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Controlling variables and emission factors of methane from global rice fields

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Abstract. Rice cultivation has long been known as one of the dominant anthropogenic contributors to methane (CH_4) emissions, yet there is still uncertainty when estimating its emissions at the global or regional scale. An increasing number of rice field measurements have been conducted globally, which allow us to reassess the major variables controlling CH_4 emissions and develop region- and country-specific emission factors (EFs). The results of our statistical analysis show that the CH_4 flux from rice fields was closely related to organic amendments, the water regime during and before the rice-growing season, soil properties and agroecological conditions. The average CH_4 fluxes from fields with single and multiple drainage were 71 % and 55 % that of continuously flooded rice fields. The CH_4 flux from fields that were flooded in the previous season were 2.4 and 2.7 times that of fields previously drained for a short and long season, respectively. Rice straw applied at 6 t ha^{-1} in the preseason can decrease CH_4 emissions by half when compared to that applied shortly before rice transplanting. The global default EF was estimated to be 1.19 kg CH_4 ha^{-1} day^{-1} with a 95 % confidence interval of 0.80 to 1.76 kg CH_4 ha^{-1} day^{-1} for continuously flooded rice fields without organic amendment and with a preseason water status of short drainage. The lower EFs were found in countries from South Asia (0.85 kg CH_4 ha^{-1} day^{-1}) and North America (0.65 kg CH_4 ha^{-1} day^{-1}) relative to other regions, indicative of geographical variations at sub-regional and country levels. In conclusion, these findings can provide a sound basis for developing national inventories and mitigation strategies of CH_4 emission from rice fields.

1 Introduction

Atmospheric methane (CH_4) is an important greenhouse gas (GHG), and its global mean concentration has increased by a factor of 2.5 since the pre-industrial era (Dlugokencky et al., 2011). It has long been recognized that rice cultivation is one of the dominant anthropogenic contributors to CH_4 emissions (Ciais et al., 2013; Koyama, 1963). Over the last century, the observed expansion of rice fields was the dominant factor for the increase of global CH_4 emissions from rice cultivation (Fuller et al., 2011; Zhang et al., 2016). Owing to the increasing area of rice grown globally, the increase in CH_4 emission is expected to continue in the near future (EPA, 2012; FAO, 2016).

While the total global CH_4 source is relatively well known, the strength of each source component and their trends remain uncertain. Over the last 3 decades, substantial progress has been made in estimating CH_4 emissions from global rice fields, but large discrepancies in magnitude exist among various studies (range: 20.8 to 170 Tg CH_4 yr^{-1}; Cicerone and Oremland, 1988; EPA, 2012; Frankenberg, 2005; Neue et al., 1990; Yan et al., 2009). Previous studies have shown that the magnitude of estimated CH_4 emissions from rice cultivation has followed a downward trend, suggesting that the estimated accuracy has improved. In general, the estimations from top-down approaches (31–112 Tg CH_4 yr^{-1}; Denman et al., 2007) were much higher than those from both inventory (25.6–41.7 Tg CH_4 yr^{-1}; EPA, 2012; FAO, 2016; Yan et al., 2009) and bottom-up (18.3–44.9 Tg CH_4 yr^{-1}) approaches (Ito and Inatomi, 2012; Spahni et al., 2011; Zhang et al., 2016). These disparities may be the result of the higher estimation of prior information on either rice field distribution or the estimated CH_4 emissions being used in the top-down studies. Furthermore, anthropogenic sources were dominant over natural sources to global CH_4 emissions in the top-down studies, while they were of the same magnitude in the bottom-up models and inventories (Ciais et al., 2013).

For national-level reporting of GHG emissions to the United Nations Framework Convention on Climate Change (UNFCCC), a range of methodological approaches has been endorsed in IPCC guidelines (i.e., 1996, 2000, 2003, and 2006), which were specified under inventory-based (i.e., Tier 1 and Tier 2) and model-based approaches (Tier 3). Accordingly, a range of approaches at various tiers is applied in the UNFCCC GHG data set, which provides emissions data communicated by member countries (UNFCCC, 2017). At the country level, the inventory-based approach is often used for estimating CH_4 emissions from rice fields. For most countries (i.e., South and Southeast Asian countries), either the Tier 1 or Tier 2 method has been used to compute CH_4 emissions from rice fields in their national reports. Although the Tier 2 method requires more specific national values, country-specific emission factors (EFs) and/or scaling factors obtained therein are simply adjusted based on those default values used in the Tier 1 method. In contrast, the Tier 3 method to date has been used by a few countries to estimate CH_4 emissions from rice cultivation in their national GHG inventory reports, including China, the United States, Japan and India (UNFCCC, 2017). Moreover, to estimate the CH_4 emissions from rice fields on a global scale, studies using the IPCC 2006 guidelines showed comparable results (EPA, 2017; FAO, 2016; Tubiello et al., 2013; Yan et al., 2009). Thus, these findings indicate that the inventory-based methods are useful in providing a reliable estimate of CH_4 emissions from rice fields.

The net CH_4 flux is determined by both the production from methanogens and the consumption from methanotrophs (Conrad, 2007). Previous studies have shown that CH_4 emissions from rice fields have been influenced by water management (Wang et al., 2012; Zou et al., 2005), nitrogen (N) fertilizer use (Banger et al., 2012), organic input (Feng et al., 2013; Wang et al., 2013) and rice varieties (Jiang et al., 2017; Watanabe et al., 1995). Using a statistical analysis of a large data set of field measurements, Yan et al. (2005a) revealed that the primary factors that control CH_4 emissions were organic amendments, the agroecological zone, water regimes during and before the rice-growing season and soil properties. These factors have been accounted for in the current IPCC guidelines, where EFs and scaling factors for CH_4 emissions from rice cultivation were revised accordingly (Lasco et al., 2006).

