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Methane Emission Factors from Vietnamese Rice Production: Pooling Data of 36 Field Sites for Meta-Analysis

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Abstract: Rice production is a significant source of greenhouse gas (GHG) emissions in the national budget of many Asian countries, but the extent of emissions varies strongly across agro-environmental zones. It is important to understand these differences in order to improve the national GHG inventory and effectively target mitigation options. This study presents a meta-analysis of CH_4 database emission factors (EFs) from 36 field sites across the rice growing areas of Vietnam and covering 73 cropping seasons. The EFs were developed from field measurements using the closed chamber technique. The analysis for calculating baseline EFs in North, Central and South Vietnam in line with the Intergovernmental Panel on Climate Change (IPCC) Tier 2 methodology was specified for the three cropping seasons being early-(E), mid-(M) and late-year (L) seasons. Calculated average CH_4 EFs are given in kg ha^{-1} d^{-1} and reflect the distinct seasons in North (E: 2.21; L: 3.89), Central (E: 2.84; M+L: 3.13) and South Vietnam (E: 1.72; M: 2.80; L: 3.58). Derived from the available data of the edapho-hydrological zones of the Mekong River Delta, season-based EFs are more useful than zone-based EFs. In totality, these average EFs indicate an enormous variability of GHG emissions in Vietnamese rice production and represent much higher values than the IPCC default. Seasonal EFs from Vietnam exceeded IPCC defaults given for Southeast Asia corresponding to 160% (E), 240% (M) and 290% (L) of the medium value, respectively.

Keywords: rice; greenhouse gas; methane; nitrous oxide; emission factor; IPCC Tier 2; Vietnam; Mekong River Delta

1. Introduction

In Vietnam, rice is produced on 7.7 million ha with a total production of 43 million tons in 2017 [1], making Vietnam the world's 6th largest rice producer and the 3rd largest rice exporting country (after India and Thailand). Vietnam's rice exports account for 6.61 million tons per year (corresponding to 9% of the global rice trade) [2] and represent a major source of revenue for the population and the national economy. Lowland rice (rainfed and irrigated) is the predominant production system, including in the two mega-deltas, namely the Mekong River Delta (MRD) with 55% of all Vietnamese rice production and the Red River Delta (RRD) with 18%.

Lowland rice production has been known to be a source of greenhouse gases (GHG) due to emissions of methane (CH_4) and, to a lesser extent, nitrous oxide (N_2O). CH_4 emissions from rice accounts for less than 1.5% of all GHG emissions globally [3], but these percentages could be fairly high at the national scale for rice-growing countries [4]. The official figures on total emissions per country can be obtained from the most recent national communications (NC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) [5]. For reference year 2013, rice production accounts for 13.5% of the total national emissions which exceeds the total amount of GHG emitted from land transport [4]. This GHG inventory is based on the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines and thus only encompasses CH_4 emissions from flooded fields. In contrast, N_2O emissions from rice are aggregated under fertilizer-borne emissions of all managed soils.

Besides the general scarcity of crop management data, the calculation of national GHG emissions from rice production systems is also constrained by the limited availability of GHG measurements to determine country-specific emission factors (EFs). In addition to crop management effects, CH_4 emissions also vary over time and space as a function of natural conditions such as soil type and climate [6]. To assess these variations, the IPCC has defined a baseline for rice management that encompasses a set of practices including continuous flooding, no addition of organic amendments and no pre-season submergence of the soil. In Vietnam, only a few field measurements were available for the previous NCs, but this situation has recently improved as this study attests.

The IPCC approach considers a differentiation of rice production systems, namely irrigated, rainfed, deep-water and upland rice, but this aspect could be disregarded in our study as more than 90 per cent of all land sown to rice in Vietnam is classified as irrigated [7]. It should be noted, however, that irrigated rice does not necessarily mean that irrigation water is added throughout the year in a standardized management protocol. The important feature from rice production in terms of GHG emissions is a ponded water layer which is conducive for the microbial production of CH_4. If more than one crop is harvested in a particular region during the year, hydrological conditions will typically differ among cropping seasons, hence, EFs should be determined for each cropping season separately.

Vietnam is characterized by high variability of climate and soil conditions, thus, the GHG measurements have to take place across different regions and seasons in order to establish a representative database. Reliable emission data are not only needed for computing baseline emissions, but also for quantifying GHG mitigation potentials.

The objectives of this study were:

- To estimate disaggregated EFs for different seasons and regions;
- To conduct an in-depth assessment on GHG emission for the MRD by considering the hydrological zones within this region; and
- To assemble a database on baseline emissions for future mitigation projects.

2. Materials and Methods

2.1. Rice Production in Vietnam

Vietnam is characterized by a pronounced North-South gradient that can be sub-divided into eight agro-ecological zones (AEZ) [8] corresponding to the administrative regions of the country. Figure 1 shows these AEZs with charts showing rice area by season based on data from the General Statistics Office (GSO) [1]. The AEZs North Mountain West (NMW) and North Midlands East (NME) have large mountainous areas and collectively also a sizable rice area (680,000 ha). The third AEZ in the North is the RRD which is one of the country's rice growing centers (1,071,000 ha).

