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RESEARCH ARTICLE

Activity data on crop management define uncertainty of CH_4 and N_2O emission estimates from rice: A case study of Vietnam

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Abstract

Background: Globally, rice systems are a major source of atmospheric CH_4 and for major rice-producing countries, such as Vietnam, CH_4 as well as N_2O emissions from agricultural land used for rice production may represent about one-fourth of total national anthropogenic greenhouse gas (GHG) emissions. However, national-scale estimates of GHG emissions from rice systems are uncertain with regard to its magnitude, spatial distribution, and seasonality.

Aims: Here, we used the biogeochemical model LandscapeDNDC to calculate emissions of CH_4 and N_2O from rice systems in Vietnam (Tier 3 IPCC approach). Our objectives were to identify hotspot regions of emissions and to assess the contribution of N_2O to the total non-CO_2 (CH_4+N_2O) GHG balance of rice systems as well as the seasonal and interannual variability of fluxes in dependence of uncertain input data on field management .

Methods: The biogeochemical model LandscapeDNDC model was linked to publicly available information on climate, soils, and land management (fertilization, irrigation, crop rotation) for calculating a national inventory in daily time steps of CH_4 and N_2O emissions from rice systems at a spatial resolution of $0.083° \times 0.083°$. Uncertainty in management practices related to fertilization, use of harvest residues or irrigation water, and its effects on simulated CH_4 and N_2O fluxes was accounted for by Latin Hypercube Sampling of probability distribution functions.

Results: Our study shows that CH_4 and N_2O fluxes from rice systems in Vietnam are highly seasonal, with national CH_4 and N_2O emissions totaling to about 2600 Gg CH_4 y^{-1} and 42 Gg N_2O y^{-1}, respectively. Highest emissions were simulated for double and triple rice cropping systems in the Mekong Delta region. Yield-scaled emissions varied largely in a range of 300–3000 kg CO_2-eq Mg^{-1} y^{-1}, with CH_4 emissions during the rice season(s) dominating (>82%) the total annual non-CO_2 GHG balance of rice systems. In our study, uncertainty in field management information (nitrogen fertilization, ratio synthetic to organic fertilization, residue management, availability of irrigation water) were major drivers of uncertainty of the national CH_4 and N_2O emission inventory.

Conclusions: Our study shows that Tier 3 approaches, that is, process-oriented model approaches combined with GIS databases, for estimating national-scale GHG emissions from rice systems are ready to be applied at national scale. Generally, this approach is powerful as it allows to identify regions with elevated emissions, thereby accounting not only for CH_4, but as well for N_2O emissions. However, our study also shows that specifically better information on land management is required to narrowing uncertainties.

KEYWORDS
biogeochemical modeling, field management, rice systems, soil CH_4 and N_2O emissions, uncertainty assessment

1 | INTRODUCTION

Non-CO_2 emissions from the agricultural sector are rising since 1990 by a rate of 0.9% per year, with CH_4 emission from paddy rice cultivation contributing approximately 9–11% or 493–723 Mt CO_2eq y^{-1} to total agricultural emissions (Smith et al., 2014). Though there is consensus that agriculture is a main driver of climate change, greenhouse gas (GHG) emissions from this sector have not been addressed. The Clean Development Mechanism, which was established under the Kyoto Protocol, failed to generate any tangible emission reductions as besides difficulties about reporting and regulation and negative impacts on food production were apprehended. This perception has partly changed with the Paris Agreement by the United Nations Framework Convention on Climate Change (UNFCCC, 2022) at its 21st Conference of Parties (COP21) as countries were requested to submit intended nationally determined contributions (INDC) followed by regular submission of updated nationally determined contributions (NDC). Depending on national circumstances, these NDCs can also include mitigation measures in the agricultural sector. Already in the first round, 80% of INDCs submitted included commitments to action on agricultural mitigation (CCAFS, 2016). However, public policies to mitigate GHG emissions from agriculture is crucially dependent on reliable and traceable GHG emission inventories. While the IPCC guidelines allow for different Tiers in those calculations (IPCC, 2021), it is commonly accepted that the use of advanced software, that is, simulation models alongside with GIS-based inventories (Tier 3), ensures high levels of transparency, accuracy, completeness, comparability, and temporal consistency. Model-GIS systems will allow countries to better understand the effect of different productivity measures on emissions. Therefore, such systems may be used for an informed planning of nationally appropriate mitigation actions and for identifying low emission development strategies in the agricultural sector (Ogle et al., 2013). Moreover, advanced inventories are as well a prerequisite to qualify a country for participating in international climate finance.

In addition to government efforts as part of their National Communications (NCs) to the UNFCCC, different institutions compile national inventories of GHGs at global level, for example, the Statistics Division of the FAO (Tubiello et al., 2013, 2021) or the Emissions Database for Global Atmospheric Research (EDGAR) of the European Joint Research Center (Crippa et al., 2021). Estimates of GHG emissions from rice production are commonly based on Tier 1 or Tier 2 approaches in which emissions are calculated by multiplying rice growing areas with universal (Tier 1) or country-specific (Tier 2) emission factors. In a generalized way, this approach allows to consider differences in rice growing systems (e.g., rainfed versus irrigated) and management, for example, amount of straw and fertilizer input. On basis of these calculations, it became evident that the major rice-producing countries do not only vary in the magnitude of rice-based emissions, but also in the relative importance of this source within the national GHG inventory. While at about 2010, paddy rice contributed 2.2% to the total anthropogenic GHG emissions in China, the globally largest rice producer; the contributions are 14–16 and 44% for Vietnam and the Philippines, respectively (Richards et al., 2015; UNFCCC, 2022: see within the National Communications by Vietnam [NC3, 2019], Thailand [2011], China [2012], and the Philippines [2014]).

In Vietnam, rice is the single most important staple food and a major source of national income as the country is the 3rd largest rice exporter (FAOSTAT, 2022a). Rice is produced on approximately 70–80% of the total agricultural area and has been considerably intensified in this country with the change to a market-oriented economy in the late 1980s and beyond (L. H. Vu & Nguyen, 2021). About 54% of the country's rice production takes place in the Mekong River delta (MRD)—also known as the 'Rice Bowl' of Vietnam—and another 14% in the Red River delta (RRD). These regions, which produce about 5% of global rice, are estimated to contribute approximately 10% of the total global CH_4 emissions from rice production (Carlson et al., 2017). However, it is debatable if Tier 1 and Tier 2 approaches are sufficiently accurate for reporting CH_4 emissions from rice systems and developing mitigation strategies. These lower Tiers do not account for the fact that emissions (1) vary considerably across the growing season, a piece of information that is essential for understanding seasonal changes in atmospheric composition, but also affects estimates of the magnitude of emissions (2) depend on reliable data on water, residue and fertilizer management that can vary substantially in time and space (i.e., factors currently not sufficiently mirrored by Tier 1 or 2 approaches, resulting in major uncertainties of current inventories), (3) depend on local soil properties such as soil organic matter concentrations, texture or pH, and (4) are not properly reflected in the structure of the IPCC guidelines that distinguish one separate chapter for calculating CH_4 emissions from rice, whereas N_2O emissions are considered in the chapter on soil-borne emissions without specifying rice production. These shortcomings hamper the identification of GHG emission hot spots and the potential effectiveness of the most promising mitigation measures as those will be region specific as a function of management and environmental conditions.