After more than a decade since the study of Yan et al. (2005a) was published, numerous field measurements in Asian countries have become available. Outside of Asia, many studies to date have investigated the impact of various factors on CH_4 emissions from rice fields, while they were not included in the previous analysis (Yan et al., 2005a). Through an updated analysis, the objectives of this study were therefore (1) to reassess the impacts of major variables controlling CH_4 emissions from rice fields and (2) to develop the region- and country-specific EFs for which sufficient number of measurements were available.

2 Materials and methods

2.1 Data compilation

Since 2004, there has been a large body of field measurements of CH_4 emissions from rice fields across the world. With a cut-off date of 31 June 2017, the data set of Yan et al. (2005a) was updated and expanded to include all available observations of CH_4 emissions from rice fields around the world. We conducted a comprehensive search of the literature reporting the field measurements of CH_4 as described previously (Yan et al., 2005a). This included a keyword search using the ISI Web of Science (Thomson Reuters, New York, NY, USA) and Google Scholar (Google, Mountain View, CA, USA). For individual studies, the following documented information was compiled: the average CH_4 flux in the rice-growing season, integrated seasonal emission, the water regime during and before the rice-growing season, the timing, type and amount of organic amendments, soil properties (i.e., SOC and soil pH), location, the agroecological zone and the year, duration and season of measurement. As suggested previously (Yan et al., 2005a), hourly or daily flux can be a better index of emission strength than seasonal integrated emission. When the average seasonal CH_4 flux was not directly reported, it was thus estimated from integrated seasonal emissions and the measurement period, and vice versa. The raw data were either obtained directly from tables and texts or extracted by digitizing graphs using the G3DATA software (http://www.frantz.fi/software/g3data.php, last access: February 2014).

As shown in Table 1, the water regime in the rice-growing season was determined as continuous flooding, single drainage, multiple drainage, wet season rainfed, dry season rainfed, or deep water. The preseason water status was classified as flooded, long drainage, short drainage or two drainage. Note that although we tried our best to judge the water status of rice fields from the papers, the water regimes in both the rice-growing season and preseason could still not be determined for some studies; thus, a level of "unknown" was assigned. For organic amendments, the materials used

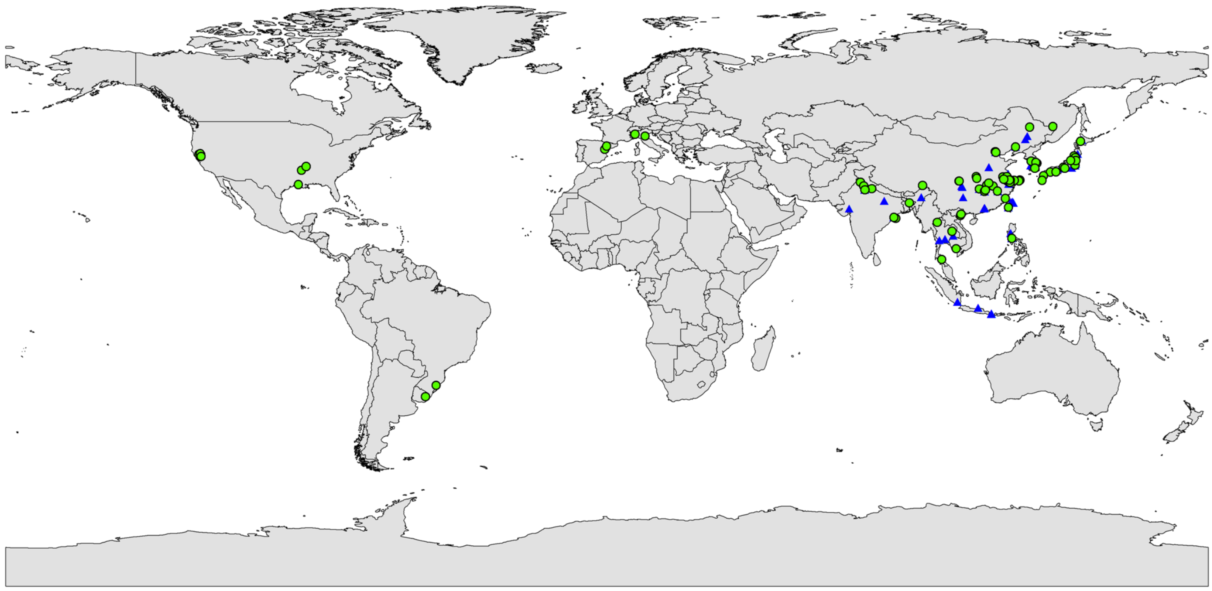

Figure 1. Global distribution of field experiments measuring the CH_4 flux from rice fields. The circles and triangles indicate experimental sites added in this study and included in Yan et al. (2005a), respectively.

in the original papers were classified as compost, farmyard manure, green manure or straw. The timing of rice straw application was differentiated as on-season or off-season. The amount of organic amendment was recorded directly from the original papers with dry weight for straw and fresh weight for other materials. To account for the spatial variability of CH_4 emissions on the global scale, experimental sites were classified into different zones based on their climatic conditions. On the basis of temperature and rainfall differences, rice fields in Asia were placed into seven agroecological zones (AEZs 1–3 and 5–8) in the FAO zoning system (IRRI, 2002). Rice fields from regions of Latin America, Europe and the United States were grouped into three zones.

Because of the limited availability of information on other properties, only SOC and soil pH as continuous variables were included in our data set. If soil organic matter content rather than SOC was reported, it was converted to SOC using a Bemmelen index value of 0.58. In order to meet the requirement of the statistical model, we excluded these measurements with the absence of available information for these three continuous variables (SOC, soil pH and the amount of organic amendment). Thus, the final data set included 1089 measurements from 122 rice fields across the world, which were used in our analysis. In this data set, measurements from Asian rice fields increased from 554 (Yan et al., 2005a) to 942, and 147 from the other regions of the world were newly added (Data set S1, Fig. 1).

