

Methane emission from different rice cultivation systems in Bangladesh: A model based approach

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Abstract

Globally, a large amount of methane (CH_4) emission is generated from agricultural systems including rice farming in many Asian countries including Bangladesh. However, a reliable estimate of CH_4 emission from rice cultivation is not available, particularly considering the different rice types (*i.e.*, local land races, high yielding varieties (HYV), and hybrid varieties) grown under diverse conditions. Here, we estimated current and future CH_4 emission (both rate and amount) from different rice farming systems in Bangladesh using the IPCC Tier1 method. Model based estimates were validated with a pilot survey and with other studies. Across all rice types grown in different seasons, (*i.e.*, *Aus* from March to August, *Aman* from July to December and *Boro* from December to June), the estimated CH_4 emission in 2020 was at $2348 \text{ Gg CH}_4 \text{ yr}^{-1}$ (95% CIs of $799\text{--}5628 \text{ Gg CH}_4 \text{ yr}^{-1}$) while a slightly higher CH_4 emission was estimated at $2376 \text{ Gg CH}_4 \text{ yr}^{-1}$ for the year 2060 after considering a 0.5 % cultivable rice land migration to non-agricultural activities. We also found significant differences in CH_4 emission rates among types of rice cultivation and growing season. Average across all seasons, the highest CH_4 emission was from hybrid varieties ($225 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$), while the lowest ($128 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$) from local land races. In contrast, the same local land races showed the highest emission rates when normalized against yield. Across all rice types, the largest CH_4 emission was during *Aman* season accounting 61% of the total annual emission. Our model-based estimates reasonably compare with survey-based estimates ($r^2 = 0.94$, $p < 0.01$) and fall within one standard deviation of a log-normal distribution of measurement based CH_4 emissions. Our findings, therefore, provide a deeper insight into CH_4 emissions from rice cultivation systems.

1. Introduction

Global warming is one of the most pressing challenges, which is affecting the global energy balance and many other related processes. This unwanted increase in the global surface temperature is affecting lives, living conditions and welfare on the planet (Hoegh-Guldberg et al. 2018). The underlying driving force of global warming is the increase in concentrations of different greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Anthropogenic contributions such as fossil fuel burning and land use change are the most responsible agents for the increased atmospheric concentrations in CO_2 , CH_4 , and N_2O , accounting for 64%, 17%, and 6% of the total radiative forces, respectively (IPCC 2013).

Methane is considered as the second dominant greenhouse gas after CO_2 since it is 28 times more powerful than CO_2 , signifying its contribution (~ 16%) to the global warming potential (GWP) (Aydin et al. 2010). Although CH_4 emission from fossil fuel burning is considered to be low, the CH_4 concentration in the atmosphere reached to 1803 ppb in 2011, a 2.5 times increment compared to the pre-industrial era (722 ppb in 1750) (IPCC 2013). This clearly indicates that anthropogenic contributions from sources other than fossil burning are equally important for changing the radiative balance.

About 60% of the global CH₄ is emitted from anthropogenic sources, whereas 40% of the emissions come from natural sources (Karakurt et al. 2012). The major natural sources of CH₄ are wetlands and oceans, termites, wildfires, grassland (Jones et al. 2005; Agarwal et al. 2009; Cai et al. 2011) while the major anthropogenic sources include enteric fermentation in ruminants, anaerobic decay of organic matter in rice paddies, municipal solid waste landfills, cattle ranching, and manure management (Guisasola et al. 2009; Yang et al. 2009; Park et al. 2011; Chang et al. 2012; Yusuf et al. 2012). While the agricultural sector contributes the highest amount of CH₄, accounting for 53% of global emissions (Yusuf et al. 2012), rice paddies alone contribute over 11% of anthropogenic CH₄ emissions (IPCC 2013), placing paddy rice cultivation at the top of all other cereals (Linquist et al. 2012). The carbon foot print of global rice production is large ($49 \pm 4.5 \text{ Mt CO}_2\text{-e yr}^{-1}$) (IPCC 2014). The carbon foot print of rice cultivation may escalate further in the future due to additional rice production for meeting the food demand of the increasing global population.

The CH₄ emission from rice paddies depends on many factors including water management (Wang et al. 2012), organic fertilizer input (Feng et al. 2013), nitrogen (N) fertilizer use (Banger et al. 2012), soil temperature (Khalil et al. 1998), and rice cultivars (Qin et al. 2015). It is also influenced by elevated CO₂, temperature (Dijkstra et al. 2012; Bhattacharyya et al. 2013) and soil properties (*i.e.*, SOC and soil pH) (Yan et al. 2005). Among these factors, water management and organic matter application are usually positively associated with CH₄ production.

In Bangladesh, rice is traditionally cultivated in three seasons namely, *Aus* (from March to August), *Aman* (July - December), and *Boro* (December - June) with diverse growing conditions (details of rice growing conditions can be found in SI). Among the three seasons, rice cultivation in *Aus* and *Aman* seasons are mostly rainfed while in *Boro* season, except for deep water rice, it is cultivated entirely under irrigated conditions (Shelley et al. 2016). The formation of CH₄ occurs under anoxic conditions, and CH₄ emission varies widely when rice is grown in irrigated or rainfed conditions (Haque et al. 2019). Additionally, various types of rice, *i.e.*, high yielding varieties (HYV), hybrid varieties, and local land races (cultivars) are grown in each of the three rice growing seasons in Bangladesh, differing in growth period, cultivation conditions and productivity. It is expected that CH₄ emission from modern varieties are higher than local varieties due to longer growth periods, chemical fertilizer input, and water management practices. In contrast, this scenario could be completely opposite when emission rates are normalized against yield, since the yield of local rice is lower than of HYV. However, it is not known how CH₄ emission changes for rice types grown under diverse conditions.

While field-based measurements could provide reliable estimates of CH₄ emission, it is often difficult to do so for the whole country considering all rice growing seasons and types. As an alternative, modelling of CH₄ emissions using measurement based data was proposed and advocated (Yan et al. 2005; IPCC 2006, 2019). Among the various model-based approaches, IPCC 2019 guidelines for National Greenhouse Gas Inventories are considered to be acceptable and most used for reporting of GHG emissions at the national scale. These guidelines are either inventory based (*i.e.*, Tier 1 and Tier 2) or model-based (Tier 3).