More recently, toward Tier 3 approach, biogeochemical models have been increasingly used to help fill these data gaps, as once calibrated, they allow for multiannual simulations, and, for example, to test the effects of changing land management on emissions (Fitton et al., 2017; Kraus et al., 2022). In this study, we applied the biogeochemical LandscapeDNDC model (Kraus et al., 2015) to rice systems of Vietnam to (1) calculating a national soil N_2O and CH_4 inventory, (2) to identify regional hotspots of emissions, and (3) to test a new approach to address and limit uncertainties of the inventory due to uncertainties in water, residue, and fertilizer management.

2 | MATERIALS AND METHODS

2.1 | Ecosystem model LandscapeDNDC

The ecosystem simulation framework LandscapeDNDC (Haas et al., 2013; Kraus et al., 2015) is used for simulating CH_4 and N_2O emissions from rice fields in Vietnam. LandscapeDNDC allows different combinations of sub-models describing water, carbon and nitrogen cycling and exchange processes with the atmosphere and hydrosphere of forest (Dirnböck et al., 2020; Grote et al., 2020), grassland (Liebermann et al., 2020; Petersen et al., 2021), and cropland ecosystems (Molina-Herrera et al., 2016; Smerald et al., 2022). The model selection that is applied in this study corresponds to Kraus et al. (2015, 2016, 2022) including the biogeochemical MeTr^x model that predicts CH_4 and N_2O emissions from lowland and upland cropping systems. Spatially, the model represents a one-dimensional soil column (assuming horizontal homogeneity), which is discretized by 0.01 m (top-soil)–0.1 m (bottom-soil) soil layer dimensions. Each grid cell in the horizontal domain represents a standalone simulation unit without lateral connection to neighboring cells. The horizontal resolution of this study is adapted to the model inputs databases and set to 0.083° × 0.083°. The applied temporal model resolution is set to 2 h.

2.2 | Simulation domain

Vietnam is located between the latitudes 8° and 24°N and the longitudes 102° and 110°E forming the eastern border of the Indochina Peninsula in Southeast Asia (Figure 1A). The northern part of Vietnam has a subtropical to temperate climate being subject to the Northeast Monsoon with hot and rainy weather from April/May to September/October. During winter months, weather is characterized by lower temperature and little precipitation. In contrast, the South of Vietnam has tropical climate with hot temperatures throughout the year. The rainy season is similar as in the North from May to October (Rubel & Kottek, 2010).

2.3 | Soil, climate, and atmospheric composition

Soil profile information of soil organic carbon and nitrogen, bulk density, texture (clay, sand, silt content), and pH were derived from the ISRIC-WISE Soil Properties Global Grid database (Batjes, 2012). The spatial resolution of this database (0.083° × 0.083°) corresponds to the defined resolution of the simulation domain. Only the dominant soil unit (largest spatial coverage within a given pixel) of the ISRIC-WISE database for each pixel was considered. Daily weather information (air temperature, precipitation, and solar radiation) was taken from Muñoz-Sabater et al. (2021) in a spatial resolution of 0.1° × 0.1° and reprojected onto the defined inventory base resolution of 0.083° × 0.083°. For model simulations, the atmospheric concentration of CO_2 was assumed to increase from about 390 to 400 ppm between 2010 and 2020 (WMO, 2021). Average total nitrogen deposition for the simulation domain was derived from Lamarque et al. (2013) and varied between 4 and 20 kg N ha^{-1} y^{-1}.

2.4 | Land use and management

Rice fields are a dominant land use in Vietnam, covering about 14% or 42,500 km2 of the total land area (Phan et al., 2021) (Figures 1B and C). Cultivation practice of rice is strongly heterogeneous regarding, for example, cropping rotation, irrigation scheme, fertilizer use, and fate of harvest residues. Due to the general lack of data, various spatial aggregation steps and scenario simulations based on Latin Hypercube Sampling (LHS) of key field management operations (see Section 2.5) have been carried out and details on methodological aspects are presented in the following paragraphs. In total, 1000 individual inventory runs were carried out to calculate GHG emissions (here CH_4 and N_2O) and uncertainties from rice systems in Vietnam, which were finally averaged across the time period 2010–2019.

2.4.1 | Cropping calendar and crop rotations

Cropping calendar: Rice is cropped in single-, double-, or triple-rotation systems depending on factors such as water availability/ infrastructure, floods, droughts, salinization, and rice diseases (Guan et al., 2016) (Figure 1D). Technical progress as well as climatic and economic changes led to regular temporal transformations of cropping rotations. For example, Kontgis et al. (2015) report that the area under triple-cropped rice in the MRD expanded by almost 30 % within the period 2000–2010, replacing predominantly double-cropped

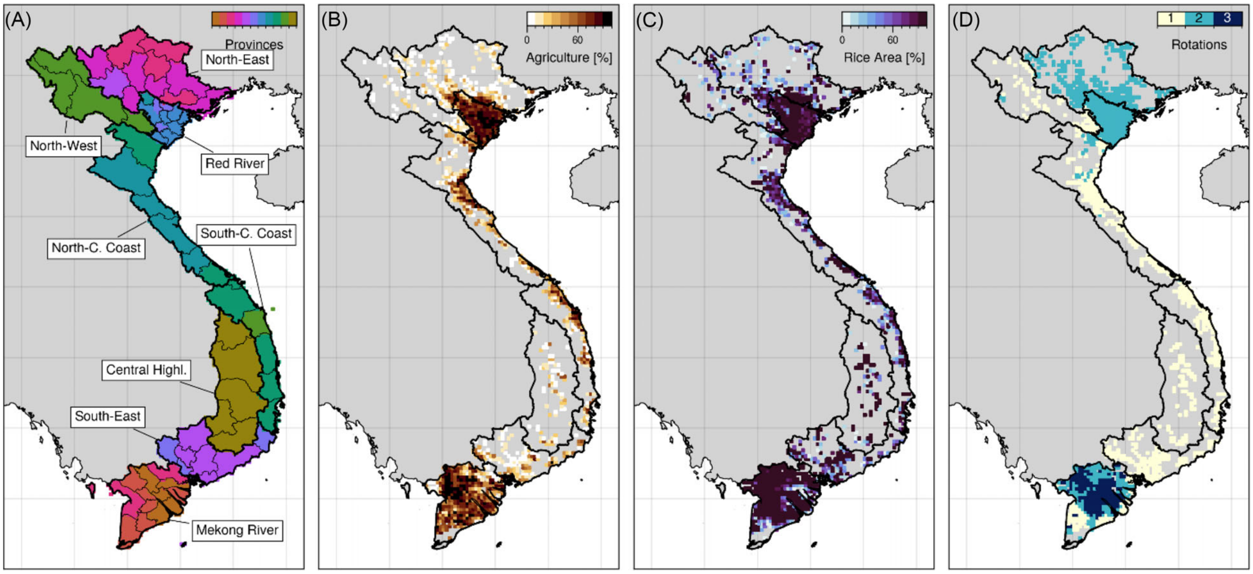


FIGURE 1 Administrative and management data layers used to build a regionalized national management database. Note that provinces/regions (A) were used to spatially register nonspatial data. (B) Relative share of agricultural area with at least one cropping season with rice per grid cell; (C) fraction of rice paddies per agricultural land area; (D) number of rice rotations per year (D).

rotations. A spatially explicit cropping calendar was created based on a satellite image dataset providing information about the number of crops in the year 2010 (Guan et al., 2016). Planting and harvest dates on a provincial level were derived from the global RiceAtlas cropping calendar (Laborte et al., 2017).