2.2 The statistical model for controlling factors

The CH_4 emission data sets did not arise from systematically designed experimental results; instead we used them because they were available. It has been suggested that a linear mixed model is suitable for analyzing unbalanced data, that is, data having unequal numbers of observations in the subclasses (Speed et al., 2013). For example, Bouwman et al. (2002) and Yan et al. (2005b) used a linear mixed model to analyze log-transformed data of nitrogenous gas emissions from both agricultural and global soils, respectively. The data set of this study is of this nature; therefore, in line with our previous study (Yan et al., 2005a), a linear mixed model is thus used to explore the effect of controlling variables on CH_4 flux from rice fields. Fluxes of CH_4 do not fit a normal distribution, but rather they fit a log-normal distribution. The linear model was used to analyze the log-transformed data of CH_4 flux as follows:

$$\begin{aligned}\ln(\text{flux}) = {} & \text{constant} + a \times \ln(\text{SOC}) + \text{pH}_h + \text{PW}_i + \text{WR}_j \\ & + \text{AEZ}_k + \text{OM}_l \times \ln(1 + \text{AOM}_l), \qquad (1)\end{aligned}$$

where "flux" is the average CH_4 flux ($\text{mg CH}_4\,\text{m}^{-2}\,\text{h}^{-1}$) during the rice-growing season; SOC and a represent the SOC content (%) and its effect, respectively; pH_h is the effect of soil pH which was treated as a categorical variable and grouped into the following classes (h): < 4.5, 4.5–5.0, 5.0–5.5, 5.5–6.0, 6.0–6.5, 6.5–7.0, 7.0–7.5, 7.5–8.0 and ≥ 8.0; PW_i is the effect of the preseason water status (i is flooded, long drainage, short drainage, double drainage or unknown); WR_j is the effect of the water regime in the rice-growing season (j is continuous flooding, single drainage, multiple drainage, wet season rainfed, dry season rainfed, deep water or unknown); AEZ_k is the effect of the agroecological zone; OM_l is the effect of added organic materials (l is compost, farmyard manure, green manure, rice straw used on-season

Table 1. Description of the selected variables controlling CH_4 emissions from rice fields.

Variables	Description
Preseason water status	
Flooded	Permanently flooded rice fields are assumed to have a preseason water regime of "flooded". Late rice in China is usually planted immediately after early rice on the same field and is therefore regarded as having a preseason water regime of "flooded".
Long drainage	If rice is planted once a year and the field is not flooded in the non-rice growing season, the preseason water regime is classified as long drainage.
Short drainage	Rice is planted more than once a year, but there is more than 1-month fallow time between the two seasons, short drainage is usually classified as preseason drainage.
Two drainage	For measurements conducted on rice fields that are preceded by two upland crops or an upland crop and a drained fallow season, the preseason water of such experiments is classified as two drainage.
Water regime in the rice-growing season	
Continuous flooding	Rice is cultivated under continuously flooded conditions but sometimes includes end-season drainage before rice harvest.
Single drainage	One mid-season drainage and an end-season drainage are adopted over the entire rice-growing season.
Multiple drainage	Water regime of "intermittent irrigation", but number of drainage instances was not clear. Alternate wetting and drying (AWD) is included in multiple drainage.
Rainfed, wet season	Rice cultivation relies on rainfall for water; in this case the field is flood prone during the rice-growing season.
Rainfed, dry season	Rice cultivation relies on rainfall for water; in this case the field is drought prone during the rice-growing season.
Deep water	Rice grown in flooded conditions with water depth more than 50 cm deep.
Organic amendment	
Straw on-season	Straw applied just before rice transplanting considered on-season; straw that is left on the soil surface in the fallow season and incorporated into the soil before the next rice transplanting is also categorized as on-season. The amount of straw return is expressed in dry weight.
Straw off-season	Straw incorporated into soils in the previous season (upland crop or fallow) is categorized as off-season. The amount of straw return is expressed in dry weight.
Compost, farmyard manure, green manure	The amount of organic materials is expressed in fresh weight.
Agroecological zone	
AEZ 1	Warm arid and semiarid tropics
AEZ 2	Warm subhumid tropics
AEZ 3	Warm humid tropics
AEZ 5	Warm arid and semiarid subtropics with summer rainfall
AEZ 6	Warm subhumid subtropics with summer rainfall
AEZ 7	Warm/cool humid subtropics with summer rainfall
AEZ 8	Cool subtropics with summer rainfall

or rice straw used off-season); AOM_l is the amount of the corresponding organic material added in $t\,ha^{-1}$. These variables are described in detail in Table 1.

The last part of Eq. (1) reflects the effect of organic amendments on the CH_4 flux from rice fields, which is an interaction of the type and amount of organic materials used. In cases where the amount of organic amendment is zero in the analysis, it is assumed to be the result of each type of organic material at zero application rate. Obviously, this assumption will result in more data points in the analysis than there were in real observations. To ameliorate this problem, the residuals of observations were weighted with organic amendments as 1 and those without as 0.2 (as the observational result was repeated five times for the five types of organic materials). The effects of the controlling variables on the CH_4 flux were computed by fitting Eq. (1) to field observations using the SPSS Mixed Model procedure (version 24.0, SPSS Inc., Chicago, IL, USA).