The Tier 1 approach provides for simple estimations, based on a generalized default emission factor and scaling factors while the Tier 2 approach uses nation specific default and scaling factors. In contrast, Tier 3 approach typically estimates CH₄ emissions by combining detailed geospatial information into a model. Since, the data required for Tier 2 and 3 to estimate CH₄ emission are not available and Tier 1 allows for using agronomical data (*i.e.*, crop cultivation area, yield, etc.) that are typically collected by the Department of Agricultural Extension, Ministry of Agriculture, we made a national CH₄ emission inventory using the IPCC 2019 Tier 1 method. We also estimated the contributions of different rice types and seasons. We believe that the Tier 1 method could prove a reliable estimate of CH₄ emission for Bangladesh since most of the input data is available.

Following a similar approach, a number of studies estimated CH₄ emission for Bangladesh (Bachelet and Neue 1993; ALGAS 1995; Rahman et al. 1998; MoEF 2012, 2002; Yan et al. 2003, 2009; U.S. EPA 2012; Khan and Saleh 2015; Peters et al. 2017). However, none of these studies considered the large diversity in rice farming systems such as rice growing season, soil topography, soil organic matter content and organic amendments, rice type (hybrid varieties, HYV, and traditional land races) and growth period. Thus, the projected CH₄ emission estimates by these studies are possibly quite far from the real emission while the projections among these studies are also diverse requiring a reliable estimate. For example, using the IPCC 2006 methodology, Yan et al. (2009) estimated CH₄ emission at 1660 Gg CH₄ yr⁻¹ from all types of rice fields in Bangladesh for the year 2000. Recently, Khan and Saleh (2015) estimated the national CH₄ emission from the rice fields in Bangladesh for 2009 at 1146 Gg CH₄ yr⁻¹ using the same methodology. Moreover, use of more complex models such as CH₄MOD_{2.5}, AIRS, SCIAMACHY, and GOSAT created further uncertainty with large variability in estimates ranging between 438 and 6680 Gg CH₄ yr⁻¹ (Khan and Saleh 2015; Peters et al. 2017).

The acreage of different rice types is under continuous changes due to the adoption of modern varieties (hybrid and HYV) replacing local land races. Population pressure may accelerate the adoption process further necessitating a reliable future projection to estimate its contributions to global radiative forcing. Considering the diversity in rice types and growing conditions, the current study was conducted to estimate CH₄ emission from different rice types grown under different growing seasons for 2020 to 2060.

2. Methodology

2.1 Rice cultivation systems in Bangladesh

In Bangladesh, rice is grown in three possible rice growing seasons namely *Aus*, *Aman*, and *Boro* (Siddique et al. 2016a). Among the three rice growing seasons, rice in *Aman* (broadcast and transplanted) is generally planted between the month of July and August and harvested from November to December whereas rice in *Boro* is planted from December to early February and harvested between April and June. The *Aus* rice is either broadcast seeded or transplanted during March and April after the pre-monsoon shower and harvested between July and August (Shelley et al. 2016). The rice types grown in different

seasons are categorised as local land races, inbred modern varieties known as HYV and, heterosis exploring rice, the hybrid varieties. The three different rice types are grown during all three seasons, except for hybrid varieties that are usually not grown during *Aus*. More detail about rice cultivation in Bangladesh is provided in the SI.

2.2 Data collection

The annual harvested area and yield of different rice types (local, HYV and hybrid) in three possible growing seasons (*Aus*, *Aman*, and *Boro*) were collected from the Department of Agricultural Extension (DAE) and Bangladesh Bureau of Statistics (BBS) (BBS 2020a, b, c; DAE 2021). The data were documented for each of the administrative districts. Moreover, the growth duration of different rice cultivars were collected from the Seed Certificate Agency (SCA 2014).

2.3 Methods for estimating methane emission

The IPCC 2019 Tier 1 guideline was used for estimating CH_4 emissions from rice cultivation systems in Bangladesh. The calculation procedure is outlined in Fig. 1. Having data of the administrative districts, the national emission was calculated from the CH_4 emissions in different districts while the CH_4 emission from each district was calculated separately for different rice types (local, HYV and hybrid) grown under three different growing seasons (*Aus*, *Aman*, and *Boro*).

2.4 Calculation of CH_4 emission from rice cultivation systems

In the Tier 1 method, CH_4 emissions from different rice farming systems were estimated using Eq. (1)

See equation 1 in the supplementary files section.

Where, CH_4_{rice} is the annual CH_4 emission from rice cultivation in Gg $\text{CH}_4 \text{ yr}^{-1}$, $\text{EF}_{i,j,k}$ is the daily emission factor for i , j , and k conditions in kg $\text{CH}_4 \text{ ha}^{-1} \text{ day}^{-1}$, $t_{i,j,k}$ 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 yr^{-1} , and i , j , and k represent the different ecosystems, such as, water regimes, type and amount of organic amendments, and other conditions under which CH_4 emissions from rice may vary while 10^{-6} is the conversion factor of methane emission to Gigagram.

As shown in equation (1), the daily specific emission factor was calculated by multiplying the baseline emission factor (EF) with various scaling factors (SF) to account for the contributing factors using Eq. (2)

See equation 2 in the supplementary files.

Where, $\text{EF}_{i,j,k}$ 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 to account for the differences in water regime during the cultivation period, SF_p is the scaling factor to

account for the differences in water regime during season prior to rice cultivation, SF_o is the scaling factor accounting for both type and amount of organic amendments applied, and $SF_{s,r}$ is the scaling factor for soil type, rice cultivar etc. The latter scaling factor was not considered in this study.

2.5 Baseline emission factor for continuously flooded fields without organic amendments

The IPCC provides a default CH_4 emission of $0.85 \text{ kg ha}^{-1} \text{ day}^{-1}$ with confidence intervals (CI) of 0.58-1.26 for a continuously flooded rice cultivation during the entire growth period without any organic amendments for the South Asia region (IPCC 2006, 2019). Since there is no country specific data for Bangladesh, we used this value as the base line emission factor.

2.6 Scaling factor for water regime pre and during rice cultivation

IPCC provided scaling factors for pre and in-season water regime (SF_w) highlighting two different scenarios, *i.e.*, an aggregated case and a disaggregated case (Table S1). The SF_w for different rice types grown in different seasons in Bangladesh were based on Yan et al. (2005), customized from the IPCC scaling factors by considering the ecology of rice cultivation, soil physiography, climatic data and management practices (Table 1).

2.7 Scaling factor for organic amendment

IPCC 2019 provided the scaling factor for both type and amount of organic amendment incorporated during the rice cultivation (Table S3). According to IPCC guidelines, the scaling factor for organic amendments was calculated using Eq. (3)

See equation 3 in the supplementary files section.

