Greenhouse gas emissions from rice production in the Vietnamese Mekong River Delta as affected by varietal selection and water management

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PUBLICATIONS

2023	**Vo**, T.B.T., Johnson, K., Wassmann, R., Sander, B.O., Asch, F. Varietal effects on greenhouse gas emissions from rice production systems under different water management in the Vietnamese Mekong delta. 2023, [Manuscript submitted for publication]. Journal of Agronomy and Crop Science
2023	Johnson, K., **Vo**, T.B.T., Asch, F. Duong, V.N. Genotypic responses of rice to alternate wetting and drying irrigation in the Mekong Delta. 2023, [Manuscript submitted for publication]. Journal of Agronomy and Crop Science.
2023	Asch, F., Johnson, K., **Vo**, T.B.T., Sander, O., Duong, V.N, Wassmann, R. Varietal effects on methane productivity of paddy fields under different irrigation management. 2023, [Manuscript submitted for publication]. Journal of Agronomy and Crop Science.

2023 Wassmann R, Nelson K., Bui T.Y., Nguyen-Van-Hung, Gummert M., Asch F., **Vo** T.B.T., Butterbach-Bahl K., Kiese R., Janz B., Mai V.T. and Sander B.O. Context-specific Assessments of Carbon Footprints of the Rice Value Chain: From Product-Labelling to Potential Mitigation Impact. 2023, [Manuscript submitted for publication]. International journal of life cycle assessment.

2020 **Vo**, T.B.T., Wassmann, R., Mai, V.T., Vu, D.Q., Bui, T.P.L., Vu, T.H., Dinh, Q.H., Yen, B.T., Asch, F., Sander, B.O. Methane Emission Factors from Vietnamese Rice Production: Pooling Data of 36 Field Sites for Meta analysis. *Climate* 2020, *8, 74. Climate* 2020, *8*, 113. https://doi.org/10.3390/cli8100113

2019 Wasmann R., Phong, N.D., Tho, T.Q., Hoanh, T.T., Khoi, N.H., Hien, N.X., **Vo**, T.B.T., Tuong, T.P. High-Resolution Mapping of Flood and Salinity Risks for Rice Production in the Vietnamese Mekong Delta. *Field Crops Res*. 2019, 236, 111–120. doi:10.1016/j.fcr.2019.03.007

2019 Wassmann, R., Villanueva, J., Khounthavong, M., Okumu, B.O., **Vo**, T.B.T., Sander, B.O. (2019). Adaptation, mitigation and food security: Multi-criteria ranking system for climate-smart agriculture technologies illustrated for rainfed rice in Laos. *Global Food Security, 23(), 33–40.* doi:10.1016/j.gfs.2019.02.003

2019 Wassmann, R. Pasco, R., Zerrudo, J., Ngo, D.M., **Vo,** T.B.T. and Sander, B.O. (2019): Introducing a new tool for greenhouse gas calculation tailored for cropland: rationale, operational framework and potential application, *Carbon Management*, DOI:10.1080/17583004.2018.1553436

2018 Thi Bach Thuong **Vo,** Reiner Wassmann, Agnes Tirol-Padre, Van Phuong Cao, Ben MacDonald, Maria Victoria O. Espaldon & Bjoern Ole Sander (2018) Methane emission from rice cultivation in different agro-ecological zones of the Mekong river delta: seasonal patterns and emission factors for baseline water management, Soil Science and Plant Nutrition, 64:1, 47-58, DOI: 10.1080/00380768.2017.1413926

2016 Mai Van Trinh, Bui Thi Phuong Loan, Vu Duong Quynh, Cao Van Phung, Tran Kim Tinh, Pham Quang Ha, Nguyen Hong Son, Tran Van The, Bjoern Ole Sander, Tran Tu Anh, Tran Thu Ha, Hoang Trong Nghia, **Vo** Thi Bach Thuong (2016). Handbook on measuring GHG emissions from rice (in Vietnamese)

PRESENTATION

2022 **Vo**, T.B.T., Wassmann, R., Sander, B.O., Asch, F. (2022): GHG emissions from rice production depend on season, water management, and variety. Hybrid Tropentag Conference, Germany (poster).

2022 Johnson K., **Vo**, T.B.T., Asch, F. The effect of alternate-wetting-and-drying irrigation on rice phenology and yield. Hybrid Tropentag Conference, Germany (oral presentation).