2.3 Developing global and region- and country-specific emission factors

The estimated effects of various variables were used to derive a default EF. In the model, the CH_4 emissions from rice fields are a combination of the effects of SOC and soil pH, preseason water status, the water regime in the rice-growing season, organic amendments and the agroecological conditions. An assumption was made to provide a default EF; that is, all observations in the data set have a water regime of continuous flooding, a preseason water status of short drainage and no organic amendments, while keeping other conditions as stated in the original papers. Then, we derived a default EF (kg CH_4 ha^{-1} day^{-1}) for continuously flooded rice fields with a preseason water status of short drainage and without organic amendments using Eq. (2):

$$\mathrm{EF} = e^{\mathrm{constant}} \times \left(\frac{1}{n} \sum_{i=1}^{n} \mathrm{SOC}_i^a \times e^{\mathrm{pH}_i} \times e^{\mathrm{AEZ}_i} \right) \times e^{\mathrm{PW}_{\text{short drainage}}} \times e^{\mathrm{WR}_{\text{continuous flooding}}} \times 24/100, \quad (2)$$

where "constant" and "a" are the values estimated in Eq. (1), n is the total number of observations in the data set, pH_i and AEZ_i are the effects of pH and agroecological zone of the ith observation, respectively, and $\mathrm{PW}_{\text{short drainage}}$ and $\mathrm{WR}_{\text{continuous flooding}}$ are the effects of preseason short drainage and continuous flooding in the rice season, respectively.

In the 2006 IPCC guidelines, the Tier 1 method is meant to be applied to countries in which CH_4 emissions from rice cultivation is not a key category or for which country-specific EFs do not exist (Lasco et al., 2006). Thus, in the Tier 2 method the use of country-specific EFs is encouraged. To take advantage of the estimated effects of various variables at the global level, region- and country-specific EFs can be developed for some regions where a sufficient number of CH_4 emission measurements from rice fields to date are available.

3 Results and discussion

3.1 The advantages of the statistical model

An advantage of this linear mixed model is that it can handle many variables together, and makes use of the large number of unsystematic field measurements (Jørgensen and Fath, 2011; Yan et al., 2005a). The results of our previous modeling analysis (Yan et al., 2005a) have been adopted by the 2006 IPCC guidelines as the inventory-based (i.e., Tier 1 and 2 methods) approaches in which a baseline default EF and various scaling factors were estimated (Lasco et al., 2006). Moreover, the results of Yan et al. (2009) suggest that the estimated global CH_4 inventory from rice cultivation using the 2006 IPCC guidelines was comparable to other estimations (Tubiello et al., 2013; EDGAR, 2017). Although empirical or mechanistic models are also encouraged to be used for estimating CH_4 emissions during rice cultivation, only a few countries such as China (CH4MOD; Huang et al., 2004), the US (DAYCENT; Cheng et al., 2014) and Japan (DNDC-Rice; Katayanagi et al., 2016) used this approach in their submitted national reports to the Conference of the Parties (UNFCCC, 2017). For most countries, either the default or country-specific EFs (if available) are used to develop their national inventories of CH_4 emissions from rice fields. Thus, it is still necessary to develop a global default or region- and country-specific EFs with statistical modeling.

The variables considered in the present model were SOC, soil pH, the preseason water status, water regime in the rice-growing season, organic amendments and agroecological conditions (Table 2). Although the CH_4 emissions from rice fields can also be influenced by many other factors such as other soil properties, N fertilization and rice cultivar (Aulakh et al., 2001; Banger et al., 2012; Conrad, 2007), those factors were not considered here because of either contradictory reports on their effects or due to very limited information on the variables per se. For instance, to date there is no consensus on the impacts of N fertilization on CH_4 emissions from rice fields. It is likely attributed to the highly complex nature of the effect of N fertilizer on CH_4 emissions, which can strongly interact with other factors such as the amount and type of N fertilizer and the water regime (Schimel, 2000; Banger et al., 2012). Furthermore, very few countries (e.g., Indonesia) considered the effects of soil type and rice cultivar on CH_4 emissions from rice fields in their national reports. There is also large interannual variability in the CH_4 flux (Shang et al., 2011; Wang et al., 2012), which cannot be reflected in the current model. Nevertheless, the selected variables in the current model account for 50 % of the variability in CH_4 emissions on the global scale.

3.2 Effects of controlling variables

At the global scale, SOC and soil pH were the soil properties controlling CH_4 emissions from rice fields, while the contribution of SOC to the variance was the smallest among all variables considered here ($F_{(1,3391)} = 39.8$, $P < 0.0001$; Table 2). This finding may indicate that the controlling effect of SOC on CH_4 emissions from rice fields on a global scale may be outweighed by other variables (i.e., organic amendments). For example, although a recent synthesis by Banger et al. (2012) showed a positive but weaker ($R^2 = 0.21$) relationship between the SOC content and the CH_4 flux, they did not consider CH_4 emissions from rice fields with organic amendments. Furthermore, in a Chinese double rice-cropping system, the long-term (approx. 11-year) organic amendment-induced increase in SOC may be responsible for the observed significant correlation between SOC and CH_4 emissions (Shang et al., 2011). Previous studies have also suggested that the content of readily mineralizable carbon rather than SOC was significantly correlated with CH_4

Table 2. Statistical results for fixed effects obtained by fitting the model to the observed log-transformed CH_4 fluxes (mg CH_4 m^{-2} h^{-1}).