Upland cropping: In some parts of Vietnam, rice is cultivated in rotation with upland crops (e.g., maize, vegetable). Emissions of CH_4 can be strongly affected by soil aeration and root and harvest residues from previous cropping seasons (Janz et al., 2019; Kraus et al., 2015). Therefore, two basic management scenarios were developed: (1) rice cultivation only (rice only), that is, without upland intercropping, including systems where rice was grown in one season only or twice or three times per year (double and triple rice growing seasons), and (2) single or double cropping of rice in combination with an upland crop in at least one of the 2 or 3 growing seasons (rice mixed). For simplicity, maize was used as a general representative of upland crop, motivated that in Vietnam, maize is the most important annual upland crop mainly used as feed for poultry and livestock (EACC, 2010). The total of 1000 simulated scenario inventories refer to two LHS (see Section 2.5), one for rice only and one for rice mixed, each consisting of 500 realizations each. The weighting between rice only and rice mixed for the final inventory was determined under the constraining of the reported harvested area for paddy rice by FAOSTAT (2022c), which resulted in a calculated share of 79% rice only and 21% rice mixed. The weighting was conducted on each pair of LHS samples and over all grid cells consistently.

Rice cultivar: Nowadays, the great majority of rice cultivars in Vietnam are high-yielding modern varieties (Thi Ut & Kajisa, 2006). Due to lack of spatial information and parameterization of local crop varieties, a high-yielding rice variety (IR72) parameterized in previous studies (Kraus et al., 2015) was used as representative. Phenology-related parameters of growing degree days are spatially explicit adjusted per grid cell to ensure crop maturity within the given growing season length as reported by Laborte et al. (2017).

2.4.2 | Fertilizer application rates

Both, synthetic (mostly urea) and organic fertilizer (farmyard manure, about 20% or less of total N applied; Trinh Mai, Institute for Agricultural Environment [IAE], pers. comm.) are used in rice systems in Vietnam (Phuong et al., 2006; UNEP, 2005; T. K. V. Vu et al., 2007). The amount of nitrogen fertilizer that is applied by farmers varies between intensively managed modern systems such as in the RRD and less-intensive systems mostly found in rural hilly regions. In the absence of a comprehensive database that provides information on the spatial use of fertilizers, studies often rely on on-site surveys (Phuong et al., 2006). Based on expert knowledge, specifically staff of the IAE, Vietnam, region-specific seasonal fertilizer rates have been defined (Table 1). For the LHS sampling (see Section 2.5), fertilizer rates have been varied by $\pm 50\%$ around the region-specific mean value given in Table 1. In a further step, the resulting amount of fertilizer from the LHS sample was randomly assigned to a fraction (see Figure 2) applied as synthetic fertilizer (urea) and a fraction applied as organic fertilizer (farmyard manure) (Figure 2). For farmyard manure, a C/N ratio of approximately 6 was assumed following the data presented by Phuong et al. (2006).

2.4.3 | Residue management

The amount of harvest residues from preceding cropping seasons has a strong positive effect on CH_4 emissions (Wassmann et al., 2000). In Vietnam, the fate of rice straw is highly variable in space and time as it

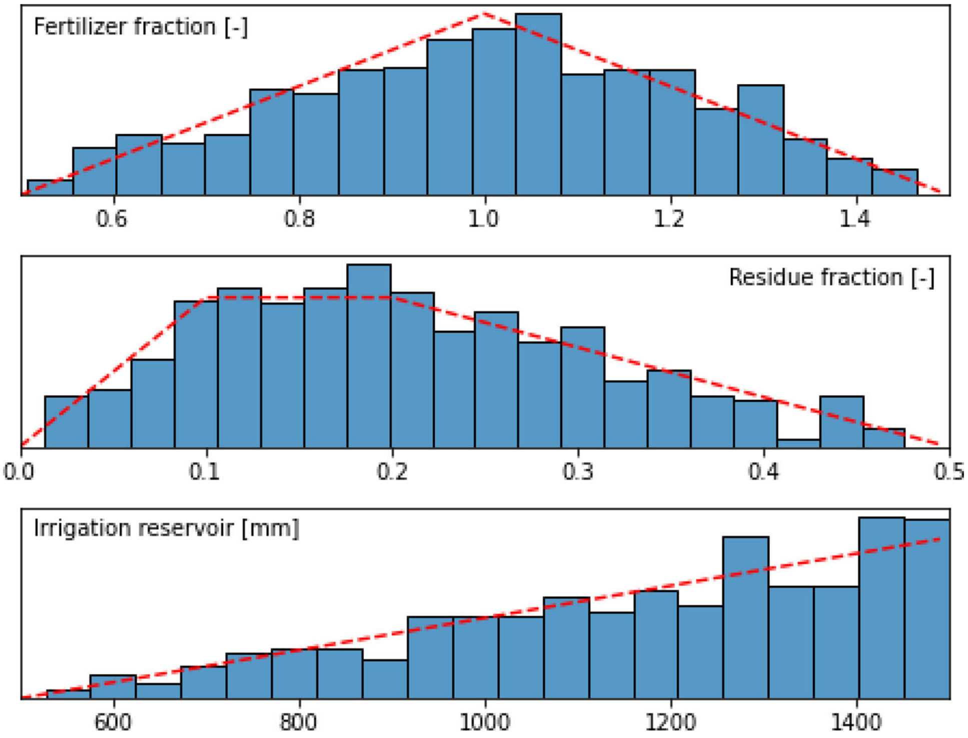


FIGURE 2 Latin Hypercube Sampling distribution (sample size: 500) for different field management actions. Fertilization scalar: ±50% of total regional N application rate (Table 1). Harvest residue values: 0.5 = 50% of total simulated leaf and stem biomass incorporated (0–20 cm) in the field at the beginning of land preparation. Irrigation reservoir: mm of irrigation water available during a cropping season.

TABLE 1 Average amount of N-fertilizer (synthetic + organic) application per growing season in different regions of Vietnam (estimates based on expert knowledge)

Region	Total N-fertilizer application(kg N ha^{-1} $season^{-1}$)
North-West (NW); North-East (NE)	70
Red River (RR) delta	120
North Central Coast (NCC); South Central Coast (SCC)	70
Central Highlands (CH)	70
South-East (SE)	70
Mekong River (MR) delta	120

Note: For definition of regions see Figure 1.

may be burned on the field or used for, for example, energy production, mushroom cultivation, animal feed, or soil incorporation (Truc et al., 2012). While in the past, farmers used rice straw for cattle feeding and fuel for cooking, nowadays, burning rice straw is by far the most common practice (Duong & Yoshiro, 2015; Truc et al., 2013). Vietnamese farmers tend to burn rice straw after harvesting, 70–80% in the north and nearly 90% in the south (Duong & Yoshiro, 2015), so only around 10% of residues are left on the field (Truc et al., 2012). In the past years, intensification of rice production, that is, the use of harvesters in combination with short fallow periods between consecutive cropping seasons led to decreasing collection of rice straw and increasing burning or burying of rice straw (Van Nguyen et al., 2016). According to surveys in 2011 in Quang Binh, Central Vietnam, approximately 25% of rice straw is utilized, while 25 and 50% are burnt or applied to the field, respectively (SNV, 2012). In Can Tho, MRD, the 2011 survey results show a higher percentage of 60% rice straw burning and slightly less soil incorporation (40%) (SNV, 2012). However, in recent years, the total amount of residues burned was likely reduced to 25–35% burning (MONRE, 2018). Based on this information, for the LHS sampling (see Section 2.5), the amount of harvest residues left on the field has been varied between 0 and 50%, with the range of 10–20% being most likely.