2021 **Vo**, T.B.T., Wassmann, R., Duong, V.N., Sander, B.O., Asch, F. (2021): Methane emission from rice production as affected by rice variety selection. Hybrid Tropentag Conference, Germany (poster).

2020	**Vo**, T.B.T., Asch, F., Wassmann, R., Sander, B.O. (2020): Zonal and Seasonal Methane Emissions from Rice Production in the Vietnamese Mekong Delta. Virtual Tropentag Conference, Germany (poster).
2020	Detering, T., **Vo**, T.B.T, Wassmann, R., Sander, B.O., Asch, F. (2020): Methane emissions of different Rice Varieties: Diurnal emission patterns of three development stages. Virtual Tropentag Conference, Germany (poster).
2018	**Vo**, T.B.T., Wassmann, R., Espaldon, M.V.O., Pulhin, F.Y., Sander, B.O. (2018). Multi-disciplinary Researchfor Greenhouse Gas Calculation of Rice Cultivation: Field Measurements and Crop management Surveys Conducted in the Mekong Delta, Vietnam. 5th International Rice Congress 2018, Singapore (oral presentation).

Stuttgart, March 22, 2023 — Vo Thi Bach Thuong

Place, Date — Signature

Annex 3
Declaration in lieu of an oath on independent work

according to Sec. 18(3) sentence 5 of the University of Hohenheim's Doctoral Regulations for the Faculties of Agricultural Sciences, Natural Sciences, and Business,Economics and Social Sciences

1. The dissertation submitted on the topic "Greenhouse gas emissions from rice production in the Vietnamese Mekong River Delta as affected by varietal selection and water management"
   is work done independently by me.
2. I only used the sources and aids listed and did not make use of any impermissible assistancefrom third parties. In particular, I marked all content taken word-for-word or paraphrased fromother works.
3. I did not use the assistance of a commercial doctoral placement or advising agency.
4. I am aware of the importance of the declaration in lieu of oath and the criminal consequencesof false or incomplete declarations in lieu of oath.

I confirm that the declaration above is correct. I declare in lieu of oath that I have declared only the truth to the best of my knowledge and have not omitted anything.

Stuttgart, March 22, 2023 Vo Thi Bach Thuong

Place, Date Signature

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Summary

The topic of this dissertation deals with rice production, the predominant source of daily nourishment for more than half of the world's population. Rice production is directly affected by global climate change through aggravating climatic conditions, but is also one of the major sources of greenhouse gases (GHG) in the agricultural sector. The latter aspect is investigated in 4 publications by assessing the factors contributing to emissions, the quantification of GHG emissions across different scales, and possible mitigation of GHG emissions. In totality, these studies aim at bridging the gap between field measurements to national extrapolations in view of both GHG inventories and future mitigation programs. In terms of methodologies, the publications compiled in the following chapters represent a broad spectrum ranging from field measurements to meta-analysis, but they all deal with the emission of methane (CH4) which is generated in rice fields due to the unique feature of 'semi-aquatic' soils. The publications based on newly conducted field measurements also a nitrous oxide (N2O) which is a potent GHG emitted typically emitted from rice fields in low quantities.

Chapter 2 (Vo et al. 2018) compiles field measurements from the Vietnamese Mekong River Delta (MRD) which accounts for more than 50% of the country's rice production. Emission factors (EFs) are used to estimate total emissions associated with the area of rice production. The Intergovernmental Panel on Climate Change (IPCC) has given the default EFs that are based on global averages as Tier 1 approach. However, the IPCC guidelines encourage national reporting institutions to conduct field measurements of GHG emissions and to determine country-specific EFs as the basis of the Tier 2 approach. Tier 2 further accounts for the fact that emissions may also be highly variable within a given country by requesting for disaggregation of EF at a sub-national scale. Therefore, the most recent GHG inventories for Vietnam are based on region-specific EFs under the IPCC Tier 2 approach, which is implemented using national activity data (i.e., national average cultivation period of rice and harvested area). In Chapter 2, we developed the specific EFs for different hydrological sub-zones and growing seasons in the MRD to achieve disaggregated EFs that could be used for the National Communications submitted to the United Nations Framework Convention on Climate Change (UNFCCC). Due to the distinct bio-physical condition and cropping cycle, the results show the lowest emissions in the saline sub-zone. While alluvial, acid sulfate soils had intermediate levels, the highest emissions were found in the deep flood sub-zone.