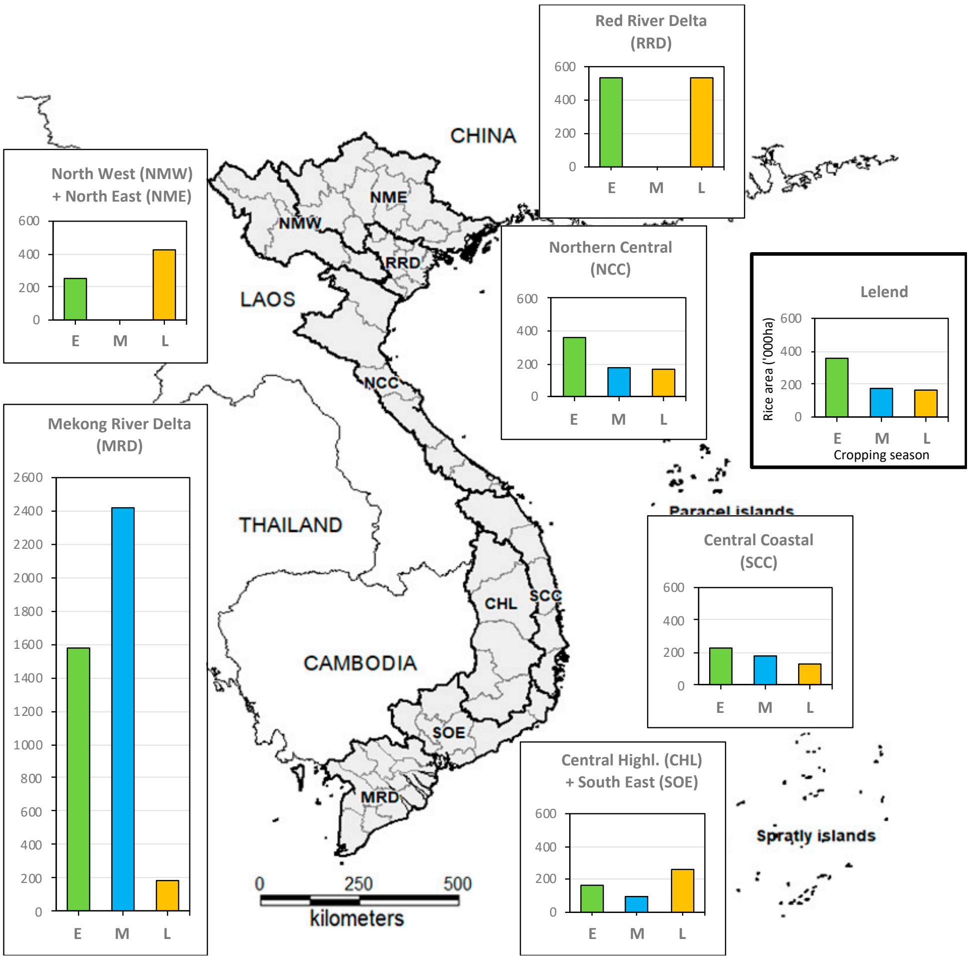

Figure 1. Distribution of rice area (in thousand ha) per region/agro-ecological zones (AEZ) and season in 2017 according to the General Statistics Office (GSO) [1]; rice crops in the early year (E), mid-year (M) and late-year (L) seasons are named spring, autumn and winter paddy in GSO statistics, respectively.

In the central part of Vietnam, rice production is very common in the extensive plains of the AEZs North Central Coast (NCC, 703,000 ha) and South Central Coast (SCC, 550,000 ha). A similar situation applies to the AEZs Central Highlands (CHL) belonging to Central Vietnam and the neighboring South East (SOE) belonging to South Vietnam that collectively comprise 515,000 ha. The MRD is the main rice producing region in Vietnam (4,185,000 ha) and is called the country's rice granary. This area has an average elevation of around 0.8 m [9] so that flooding and salinity are severe problems in coastal areas over several months of the year.

The GSO compiles official data for Vietnam's economic activities, making it also as a reliable source of national rice area data. However, it may not always cover the complexity and dynamics of rice cropping at the local scale. We recognize that individual studies have quantified rice areas at higher resolution for given regions (e.g., in Vietnam through remote sensing). As our study was conducted in the context of a GHG assessment at the national scale, however, we focused on GSO statistics as a means to avoid methodological inconsistencies created by different approaches.

GSO statistics mention three rice crops labelled as spring, autumn and winter paddy. During the course of our work, however, we realized that these terms created some confusion when applied to locally used names for cropping seasons in different parts of the country. This confusion was caused by two reasons, namely (i) ambiguity between climatic seasons, i.e., the winter paddy in the North is typically harvested in October; and (ii) enormous overlaps in the time windows of autumn and winter paddy at the national scale. Thus, we opted to use more generic names for the crops across the country corresponding to annual time windows, namely early year (E: October to June), mid-year (M: May to November) and late-year season (L: June to December, but in some locations in the South it could extend up to January).

This modified terminology maintained the compatibility of our assessment with GSO data, at the same time avoiding eventual conflicts of climatic seasons and cropping seasons. Due to the complexity of spatial and temporal patterns, this study has given special emphasis to an in-depth assessment of GHG emissions from rice production in the MRD.

2.2. Methodology of GHG Measurements

In this meta-analysis, data from 10 different projects and measurement campaigns conducted under the leadership of either the Institute for Agriculture Environment (IAE) or the International Rice Research Institute (IRRI) from 2011 to 2018 were compiled. Site characteristics are shown in the Supplementary Materials (Tables S1–S3) while more information on local conditions can be obtained from the respective publications cited in these tables. All emission measurements used the closed chamber approach for field sampling in combination with laboratory analysis of CH_4 and N_2O concentrations. The field design consistently encompassed three replicates with IPCC baseline management while sampling was done in weekly intervals. In spite of smaller differences in chamber design (e.g., base area, height and material) and laboratory equipment (e.g., different models of gas chromatographs), the projects followed common practices for the closed chamber method [10] and established a coherent database for inter-comparisons of emissions from rice fields cutting across the rice-producing regions of Vietnam.

The fluxes of CH_4 and N_2O were determined using the static flux chamber technique and gas chromatographic analyses of gas samples, following the recommendations of Rochette and Eriksen-Hamel [11]. Each gas sampling chamber consisted of a permanently installed base unit (open bottom) and a removable top. The base was a stainless steel unit with a water-filled groove (0.05 m in depth) at the top, which was inserted 0.1 m into the soil at least 1 day before the transplanting day to avoid lateral diffusion of gases. The removable top made out of plastic was mounted on the base chamber (sealed by the water-filled groove) during sampling and was removed when gas sampling was finished. A rubber septum, thermometer, and two mini-fans (12 V) were installed at the top of each chamber [12] together with a pressure equilibration device (plastic tube: 7.6 m length and 1.5 mm diameter) [13].

Wooden boardwalks were set up at the beginning of the rice season to avoid soil disturbance and border effects during the sampling process. Sampling frequency was either weekly or in 10-day intervals except for the period right after fertilizer application when sampling was done on a daily basis. Sampling took place between 8:00 to 11:30 am. After placing the top chamber on the base, gas samples were taken at 10-min intervals at 0, 10, 20 and 30 min (20-min intervals for the datasets from [14,15]) using 60 mL syringes, depending on the specific protocol used at the 36 study sites. Collected gas samples were immediately transferred into pre-evacuated vacuum glass containers. Gas samples were shipped to the laboratory and analyzed within 3 weeks of sampling.

The gas samples for sites N1, N6 and N8 were analyzed using gas chromatographs (GC) in the laboratory at Copenhagen University (GC: Bruker 450-GC 2011), for sites N2–N5, N7, N9, N10, C1–C11 and S1–S4 at the IAE (GC: Shimadzu 2014), for sites C12–C14 and S10 at the Hue University of Agriculture and Forestry (GC: SRI 861 °C) and for the sites S5–S13 at the laboratory of the Cuu Long Rice Research Institute (CLRRI) (GC: SRI 861 °C). Details of the analytical procedures can be obtained from the respective publication [14,16–18]. The gas fluxes were calculated using the equation given by Smith and Conen [19].

Our data set was derived from the GC analysis of more than 5000 gas samples encompassing 73 individual growing seasons; sampling was conducted in average with three replicates, 10 sampling dates per season and four gas samples per chamber exposure. Comparison of average CH_4 emission rates among seasons and edapho-hydrological zones was performed using one-way analysis of variance (ANOVA) in SPSS v.20.

Grain yield (dry weight) was calculated based on a harvest of whole areas of each experiment plot. Grains were threshed from the harvested rice plant and weighed for fresh weight. Then, 200 g of fresh grain was taken and dried at 105 °C for 24 h (or until no further weight change) to determine the dry matter content. Grain yield is given in grain dry matter (t ha^{-1}). The measurement protocol also included recording the day of seeding as well as harvesting, so that the cultivation period (in days) could directly be calculated from the field data of each measurement.

2.3. Measurement Sites and Seasons

Figure 2 shows the locations of all field sites that are scattered quite evenly across North (10 sites/20 seasons), Central (14 sites/29 seasons) and South Vietnam (12 sites/23 seasons). Agronomic management details of all sites can be found in Tables S4–S6, respectively. In both North and South regions, all experiment sites are located within a small radius of about 100 km in the RRD and MRD, respectively. In the Central region, however, the sites comprise a long stretch of 700 km.