2.4.4 | Field irrigation

Agricultural irrigation, mainly rice, accounts for more than 80% of Vietnam's total water use (ADB, 2009). According to statistics for the year 2010 (FAO AQUASTAT, 2022; MONRE, 2014), more than 90% of cultivated rice area is under irrigation. However, irrigated rice cultivation in Vietnam is regularly impaired by drought, specifically during extreme weather events such as El Nino episodes. To account for potential situations of water scarcity of irrigated rice fields, our simulations assumed varying amounts of seasonally available irrigation water. Therefore, the simulation assumed virtual irrigation reservoirs to be tapped as soon as natural precipitation did not sustain flooded field conditions. As data were lacking and for assessing uncertainties, the capacity of those virtual irrigation reservoirs was varied in a range of 500–1500 mm

TABLE 2 Total rice growing area, percentage of rice growing area considering single-, double-, or triple-cropping systems, and mean total simulated and reported rice harvest for the years 2010–2019

						Total rice grain harvest (Gg y^{-1})	
Region	Rice growing area (km^2)	Single cropping	Double cropping[b]	Triple cropping[a]	Total harvested rice growing area per year[b]	LandscapeDNDC 2010–2019	FAOSTAT 2010–2019
Mekong River delta	18,204	2732	6217	9255	42,358	28,804	
Red River delta	9605	122	9483	–	19,062	12,435	
All other regions	5226	9113	3116	–	13,431	5858	
	33,035	11,967	18,816	9255	74,852	49,097	56,248
						(42,000–56,500)[c]	(53,000–58,000)[c]

[a] Double- and triple-growing areas include areas where at least one season is used for rice, while the other seasons may be used for rice or other upland crops (in our simulations, maize was simulated as upland crop).

[b] *Note* that the harvested rice area includes double- or triple-cropping systems.

[c] For LandscapeDNDC, median values (5–95 percentile values) are provided. FAOSTAT (2022c): mean value (SD).

per season with a higher probability toward sufficient irrigation water availability (see Section 2.5).

2.5 | Uncertainty analysis and importance of covariates

Uncertainty in management practices related to fertilization, use of harvest residues and irrigation water was accounted for by LHS of probability distribution functions with a sample size of 500 (see Figure 2) for rice-only and rice-mixed simulations each.

Proportional marginal variance decomposition using the statistical R package “*relaimpo*” of Grömping (2007) was used to analyze the relative importance of model initialization parameters such as soil properties (soil organic C and N, pH, etc.) or factors related to management, that is, application rates of fertilizers, residues, or irrigation water at the scale of Vietnam. The global warming potential of soil CH_4 and N_2O fluxes was calculated using conversion factors of 34 and 298 for CH_4 and N_2O, respectively, for a 100-year time horizon (Myhre et al., 2013).

3 | RESULTS

3.1 | Rice growing area and rice yields

Vietnam has two main rice-growing regions, namely the MRD in the South and the RRD in the North. Total agricultural land used for rice cropping in these two regions is about 18,204 km2 (MRD) and 9605 km2 (RRD). Total harvested area significantly differs from rice growing areas as double and even triple cropping is a common feature across Vietnam. Based on our spatial database, the rice cultivated area in Vietnam under single-, double-, and triple-cropping rotation is 29.9, 47.0, and 23.1%, respectively (Table 2). Double-cropped rice systems represents the dominant cropping rotation in the North, while single-cropped rice is more prevalent in the Northern Central and Central Highlands. The MRD in the South is predominantly characterized by double- and triple-cropped rice systems, whereas single-cropped rice is found in areas with prevalent aquaculture.

Based on our simulations, the MRD region produced an average of about 28,800 kt y^{-1} for the years 2010–2019. This corresponds to 58.8% of the simulated rice yields for total Vietnam (49,000 kt y^{-1}), which is about 10% lower as reported by FAO (56,248 kt y^{-1}) (Table 2).

3.2 | CH_4 emissions from rice systems

Annual CH_4 emissions from rice fields varied between 100 to 1500 kg CH_4-C ha^{-1} y^{-1}. The lowest values were simulated for rainfed single rice cropping systems in mountainous areas, for example, in central and northern Vietnam, while the highest CH_4 emissions were associated with triple rice growing systems in the MRD region (Figures 3 and S1).

About 75% of total national CH_4 emissions from rice systems, that is, the median value for 2010–2019 of 1978 Gg CH_4 y^{-1}, were simulated for the MRD region, while most of the remaining emissions occurred in the RRD region. CH_4 emissions from all other regions were comparable marginal (Table 3 and Figure S1).

For both regions, that is, the MRD and the RRD, the simulations resulted in a pronounced seasonality of CH_4 emissions. While for the MRD region the period with high emissions (mean simulated CH_4 emissions >2 kg C ha^{-1} d^{-1}) starts end of August and ends approximately mid-February, the period with high emissions was confined between July and the end of October for the RRD region (Figures 4 and S2). These differences were due to the prevalence of double and triple rice growing systems in the MRD region. In contrast, double and occasionally triple growing systems in the RRD typically encompass upland crops, specifically maize, with rice not being grown in the winter months (mid-November to end of February).

Most important covariates determining the magnitude of CH_4 emissions from rice systems at the national scale were the amount of residue C input ($C_{residue}$), total rate of N fertilization (synthetic plus organic N input: N_{Total}), and manure C input (C_{Manure}) (Figure 5). In some regions, like the South-East and the South-Central coastal regions, also soil texture was an important covariate of CH_4 emissions.