In Chapter 3 (Vo e al. 2018), we expanded the geographical scope of the GHG assessment to the entire country. This meta-analysis of CH4 data covers 73 cropping seasons at 36 field sites across the rice-growing areas of Vietnam under the IPCC's baseline conditions (i.e.,

continuously flooded, no organic amendments) in the three main cropping seasons. As an output of this study, a structured database contained the location and season of each measurement as well as site-specific bio-physical factors and crop management at the site scale. In the next step, we developed disaggregated EFs for different zones and cropping seasons across the country that can be used for future reporting commitments of Vietnam as part of a more accurate Tier 2 assessment. The calculated EFs were generally higher than the IPCC defaults and the values used for Vietnam's 3rd National Communications for the North, Central, and South Vietnam.

Chapter 4 (Vo et al. 2023) has to be seen in the context of Vietnam's climate change policy that aims at reducing GHG emissions from rice production. Mitigation in rice production will be crucial for Vietnam because CH4 from rice accounts for about 15 % of the national GHG which is more than the entire transport sector even without considering CO2 and N2O emissions along the rice value chain. Previous studies have assessed the potential practices by changes in farming practices, namely water, nutrient, and straw management, and almost uniformly concluded that Alternate Wetting and Drying (AWD) is the most promising strategy for achieving a sizable mitigation of GHG emissions. Given the intense rainy season in southeast Asia, however, the precipitation is often too high to implement this water regime and will not provide any economic benefit from water saving. In turn, it is important to consider other mitigation strategies such as the selection of low-emitting cultivars. We conducted a field screening of 20 rice varieties that was expanded by assessing the interactive effect of variety selection and AWD. An experimental layout with 120 plots (based on 3 replicates) was required to assess this interaction of variety and water management in the field using the closed chamber method to collect air samples followed by lab analysis (using a gas chromatograph) to quantify the CH4 and N2O concentrations. The results of this study confirmed that GHG emissions from rice fields are dominated by CH4 emissions whereas N2O emissions were negligible. Compared with IPCC default values, the data set from two dry seasons yielded higher emissions under a baseline of continuous flooding (EF = 2.96 kg CH4 ha-1 d-1) and lower Scaling Factors (SF) of AWD (SF = 0.4).

Chapter 5 (Asch et al. 2023) deals with the agronomic aspects of both AWD and variety selection and their implications on the economic viability of future mitigation efforts. While AWD is more efficient in reducing CH4 emissions than variety selection, this water management practice resulted in a slight yield decrease in our field study. Given the limited applicability of AWD, the selection of varieties is a much more adaptable approach and is also beneficial in terms of farmers' adoption because it does not require any crop management

changes. However, this strategy could also impact profits since the lowest-emitting variety may not have the highest rice yields.

In the context of future mitigation programs in the MRD, the dry season allows good control of the water table, so AWD should be the core of any mitigation effort. Variety selection on the other hand should be targeted in those seasons and locations that do not allow draining the fields. In turn, low-emitting varieties should become an integral part of future mitigation programs to supplement AWD within a systematic out scaling. In terms of economic trade-offs for the farmers, we assumed a scenario with compensation derived from the still premature carbon markets. The potential profit increments are very low and not attractive if distributed to farmers directly, but may collectively be used for investments in rural development by government agencies for benefitting farmers indirectly, e.g. by improving the irrigation infrastructure.

Zusammenfassung

Das Thema dieser Dissertation befasst sich mit dem Reisanbau, der wichtigsten Quelle für die tägliche Ernährung von mehr als der Hälfte der Weltbevölkerung. Die Reisproduktion ist durch die Verschärfung der klimatischen Bedingungen direkt vom globalen Klimawandel betroffen, ist aber auch eine der Hauptquellen von Treibhausgasen (THG) im Agrarsektor. Der letztgenannte Aspekt wird in vier Veröffentlichungen untersucht, in denen die Faktoren, die zu den Emissionen beitragen, die Quantifizierung der Treibhausgasemissionen in verschiedenen Skalen und mögliche Maßnahmen zur Verringerung der Treibhausgasemissionen bewertet werden. Insgesamt zielen diese Studien darauf ab, die Lücke zwischen Feldmessungen und nationalen Hochrechnungen sowohl im Hinblick auf THG-Inventare als auch auf künftige Minderungsprogramme zu schließen. Die in den folgenden Kapiteln zusammengetragenen Veröffentlichungen weisen ein breites methodisches Spektrum auf, das von Feldmessungen bis hin zu Meta-Analysen reicht. Sie befassen sich jedoch alle mit der Emission von Methan (CH_4), das in Reisfeldern aufgrund der einzigartigen Eigenschaft "semiaquatischer" Böden entsteht. Die Veröffentlichungen, die auf neu durchgeführten Feldmessungen beruhen, befassen sich zudem auch mit Lachgas (N_2O), einem potenten Treibhausgas, das von Reisfeldern in der Regel jedoch nur in geringen Mengen emittiert wird.