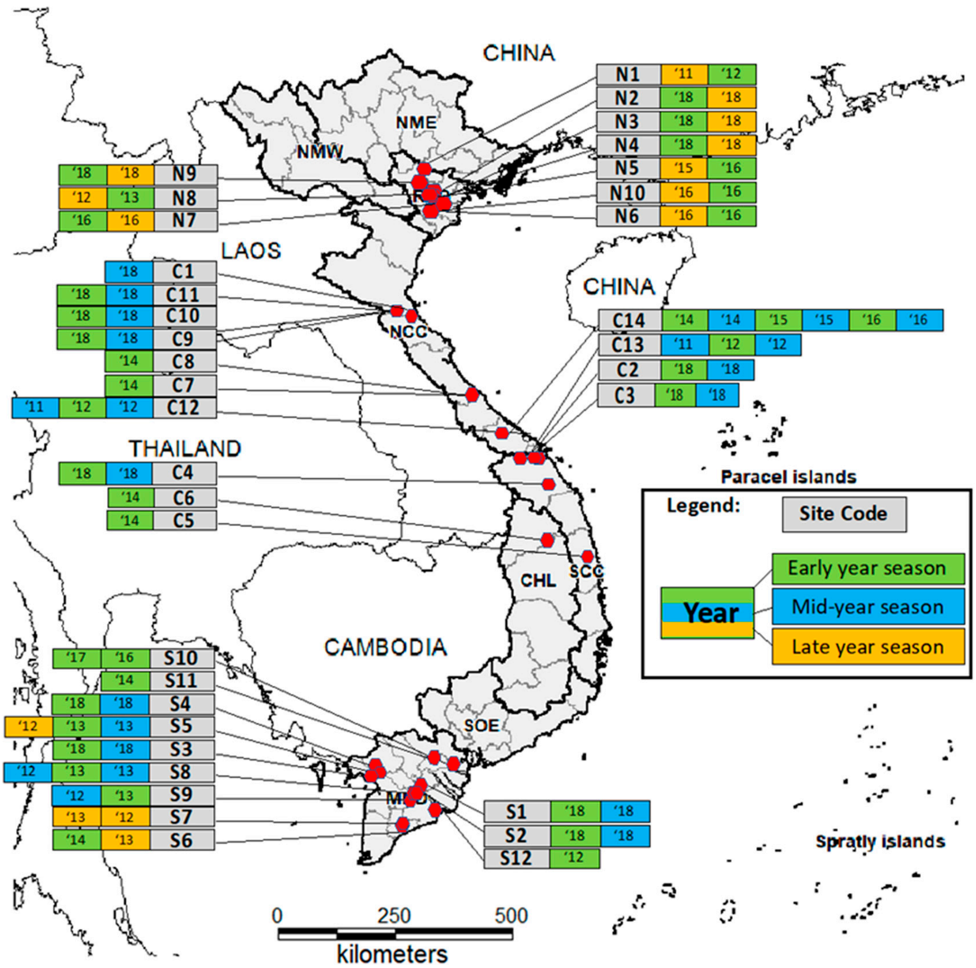

Figure 2. Overview of field sites and recorded seasons.

The presented database for MRD corresponds in part to the publications by Vo et al. [18] that included 8 sites (S5–S12) out of the 12 sites shown here. In terms of zoning, our assessment refers to the publication by Wassmann et al. [20] that provided a high-resolution map on the edapho-hydrological zones in the MRD shown in Figure 3. Subsequently, we have also adopted the terminology used in this publication for the different zones, namely alluvial (incl. acid sulfate), deep flood and saline zones. We recognize that a variety of different names can be found for these zones in the literature such as flood-prone or salt-affected zone. Those sub-regions of the MRD are even called AEZ in some studies whereas we prefer the term edapho-hydrological zone to avoid any mix-up with the AEZs at a larger scale.

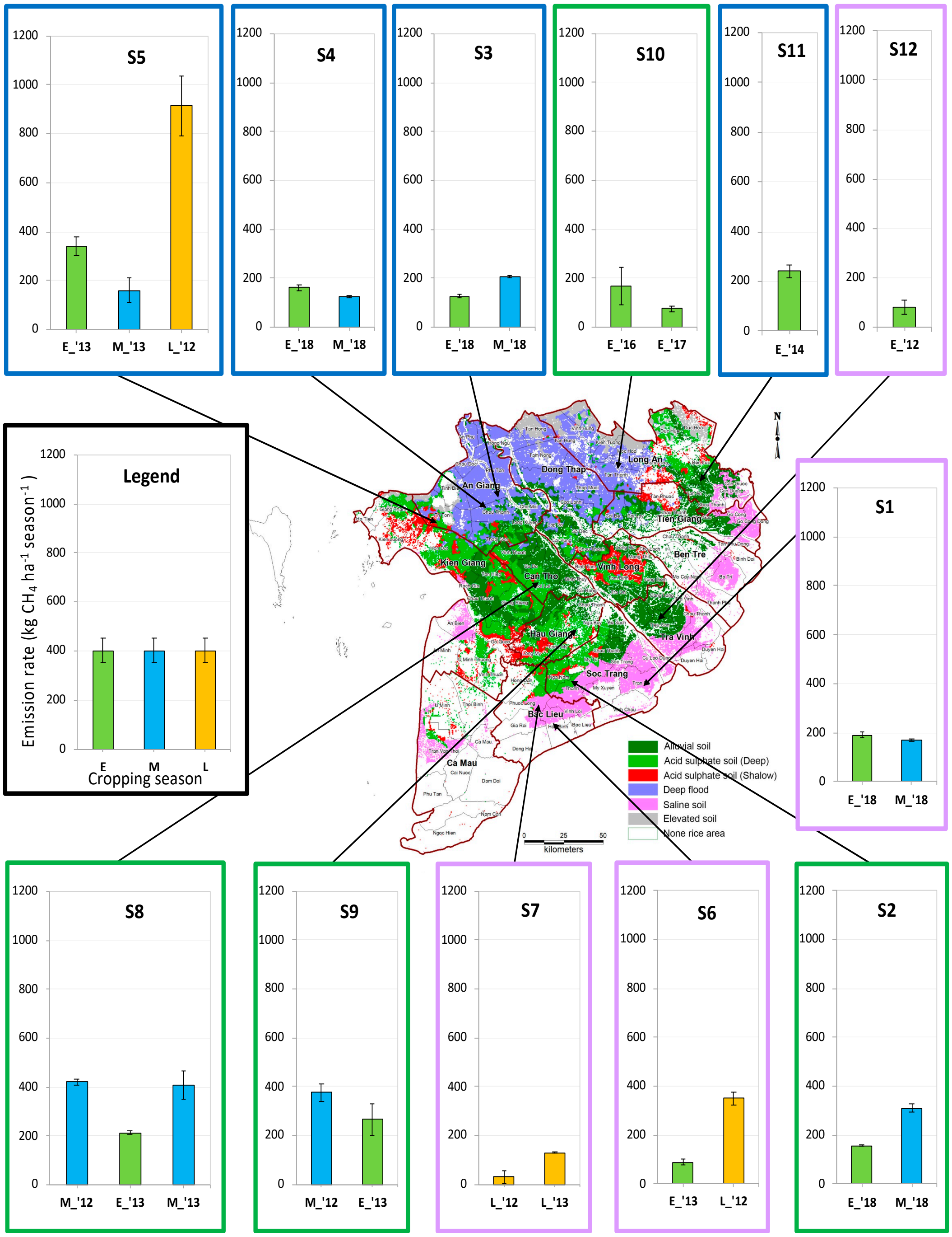

Figure 3. Seasonal emission rates in field experiments in South Vietnam with field sites marked in a map adopted from Wassmann et al. [20], colored frames indicate alluvial (green), deep flood (blue) and saline (magenta) zones; rice crops in the early year (E), mid-year (M) and late-year (L) seasons are named spring, autumn and winter paddy in General Statistics Office (GSO) statistics, respectively; standard errors among three replicates shown as error bars, crops are shown in sequential order which does not always correspond to the chronological order shown in Figure 2.