Effect	Estimate	Standard error	*t* value	*df*	*P* value	95 % confidence interval	
						Lower	Upper
Constant	−0.478	0.171	3391	−2.79	0.005	−0.814	−0.142
SOC[a]	0.190	0.030	3391	6.31	0.000	0.131	0.249
pH							
< 4.5	2.045	0.210	3391	9.75	0.000	1.634	2.456
4.5–5.0	1.124	0.106	3391	10.60	0.000	0.916	1.332
5.0–5.5	1.299	0.094	3391	13.88	0.000	1.116	1.483
5.5–6.0	0.825	0.091	3391	9.09	0.000	0.647	1.004
6.0–6.5	0.312	0.084	3391	3.69	0.000	0.146	0.477
6.5–7.0	0.151	0.088	3391	1.73	0.085	−0.021	0.323
7.0–7.5	0.181	0.097	3391	1.86	0.063	−0.010	0.372
7.5–8.0	0.099	0.093	3391	1.07	0.285	−0.083	0.280
≥ 8.0	0[d]						
Preseason water status							
Flooded	0.763	0.064	3391	11.94	0.000	0.638	0.888
Long drainage	−0.228	0.054	3391	−4.20	0.000	−0.335	−0.122
Short drainage	−0.116	0.061	3391	−1.90	0.058	−0.237	0.004
Two drainage	−0.648	0.184	3391	−3.52	0.000	−1.008	−0.287
Unknown	0[d]						
Water regime							
Continuous flooding	0.851	0.138	3391	6.16	0.000	0.580	1.122
Deep water	−1.897	0.309	3391	−6.14	0.000	−2.503	−1.291
Multiple drainage	0.247	0.142	3391	1.74	0.082	−0.032	0.525
Single drainage	0.505	0.147	3391	3.45	0.001	0.218	0.793
Rainfed, wet season	0.236	0.161	3391	1.46	0.144	−0.081	0.552
Rainfed, dry season	−0.972	0.199	3391	−4.89	0.000	−1.361	−0.582
Unknown	0[d]						
Organic amendment							
Compost	0.218	0.047	3391	4.65	0.000	0.126	0.309
Farmyard manure	0.247	0.028	3391	8.90	0.000	0.193	0.302
Green manure	0.400	0.026	3391	15.47	0.000	0.349	0.450
Straw on-season[b]	0.591	0.022	3391	27.49	0.000	0.549	0.633
Straw off-season[b]	0.228	0.036	3391	6.39	0.000	0.158	0.299
Unknown	0[d]						
Agroecological zone[c]							
AEZ 1	1.523	0.508	3391	3.00	0.003	0.528	2.518
AEZ 2	1.005	0.089	3391	11.24	0.000	0.829	1.180
AEZ 3	0.307	0.074	3391	4.17	0.000	0.163	0.451
AEZ 5	0.525	0.098	3391	5.38	0.000	0.334	0.717
AEZ 6	1.127	0.070	3391	16.00	0.000	0.989	1.265
AEZ 7	0.605	0.076	3391	7.94	0.000	0.455	0.754
AEZ 8	0.526	0.078	3391	6.76	0.000	0.373	0.678
South America	0.403	0.150	3391	2.68	0.007	0.108	0.697
Europe	1.321	0.101	3391	13.08	0.000	1.123	1.520
North America	0[d]						

[a] Soil organic carbon is expressed as % in the model. [b] The effect of the organic amendment is determined by the interaction of the specific organic material type and application rate (t ha^{-1}). Straw on-season indicates straw applied shortly before rice transplanting, and straw off-season indicates straw applied in the previous season. Note that rice straw that was left in situ and incorporated into soil just before rice transplanting is classified as straw on-season. [c] Experimental sites are classified as one of the agroecological zones according to the FAO zoning system. [d] For each categorical variable, the effect of one subclass is set to zero.

emissions from rice fields (Yagi and Minami, 1990). Thus, we believe that a weak relationship between SOC and CH_4 emissions at the global scale can be largely attributed to the fact that the dominant factors controlling CH_4 emissions are labile C substrates derived from inherent and exogenous sources (Wang et al., 2013; Yagi and Minami, 1990).

The effect of soil pH on controlling CH_4 emission from rice fields was not monotonic ($F_{(8,3391)} = 75.3$, $P < 0.0001$; Table 2), which was consistent with the previous results (Yan et al., 2005a). It is often accepted that CH_4 production under anoxic conditions is very sensitive to variations in soil pH, as the activity of methanogens is usually optimum around neutrality or under slightly alkaline conditions (Aulakh et al., 2001; Garcia et al., 2000). However, soils with a pH of 5.0–5.5 showed much higher emissions than other soils, which corroborates the observed relationship between soil pH and CH_4 emissions in Indonesian rice fields (Yan et al., 2003). The largest effects of soil pH below 4.5 may not be reliable because of limited observations from only two studies with distinct water regimes, soil properties and organic amendments. Given that methanogens and methanotrophs are tolerant to pH variations in soil (Dunfield et al., 1993), and CH_4 emission is the result of its production, consumption and transfer in soil to the atmosphere (Conrad, 2007), we suppose that it is not soil pH itself, but some other soil properties or microbial activities correlated with soil pH that control these processes. Thus, we conclude that such correlation between soil pH and CH_4 emission at the global scale may be reasonable.

As expected, water regime in the rice-growing season was a main factor controlling CH_4 emissions from rice fields ($F_{(6,3391)} = 80.5$, $P < 0.0001$; Table 2). Relative to continuous flooding, the average seasonal CH_4 flux in the rice-growing season can be reduced by 29 % and 45% by single and multiple drainage, respectively (Table 3). In the updated data set, the magnitude of reduced CH_4 emissions following single drainage was smaller than in previous results (Yan et al., 2005a). This may be due not only to the approximately 3-fold increment of available observations (Data set S1) but also to the inevitable confusion in identifying the water regime from different studies. The average CH_4 fluxes from wet-season and dry-season rainfed rice fields were 54 % and 16 %, respectively, that of continuously flooded fields, lower than the IPCC values of 80 % and 40 % for flood-prone rainfed and drought-prone rainfed rice fields, respectively (IPCC, 1997). Compared with the previous results (Yan et al., 2005a), the greater average CH_4 flux from wet-season rice fields was mainly attributed to the observed high fluxes from rainfed rice fields in Thailand and India (Kaewpradit et al., 2008; Kantachote et al., 2016; Rath et al., 1999). However, the CH_4 flux from deep water rice, only 6 % that of continuously flooded rice fields, remained less reliable due to the lack of sufficient observational data in the current analysis.