Where, SF_o is the scaling factor for both type and amount of organic amendment applied, ROA_i is the application rate of organic amendment i , in dry weight for straw and fresh weight for others in t ha^{-1} , $CFOA_i$ is the conversion factor for inclusion of the relative effect of organic amendment i .

The organic matter amendments in rice fields of Bangladesh include rice straw and compost or cow dung amendments. The straw incorporation rate was calculated from the projection of straw yields using the grain yield data, collected from the Department of Agricultural Extension, Ministry of Agriculture while the straw retention rate was determined by synthesizing physiography, rice types, and growing seasons. For detailed calculations see the SI (Tables S5 and Figs. S1-3).

In Bangladesh, the application of compost/farm yard manure (FYM) is diverse while the rate of application is unknown. It is also not possible to have a valid rate of compost/FYM application since there is no documented information in the Department of Agricultural extension (DAE) in Bangladesh.

Generally, agriculture lands receive a variable amount of Compost/FYM. Based on expert's opinion, we considered that the average compost/FYM application rate is 2.5 t ha^{-1} as a fresh weight, irrespective of land types. However, we did not consider the compost/FYM application for local rice cultivation because it is principally cultivated in rainfed low land and deep-water conditions. On the other hand, green manure is also being applied in rice fields, but the incorporation rate is very low. So, in this study, we did not consider any green manure amendments. For timing of organic matter amendments, we considered that the organic amendment was made within 30 days prior to seedling transplanting (BRRI 2018).

2.8 Growth duration of rice

In order to calculate the duration of rice cultivation, we followed a systematic scheme where the weighted average value was computed using the lifespan of individual rice cultivars and the harvested area by applying Eq. (4)

See equation 4 in the supplementary files section.

The lifespan of modern cultivars was taken from the Seed Certification Agency (SCA 2014). On the other hand, we used the literature data and expert judgment for estimating growth duration of local land races (Rahman et al. 2008, 2009, Siddique et al. 2013, 2016b, Akter et al. 2016, 2017, 2018; Halder et al. 2016; Islam et al. 2018a, b; Mia et al., in preparation)

2.9 Validation of the estimate with a survey

A survey was conducted among the farmers in six different districts (Bagerhat, Barishal, Patuakhali, Tangail, Rangpur and Cox's bazar) to validate the scaling factors including 20 farmers from each district. The questionnaire and procedure of survey conduction can be found in SI (S 3.3). Emission factors for each of the districts were calculated for different types of rice (local, HYV and hybrid) grown in different seasons (*Aus*, *Aman* and *Boro*) using the farmers' data. Next, survey based CH_4 emission rate was plotted against the model-based estimate to determine the fit while this plot was also compared with one-to-one line.

2.10 Spatial distribution of CH_4 emission

The annual CH_4 emission from different districts was visualized using ArcGIS 10.8.

2.11 Prediction of future emission

For future projections of methane emission up to 2060, the rice acreage was analysed using a suitable curve fitting on the historical acreage (Fig. S4). Using the parameters of the best fit equations, we calculated the future acreage of rice. Similarly, we analysed the hybrid coverage increment between 2007 and 2017. An average of this increment was $\sim 1\%$, which we used for projecting the hybrid rice acreage in the future. Additionally, we considered that 0.5% of the land will be migrated due to the non-agricultural activities although this figure was suggested to be $\sim 1\%$ (Hasan et al. 2013). However, all other possible

changes in soil-atmospheric conditions including climate change were not considered for. Finally, the emission of each of the rice types was projected by multiplying acreage with respective current emission rate of that rice types.

2.12 Statistical analysis

Calculated emission rates were analysed using JMP 8.0 (SAS Institute) to examine effects of rice type (*i.e.*, Local, HYV, and Hybrid) and cultivation season (*Aus*, *Aman*, and *Boro*). One-way analysis of variance (ANOVA) was performed on mean emission rates from different districts while the districts were used as random factor. The means were separated using Tukey's HSD (Honestly Significant Differences) considering a probability of 5%.

3. Results

3.1 Spatial CH₄ emission

Spatial distribution of methane emission can help to make policy makers aware about their roles in reducing emissions. In Bangladesh, the annual CH₄ emission rates varied widely among different regions (divisions) ($p<0.001$, Fig. 2). Across all rice growing seasons, the largest emission rate was estimated at 283 kg CH₄ ha⁻¹ yr⁻¹ from *Aman* rice in Chittagong while the lowest rate (258 kg CH₄ ha⁻¹ yr⁻¹) was estimated in Shylet. Similarly, the largest annual emission rate was estimated at 173 kg CH₄ ha⁻¹ yr⁻¹ from *Boro* rice in Shylet while the lowest estimation (99 kg CH₄ ha⁻¹ yr⁻¹) was in Barisal. The highest annual CH₄ emission rate in *Aus* season was from Dhaka (59 kg CH₄ ha⁻¹ yr⁻¹), while the lowest rate was estimated at 56 kg CH₄ ha⁻¹ yr⁻¹ for Mymensingh. When accounting for land area for each rice type and season, the variability was evident for different districts (Fig. 3, see details in Figs. S6-8 and Table S7). As shown in Fig. 3, methane emission was relatively large in the district Dinajpur, Mymensingh, Naogaon, and Sunamganj, while it was relatively small in Bandarban, Chuadanga, Dhaka, Jhalakati, Khagrachhari, Madaripur, Manikganj, Meherpur, Munshiganj, Narayanganj, Rajbari, Rangamati, and Shariatpur districts.

Averaged across all rice types and growing seasons, our estimated national CH₄ emission rate from rice cultivation was 2348 Gg CH₄ yr⁻¹ with 95% CIs of 799-5628 Gg CH₄ yr⁻¹ in the year 2020.

3.3 Annual CH₄ emissions from different rice types

Across all rice growing seasons, the CH₄ emission rate varied significantly for different rice types ($p<0.001$, Fig. 4A). The CH₄ emission rate from hybrid varieties was 76%, and 37% higher than for local varieties and high yielding varieties, respectively. When emission was scaled against yield, the largest emission rate was estimated for local rice varieties (88 g CH₄ kg⁻¹), or 69% and 34% larger than hybrid and HYV varieties, respectively (Fig. 4B).