3. Results and Discussion

We use the term 'emission rates' for an individual field experiment to distinguish this value from EFs that are derived from emission rates for an entire region. We have computed both CH_4 emission rates per day which is called EF in line with the IPCC terminology as well as CH_4 emission rates per harvested crop which is termed as seasonal emission and plotted in Figures 3–5.

3.1. Spatio-Temporal Variations Of Emissions in North and Central Vietnam

In North Vietnam, seasonal emissions in the late-year season are consistently higher than in the early year season (Figure 4). With only one exception, CH_4 emission rates in the late-year season are higher than 200 and go up to 749 kg ha^{-1} season^{-1}. Seasonal CH_4 emissions in the early year season are on average only 63% of those emissions in the late-year season and reach a maximum of 416 kg ha^{-1} season^{-1}. The respective emission rates can be found in Table 1.

The GSO statistics show three possible rice crops in Central Vietnam, with the early year season comprising about twice the area for the mid-year and late-year seasons. In contrast to MRD, however, there are effectively no farms with triple seasons per year.

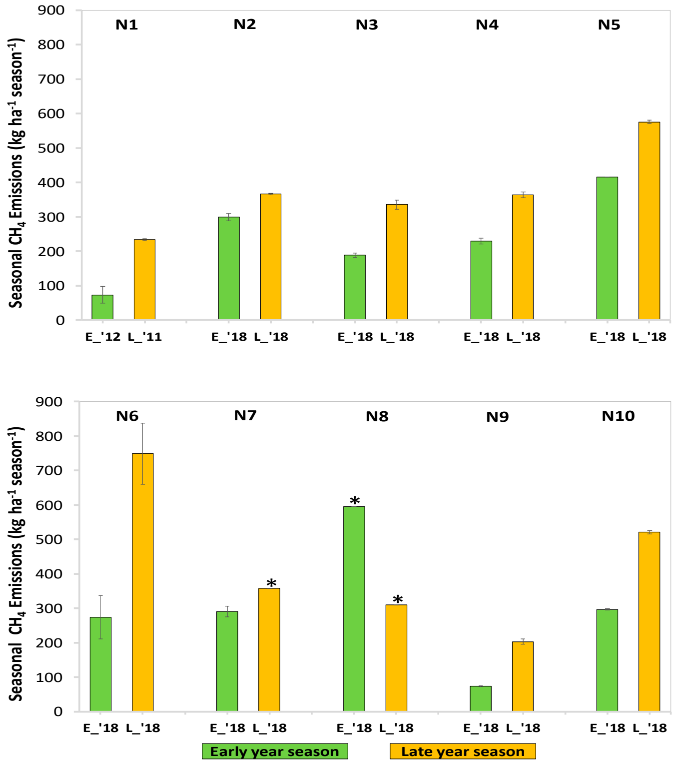

Figure 4. Seasonal CH_4 emission rates (kg ha^{-1} season^{-1}) of field measurements in North Vietnam; standard errors among three replicates shown as error bars or marked by asterisks if not available. Crops are shown in sequential order which does not always correspond to the chronological order shown in Figure 2.

Table 1. Field measurements of daily CH_4 emission rates and cultivation period in North Vietnam. For site locations, refer to Figure 2; Cult. per.—cultivation period; error—standard error.

Site	Early Year Season			Late-Year Season		
	CH_4 Emission Rates (kg ha^{-1} d^{-1})	Cult. per. (d)	Yield (t ha^{-1})	CH_4 Emission Rates (kg ha^{-1} d^{-1})	Cult. per. (d)	Yield (t ha^{-1})
N1	0.660 ± 0.223	112	5.6	2.816 ± 0.036	83	4.8
N2	2.413 ± 0.079	124	6.1	3.461 ± 0.020	106	5.7
N3	1.512 ± 0.050	125	6.1	3.197 ± 0.124	105	5.2
N4	1.897 ± 0.068	121	8.0	3.404 ± 0.078	107	5.8
N5	3.331 ± nd	125	4.3	5.482 ± 0.049	105	5.3
N6	2.245 ± 0.517	125	4.5	7.565 ± 0.897	99	3.6
N7	2.328 ± 0.126	124	5.2	3.405 ± nd	105	4.8
N8	4.763 ± nd	125	5.4	2.824 ± 0.000	110	4.9
N9	0.610 ± 0.009	122	4.1	1.816 ± 0.064	112	5.9
N10	2.374 ± 0.017	125	5.9	4.962 ± 0.046	105	5.3

The differences in CH_4 emissions between two seasons at one site are relatively small Figure 5). Seasonal emissions range from 125 to 468 kg ha^{-1} season^{-1} in the early year season and 83 to 1029 kg ha^{-1} season^{-1} in the late-year season. The respective emission rates are shown in Table 2.

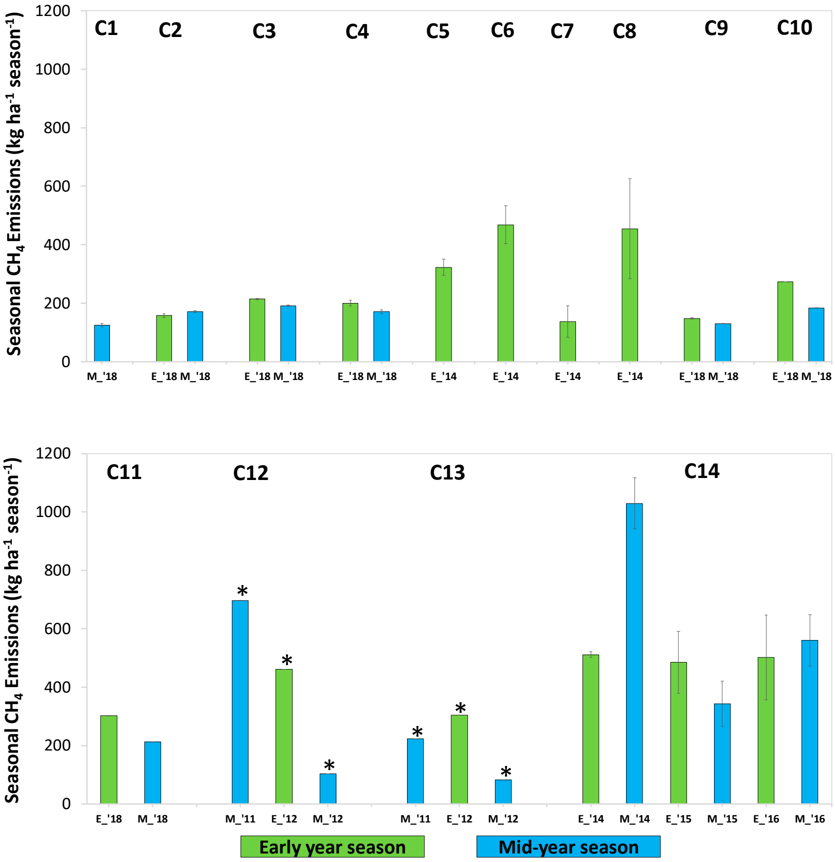

Figure 5. Seasonal emission rates of field measurements in Central Vietnam; standard errors among three replicates shown as error bars or marked by asterisks if not available. Crops are shown in sequential order which does not always correspond to the chronological order shown in Figure 2.