This statistical model clearly identified the effects of preseason water status on CH_4 emissions in the rice-growing season ($F_{(4,3391)} = 94.9$, $P < 0.0001$; Table 2). A negative correlation was found between CH_4 emissions and the drainage period before the rice season, such that the average CH_4 flux from a rice field that was flooded in the previous season was 2.4–4.1 times as high as that from fields that experienced different durations of drained season (Table 3). As shown in Table 1, the preseason water status was determined mainly by the crop rotation system, except in rice fields that are flooded during the fallow season. This effect of preseason water conditions can explain some of the regional and seasonal differences of CH_4 emissions from rice fields and suggested that crop rotation of rice and upland crops have the potential to mitigate CH_4 emissions from rice fields.

Table 3. Relative CH_4 fluxes for different water regimes in the rice-growing season and for different preseason water statuses.

Variables	Relative flux	95 % confidence interval	
		Lower	Upper
Water regime in rice season			
Continuously flooded	1*		
Deep water	0.06	0.03	0.12
Multiple drainage	0.55	0.41	0.72
Single drainage	0.71	0.53	0.94
Rainfed, wet season	0.54	0.39	0.74
Rainfed, dry season	0.16	0.11	0.24
Preseason water status			
Short drainage	1*		
Long drainage	0.89	0.80	0.99
Two drainage	0.59	0.41	0.84
Flooded	2.41	2.13	2.73

* Other values in this column are based on continuously flooded and short drainage fluxes set to 1.

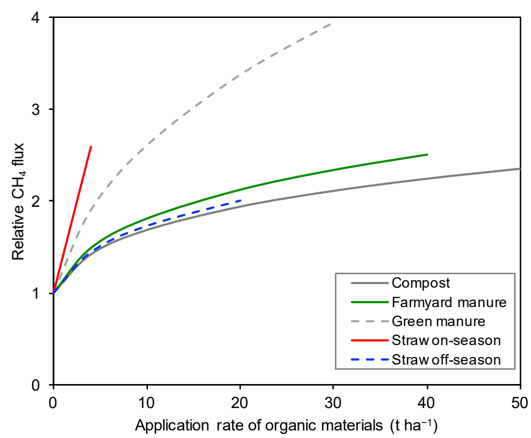

Figure 2. Simulated effect of different organic amendments on CH_4 emissions from rice fields. The CH_4 flux for the field without any organic amendments is assumed to be 1.

Table 4. The regional- and country-specific emission factors for CH_4 emission (kg CH_4 ha^{-1} day^{-1}) from flooded rice fields with a preseason water status of short drainage and without organic amendments.

Region		Emission factor	95 % confidence interval[1] Lower	Upper	Country	Emission factor	95% confidence interval[1] Lower	Upper
World		1.19	0.80	1.76				
Asia	East Asia	1.32	0.89	1.96	China	1.30	0.88	1.93
					Japan	1.06	0.72	1.56
					South Korea	1.83	1.24	2.71
	South Asia	0.85	0.58	1.26	India	0.85	0.57	1.25
					Bangladesh	0.97	0.65	1.43
	Southeast Asia	1.22	0.83	1.81	Philippines	0.60	0.41	0.89
					Vietnam	1.13	0.76	1.67
					Indonesia	1.18	0.80	1.74
Americas	North America[2]	0.65	0.44	0.96	USA			
	South America	1.27	0.86	1.88	Brazil	1.62	1.10	2.40
					Uruguay	0.80	0.54	1.18
Europe		1.56	1.06	2.31	Spain	1.13	0.77	1.68
					Italy	1.66	1.12	2.46

[1] Including the uncertainties of the effects of continuous flooding and preseason water status. [2] All data for North America come from the USA.

Among all the selected variables, the effect of organic amendments was the largest ($F_{(5,3391)} = 181.5$, $P < 0.0001$), suggesting that the use of organic materials is the main variable controlling CH_4 emissions from rice fields. Among all the organic materials, straw used on-season showed the strongest stimulating effect on CH_4 emissions, followed by green manure. Such a difference may be attributed not only to the decomposition but also to the different moisture contents of organic materials recorded in the literature (Table 1). If rice straw was applied at a rate of 6 t ha^{-1} (dry weight) before rice transplanting, the CH_4 emissions were 3.2 times that of fields without any organic amendment (Fig. 2). However, when this amount of rice straw was incorporated into the soil immediately after harvest in the previous year and left unflooded, the stimulating effect on CH_4 emissions was only a factor of 1.6. This indicates that straw applied off-season was an effective way to reduce CH_4 emissions from rice fields. The stimulating effects of compost and farmyard manure were comparable to that of rice straw applied off-season.

Although the agroecological zones affected CH_4 emission significantly ($F_{(9,3391)} = 52.4$, $P < 0.0001$), their contribution to the variance was smaller than other factors considered in the model. This was probably because the model considered soil properties and the water regime during and before the rice-growing season, which partially reflected the effect of agroecological conditions. As shown in Table 2, the highest effect of AEZ 1 with extremely large variability was still unreliable, because there were no new data added to our data set. The higher CH_4 emissions can be identified clearly for AEZ 2 and 6 and Europe as the 95 % confidence intervals of their effects did not overlap with others.

3.3 Region- and country-specific emission factors

Globally, for continuously flooded rice fields with the preseason water status of short drainage without organic amendment, the EF was estimated to be 1.19 kg CH_4 ha^{-1} day^{-1} with an error range of 0.80–1.76 kg CH_4 ha^{-1} day^{-1} (Table 4). We find that our estimate is lower and has relatively small variation when compared with the latest IPCC default EF (mean: 1.30 CH_4 ha^{-1} day^{-1}, error range: 0.80–2.20 kg CH_4 ha^{-1} day^{-1}; Lasco et al., 2006; Yan et al., 2005a). Such a difference could be mainly attributed to the number of field measurements in the present data set, approximately 2 times greater than in the previous study. As shown in Table 4, we estimated the region- and country-specific EFs for which sufficient number of CH_4 emission measurements from rice fields were available.