3.4 Annual CH₄ emission rates from different rice season

Average across all rice types, the estimated CH₄ emission rate varied significantly among rice growing seasons ($p<0.001$, Fig. 5A). Among the rice growing seasons, the CH₄ emission rate was significantly larger in *Aman* (242 kg CH₄ ha⁻¹ yr⁻¹), followed by *Boro* (160 kg CH₄ ha⁻¹ yr⁻¹) and *Aus* season (58 kg CH₄ ha⁻¹ yr⁻¹). Similarly, the yield normalized CH₄ emission also varied among rice growing season with the largest emission rate (109 g CH₄ kg⁻¹) from *Aman* cultivation while it was 75% lower from *Aus* rice cultivation when compared with *Aman* cultivation (Fig. 5B).

3.5 Validation of the methane emission rate

The survey based CH₄ emission rate was linearly related to our model-based estimates ($r^2=0.94$, $p<0.01$). However, the survey-based estimate is lower by ~10% than our model-based estimate and thus, the plot fell below the one-to-one line with more inclination for the HYV and hybrid rice (Fig. 6).

3.6 Future projection of methane emission

The projection of total CH₄ emission from different rice types is presented in Fig. 7 (see details in Fig. S5). Provided that all management remains similar and changes in rice cultivation follow the past trends (Fig. S4), the total CH₄ emission was projected to increase from 2348 Gg CH₄ yr⁻¹ in the year 2020 to 2392 Gg CH₄ yr⁻¹ in 2060, a 1.87% increase in CH₄ emission when no land would be migrated from agricultural to non-agricultural purposes. However, the increment will be only 1.18% if 0.5% of the agricultural lands would migrate to non-agricultural activities. Moreover, the projection without land migration showed that the CH₄ emission from modern rice varieties (HYV and hybrid) would increase by 3.5% in 2060 whilst the emission from local varieties would decrease by 9% (Fig. S5).

4. Discussion

4.1 CH₄ emission from different rice cultivation systems in Bangladesh

Diversity in rice growing conditions and management practices can affect CH₄ emission rates. The CH₄ emission rates varied across different regions of the country because of the specificity of rice adoptions under diverse agro-climatic conditions. Among different districts, the cumulative CH₄ emissions from three rice growing seasons was higher in Dinajpur, Mymensingh, Naogaon, and Sunamganj districts. This was possibly due to larger acreage of rice cultivation with modern varieties (Table S7). In addition, water management could also have contributed to this larger emission rates, since irrigation (i.e., intermittent drainage) is also practised.

Rice types (local vs HYV), when grown in different conditions can generate different amounts of CH₄. Across growing seasons, the CH₄ emission rates from modern rice varieties i.e., hybrid and HYV were 76 and 37% higher than for local varieties (Fig. 4). This was probably associated with multiple factors, specifically water regime in and before growing season, and organic matter amendment (Wang et al. 2012; Feng et al. 2013). First, local *Aus* rice cultivars are usually grown without irrigation and often are affected by drought. Therefore, the in-season water management emission factor (EF) is considered as 0.16 while its pre-season water regime is quite dry, i.e., long drainage, (EF ~0.89, Table 1). Moreover, in the *Boro* season, it is usually grown in the lowlands as deep-water rice. Therefore, the in-season water management EF is low, 0.06. In contrast, the assigned in-season water management emission factors for HYV and hybrids are much higher since they are grown with multiple drainage in the *Boro* season (EF= 0.55) and regular rainfed conditions (EF=0.54) in the *Aman* season. Similarly, the pre-season water management EF was also high, i.e., 1.0 and 2.41 during *Aus*, *Aman* and *Boro* season, respectively (Table 1). Secondly, the HYV and hybrids are cultivated with high inputs including organic matter and nitrogenous fertilizers (Table S3 and S4) while local rice is cultivated with minimal or without any organic or inorganic fertilizers.

The yield normalized CH₄ emission from local rice varieties was higher than modern rice varieties (HYV and Hybrid) (Fig. 4) suggesting that local rice has a much higher carbon foot print than modern cultivars. Therefore, reducing carbon foot print of rice production without compromising yield, HYV and hybrid cultivation should be considered.

The rice growing seasons in Bangladesh with large variability in growing conditions including water regimes can affect CH₄ emission rates. These changes in growing conditions also change the adaptability of rice varieties (local, HYV and hybrids). The estimated CH₄ emissions from different rice growing seasons were different with the largest rates from different rice grown during *Aman* season (Fig. 5). The higher EF associated with in- and pre-season water regime likely contributed to the larger CH₄ emission. For example, the EF for pre-season was 2.41 in *Aman* season vs 1.00 in *Boro* (Table 1). A relatively larger emission from the rice grown during *Boro* season than *Aus* season, was due to a larger coverage of HYV and hybrid (99% in *Boro* vs 88% in *Aus* season). Moreover, the duration of the *Boro* rice was longer than rice grown in other seasons. For instance, the average duration of HYV and hybrid rice was 149 d during *Boro* season while it was 117 d for the same rice grown in *Aus* season (data not presented).

4.2 Comparison between earlier estimates of CH₄ emission from rice fields using IPCC methodology

Methane emission estimates for Bangladesh reported in different studies were quite diverse ranging between 375 and 3110 Gg CH₄ yr⁻¹ with a median value of 1032 Gg CH₄ yr⁻¹ (Fig. 7). Across all rice types grown in different seasons, the estimated annual CH₄ emission rate in our study was 2348 Gg CH₄ yr⁻¹

(Fig. 7), which was higher than most of the previous estimates made using the same method (ALGAS 1995; MoEF 2002, 2012; Sass 2003; Yan et al. 2009; U.S. EPA 2012; Khan and Saleh 2015; FAO 2020). This discrepancy was possibly due to not accounting for several contributing factors, such as duration of rice cultivation, water management, and organic matter amendments in the other studies, but which, were included in the current study (MoEF 2002, 2012; Yan et al. 2009; Khan and Saleh 2015). Besides, we used topography customized scaling factors for water management practices (during and before rice cultivation), which, were not considered in the previous estimation studies (MoEF 2002, 2012; Khan and Saleh 2015). Although, it was not possible to access data for organic matter and straw incorporation, we used projected values using literature data and expert judgement (see Figs. S1-3 and Table S5). Therefore, it is not unlikely that our estimate surpassed most of the previous estimates. However, given the importance of organic matter incorporation for CH_4 emission in rice (e.g., Yan et al. 2005; Das and Adhya 2014), we believe that this type of management needs to be included for more accurate estimates of CH_4 emission. Our estimate is also somewhat inconsistent with estimates based on GIS and process-based simulation models. Different values are also evident between model (log mean=3.25, dispersion=0.43) and GIS based estimates (log mean of 3.01 and dispersion of 0.30) (Fig. S10). Multiple factors could be responsible for these observed differences. For instance, GIS and processes-based estimates applied different methodological approaches while the models also require different input variables (see supplementary Fig. S9) (Yao et al. 2006).