Table 2. Field measurements of daily methane emission rates and cultivation period in Central Vietnam. For site locations, refer to Figure 2; Cult. per.—cultivation period; nd—not determined; ↔—no rice crop grown; error—standard error.

Site	Early Year Season			Mid–Year Season		
	CH_4 Emission Rates (kg ha^{-1} d^{-1})	Cult. per. (d)	Yield (t ha^{-1})	CH_4 Emission Rates (kg ha^{-1} d^{-1})	Cult. per. (d)	Yield (t ha^{-1})
C1	↔	–	–	1.190 ± 0.101	105	6
C2	1.444 ± 0.058	109	7.6	1.693 ± 0.028	101	7.7
C3	1.948 ± 0.019	110	7.5	1.913 ± 0.024	100	7.7
C4	1.853 ± 0.088	108	7.3	1.660 ± 0.068	103	7.5
C5	2.542 ± 0.216	127	7.9	↔	–	–
C6	3.657 ± 0.510	128	8.8	↔	–	–
C7	0.954 ± 0.377	143	6.7	↔	–	–
C8	3.246 ± 1.221	140	6.1	nd	–	–
C9	1.333 ± 0.023	111	7.4	1.238 ± 0.006	105	6.2
C10	2.459 ± 0.001	111	7.2	1.752 ± 0.004	105	5.8
C11	2.721 ± 0.007	111	6.9	2.029 ± 0.003	105	5.7
C12	nd	–	–	7.565 ±nd	92	5.5
C12	5.066 ± nd	91	5.7	1.120 ±nd	92	5.5
C13	nd	–	–	2.435 ±nd	92	6.1
C13	3.341 ± nd	91	6.1	0.902 ±nd	92	5.7
C14	4.482 ± 0.085	114	5.5	10.719 ± 0.915	96	4.7
C14	4.663 ± 1.019	104	4.5	3.573 ± 0.817	96	5.3
C14	4.183 ± 1.210	120	3.3	5.333 ± 0.844	105	3.3

3.2. Spatio-Temporal Variations of Emissions in South Vietnam Based on an In-depth Assessment of the Mekong River Delta

The assessment of emission rates in South Vietnam focuses on the MRD (Table 3) while the small area of the South-East is not represented in this database. According to GSO statistics (Figure 1), the mid-year season (2422,000 ha) in the MRD comprises the bulk of the regional rice area followed by the early year season (1579,000 ha). The late-year season, however, is recorded with only a small area (184,000 ha). The logical conclusion from this statistic is that the area with triple rice cropping in the MRD is not larger than this value. While we recognize that some in-depth studies have reported larger areas for triple rice cropping in the MRD [21], our discussion is based on GSO data to avoid methodological inconsistencies with a GHG assessment at the national scale.

When compiling emission data from the MRD, our working hypothesis was that the pronounced differences among edapho-hydrological zones would also be reflected in different levels of CH_4 emissions, namely highest emissions obtained in the deep flood zone and lowest emissions in the saline zone than the alluvial/acid-sulfate zones. Even though individual measurements supported this assumption, the entirety of the available data did not confirm the hypothesis. The ANOVA analysis (Table S7) shows that daily emission rates are not significantly different between the edapho-hydrological zones. Based on the currently available data, season-specific effects seem to supersede the zone-specific effects on CH_4 emissions (see below the discussions on emission factors listed in Table 4 and Table S7). We attribute this counterintuitive finding to two drivers:

1. Avoidance of adverse seasonal effects through adjusted cropping calendars;
2. Protection of rice area from adverse seasonal effects through improved infrastructure in canals and sluices.

These two drivers appear across all zones in different forms; hence, they are discussed separately for each individual zone as follows:

Table 3. Field measurements of daily CH_4 emission rates and cultivation period in South Vietnam. For site locations and zones, refer to Figures 2 and 3. (A—alluvial zone, F—deep flood zone, S—saline zone); Cult. per.—cultivation period; nd—not determined; ↔—no rice crop grown; error—standard error.

Site	Zone	Early—Year Season			Mid–Year Season			Late–Year Season		
		CH_4 Emission Rates (kg ha^{-1} d^{-1})	Cult. per. (d)	Yield (t ha^{-1})	CH_4 Emission Rates (kg ha^{-1} d^{-1})	Cult. per. (d)	Yield (t ha^{-1})	CH_4 Emission Rates (kg ha^{-1} d^{-1})	Cult. per. (d)	Yield (t ha^{-1})
S1	S	1.752 ± 0.109	109	5.7	1.667 ± 0.044	102	5.4	↔	–	–
S2	A	1.463 ± 0.008	108	5.4	3.079 ± 0.153	101	5.1	↔	–	–
S3	F	1.156 ± 0.063	109	5.2	2.039 ± 0.041	102	5.5	nd	–	–
S4	F	1.464 ± 0.088	110	5.6	1.235 ± 0.037	102	5.7	↔	–	–
S5	F	3.410 ± 0.395	100	nd	1.590 ± 0.504	100	nd	9.140 ± 1.227	100	nd
S6	S	0.918 ± 0.107	98	nd	3.571 ± 0.282	98	nd	nd	–	–
S7 *	S	nd	–	–	nd	–	–	0.310 ± 0.267	100	nd
S7 *	S	nd	–	–	nd	–	–	1.300 ± 0.023	100	nd
S8 *	A	2.130 ± 0.075	100	nd	4.442 ± 0.132	95	nd	nd	–	–
S8 *	A	↔	–	–	4.080 ± 0.596	100	nd	nd	–	–
S9	A	2.650 ± 0.664	95	nd	3.760 ± 0.349	95	nd	nd	–	–
S10	A	1.670 ± 0.765	100	nd	nd	–	–	nd	–	–
S10	F	0.789 ± 0.123	95	6.5	nd	–	–	nd	–	–
S11	F	2.410 ± 0.261	100	4.3	nd	–	–	nd	–	–
S12	S	0.820 ± 0.295	100	6.7	nd	–	–	↔	–	–

* identical season in two different years (see Figure 3).

Table 4. Statistics on calculated emission factors (daily and seasonal) specified per agro-ecological zone (AEZ) and season; average (± standard deviation), maximum and minimum of emission rates listed alongside average length of cultivation period (from seeding to harvest); values for Southern Vietnam are aggregated across all edapho-hydrological zones. (No—number of observations; Cult. per.—cultivation period; Avg—average daily/seasonal emission factor; std—standard deviation; Max, Min—maximum and minimum daily/seasonal emission factor; IPCC index—observed value over IPCC default emission factors for Southeast Asia (IPCC 2019).