3.3.1 East Asia

Approximately 90 % of the world's rice fields are located in Asia, of which 23 % occur in East Asia (FAO, 2016). In our data set, about half of CH_4 emission measurements were compiled from this region (Fig. 1; Data set S1). The region-specific EF for East Asia is estimated to be 1.32 kg CH_4 ha^{-1} day^{-1}, and there were differences in the country-specific EF following the order of South Korea > China > Japan (Table 4). For China, as the largest rice producer in the world, there has been a growing body of CH_4

emission measurements from rice fields since the late 1980s (Fig. 1). We collated 388 field observations conducted on more than 40 sites in China, which allowed us to make a relatively reliable estimate of the country-specific EF. Although the EF of 1.30 kg CH_4 ha^{-1} day^{-1} (error range: 0.88–1.93 kg CH_4 ha^{-1} day^{-1}) is the same as the latest IPCC default EF, its variability is smaller with an error range of 0.80–2.20 kg CH_4 ha^{-1} day^{-1} as noted above (Lasco et al., 2006). This was supported by the evidence that the CH_4 emissions from Chinese rice fields estimated using the Tier 1 method in the 2006 IPCC guidelines or country-specific EF were almost identical (7.22-8.64 Tg yr^{-1}; Yan et al., 2003, 2009). Even though the estimation of CH_4 emission is beyond the scope of this study, we believe, to some extent, that developing and using the country-specific EF is a promising approach for national CH_4 inventory. For example, using the process-based model CH4MOD and empirical methods to account for different EFs in various rice ecosystems, CH_4 emissions from rice cultivation in year 2012 were estimated to be 8.46 Tg yr^{-1} in China's First Biennial Update Report (BUR) of its national reports (NDRC of China, 2016). These estimates, accounting for various EFs under different conditions, fall into the range of 4.98–14.19 Tg yr^{-1} of other reports (EDGAR, 2017; EPA, 2017; FAO, 2016).

In Japan's latest national greenhouse gas inventory report,, country-specific EFs for rice fields under different water regimes during the rice-growing season were estimated using the DNDC-Rice model (Katayanagi et al., 2016; MoE of Japan, 2017). For comparison, the length of the single rice season in East Asia was assumed to be 130 days (Yan et al., 2005a), and we found that our estimate (1.06 kg CH_4 ha^{-1} day^{-1}, error range: 0.72–1.56 kg CH_4 ha^{-1} day^{-1}) falls into a range of the model-derived EF of 0.06 to 1.79 kg CH_4 ha^{-1} day^{-1} for continuously flooded rice fields without organic amendment across Japan (Katayanagi et al., 2016). Likewise, using the Tier 1 method, Yan et al. (2009) estimated the CH_4 emission in year 2000 from Japanese rice fields to be 407 Tg yr^{-1}, which was lower than the 510 Tg yr^{-1} in their latest report (MoE of Japan, 2017). We argued that such a discrepancy may be primarily related to different classifications for intermittently flooded (i.e., single drainage vs. multiple drainage) and type and amount of organic amendments used in their estimations. As such, we believe that when reliable information regarding water management and organic amendment becomes available, there is still merit in using the current country-specific EF for national CH_4 emission from rice cultivation. Additionally, it could also be the case for South Korea, because CH_4 emission estimate using the Tier 1 method appears comparable to that of their national reports (Yan et al., 2009).

3.3.2 South Asia

The rice harvest area of countries in South Asia accounts for 42 % of the Asian total rice harvest for the year 2010 (FAO, 2016). India is currently thought to have the second largest CH_4 emissions from rice cultivation in the world. In the present study, the estimated EF of CH_4 from Indian rice fields was 0.85 kg CH_4 ha^{-1} day^{-1} (error range: 0.57–1.25 kg CH_4 ha^{-1} day^{-1}). We find that our estimate agrees with the overall average of 0.59 ± 0.35 kg CH_4 ha^{-1} day^{-1} ($\pm$ standard deviation, the length of the rice season was assumed to be 125 days), which was used for the CH_4 emission inventory from Indian rice cultivation (MoEFCC of India, 2015). Interestingly, if the scaling factors (Table 3) were applied for subcategories of water regime during the rice-growing season as in the Tier 1 method (Lasco et al., 2006), our estimates for irrigated rice fields were almost identical to those of Manjunath et al. (2009), which have been consistently used in their national CH_4 inventory. By contrast, the values for rainfed and deep water fields were greatly underestimated. This discrepancy is primarily because peer-reviewed studies from India were only considered in our current data set, while 471 observations collected from farmers' fields over India were used by Manjunath et al. (2009). The aforementioned limited data points from wet- and dry-season rainfed rice fields may also lead to biased estimates, despite the fact that approximately half of India's rice cultivation is under rainfed conditions in India's first BUR. Therefore, further available observations of CH_4 emissions from rainfed and deep water rice fields are required to improve the statistical estimates.

For Bangladesh, albeit based on one study, the estimated EF (0.97 kg CH_4 ha^{-1} day^{-1}) of CH_4 emission from rice fields has became available for the first time. Previous studies often used an EF value from neighboring countries for CH_4 emission estimates from rice cultivation (FAO, 2016; Manjunath et al., 2014; Yan et al., 2003, 2009). Interestingly, our estimate was similar to the seasonally integrated EF value of 10 g CH_4 m^{-2} used in their national reports (MoEF of Bangladesh, 2012) or other reports (FAO, 2016). Furthermore, previous studies have shown that the national CH_4 estimates were comparable when using the EF from their neighboring countries (Manjunath et al., 2014; Yan et al., 2009). Thus, either the region (0.85 kg CH_4 ha^{-1} day^{-1}) or these country-specific EFs could be used for CH_4 emission estimates from the rest of the countries of South Asia, i.e., Pakistan, Sir Lanka and Nepal, where direct measurements to date were either not available or insufficient (Table 4).