We compared our estimated CH_4 emission with the field-based emission rates of 1081 field experiments in different countries across the world (Fig. 9). The log normal mean emission rate of these experiments was $0.10 \text{ kg CH}_4 \text{ ha}^{-1} \text{ d}^{-1}$ with a standard deviation of $0.53 \text{ kg CH}_4 \text{ ha}^{-1} \text{ day}^{-1}$. Our mean estimated daily CH_4 emission rate was $0.07 \text{ kg CH}_4 \text{ ha}^{-1} \text{ day}^{-1}$ which was within one standard deviation of the normal probability distribution. Similarly, the estimated daily emission rate from local, HYV and hybrid rice types (averaged across season) and during *Aus*, *Aman*, *Boro* (average across rice types) were also close, within one standard deviation of the normal distribution. However, our mean estimate was lower than the average value across all observations. Moreover, we observed a significant relationship between the survey-based CH_4 emission rates with model-based estimates ($r^2=0.94$, $p<0.01$) although survey-based estimate underestimated the emission by ~10%. Considering all these together, we believe that our estimate is reliable although estimates based on actual measurements could provide a more accurate result.

4.3 Limitations of the study

Methane emissions from rice fields do not only depend on the duration of rice growing season, water regime during and before the cultivation season, and types and amount of organic matter amendments, but also on various agro-climatic factors, such as soil pH, rice cultivars, root exudates, etc., which were not considered in this study. It is also possible that individual rice cultivars may be different under each of the rice type categories (*i.e.*, local, HYV and hybrids), which however, were not considered in this study. In

future work, inclusion of these contributing factors could improve the CH₄ emission estimates from rice fields in Bangladesh. We acknowledge that assignment of scaling factors and default emission factors carry some uncertainties since these were based on literature and modelled data. Moreover, our prediction of CH₄ emission carries some uncertainties since the calculation was based on literature data and on expert opinion.

5. Conclusions

This study estimated CH₄ emission rates from different rice cultivation systems in Bangladesh using the IPCC Tier 1 method. The CH₄ emission from all rice types grown under three different seasons was estimated at 2348 Gg CH₄ yr⁻¹ with 95% CIs of 799-5628 Gg CH₄ yr⁻¹. Our estimate exceeds most of the previous estimates, possibly due to the inclusion of additional contributing factors to CH₄ emission, while it falls within one standard deviation of the normal probability distribution of measurement-based estimates. Additionally, our results indicated that production of modern rice varieties (HYV and hybrid) contributed 87% of the annual methane emission while rice grown in the *Aman* season contributed the highest CH₄ emission (61%). In contrast, the yield normalized CH₄ emission showed a completely opposite scenario with the largest emission rate from local rice varieties, 67% higher than for modern rice varieties (HYV and hybrid). Moreover, our results provide compelling evidence that the emission will not significantly change by 2060, if 0.5% agricultural land migration to non-agricultural activities are included. Therefore, our findings provide important insights into CH₄ emissions from different rice types grown under diverse growing conditions.

Declarations

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Table

Table 1

Season	Rice types	Growth conditions	Water regime during the cultivation*	Water regime before the cultivation*
<i>Aus</i>	Local	Usually cultivated as rainfed during the months of March to June when soil moisture is less than required.	Drought prone (0.16)	Long drainage (0.89)
	HYV	Usually cultivated rainfed lowland area during the months of April to August.	Regular rainfed (0.54)	Short drainage (1)
<i>Aman</i>	Local	Mostly cultivated as rainfed lowland, tidal wetlands area during the months of July to December	Regular rainfed (0.54)	Flooded (2.41)
	HYV		Regular rainfed (0.54)	Flooded (2.41)
	Hybrid		Regular rainfed (0.54)	Flooded (2.41)
<i>Boro</i>	Local	Usually cultivated low-lying lands where flood water accumulates during rainy season and standing water depth varies from 50 cm to more than 3 m during the months of November to May	Deep water (0.06)	Flooded (2.41)
	HYV	Grown completely under the irrigated ecosystem during the months of December to June	Multiple drainage (0.55)	Short drainage (1)/Flooded (2.41) (for details calculation see Eq. S1)
	Hybrid		Multiple drainage (0.55)	Short drainage (1)/Flooded (2.41) (for details calculation see Eq. S1)

* Values within the parentheses are the customized scaling factors used in this study (adopted from IPCC 2019 guidelines)