AEZ			Daily CH_4 Emission Factor ($kg\ ha^{-1}\ d^{-1}$)							Seasonal CH_4 Emissions ($kg\ ha^{-1}\ season^{-1}$)		
Season	**No**	**Cult. per; (d)**	**Avg ± std**	**p ***	**IPCC Index**	**Max**	**IPCC Index**	**Min**	**IPCC Index**	**Avg ± std**	**Max**	**Min**
N Early	10	123	2.213 ± 1.220	0.019	1.81	4.763	2.63	0.610	0.77	271 ± 150	584	75
N-late	10	104	3.894 ± 1.664		3.19	7.565	4.18	1.816	2.19	404 ± 173	785	188
C-early C-mid	13 16	107	3.097 ± 2.218	0.398 **	2.54	10.720	5.92	0.900	0.92	321 ± 237	1110	93
S-early	10	101	1.718 ± 0.807	0.033	0.59	3.410	1.88	0.789	0.95	174 ± 82	245	80
S-mid	8	99	2.797 ± 1.168		2.29	4.220	2.33	1.235	1.49	277 ± 116	417	122
S-late	3	99	3.583 ± 4.838	nd	2.94	9.140	5.05	0.310	0.37	356 ± 481	908	31

* The statistical significance value (p) at the confidence of 95% determined by one-way ANOVA. ($p \leq 0.05$: average emission factor of the two seasons are statistically significant different).
** *p*-value based on seasonal averages and standard deviations of 2.844 ± 1.380 (C-early) and 3.126 ± 1.687 (C-mid), respectively; due to insignificant differences, the two seasonal data sets were merged into one.

3.2.1. Alluvial Zone

In the alluvial zone (green frames in Figure 6), CH_4 emissions are generally at a moderately high level ranging from 158 to 422 kg ha^{-1} $season^{-1}$. This amplitude is much lower than the emission rates observed from the deep flood and saline zones (see below). Our assessment for the alluvial zone also includes the areas with acid-sulfate soils. High sulfate contents inhibit microbial CH_4 production in flooded soils [22], hence, the addition of sulfate was discussed as a mitigation strategy to curtail CH_4 emissions from rice fields [23]. In the case of the MRD, however, large-scale land development programs have improved soil conditions so that high sulfate concentrations can effectively be prevented. This condition for CH_4 emissions then becomes very similar to that of the alluvial soil zone which justifies the merging of these two zones [18]. In terms of seasonality, this extended alluvial zone is characterized by higher emissions in the mid-year season than the early year season. This difference can be attributed to strong rainfall during the second half of the mid-year season Figure 6).

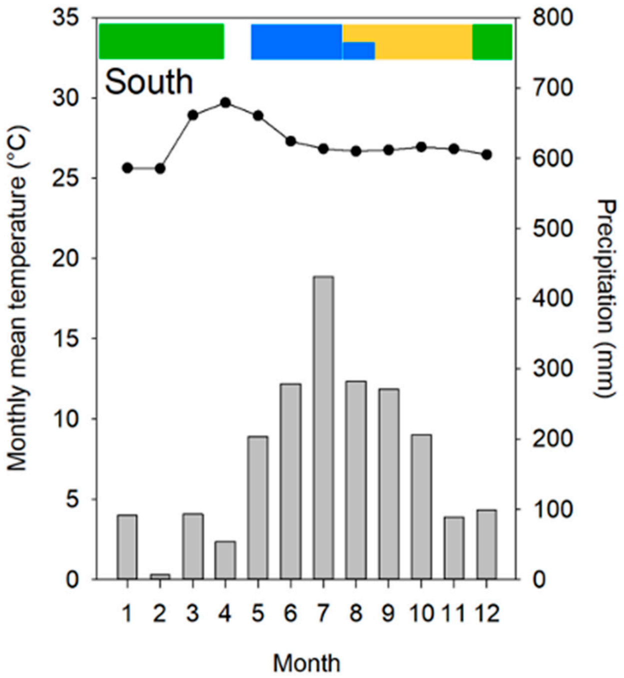

Figure 6. Time windows of cropping seasons in the Mekong River Delta (MRD) (E—green, M—blue, L—gold) shown with rainfall/temperature data (values from 2018 at Soc Trang).

3.2.2. Deep Flood Zone

CH_4 emission rates in the deep flood zone show an enormous variability ranging from 75 to 914 kg ha^{-1} $season^{-1}$. Extraordinary high emissions can be attributed to heavy rainfall in the late-year season because the floodwater has to be pumped up to the water level of the surrounding river or canal. Our database encompasses a singular event for the late-year season in the deep flood zone, so we see high emissions at site C5 (An Giang province) as a result of very high rainfall in the period of August to November. Given the small area of late-year season rice, we consider these site-specific conditions as unusual effects in terms of emission estimates, so that this lack of more evidence on this pattern will not weaken the overall validity of the database on emission rates presented in this study.

In the deep flood zone (blue frames in Figure 6), rice is typically grown in the seasons before and after the peak water levels corresponding to mid-year and early year season, respectively. The hydrological conditions during these two growing seasons will be similar as in other parts of the MRD. Over recent years, however, the deep flood zone of the MRD has experienced enormous investments to improve flood protection. At this point, many locations are fully protected from flashfloods that were previously caused by river or canal breaches. While this protection allows triple rice systems, the third rice crop (corresponding to the late-year season) is vulnerable to stagnant flooding caused by heavy rainfall during periods when surrounding water levels are high and draining of rice fields is constrained by pumping capacities. Drainage relies on pumping as long as water levels in rivers and canals are above the soil surface. Heavy rainfall events will also affect the other zones of the MRD in the rainy season and often cause temporary submergence at a landscape scale. In those areas, however, drainage conditions will improve once the rainfall has stopped.

The difference between these two crops does not follow a clear pattern as different locations have the highest emissions either in the early-year or late-year season. In this zone, triple rice is grown in locations where dikes have been elevated to ensure full flood protection. The season of high water levels coincides with the late-year season that shows extremely high CH_4 emissions in our measurements at site S12 (An Giang). According to GSO data, the provinces of An Giang, Dong Thap and Long An have basically grown no rice in the late-year season which is locally called the autumn-winter crop. As stated previously, this may reflect the recent development of large areas shielded from floods by elevated dikes, but GSO data have to be seen as the basis for any official GHG assessment.

3.2.3. Saline Zone

The range of CH_4 emission rates in the saline zone is lower than in the other two zones (31 to 350 kg ha^{-1} season^{-1}), but only slightly below the range in the alluvial zone. It is important to distinguish between two distinct mechanisms affecting rice production in this zone:

1. Soil-borne salinity that can be controlled as long as freshwater is available for irrigation, but leads to rice yield losses in years with low river discharge and rainfall;
2. Salt intrusion from the sea through the canal system causing drought conditions for rice because this canal water is unsuited for irrigation.

Both mechanisms coincide in the time window from February to April [20], so there will be some degree of fluidity in their distinction in certain locations and years. These mechanisms also show congruent trends in terms of CH_4 emissions. Microbial methane production is highly sensitive to salinity (Mechanism no. 1), so that saline conditions in the soil will inherently reduce CH_4 emissions to very low values. Salt intrusion into canals (Mechanism no. 2) will not affect microbial methane production directly, but drought conditions for the crop could also cause reduction in CH_4 emissions.

