reduction.

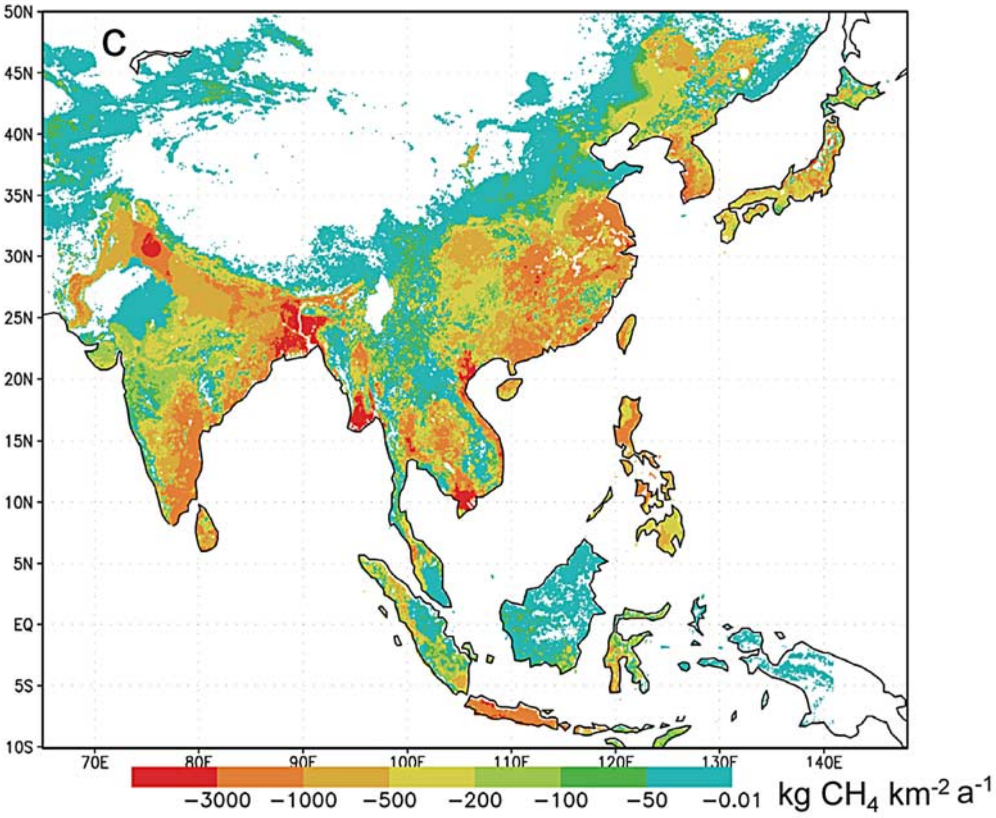

Figure 4. (continued)

therefore, the applicability of using rice straw off season would be limited. In addition, the relatively large proportion of rain-fed rice fields in India, Bangladesh and Indonesia leaves little room for mitigation through draining continuously flooded rice fields. For Vietnam, Pakistan, Japan, North Korea and the United States, the mitigating effect is greater than 40%. These countries either have a large proportion of continuously flooded rice fields or plant rice only once a year. However, it is important to note that this estimation of mitigation potential is rather arbitrary because it was determined using the proportion of the rice fields that were continuously flooded during the rice-growing season, and the rate of rice straw application. These parameters were determined using data that were rare and indirect.

[39] It is well known that the water regime exerts a trade-off effect on CH_4 and nitrous oxide (N_2O) emissions from rice fields [*Cai et al.*, 1997; *Akiyama et al.*, 2005]. The IPCC guidelines estimate that, on average, 0.31% of the nitrogen fertilizer applied to rice paddies is emitted as N_2O [*IPCC*, 2007a]. This emission factor was based on an analysis conducted by *Akiyama et al.* [2005], in which they calculated a N_2O emission factor of 0.22% for continuously flooded rice paddies and an emission factor of 0.37% for intermittently irrigated rice paddies. We estimate that 27 million hectares of the global rice area is continuously flooded. Assuming an average fertilizer application rate of 150 kg N ha^{-1}, if these continuously flooded rice fields were all drained at least once during the rice-growing season, the N_2O emission from rice fields would increase by approximately 9.5 Gg (in N_2O). Even though the global warming potential of 1 kg of N_2O is approximately 12 times higher that of 1 kg of CH_4 [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007b], the increased global warming potential resulting from this amount of N_2O emission is only approximately 2.7% of the reduced global warming potential that would result from the 4.1 Tg reduction in CH_4 emission. Therefore, it is favorable to reduce CH_4 emissions from rice fields by draining the fields.

4. Summary

[40] Using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and country-specific activity data, we estimated that the emission of CH_4 from global rice fields is 25.6 Tg a^{-1}, with a 95% certainty range of 14.8–41.7 Tg a^{-1}. Although the estimated emissions for individual countries do not always agree well with the national communications, the estimated global emissions are very close to the sum of the individual national communications. These results indicate that the emission of CH_4 from rice paddies was overstated in most earlier atmospheric models, which allows for a new CH_4 source or higher estimated CH_4 emissions for other sources. In addition, the amount of rice straw applied to fields and the total area of rice paddies that are continuously flooded were found to exert a strong effect on the

Table 6. Mitigation Potential of Methane Emission From Rice Cultivation in Major Rice Producing Countries by Applying Rice Straw Off Season Where Possible, Draining All Continuously Flooded Rice Fields, and Adopting Both Options Simultaneously[a]

Country	Rice Straw Off Season	Draining Rice Field	Both Options
China	12.8	15.6	26.4
India	16.3	13.6	27.5
Bangladesh	22.4	4.4	25.9
Indonesia	8.4	21.7	28.6
Vietnam	5.7	36.6	40.7
Myanmar	15.9	19.8	33.2
Thailand	20.2	4.7	24.2
Philippine	9.0	22.7	30.0
Pakistan	25.1	28.7	46.7
Japan	33.6	15.6	43.9
United States	35.2	21.8	49.3
Cambodia	27.9	6.6	33.4
South Korea	26.7	12.0	35.5
North Korea	35.5	19.2	47.9
Nepal	19.0	16.7	32.6
Nigeria	19.6	6.3	24.7
Sri Lanka	18.5	24.5	38.8
Brazil	27.7	17.0	39.9
Madagascar	22.7	2.8	24.8
Malaysia	16.4	23.5	36.6
Globe	16.1	16.3	30.1

[a]Values given in percent.

estimated CH_4 emissions. Therefore, global emissions can be reduced by 4.1 Tg a^{-1} by applying rice straw off season where possible. In addition, draining the continuously flooded rice paddies once or more during the rice-growing season would also reduce global emissions by 4.1 Tg CH_4 a^{-1}. Furthermore, the increased global warming potential resulting from increased N_2O emission due to draining the fields would be negligible when compared to the reduction in global warming potential that would occur as a result of the reduced CH_4 emissions.

[41] The geographical distribution of the estimated emissions was determined on the basis of direct estimations made at the national or subnational level and using a fine rice distribution map. The seasonal distribution was scaled from *Matthews et al.* [1991]. The resulting emission data set, which has a 0.5 by 0.5 degree resolution and is available at http://www.jamstec.go.jp/frcgc/research/p3/emission.htm, has been established for use in relevant atmospheric models.

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