Figures

Fig. 1

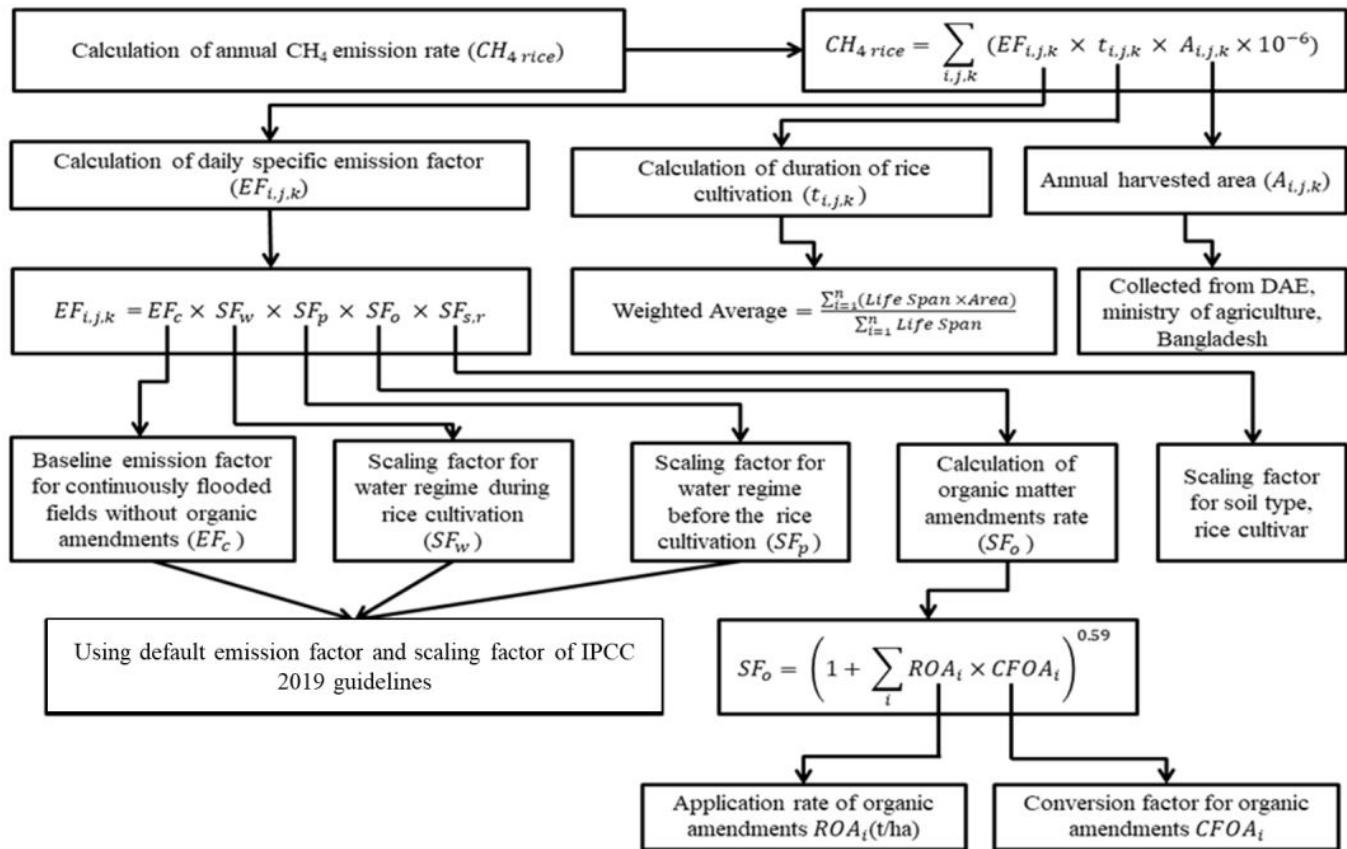


Figure 1

Flow diagram of the methodology adopted for methane emission estimation from rice-based farming system in Bangladesh

Fig. 2

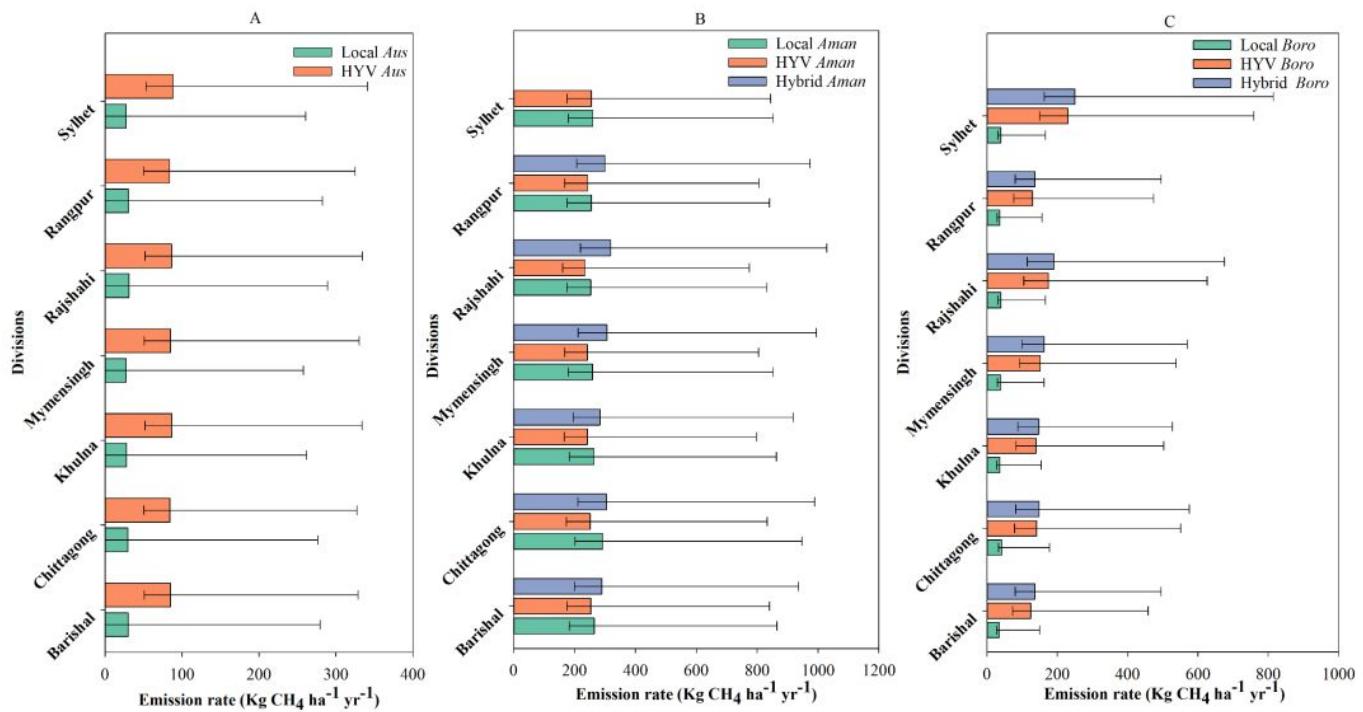


Figure 2

Division-wise annual CH₄ emission rates from Aus (A), Aman (B), and Boro (C) rice varieties. The error bars show 95% confidence intervals.