The most common strategy for coping with adverse conditions in the saline zone is adjusting the cropping calendar. The peak salt intrusion occurs in the early year season, so this crop is limited to locations with improved control of salt intrusion into the canals [24]. In those areas with persistent salinity intrusion, the dominant land use is shrimp farming instead of rice. This can be seen in the map of Figure 3 that depicts non-rice areas as white stretches along the coastlines as well as in the Ca Mau peninsula. Thus, the rice seasons in this zone are characterized by similar conditions for microbial methane production as in other zones—even though the name of the zone suggests otherwise.

The direct and indirect impacts of salinity intrusion show a pronounced inter-annual variability which is mainly driven by the irregular discharge of the Mekong River caused by rainfall variations and upstream development of reservoir. In the 2015–2016 El Niño, nearly 250,000 ha of rice were damaged [25] and it seems safe to assume low emission rates in the saline zone during these events. The saline zone has also experienced intense infrastructure development to optimize growing conditions for rice [26], but the nature of salinity intrusion into the large river mouths of the Mekong branches makes it almost impossible to achieve a full protection from salinity damage. While this occasional damage of the crop will obviously result in extremely low CH_4 emissions, the quantification of this year-to-year variation is beyond the scope of this study.

3.3. Determining Tier 2 Emission Factors for Vietnam

3.3.1. IPCC Guidelines for Quantifying CH_4 Emissions

The reporting commitments required by the UNFCCC have led to the development of the IPCC guidelines on national GHG inventories that have been released in several documents. The '1996 Revised IPCC Guidelines for National Greenhouse Gas Inventories' [27] represented the first comprehensive guidance for countries and the 'Good Practice Guidance' [28] has clarified definitions and practical procedures in compiling national GHG inventories. To date, the compulsory statistics for national GHG inventories are contained in the '2006 IPCC Guidelines for National Greenhouse Gas Inventories' [29], a consolidation and updated version of the previous documents. In these guidelines, agriculture and land use merged into a single sector labeled 'Agriculture, Forestry and Other Land Uses'. Future GHG assessments must be based on the 2019 Refinement [30] that largely corresponds to the 2006 guidelines for rice production with only a few modifications.

The following equation 1 is the basic equation to estimate CH_4 emissions from rice cultivation for Tier 1 as well as Tier 2 (From equation 5.1 of the IPCC 2019 Refinement/Chapter 5):

$$CH_{4\ Rice} = \sum(EF_{i,j,k} \cdot t_{i,j,k} \cdot A_{i,j,k} \cdot 10^{-6}) \quad (1)$$

where:

$CH_{4\ Rice}$—annual methane emissions from rice cultivation, Gg yr^{-1}
EF_{ijk}—a daily methane emission factor for *i*, *j* and *k* conditions, kg ha^{-1} d^{-1}
t_{ijk}—cultivation period of rice for *i*, *j* and *k* conditions, day
A_{ijk}—annual harvested area of rice for *i*, *j* and *k* conditions, ha yr^{-1}
i, *j* and *k*—represent different ecosystems, water regimes, type and amount of organic amendments and other conditions under which CH_4 emissions from rice may vary

As much as possible, the IPCC guidelines encourage disaggregation of EFs and respective activity data for distinct rice regions and cropping seasons within a country.

The annual amount of CH_4 emitted from a given area of rice field is also a function of the daily emission factor (EF_{ijk}) that is defined as follows (from equation 5.2A of the IPCC 2019 Refinement/Chapter 5):

$$EF_i—EF_c \cdot SF_w \cdot SF_p \cdot SF_o \cdot SF_s \cdot SF_v \quad (2)$$

where:

EF_i—adjusted daily emission factor for a particular harvested area
EF_c—baseline emission factor (continuously flooded fields) without organic amendments
$SF_{w,p,o,s,v}$—scaling factors to account for the differences in water regime during the cultivation period (w), water regime in the pre-season before the cultivation period (p), type and amount of organic amendment applied (o), different soil types (s) and rice variety (v), if available.

This study focuses on baseline management and thus on EF_c. The other scaling factors are given a value of 1 in this study because those were considered an integral part of the baseline management in their neutral form (continuous flooding during cultivation, only short-term pre-season flooding, no organic amendments, etc.).

The IPCC 2019 Refinement specifies a default Tier 1 EF for sub-continental regions, i.e., the default EF of CH_4 for Southeast Asia is given as 1.22 kg ha^{-1} d^{-1} with a range of 0.83 to 1.81 kg ha^{-1} d^{-1}. This is similar to the global default value of 1.19 (0.80–1.76) kg CH_4 ha^{-1} d^{-1}. The guidelines also contain default values for the cultivation period at a sub-continental scale that is shorter in Southeast Asia (102 days with a range of 78–150 days) than the global default (113 days with a range of 74–152 days). Cultivation period and flooding frequency are essential parameters for calculating CH_4 emissions from rice fields; however, no statistical data or expert judgment is available for this parameter for

Vietnam. The default EF of the IPCC requires non-flooded conditions for less than 180 days prior to rice cultivation and continuously flooded conditions during rice cultivation without organic amendments.

3.3.2. Emission Factors for Different Regions and Seasons

Table 4 shows the daily EFs alongside the seasonal EFs to allow different types of uses. The daily EFs correspond to the required input data for the IPCC algorithms, but will inherently require information on cultivation period. Thus, the average cultivation period of the field experiments are also reflected in Table 4. While data on the lengths of the cultivation periods can be obtained from farmer interviews—ideally with more information on crop management—such surveys may not be feasible at the scale of a country. In future studies without data on cultivation period, we see the use of seasonal EFs as a viable alternative to assess regional emission estimates. These data could be used in combination with region-specific scaling factors of water management (SF_w) in a similar accuracy as the daily EF supplemented by cultivation period.

Due to the nature of these data aggregation, we have listed standard deviations for emission factors in Table 4 instead of standard errors that are derived from measurement replicates in Tables 1–3. These std-values are typically about half of the average of field measurements, which seems high, but can reasonably be explained by heterogeneity within the scale of one given region, namely intra-regional differentiation within North, Central and South Vietnam. In one case (S-Late), the standard deviation is even larger than the average value which can be attributed to the small number of measurements in combination with high variability of biophysical factors in the deep flood zone of the MRD during this critical period. Since only a small area is cultivated during the late season in the South, the recorded outlier in terms of extremely high emissions has only a marginal impact on the overall extrapolation of GHG emissions based on the newly generated EFs.

Table 4 shows the results of the comparison of daily emission rates between the early and late-year seasons for the North region and early and mid-year seasons for the Central and South regions using ANOVA. The daily emission rates during the late-year season in South Vietnam was not included in the analysis due to its limited number of measurements. Results show that the average daily emission rates of the two seasons are significantly different for the North and South regions (p—0.019 and 0.033, respectively), while they are not significantly different for the Central region (p—0.398). This result implies that two different EFs should be developed to estimate seasonal GHG emissions in the North and South regions, and that a single EF can be used for both early and late seasons in the Central region.