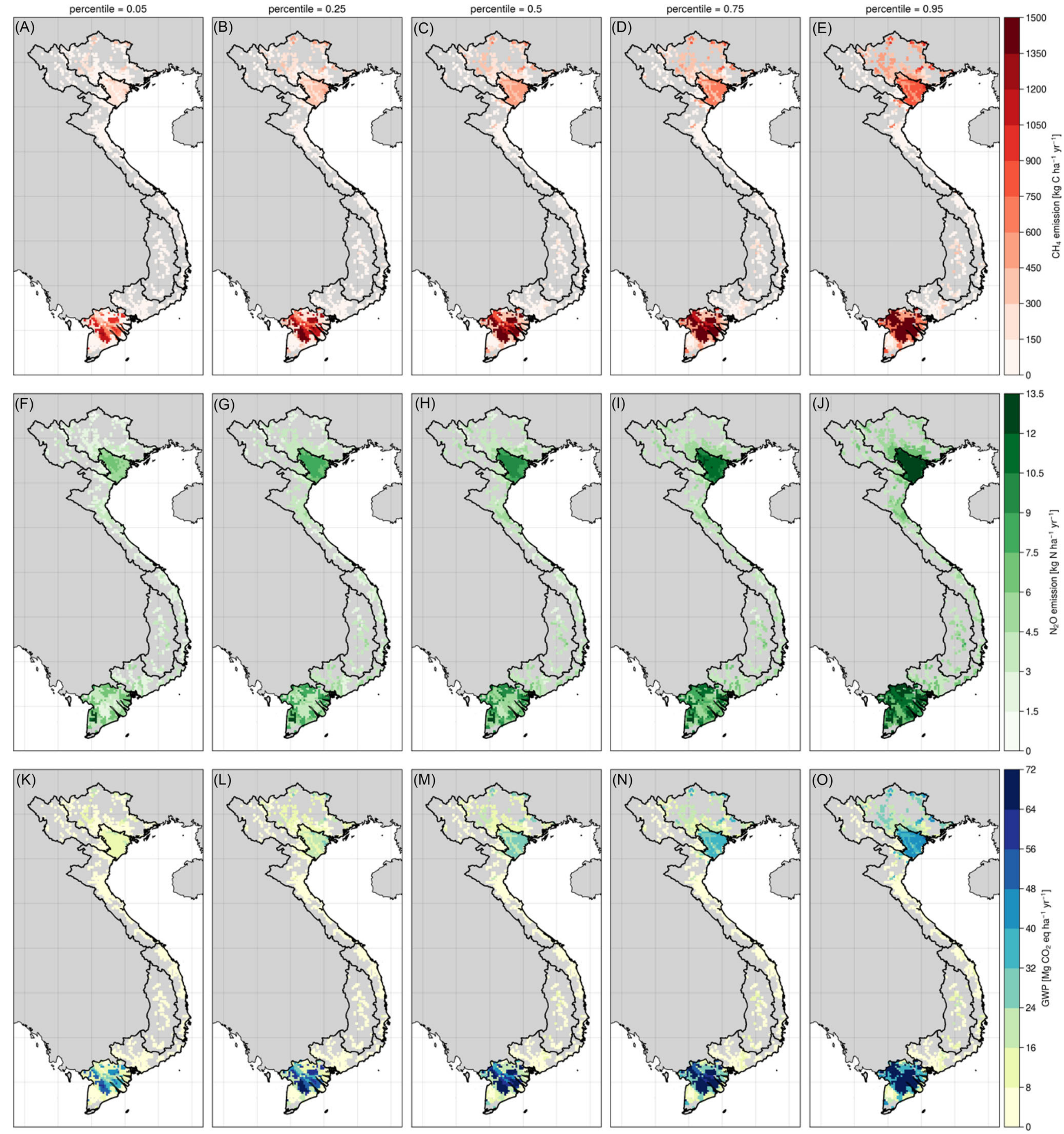


FIGURE 3 Average annual emissions (2010–2019) of CH_4 (top row) and N_2O (center row) and global warming potential GWP (bottom row) from rice systems in Vietnam. Percentiles derived from 500 Latin Hypercube samples of activity data: 5% (A, F, K), 25% (B, G, L), 50%/median (C, H, M), 75% (D, I, N), and 95% (E, J, O).

3.3 | N_2O emissions from rice systems

According to simulations based on LandscapeDNDC, N_2O emissions from fields used for seasonal rice growing (single, double, or triple growing systems, with one to three rice growing seasons) were mostly restricted to times when fields were not flooded. Specifically, these were periods used for field preparation, fallow periods, or periods used for upland crops. These periods accounted for >90% of annual N_2O emissions. Overall, the median annual N_2O emissions (simulation period 2010–2019) ranged from about 0.3–10.5 kg N_2O-N ha^{-1} y^{-1} (Figure 3; Figure S1).

As for CH_4, the MRD and RRD regions were strong regional hotspots of N_2O emissions from rice systems (Figure 3; Figure S1). Median soil N_2O emissions were higher in the RRD region, which can

TABLE 3 Total median soil CH_4 and N_2O emissions from rice fields as simulated by LDNDC for the years 2010–2019 in comparison with other reports

Source	Mekong River delta	Red River delta	All other regions	Vietnam	Base year(s)	Comments
CH_4 emissions (Gg CH_4 y^{-1})						
FAOSTAT				1356	2010–2019	FAOSTAT (https://www.fao.org/faostat/en/#data/GT)
EDGAR				1980	2010–2018	https://edgar.jrc.ec.europa.eu/dataset_ghg60
MONRE				1770	2014	Third National Communication of Vietnam to UNFCCC
Carlson et al. (2017)				2830	2000	Carlson et al. (2017), https://doi.org/10.1038/nclimate3158
This study[a]	1938 (1590–2370)	565 (440–706)	137 (94–185)	2634 (2120–3220)	2010–2019	(25% confidence intervals)
N2O emissions (Gg N2O y−1)						
FAOSTAT				37.3	2010–2019	FAOSTAT, Tier 1 approach, categories: synthetic fertilizers, manure applied to soils, manure left on pastures (25% of total),[b] crop residues. Statistics for entire Vietnam.
MONRE				80.5	2014	Third National Communication of Vietnam to UNFCCC, includes all agricultural soils
This study[a]	20.9 (17.8–24.5)	13.8 (11.6–16.3)	7.2 (6.6–8.5)	42.1 (36.0–49.3)	2010–2019	(25% confidence intervals)

[a] *Note* that for this comparison the data of this study are reported as Gg CH_4 or Gg N_2O and not as Gg CH_4-C or Gg N_2O-N, respectively.

[b] In Vietnam, harvested fields are commonly used for livestock grazing. Here, we assumed that 25% of total N_2O emissions from manure left of pastures may be assigned to harvested arable fields.

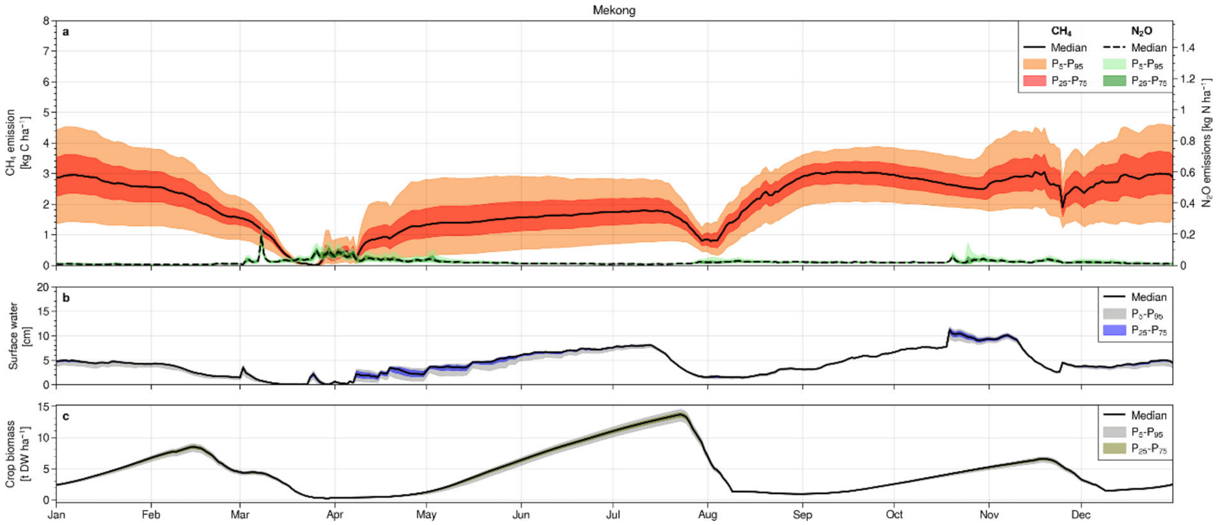
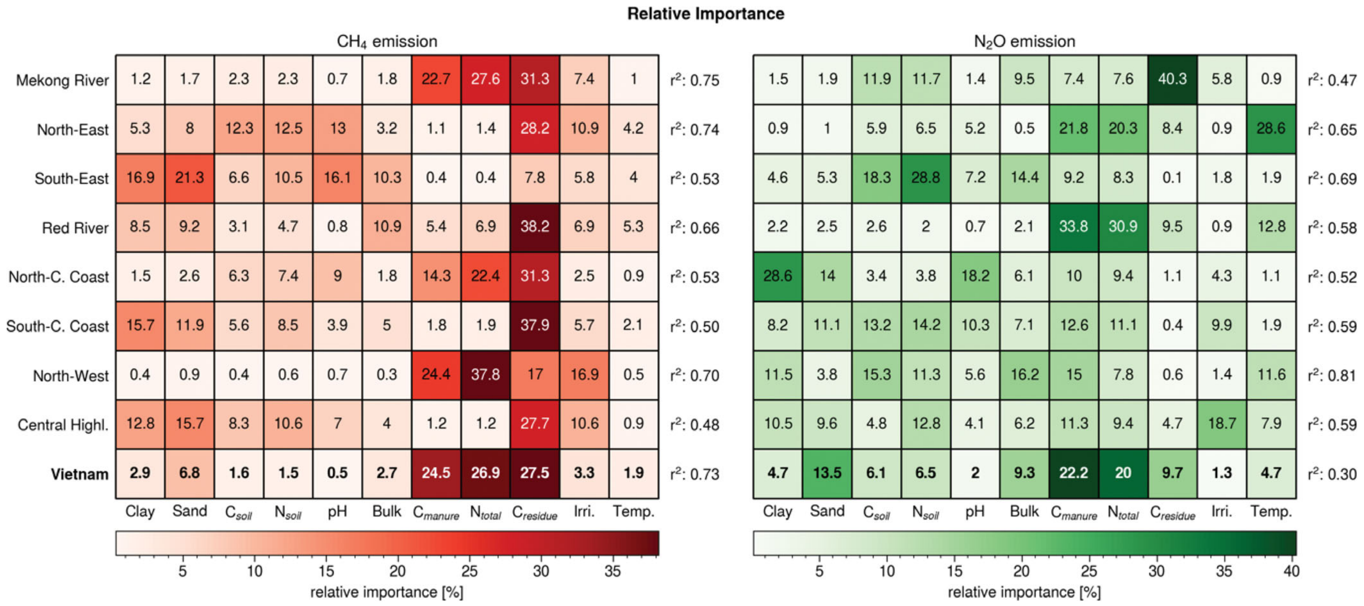