Kapitel 2 (Vo et al. 2018) umfasst Feldmessungen aus dem vietnamesischen Mekong-Flussdelta (MRD), auf das mehr als 50 % der Reisproduktion des Landes entfallen. Zur Schätzung der Gesamtemissionen im Zusammenhang mit der Reisanbaufläche werden Emissionsfaktoren (EF) verwendet. Das Intergovernmental Panel on Climate Change (IPCC) hat die Standard-EFs, die auf globalen Durchschnittswerten basieren, als Tier-1-Ansatz festgelegt. Die IPCC-Leitlinien ermutigen jedoch die nationalen Berichterstattungsinstitutionen, Feldmessungen der THG-Emissionen durchzuführen und länderspezifische EFs als Grundlage des Tier-2-Ansatzes zu bestimmen. Tier 2 trägt außerdem der Tatsache Rechnung, dass die Emissionen innerhalb eines Landes sehr unterschiedlich sein können, indem es eine Aufschlüsselung der EF auf subnationaler Ebene fordert. Daher basieren die jüngsten Treibhausgasinventare für Vietnam auf regionsspezifischen Treibhausgasemissionen für Reis im Rahmen des Tier 2 Ansatzes, der unter Verwendung nationaler Aktivitätsdaten (d. h. der durchschnittlichen nationalen Anbauperiode von Reis und der geernteten Fläche) umgesetzt wird. In Kapitel 2 haben wir die spezifischen EFs für verschiedene hydrologische Unterzonen und Wachstumsperioden in der MRD entwickelt, um disaggregierte EFs zu bestimmen, die für die bei der Klimarahmenkonvention der Vereinten

Nationen eingereichten nationalen Mitteilungen verwendet werden können. Aufgrund der unterschiedlichen biophysikalischen Bedingungen und Anbauzyklen zeigen die Ergebnisse die geringsten Emissionen in der salzhaltigen Unterzone. Schwemmlandböden und saure Sulfatböden wiesen mittlere Werte auf, während die höchsten Emissionen in der Unterzone mit tiefen Überschwemmungen zu finden waren.

In Kapitel 3 (Vo e al. 2018) haben wir den geografischen Umfang der THG-Bewertung auf das gesamte Land ausgeweitet. Diese Meta-Analyse der CH_4-Daten umfasst 73 Anbausaisons an 36 Feldstandorten in den Reisanbaugebieten Vietnams unter den IPCC-Basisbedingungen (d. h. kontinuierlich überflutet, keine organischen Ergänzungen) in den drei Hauptanbausaisons. Das Ergebnis dieser Studie war eine strukturierte Datenbank, die den Ort und die Jahreszeit jeder Messung sowie die standortspezifischen biophysikalischen Faktoren und die Pflanzenbewirtschaftung auf Standortebene enthielt. Im nächsten Schritt entwickelten wir disaggregierte EFs für verschiedene Zonen und Anbausaisonen im ganzen Land, die für künftige Berichterstattungsverpflichtungen Vietnams als Teil einer genaueren Tier-2-Bewertung verwendet werden können. Die berechneten EFs waren im Allgemeinen höher als die IPCC-Vorgaben und die Werte, die für Vietnams dritte nationale Mitteilungen für Nord-, Zentral- und Südvietnam verwendet wurden.