3.3.3. Findings on N_2O Emissions and Comparison to Published Data

N_2O emissions were generally below the detection limit (data not shown) of our measurement setup that corresponds to 0.875 kg N_2O ha^{-1} $season^{-1}$ (based on an average cultivation period of 106 d). The detection limit is determined by the accuracy of the gas chromatograph (± 6.6 ppb N_2O) as well as the height of the chambers (max. 1.13 m). The chambers were relatively high because the focus of the experiment was on CH_4 emissions which required the enclosure of intact plants in the chambers. In terms of N_2O measurements, the main objective was to detect eventual emission spikes and, to a lesser extent, to quantify very low emission rates with high accuracy. Based on the average fertilizer rate (110 kg N ha^{-1}) used in the field experiments, this detection limit corresponds to 1.1% of the applied N emitted in the form of N-N_2O.

Only in two instances were the N_2O emissions slightly above this detection limit: 1.5 kg N_2O ha^{-1} d^{-1} in C12/M'12 and 1.07 in C13/M'12. Our results clearly show that N_2O emissions in Vietnamese rice fields are with few exceptions below 1% of the applied N. The IPCC emission factor given for continuously flooded rice is 0.3% of the N-fertilizer application emitted in the form of N-N_2O. Our field experiments found larger emissions of N_2O although we cannot contribute to a more accurate quantification of this value.

As of now, the database of published emission measurements of Vietnamese rice production has been relatively small. Several of the published studies were integrated into this database [14,16–18,31] while others were pursued independently. Oo et al. [32] have analyzed samples from a terraced rice production system in Son La province in the northwest of Vietnam. Average CH_4 emissions were 61 kg and 87 kg ha^{-1} for the early and late-year seasons, respectively. These results follow the general trend described in this article that emissions in the late-year season in the North are higher than in the early year season but are much lower than the results from the RRD. This comparison indicates that there are significant differences in CH_4 emissions between different types of irrigated rice production, in this case irrigated lowland rice and irrigated terraced rice in upland areas. There is further need to develop appropriate Scaling Factors, e.g., for different soil types, production systems, etc., for further disaggregation in order to estimate emissions more accurately.

4. Conclusions

Even though our database does not cover all AEZs, we feel that the distinction into three regions can be seen as a reasonable resolution for GHG estimates at a national scale.

The results of this study highlight the following key messages:

- The database reflects an enormous variability in EFs for the country as a whole as well as within individual AEZs;
- Inter-comparisons among AEZs revealed distinct seasonal patterns, but – by and large – all EFs of CH_4 are in a similar order of magnitude (1.83–3.6 kg ha^{-1} d^{-1}) with only smaller differences among individual AEZs;
- The different edapho-hydrological zones within the MRD showed a lower impact on determining EFs than cropping season. Even though extreme events in the deep flood and salinity zones cause individual outliers in emission rates, the use of season-based EFs is preferable than zone-based EFs;
- In terms of N_2O emissions, our database confirms a generally low emission level under IPCC baseline management, but does not allow any conclusion on possible water management impacts;
- Collectively, these data clearly show that EFs for CH_4 emissions in Vietnamese rice production are well above the default IPCC value given for Southeast Asian rice production. The calculated IPCC indices show that all EFs are well above IPCC defaults with only one exception, namely late-year season in the South region which was characterized by an enormous variability in the recorded emission rates;
- Integrated over all regions and seasons, the newly generated EFs for CH_4 emission from Vietnamese rice production correspond to at least 200% of the IPCC Tier 1 defaults. The new data also exceeds the EFs previously used by the Ministry of Natural Resources and Environment (MONRE) and account for approximately 150% of those values. By the nature of global (or sub-continental) defaults, the applicability of these IPCC values at the local or regional scale can involve a bias leading to over- or under-estimations. Although a comparative assessment with other countries was beyond the scope of this study, we attribute this disparity to stable water supply by the well-developed irrigation systems in Vietnam than other rice-growing countries where even irrigated systems can be exposed to drought risks [33].

To our knowledge, no other country has yet compiled emission data in such a systematic fashion for rice or any other crop. Given the close involvement of the respective office in gathering emission rates, we see this study as a step to bridge the gap from scientific information on GHG emissions to reach policy documents under the UNFCCC process. Improved water management in rice production is clearly one of the most promising mitigation strategies within the agricultural sector which has already been mentioned in official policy documents such as the Action Plan on Nationally Determined Contributions (NDCs) for Agriculture sector phase 2020–2030 (CV 7208/BNN-KHCN) as part of the Intended Nationally Determined Contributions (INDCs) submitted by Vietnam to the UNFCCC.

The presented database is intended to be used as basic input for the forthcoming national GHG inventories to be conducted by the MONRE in the context of the forthcoming National Communications. MONRE has provided funds to IAE for a measurement campaign which has resulted in emission data from 15 out of our 32 field sites. In fact, the country-wide distribution of field sites in this publication can largely be attributed to MONRE support, so that the use of these EFs for the national commitments under the UNFCCC process appears likely.

As of now, Vietnam's GHG inventories have been based on IPCC Tier 2 guidelines using EFs derived from a capacity development program in 2014 [34], namely annual CH_4 emission of 375 kg ha^{-1} yr^{-1} in the North region, 336 in the Central region and 217 in the South region of Vietnam. These simplified EFs that are given for the entire year without seasonal differentiation have been applied in the most recent NC [5] as well as in the Biennial Updated Report [35]. The results from our study broaden the database on EFs in width and depth by recording emission at different sites (minimum of 10) within a given region and by distinguishing among seasons, respectively. This spatio-temporal resolution is required for elevating Vietnam's GHG inventories to a more substantiated Tier 2 approach.

Even though the database presented in this study does not include mitigation management, it seems obvious that the quantification of emission reduction will inherently rely on solid information of emissions under baseline management. Moreover, baseline emission data can assist in the planning process by narrowing down emission 'hotspots. For instance, in North Vietnam the database points toward prioritizing the late-year season as opposed to a uniform mitigation campaign covering both seasons.

IAE will now develop recommendations on the future use of these EFs tailored for national GHG inventories as well as mitigation assessments. As an institute under the Ministry of Agriculture and Rural Development, IAE is involved in the development of NDCs. While the initial version of the NDCs has identified rice production as a land use system to be considered for mitigation programs, future versions of the NDCs will have to define the specifics of such programs including Measurement, Reporting, Verification procedures.

Supplementary Materials: The following are available online at http://www.mdpi.com/2225-1154/8/6/74/s1, Table S1. Site characterization of the Northern sites. For site locations refer to Figure 3; nd = not determined; Not yet publ. = not yet published. Table S2. Site characterization of the Central sites. For site locations refer to Figure 3; Not yet publ. = not yet published. Table S3. Site characterization of the Southern sites. For site locations refer to Figure 3; Not yet publ. = not yet published. Table S4. Agronomic data at the Northern sites. For site locations refer to Figure 3; Transpl = transplanting; E = early year season; L = late year season; nd = not determined; Incorpor. = incorporated. Table S5. Agronomic data of the Central sites. For site locations refer to Figure 3; Transpl. = transplanting; Dir. Seed. = direct seeding; E = early year season; M = mid-year season; nd = not determined; Incorpor. = incorporated. Table S6. Agronomic data of the Southern sites. For site locations refer to Figure 3; Transpl. = transplanting; Dir. Seed. = direct seeding; E = early year season; M = mid-year season; L = late year season; nd = not determined; Incorpor. = incorporated. Table S7. Statistical comparison of CH_4 emission factor of all sites in three rice seasons among edapho-hydrological zones of the South region. (A = alluvial zone, F = deep flood zone, S = saline zone).

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