FIGURE 4 Seasonality of daily soil CH_4 and N_2O emissions (A), surface water height (B), and crop biomass (C) across all arable fields used for rice growing (either in single, double, or triple growing systems) for the Mekong River delta region. P_5-P_{95} and P_{25}-P_{95} refer to percentile bands, the line indicates the median of model results. All data are the aggregate of 500 individual simulation runs and the temporal average of the simulation period 2010–2019.

be attributed to the fact that longer periods under non- flooded conditions (only double cropping, no triple cropping) promote N_2O production through coupled nitrification-denitrification.. For Vietnam, total N_2O emissions from rice systems are about 42 Gg N_2O y^{-1}, with approximately 50% of total emissions associated with the MRD region, that is, the region with the largest harvest area of rice (Table 3).

Our simulations revealed a pronounced seasonality of N_2O emissions for the RRD region (Figure S2), with a high emission period during the winter growing period and maximum mean daily emissions across all arable fields (includes rice paddies, upland crop, and fallow fields) of 0.3 kg N ha^{-1} d^{-1}. In contrast, seasonality of N_2O emissions was rather low in the MRD region (emissions stayed <0.3 kg N ha^{-1} d^{-1}), though still showing a period of



CH_4 emission

	Clay	Sand	C_{soil}	N_{soil}	pH	Bulk	C_{manure}	N_{total}	$C_{residue}$	Irri.	Temp.	
Mekong River	1.2	1.7	2.3	2.3	0.7	1.8	22.7	27.6	31.3	7.4	1	r^2: 0.75
North-East	5.3	8	12.3	12.5	13	3.2	1.1	1.4	28.2	10.9	4.2	r^2: 0.74
South-East	16.9	21.3	6.6	10.5	16.1	10.3	0.4	0.4	7.8	5.8	4	r^2: 0.53
Red River	8.5	9.2	3.1	4.7	0.8	10.9	5.4	6.9	38.2	6.9	5.3	r^2: 0.66
North-C. Coast	1.5	2.6	6.3	7.4	9	1.8	14.3	22.4	31.3	2.5	0.9	r^2: 0.53
South-C. Coast	15.7	11.9	5.6	8.5	3.9	5	1.8	1.9	37.9	5.7	2.1	r^2: 0.50
North-West	0.4	0.9	0.4	0.6	0.7	0.3	24.4	37.8	17	16.9	0.5	r^2: 0.70
Central Highl.	12.8	15.7	8.3	10.6	7	4	1.2	1.2	27.7	10.6	0.9	r^2: 0.48
Vietnam	**2.9**	**6.8**	**1.6**	**1.5**	**0.5**	**2.7**	**24.5**	**26.9**	**27.5**	**3.3**	**1.9**	r^2: 0.73

N_2O emission

	Clay	Sand	C_{soil}	N_{soil}	pH	Bulk	C_{manure}	N_{total}	$C_{residue}$	Irri.	Temp.	
Mekong River	1.5	1.9	11.9	11.7	1.4	9.5	7.4	7.6	40.3	5.8	0.9	r^2: 0.47
North-East	0.9	1	5.9	6.5	5.2	0.5	21.8	20.3	8.4	0.9	28.6	r^2: 0.65
South-East	4.6	5.3	18.3	28.8	7.2	14.4	9.2	8.3	0.1	1.8	1.9	r^2: 0.69
Red River	2.2	2.5	2.6	2	0.7	2.1	33.8	30.9	9.5	0.9	12.8	r^2: 0.58
North-C. Coast	28.6	14	3.4	3.8	18.2	6.1	10	9.4	1.1	4.3	1.1	r^2: 0.52
South-C. Coast	8.2	11.1	13.2	14.2	10.3	7.1	12.6	11.1	0.4	9.9	1.9	r^2: 0.59
North-West	11.5	3.8	15.3	11.3	5.6	16.2	15	7.8	0.6	1.4	11.6	r^2: 0.81
Central Highl.	10.5	9.6	4.8	12.8	4.1	6.2	11.3	9.4	4.7	18.7	7.9	r^2: 0.59
Vietnam	**4.7**	**13.5**	**6.1**	**6.5**	**2**	**9.3**	**22.2**	**20**	**9.7**	**1.3**	**4.7**	r^2: 0.30

FIGURE 5 Relative importance of covariates for the simulated CH_4 and N_2O emissions for regions and the entire simulation domain (relative importance reported as fractions (%) of all considered covariates). Soil parameters: clay and sand (soil texture parameters), C_{soil} and N_{soil} (total soil organic carbon and soil total nitrogen content), pH and bulk (soil pH and bulk density [top soil, 0–20 cm]); management parameters: C_{manure} (C input by manure), N_{total} (total synthetic + organic N input), $C_{residue}$ (total amount of residue C added), Irri (total annual amount of irrigation), and Temp (mean annual air temperature). Provided R^2 values refer to the overall performance of the multiple linear regression model for a given region or entire Vietnam.

elevated median soil N_2O emissions during mid-March to mid-April (Figure 4).

The most important covariates affecting the magnitude of N_2O emissions from rice systems at national scale were the amount of manure C input and the total amount of applied synthetic and organic fertilizers (Figure 5). However, for the Mekong River region, that is, the region where triple-cropping systems dominate, the amount of residue C input was the single most important covariate affecting soil N_2O emissions. Soil texture was an important covariate in the North-Central coastal region, while it was mean annual temperature in the mountainous North-East region of Vietnam (Figure 5).