Kapitel 4 (Vo et al. 2023) ist im Zusammenhang mit der vietnamesischen Klimaschutzpolitik zu sehen, die auf eine Verringerung der Treibhausgasemissionen aus der Reisproduktion abzielt. Eine Reduzierung der Emissionen im Reisanbau wird für Vietnam jedoch von entscheidender Bedeutung sein, da CH_4 aus dem Reisanbau etwa 15 % der nationalen THG-Emissionen ausmacht, was mehr ist als die Emissionen des gesamten Verkehrssektors, selbst wenn man die CO_2- und N_2O-Emissionen entlang der Reiswertschöpfungskette nicht berücksichtigt. Frühere Studien haben Änderungen der Anbaupraktiken, insbesondere des Wasser-, Nährstoff- und Strohmanagements, bewertet und sind fast einheitlich zu dem Schluss gekommen, dass Alternate Wetting and Drying (AWD) die vielversprechendste Strategie ist, um eine beträchtliche Verringerung der THG-Emissionen zu erreichen. Angesichts der intensiven Regenzeit in Südostasien sind die Niederschläge jedoch oft zu hoch, um dieses Bewässerungsregime umzusetzen, und bieten keinen wirtschaftlichen Nutzen durch Wassereinsparungen. Im Gegenzug ist es wichtig, andere Minderungsstrategien in Betracht zu ziehen, wie etwa die Auswahl von Reissorten mit geringen Emissionen. Wir haben ein Feldscreening von 20 Reissorten durchgeführt, das durch die Bewertung der interaktiven Wirkung von Sortenwahl und Bewässerung erweitert wurde. Eine Versuchsanordnung mit 120 Parzellen (basierend auf 3 Replikaten) war erforderlich, um diese Wechselwirkung von

Sorte und Wassermanagement auf dem Feld zu bewerten. Dabei wurden Luftproben mit der ,‘closed chamber‘ Methode gesammelt und anschließend im Labor (mit einem Gaschromatograph) analysiert, um die CH_4- und N_2O-Konzentrationen zu quantifizieren. Die Ergebnisse dieser Studie bestätigten, dass die Treibhausgasemissionen aus Reisfeldern von den CH_4-Emissionen dominiert werden, während die N_2O-Emissionen vernachlässigbar waren. Im Vergleich zu den IPCC-Standardwerten ergab der Datensatz aus zwei Trockensaisons höhere emisssionen unter einer Basislinie mit kontinuierlicher Überflutung (EF = 2,96 kg CH_4 ha^{-1} d^{-1}) und niedrigere Skalierungsfaktoren der AWD (SF = 0,4).

Kapitel 5 (Asch et al. 2023) befasst sich mit den agronomischen Aspekten sowohl von AWD als auch der Sortenwahl und deren Auswirkungen auf die wirtschaftliche Tragfähigkeit zukünftiger Minderungsbemühungen. Während AWD bei der Verringerung der CH_4-Emissionen effizienter ist als die Sortenwahl, führte dieses Wassermanagementverfahren in unserer Feldstudie zu einem leichten Ertragsrückgang. Bedingt durch die begrenzte Anwendbarkeit von AWD ist die Sortenauswahl ein vielseitigerer Ansatz, der auch für die Landwirte von Vorteil ist, da er keine Änderungen in der Bewirtschaftung erfordert. Diese Strategie könnte sich jedoch auch negativ auf die Gewinne auswirken, da die Sorte mit den geringsten Emissionen nicht unbedingt die höchsten Reiserträge liefert.

Im Rahmen künftiger Programme zur Eindämmung des Klimawandels im MRD ermöglicht die Trockenzeit eine gute Kontrolle des Grundwasserspiegels, so dass AWD den Kern jeder Eindämmungsmaßnahme bilden sollte. Andererseits sollte die Sortenauswahl auf die Jahreszeiten und Standorte ausgerichtet sein, die keine Drainierung der Felder zulassen. Emissionsarme Sorten sollten daher ein integraler Bestandteil künftiger Minderungsprogramme sein, um AWD im Rahmen eines systematischen Outscaling zu ergänzen. Was die wirtschaftlichen Konsequenzen für die Landwirte betrifft, so sind wir von einem Szenario ausgegangen, bei dem die Ausgleichszahlungen von den bisher noch nicht funktions-fähigen Kohlenstoffmärkten stammen. Der zusaetzliche Gewinn ist jedoch sehr gering, so dass es nicht sinnvoll ist, wenn sie direkt an die Landwirte verteilt werden. Das Geld könnte aber insgesamt für Investitionen in die ländliche Entwicklung durch staatliche Stellen verwendet werden, und damit den Landwirten indirekt zugute kommen, z. B. durch Verbesserung der Bewässerungsinfrastruktur.

CHAPTER 1

GENERAL INTRODUCTION

1. Rice in Vietnam and the Mekong River Delta

Vietnam produces annually 43 million tonnes of rice including 4.5 million tonnes for export (GSO, 2021), making Vietnam the 5th largest rice-producing and 3rd largest rice-exporting country. Rice is cultivated in all regions across the country, of which 55% of the national rice-planted area, and similarly 56% of the production (Figure 1, chapter 1) is represented by the MRD (GSO, 2021).