Fig. 3

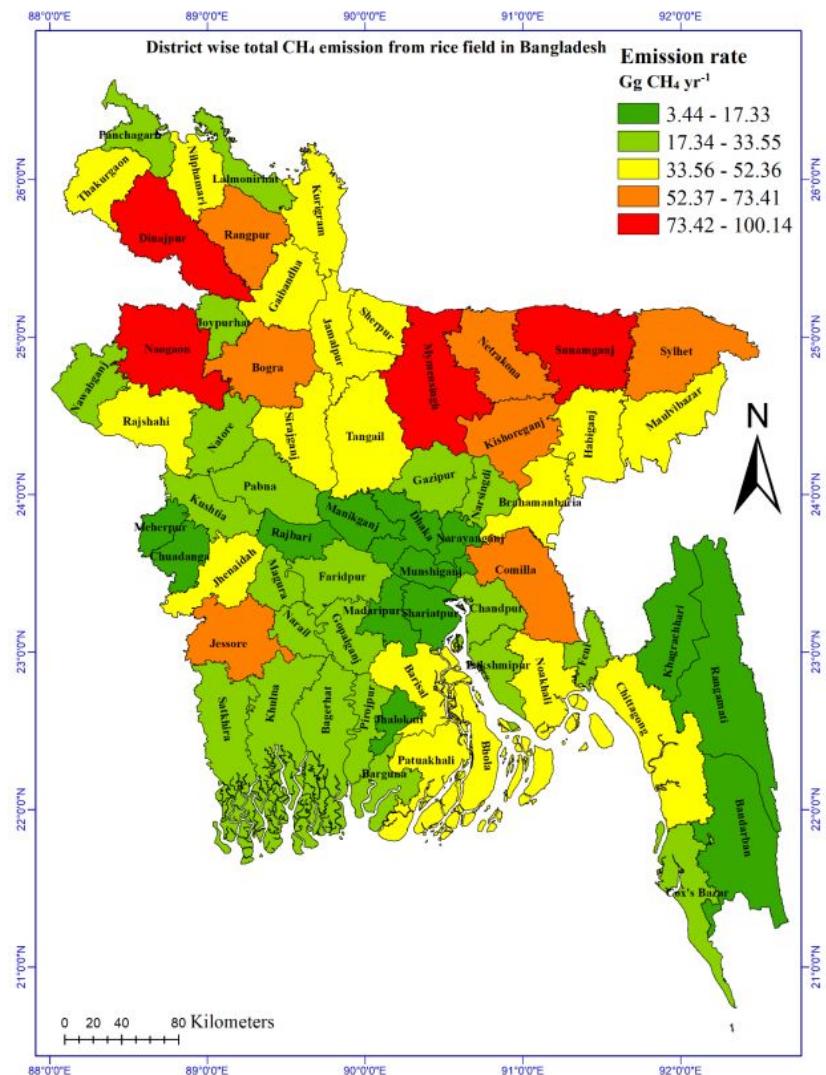


Figure 3

Annual total methane emission rates ($\text{Gg CH}_4 \text{ yr}^{-1}$) of commonly cultivated rice varieties/cultivars during different rice growing seasons from different districts of Bangladesh

Fig. 4

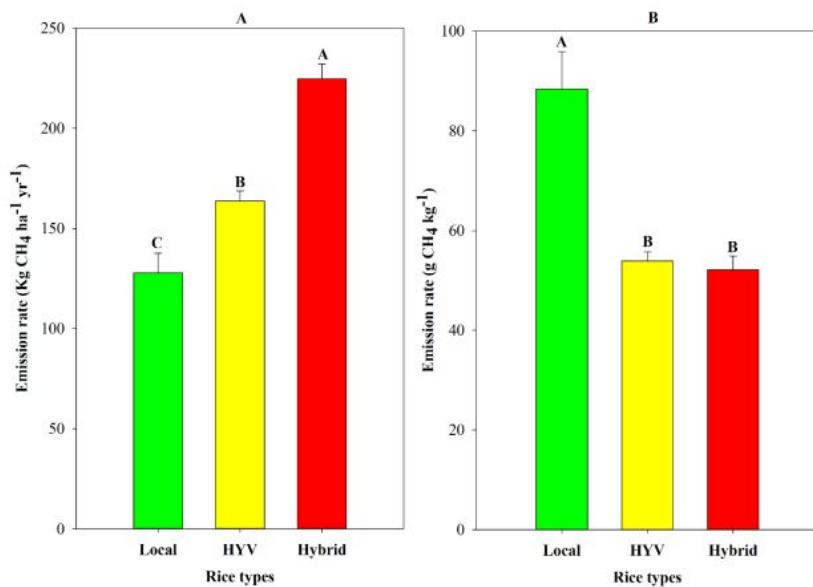


Figure 4

Methane emission rates from different rice types (A) and normalized by yield (B). Different letters above bars indicate significant differences at 5% level of probability. The error bars indicate standard error of means.

Fig. 5

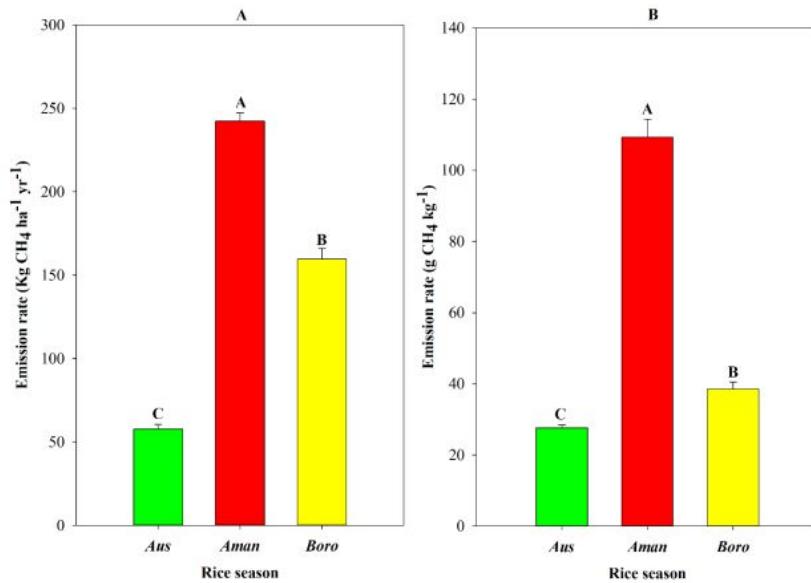


Figure 5

Methane emission rates from different rice seasons (A) and normalized by yields (B). Different letters above bars indicate significant differences at 5% level of probability. The error bars indicate standard error of means.

Fig. 6

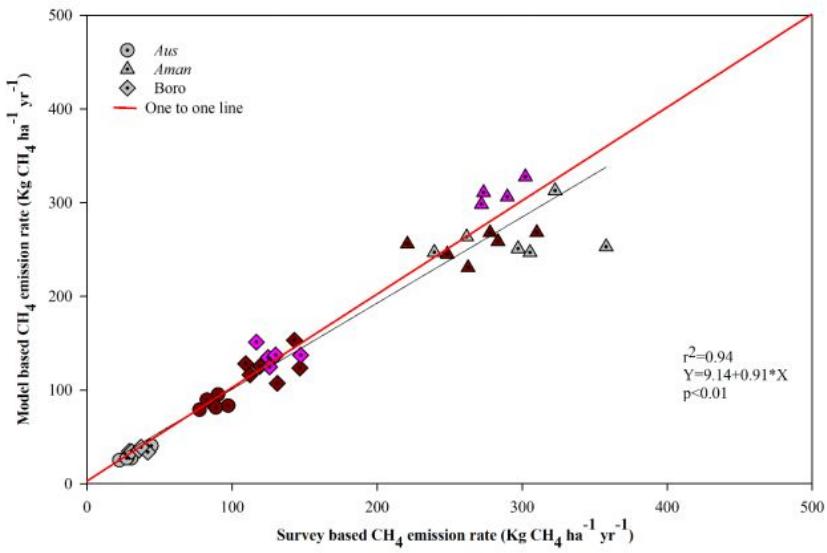


Figure 6

Validation of model-based estimate with survey-based estimates. Circles, triangles, and diamond represent the Aus, Aman and Boro rice while grey, dark red and pink indicate local, HYV and hybrid rice, respectively.