3.4 | Global warming potential of CH_4 and N_2O emissions and yield-scaled emissions

The global warming potential of soil CH_4 and N_2O fluxes expressed as CO_2 equivalents ranged from 5 to 70 Mg CO_2-eq ha^{-1} y^{-1} (Figures 3 and S3). The GWP of rice systems was three times higher for the MRD region (72,000 Gg CO_2-eq y^{-1}) as compared with RRD region 23,000 Gg CO_2-eq y^{-1}). In both regions, GWP values were dominated by CH_4 emissions, while the contribution of N_2O emissions to the regional GWP was 8.6% in the MRD region, but 17.8% in the RRD region. Overall, seasonal changes in GWP's were closely coupled to those of CH_4 emissions (data not shown).

Yield-scaled emissions on basis of total cereal yields (i.e., rice + maize yields) varied in a range of 300–3000 kg CO_2-eq Mg^{-1} y^{-1}. Lowest emissions were simulated for regions with single rice cropping systems with long fallow periods in mountainous regions, while highest yield-scaled emissions can be found in regions with year-round rice cultivation and high rates of residue return (Figure 6). For example, for the MRD region, median yield-scaled emissions for rice were 2620 kg CO_2-eq Mg^{-1} y^{-1} (25–75 percentile: 2260–3010 kg CO_2-eq Mg^{-1} y^{-1}), while for the RRD region, the median yield-scaled emissions for rice were 2010 kg CO_2-eq Mg^{-1} y^{-1} (25–75 percentile: 1680–2380 kg CO_2-eq Mg^{-1} y^{-1}) (Figure 6).

3.5 | Uncertainty assessment of rice system GHG emissions

In addition to the GHG estimates, we also assessed the uncertainty of simulated CH_4 and N_2O emissions from rice systems as a function of crop management information and other input parameters. A Monte Carlo approach combined randomized sampling from different probability distributions of crop management for model simulations (for details see Section 2). The temporal variability due to differing weather conditions in individual years was addressed by running simulations over the 10 years period 2010–2019. Results of the uncertainty assessments can be directly depicted in Figures 4 and S1 derived from the seasonality of CH_4 and N_2O emissions in the MRD and RRD regions, respectively. The graph shows that the emission strengths for the 25 and 75 percentiles for CH_4 and N_2O emissions are on average about ±20% higher or lower than the median values, respectively. Respective

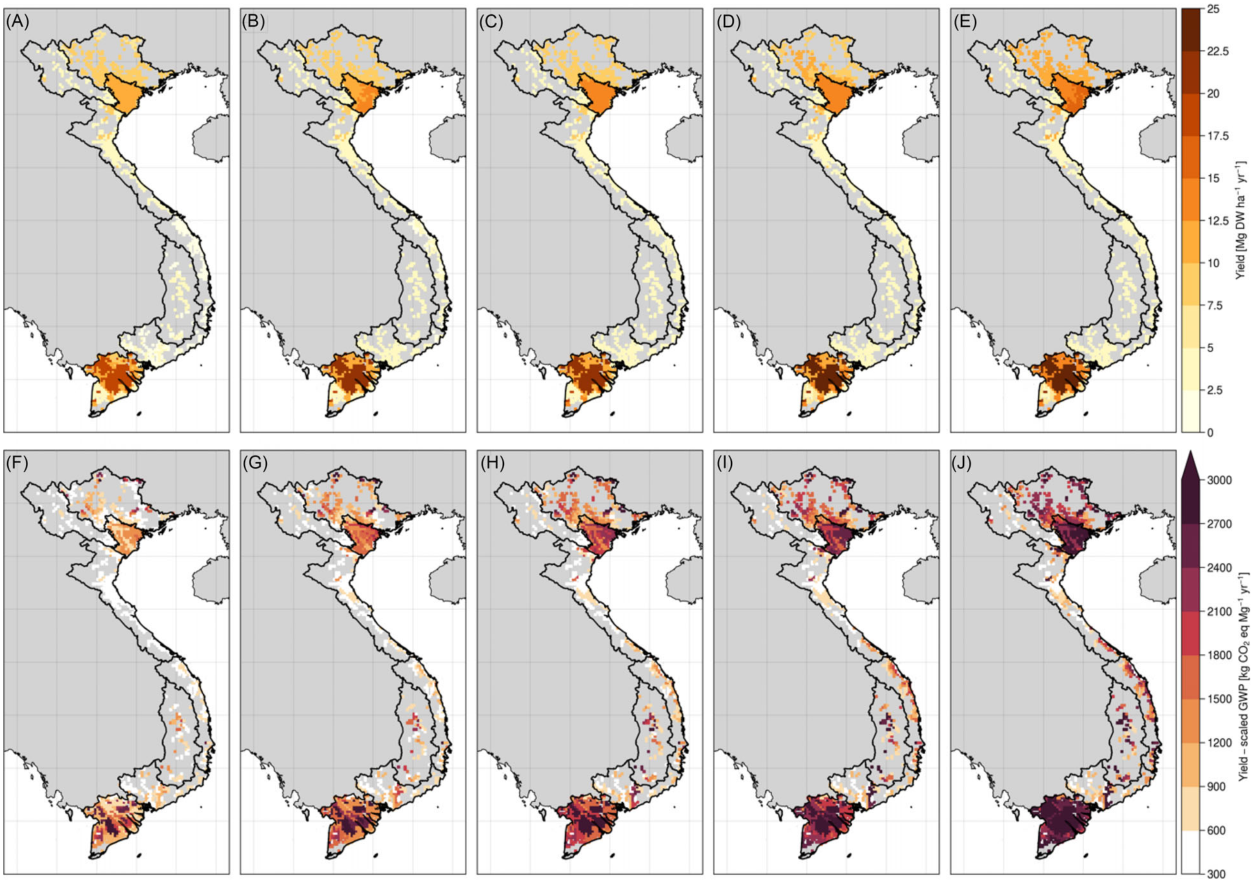


FIGURE 6 Average annual simulated grain yields (rice + maize) (top row) and yield-scaled Global Warming Potential of annual CH_4 and N_2O emissions (bottom row) from rice systems in Vietnam (2010–2019). Percentiles derived from 500 Latin Hypercube samples of activity data: 5% (A, F), 25% (B, G), 50%/median (C, H), 75% (D, I), and 95% (E, J). For details on annual CH_4 and N_2O emissions see Figure 3.

values for the 5–95 percentiles are about –50% to + 55% for CH_4 and –34% to 50% for N_2O, with minor differences (<±5%) between the MRD and RRD regions.

While the effect of the uncertainty of soil property information on soil CH_4 and N_2O emissions was not directly assessed, it can be depicted from the overall covariate analysis (Figure 5). It shows that information on texture or soil organic carbon and nitrogen concentrations are of minor importance for the MRD and RRD regions if compared with information on field management, and here specifically amounts of residue and organic and synthetic fertilizer inputs.

4 | DISCUSSION

In this study, we used the biogeochemical model framework LandscapeDNDC to assess the magnitude and temporal variability of CH_4 and N_2O emissions from rice systems at the national scale of Vietnam. First applications of LandscapeDNDC to rice systems date back to the year 2014, when Kraus et al. (2015) described the development and implementation of a new biogeochemistry module, called MeTr^x for rice systems in the LandscapeDNDC framework, and tested its performance for simulating soil N_2O and CH_4 emissions as well as crop yields for rice–rice and rice–maize systems on the Philippines. Further developments included testing of the model framework for simulating short-term and decadal changes in soil organic C stocks (Kraus et al., 2016), effects of field management such as residue management (Weller et al., 2016), or alternative wetting and drying (AWD) on GHG fluxes (Kraus et al., 2022). The latter study also describes the use of LandscapeDNDC to assess the mitigation potential of AWD at the scale of the Philippines. Besides these published studies, LandscapeDNDC has was tested and applied in cooperation with local partners to a large number (>50) of field sites used for rice cropping in South-East Asia, Kenya, Vietnam, and China, providing ample confidence that the model is ready for assessing GHG emissions from rice systems at national scale using a so-called Tier 3 approach (Ogle et al., 2013).