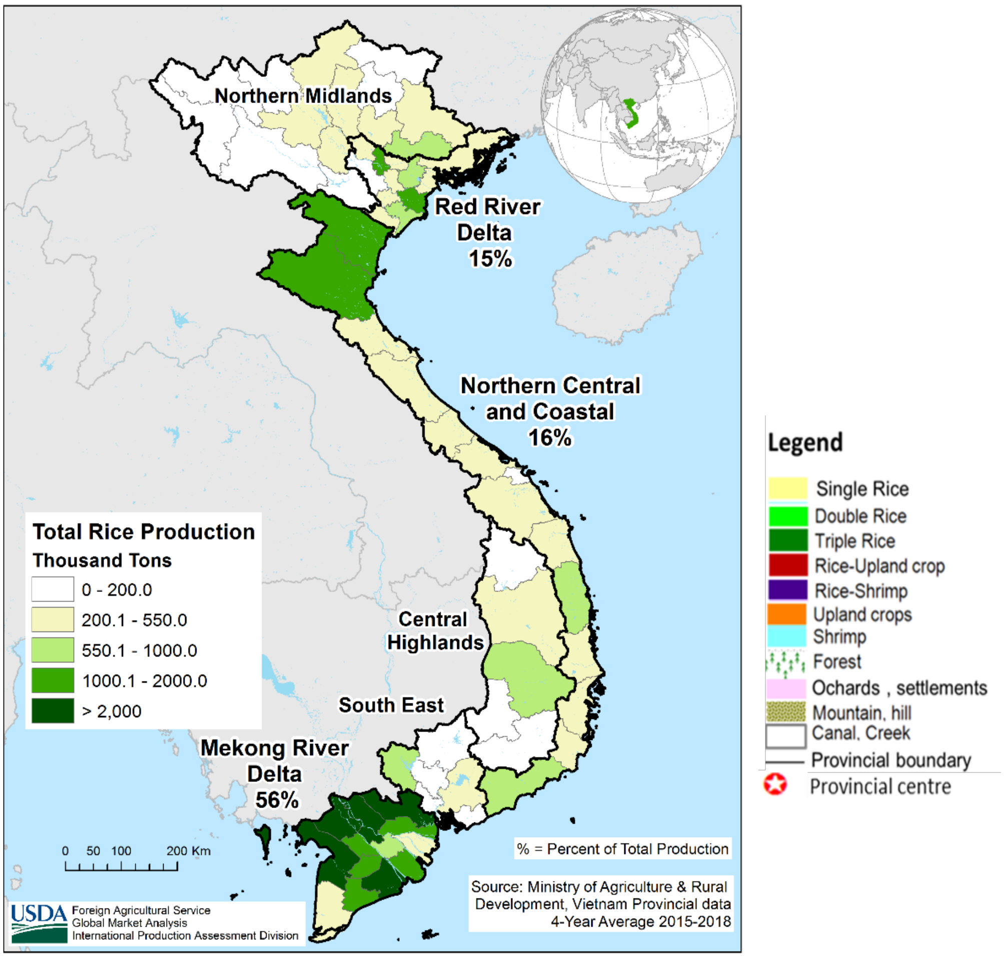

Figure 1. Vietnam total rice production.

Source:https://ipad.fas.usda.gov/countrysummary/Default.aspx?id=VM&crop=Rice (March 2023)

Vietnam is characterized by a pronounced North-South gradient in terms of climate and topography, resulting in eight agro-ecological zones (Figure 1, chapter 1). Rice is predominantly harvested twice a year throughout the country. Exceptions of this cropping patterns are found in the upper part of the MRD where triple cropping is commonly practiced

(Figure 2, chapter 1) and in some coastal areas where rice is often rotated with other land uses, namely shrimp farming in the dry season (Preston and Clayton 2003). In addition to the overall classification as one agro-ecological zone, the MRD comprises distinct bio-physical conditions (hydrology and soil type) determining land use patterns at any given site within the delta.