3.3.3 Southeast Asia

In Southeast Asia, the total CH_4 emissions from rice cultivation accounted for 21.5 % of the world total (Yan et al., 2009). The EF of 1.22 kg CH_4 ha^{-1} day^{-1} for this region was close to the global default value but differed among countries (Table 4). Country-specific EFs (kg CH_4 ha^{-1} day^{-1}) for each country were estimated to be as follows: Indonesia (1.18), the Philippines (0.60) and Vietnam (1.13). For Indonesia, an EF with an average of

160.9 kg CH_4 ha^{-1} season^{-1} was used for CH_4 inventory from rice cultivation, despite the existence of large variation in field measurements (6.7–798.6 kg CH_4 ha^{-1} season^{-1}; MoEF of Indonesia, 2015). Given that the length of the rice season in Southeast Asian countries varies from 99 to 115 days, our estimate was close to the default EF used in their first BUR (MoEF of Indonesia, 2015). For the Philippines, our estimate was much lower than 3.46 kg CH_4 ha^{-1} day^{-1} estimated by Yan et al. (2003) based on observations from only two sites. Using the Tier 1 method in the 2006 IPCC guidelines, Yan et al. (2009) found the estimates of CH_4 emission from rice fields in the Philippines and Vietnam agreed reasonably well with the values reported in their national reports (Biennial Updated Report of Viet Nam, 2014; Second National Communication of Philippines, 2014). The larger EFs estimated for Thailand and Cambodia (data not shown) had big uncertainties because they were essentially developed from very limited observations.

3.3.4 Americas

Rice cultivation in Brazil and the United States accounts for approximately 60 % of the total in the Americas (FAO, 2016). In our data set, there were only three countries from this region that had available measurements which allowed us to make country-specific EF estimates (Table 4). The country-specific EFs were estimated to be 0.65, 1.62 and 0.80 kg CH_4 ha^{-1} day^{-1} for the US, Brazil and Uruguay, respectively. By contrast, the assigned values of the seasonally integrated EF for the corresponding countries were 35, 6.5 and 28 g CH_4 m^{-2} in the FAOSTAT emission database (FAO, 2016). Using the IPCC Tier 1 method, the CH_4 emission estimate for these countries tends to be lower than that of their national inventory reports (NIRs), suggesting the importance of the country-specific EFs since differential conditions for rice cultivation being considered. For example, in the United States' latest NIR, there was an approximately 25 % increase in CH_4 emission from rice cultivation relative to the previous estimates (EPA, 2017). This change could be the result of unified continuous flooding in the rice season and the impact of winter flooding considered in the IPCC Tier 3 method (DAYCENT model). Thus, the underestimated CH_4 emission using the IPCC Tier 1 method for United States can be explained by different assumptions made for water regimes in rice cultivation (Yan et al., 2009). Nevertheless, our results should be treated with caution, because very limited observations are available for these countries.

3.3.5 Europe

As the major rice cultivating countries in Europe, the country-specific EFs for Italy and Spain were estimated to be 1.66 and 1.13 kg CH_4 ha^{-1} day^{-1}, respectively (Table 4). However, a seasonally integrated EF of 50.4 g CH_4 m^{-2} was assigned for these two countries in the FAOSTAT emission database (FAO, 2016), which was far higher than our estimates as well the values used in their NIRs. In the Italy's NIR (National Inventory Report of Italy, 2017), the EFs for continuously flooded fields without organic amendments for single and multiple drainage were 2.0 and 2.7 kg CH_4 ha^{-1} day^{-1}, respectively. It is interesting to note that these values contradict our expectation that the CH_4 emissions would be lower from rice fields with multiple draining compared to single drainage (Table 3). A possible reason for this was that they were based on experimental measurements from different rice field studies in Italy (Leip et al., 2002; Meijide et al., 2011). In the latest NIR of Spain (National Inventory Report of Spain, 2017), the global default EF (1.30 kg CH_4 ha^{-1} day^{-1}) is used for CH_4 emission estimate from rice cultivation, which is close to our estimate.

4 Conclusions

This study reports an update of the findings of Yan et al. (2005a) through extending the database of CH_4 emission from global rice fields. Our results suggest that those selected variables in the statistical model had significant effects on CH_4 emission from rice fields on a global scale, which is consistent with the previous findings based only on observations from major rice-producing countries in Asia. Moreover, the estimated values of default EF and scaling factors have changed in some cases in the updated data set; for instance, the average CH_4 fluxes from rice fields with single drainage was 71 % rather than 58 % that of continuously flooded rice fields. Our estimate of global default EF is 1.19 kg CH_4 ha^{-1} day^{-1}, which is lower and has small variation when compared with the latest IPCC default value. To our knowledge, region- and country-specific EFs have been developed for the first time for countries where a sufficient number of CH_4 emission measurements from rice fields were available. These region- and county-specific factors could reflect the local impact of a multitude of conditions (i.e., different ecosystems, water regimes, type and amount of organic amendments, etc.) on CH_4 emissions. This is important because the implementation of the Tier 2 approach in the current IPCC methodology is encouraged to develop their national CH_4 inventories. Taken together, these findings provide a sound basis for developing national emission inventories and mitigation strategies.

Data availability. The data set can be found online in the Supplement as indicated below. Correspondence and requests for materials should be addressed to Xiaoyuan Yan (yanxy@issas.ac.cn).

The Supplement related to this article is available online at https://doi.org/10.5194/acp-18-10419-2018-supplement.

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Competing interests. The authors declare that they have no conflict of interest.

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