4.1 | Comparison with other studies

In our study, simulated total national rice yields were with a median value of about 50,000 Gg y^{-1} about 10% lower as reported by FAOSTAT crops and livestock products (FAOSTAT, 2022c) (Table 2). This difference may be due to an underestimation of yields as Vietnam's farmers increasingly use input-responsive modern varieties, sufficient fertilizer, and as the irrigation systems have been expanded (GRiSP, 2013). Also, the area used for double and triple rice growing may have been underestimated.

LandscapeDNDC simulated total national CH_4 emissions from rice systems were about 2600 Gg CH_4 y^{-1} and, thus, about a factor of two higher as estimates by FAO using IPCC Tier 1 approach (FAOSTAT, 2022b). Also compared with the third national communication of Vietnam to UNFCCC (MONRE, 2018), which is as well based on the IPCC Tier 1 approach, our estimate is about 33% higher. However, our estimate on CH_4 emissions from Vietnamese rice systems is comparable in magnitude to the study of Carlson et al. (2017), which was as well based on IPCC emission factors (Table 3). The differences in CH_4 emission estimates between the different studies are very likely related to different assumptions on number of rice growing seasons, number of days with fields flooded, length of vegetation period and most importantly residue management and total amount of manure application to rice fields. However, as these data are not explicitly reported in the individual studies, a further assessment of reasons of deviations between studies is not possible. An additional major difference between Tier 1 and Tier 2 approaches used for estimating CH_4 emissions from rice paddies and the modeling approach realized here, is that off-season fluxes are included in our calculations, and, those were approximately contributing with about 10% to total annual emissions. In our study, field-scale CH_4 emissions varied between 100 to 1500 kg CH_4-C ha^{-1} y^{-1} or up to 800 kg CH_4-C $season^{-1}$. Such a huge range of emissions can be explained by the number of days a field is flooded, and, thus, if rice is cropped in one or two or three seasons per year, and on the availability of irrigation water. Similar findings, regarding the range and the driving factors of the variability, were recently reported as well in a study for the Philippines (1–940 kg CH_4-C ha^{-1} y^{-1}; Kraus et al., 2022). As discussed earlier in the Kraus et al. (2022) study, major factors affecting the magnitude of seasonal emissions are mostly related to the stimulating effect of residue incorporation on CH_4 emissions (see also Wassmann et al., [2000]), and the tremendous importance of water management related to fields experiencing multiple drainage events for stimulating root growth, due to shortage in irrigation water or in the frame of AWD management schemes, significantly reducing CH_4 emissions by 35% (Yagi et al., 2020).

Our estimate on N_2O emissions from rice system only, including off-season fluxes and fluxes from rice as well as upland crops, is about 42 Gg N_2O y^{-1} (Table 3). A direct comparison of our estimates with estimates by FAOSTAT (2022a–c) or MONRE (2018) is difficult, as these both sources refer to estimates at national scale for all agricultural soils. That is, neither of both estimates directly focus on rice systems as it is assumed that N_2O emissions during rice growing are negligible. However, it is noteworthy that estimates differing by about a factor of 2 between FAOSTAT (2022a–c) (37 Gg N_2O y^{-1}) and MONRE (2018) (80.5 Gg N_2O y^{-1}) (Table 3). Reasons for this significant deviation between FAOSTAT and MONRE are rather unclear, but are likely associated with different assumption regarding amounts of synthetic and organic fertilizer use or differences in emission factors for residue management or manure applied to soil.

In agreement with previous studies (e.g., Weller et al., 2015), also our simulations show low N_2O emissions (<0.2 kg N_2O $season^{-1}$) from permanently flooded rice fields. However, large N_2O fluxes (>1 mg N_2O m^{-2} ha^{-1} d^{-1}) occurred during periods of field drainage, for example, prior to harvest. This agrees with results from different field and upscaling studies (Janz et al., 2019; Pittelkow et al., 2013; Weller et al., 2015; Weller et al., 2016).

Our simulation show that yield-scaled emissions vary largely in a range of 300–3000 kg CO_2-eq Mg^{-1} y^{-1}, with highest median values for rice only in the MRD (2620 kg CO_2-eq Mg^{-1} y^{-1} or 2.6 kg CO_2-eq kg^{-1} rice grain). These values are well in agreement with a recent review of yield-scaled emissions for conventionally managed rice systems provide by Cheng et al. (2022).

4.2 | Uncertainties of estimates

In our study, we used two different approaches to understand the importance of input uncertainties on our final simulation results: (1) a Monte Carlo approach (LHS) to cover uncertainty of assumptions taken for fertilizer use, residue incorporation and irrigation water supply (see section 2.5) and (2) a regional relative importance analysis attributing the impact of various properties and management factors on soil CH_4 and N_2O fluxes at regional and national scale of Vietnam. It is evident from the analyses that the uncertainty in field management information, specifically rates of nitrogen fertilization, proportion of synthetic to organic fertilization, residue management as well as availability of sufficient irrigation water, specifically in drought years, are major driving factors of the uncertainty of our inventory. Furthermore, also related to uncertainties, is the still missing information on rice systems, that is, area of single-, double-, or triple-cropping systems, and location of those. In contrast, uncertainties in our emission estimates due to uncertain information on soil properties are lower (Figure 5). That specifical information on so-called activity data are key to reduce the uncertainty of GHG inventories and to target mitigation interventions in low- and mid-income countries (but as well in countries with developed economies), which has been pointed out earlier by Rosenstock & Wilkes (2021).

Though so far not assessed, a further point of uncertainty related to soil properties, is the effect of soil salinization on CH_4 emissions from rice paddies. Specifically, the RRD is experiencing large scale soil salinization problems, and studies on CH_4 emissions from rice fields with elevated saline concentrations show that emissions are about a factor of 2–3 lower as compared with other fields (Vo et al., 2018). However, salinization effects are currently not addressed by the LandscapeDNDC model.

5 | CONCLUSIONS

Our study shows that Tier 3 approaches, that is, process-oriented model approaches combined to GIS databases, for estimating national-scale GHG emissions from rice systems, are ready to be widely applied.

Generally, this approach is powerful as it allows to identify regions with elevated emissions, thereby accounting not only for CH_4, but as well for N_2O emissions (and soil C stock changes, though not reported in this study). The provided seasonal changes in emissions at regional scale from rice systems also opens up new avenues to combine bottom up and top-down (e.g., tall-tower measurements or satellite observations on column concentrations of, e.g., CH_4) for further constraining uncertainties. However, with regard to the latter, it is imperative to push for improving information on activity data, that is, field management parameters. Also, further model developments will be needed as for example, pointed out inclusion of parameters describing salinization effects on soil microbial and plant processes and associated biosphere-atmosphere GHG exchange.

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DATA AVAILABILITY STATEMENT

All data regarding soil properties, climate, and management that were used to initialize and run the model were derived from published resources as indicated in Section 2. Data processing scripts and analysis notebooks can be downloaded from https://github.com/cwerner/paper-werner-rice-vietnam. The LandscapeDNDC model source code is available upon request from the following KIT institutional website: https://ldndc.imk-ifu.kit.edu/download/download.php (last access: September 30, 2022). The revision number of the LandscapeDNDC model that has been used in this study is 10760.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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