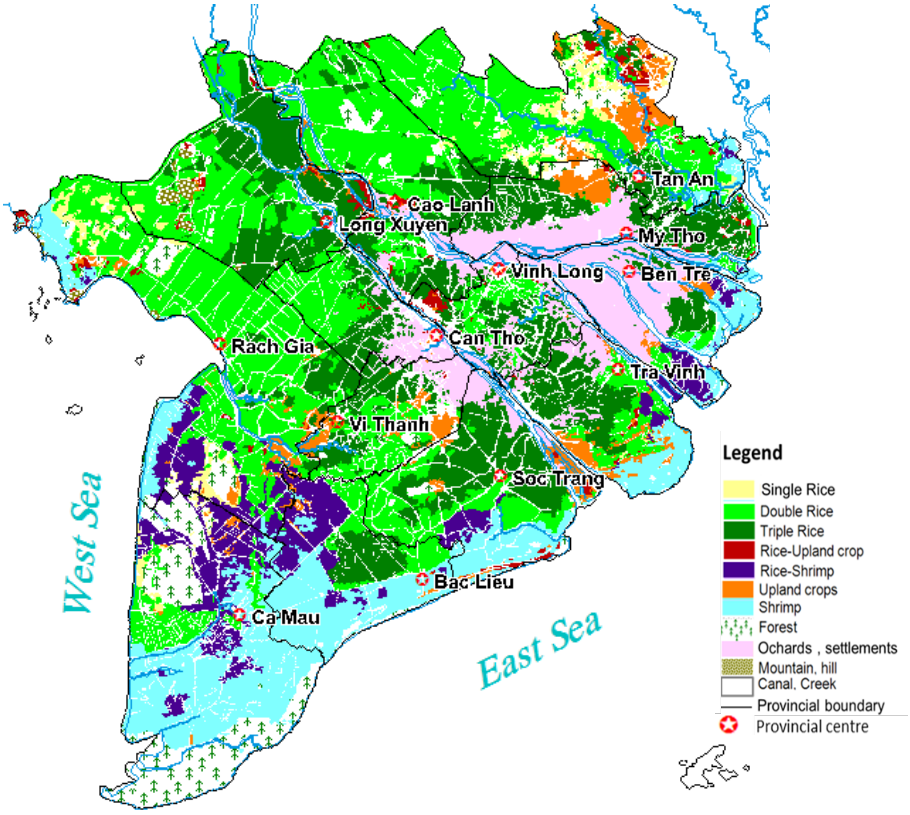

Figure 2. Land use 2010 of the Vietnamese Mekong Delta. Source: figure adopted from Wassmann et al. 2019

Rice production in the MRD can be classified according to seasons, specifically, early year (October to June), mid-year (May to November), and late year season (December to April) (Vo et al, 2020). The areas of each cropping season, however, greatly differs in the sub-zones[1] as follows: saline (close to the sea), acid sulfate, alluvial (mid-delta) and the deep flood (upper delta) (Vo et al, 2018). These spatio-temporal patterns of rice cultivation are reflected by

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[1] In Vo et al. 2018, the term “agro-ecological zone” is used to distinguish between individual parts of the MRD. In Vo et al. 2020, however, the same terms refer to the agro-ecological zones at national level, i.e. the MRD is considered one zone. To avoid confusion in the introduction and discussion of this dissertation, I consistently use the term “zone” for the differentiation at national scale and “sub-zone” for the inner differentiation of the MRD.

differences in rice yield per location and season. In general, the rice yields are higher in the early season and lower in the late season as a function of the solar radiation and hydrological conditions, specifically availability of irrigation water and salt-water intrusion in saline areas (Wassmann et al, 2009).

2. Calculating emissions at sub-national and national scales according to the IPCC guidelines

Given the emphasis on emission factors in the individual studies of this dissertation, it seems appropriate to provide some background information on the overall concept of extrapolating GHG emissions to sub-national and national scales. The IPCC is a widely recognized institution that was "created to provide policymakers with regular scientific assessments on climate change". Among the core mandate, the 4th Working group has developed the technical guidelines for national GHG inventories as part of the National Communications to be submitted to the UNFCCC. At this point, the most recent version comprises the 2019 Refinement of the 2006 Guidelines (IPCC 2019) whereas the incumbent National Communications for most countries are still based on the original version of the 2006 Guidelines (IPCC 2006). The list of countries includes Vietnam and the most recent 3rd National Communications submitted in 2019 (MONRE 2019). Concerning the emissions of CH_4 and N_2O from the agricultural sector, however, the 2019 refinements are fairly small and limited to some default values for EFs whereas the underlying equations remain unchanged.