Fig. 7

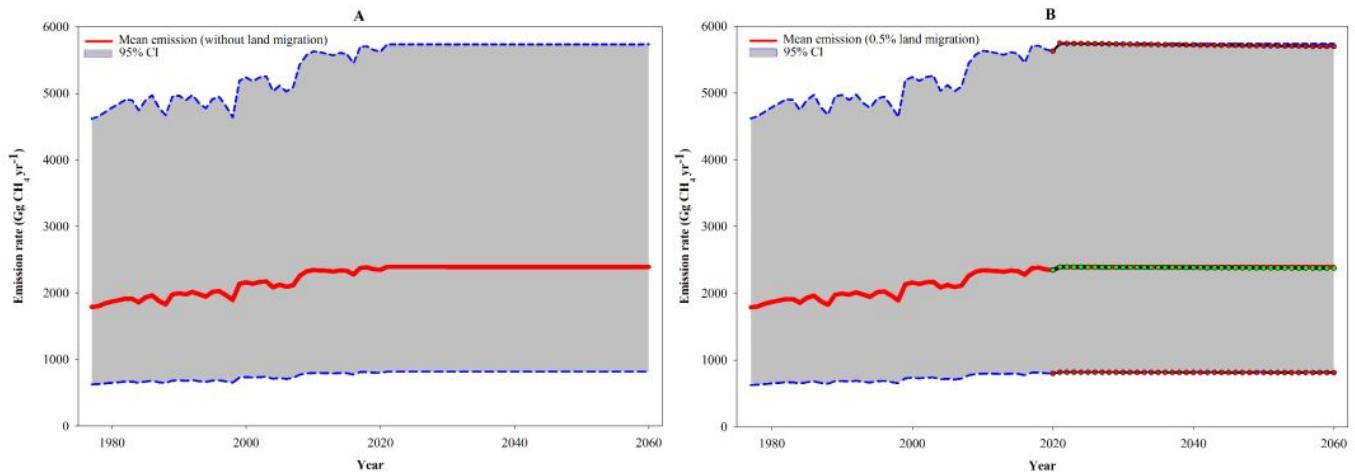


Figure 7

Estimated annual CH₄ emission from rice production between 1977 and 2060, excluding land migration (A) and including 0.5% land migration (B).

Fig. 8

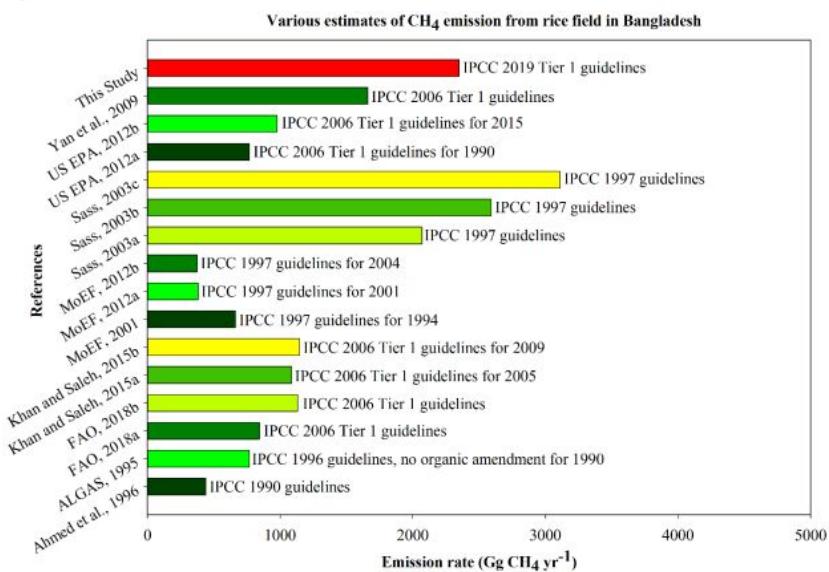


Figure 8

Comparison of methane emission rates estimated using similar methods. Next to each bar, the research method is displayed.

Fig. 9

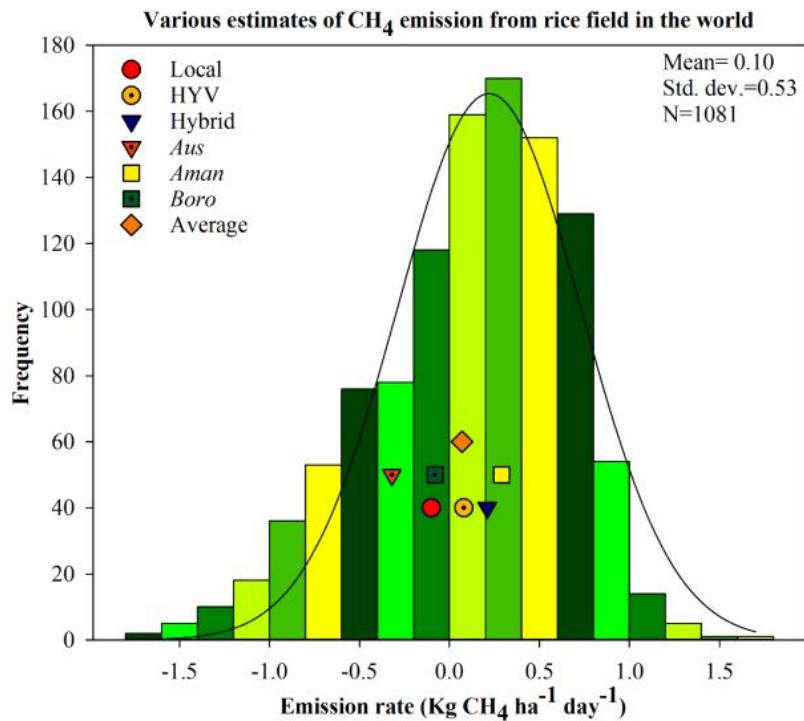


Figure 9

Log-normal distribution of methane emission rates. The data were adopted from Wang et al. (2018). The different symbols indicate the daily estimated CH₄ emission rate from different rice types and seasons for this study.

Supplementary Files

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