Regarding CH_4 from rice fields, the fundamental approach to calculate baseline emissions is expressed in Equation 1 (simplified form):

$$E_{CH4} = \sum_{i,j}(EF_{i,j} \times SF_w \times t_{i,j} \times A \times 10^{-3}) \qquad \text{(Equation 1)}$$

Where

E_{CH4} = annual methane emissions from rice cultivation (t CH_4 yr^{-1})

EF = daily emission factor for continuously flooded fields without organic amendments (in kg ha^{-1} d^{-1})

SF_w = Scaling factor for water management (unitless)

t = cultivation period of rice

A = annual harvested area of rice

i, j = represent different ecosystems and cropping seasons under which CH_4 emissions from rice may vary (disaggregation)

10^{-3} = conversion factor from kg CH_4 to t CH_4

In the field studies described below, the focus of Chapter 2 (Vo et al. 2018) and 3 (Vo et al. 2020) was on the baseline EFs to elevate the national GHG inventories from the use of a global IPCC default (Tier 1) to disaggregated values for different agro-ecologiocal zones of Vietnam and sub-zones of the MRD (Tier 2). In addition, Chapter 4 (Vo et al. 2023) also assesses the SF for water management as determined in the field measurement against the baseline condition of the IPCC default. It should be noted though that the original IPCC equation encompasses more SFs than for water management, including for organic amendment and pre-season aeration but those are irrelevant to the context of the field studies described below. In contrast to CH_4, the approach for calculating N_2O emissions is not based on area, but on the amount of nitrogen fertilizer applied (see simplified form in equation 3).

$$E_{N2O} = \sum_{i,j}(F_N \times EF_{N2O}) \times \frac{44}{28} \times 10^{-3} \qquad \text{(Equation 2)}$$

Where

E_{N2O} = annual N_2O emissions from rice cultivation (t N_2O yr^{-1})

F_N = annual amount of nitrogen fertilizer N applied to soils, kg N yr^{-1}

EF_{N2O} = emission factor for N_2O emissions from N inputs for rice production (kg N_2O–N kg N^{-1}) which is either 0.003 for continuously flooded or 0.005 for single and multiple drainage

$\frac{44}{28} \times 10^{-3}$ = conversion factors from kg N_2O-N to t N_2O

Similar to equation 1, the equation for N_2O emissions was simplified by disregarding possible N-inputs from organic amendments.

The emissions of CH_4 and N_2O are converted into CO_2e as a common metric for all GHGs which is done by multiplication with the Global Warming Potential (GWP). The GWP values used in the most recent GHG Inventory of Vietnam is 25 CO_2e for CH_4 and 298 CO_2e for N_2O. These values refer to a time horizon of 100 years and were adopted from the 4th IPCC Assessment Report. As shown in Table 1 (chapter 1), these values were updated in the ensuing Assessment Reports (IPCC 2009) indicating a slightly higher value for CH_4 and lower value for N_2O. While these changes comprise less than 10% of the previous GWP-value, it should be noted that the definition of a 100-year time horizon as a commonly accepted standard for GWP is inherently arbitrary. In light of the ambitious targets of limiting temperature increase to 1.5/ 2° C set in the Paris Agreement, the mitigation impacts have to occur over a much shorter time horizon (Van den Berg et al., 2015). Therefore, the most recent Assessment Report provides GWP-values over a 20-year horizon (Table 1). The major difference in these adjusted values is the GWP_{20} for CH_4 which is almost triple of the value of GWP_{100}. As mentioned in Chapter 4 (Vo et al. 2023), these GWP20 value of 97.7 corroborates the decisive role of targeting the reduction of CH_4 emissions to meet the targets of the Paris Agreement and thus, the significance of mitigation programs in rice within the Vietnamese context.

Table 1: GWP values of CH_4 and N_2O given in CO_2e for time horizons of 100 (GWP_{100}) and 20 years (GWP_{20}), respectively; AR4, AR5 and AR6 refer to the 4th (IPCC 2007), 5th (IPCC 20013) and 6th Assessment Report (IPCC 20021), respectively.

	AR4	AR5	AR6		Lifetime
	GWP_{100}	GWP_{100}	GWP_{100}	GWP_{20}	(years)
CH_4 - non-fossil	25[a)]	28[a)]	27 ± 11	79.7 ± 25.8	12
N_2O	298[a)]	265[a)]	273 ± 130	273 ± 118	114

[a)] No error ranges are given

3. Emission Factors used in Vietnam's National Communications

Rice production is a source of CH_4 due to flooding of the fields that generate anaerobic conditions in the soils which is the pre-requisite for microbial CH_4 formation. The global default Emission Factor (EF) given the most recent IPCC Guidelines is 1.19 kg CH_4 ha^{-1} d^{-1} and 1.22 kg CH_4 ha^{-1} d^{-1} for Southeast Asia region (IPCC 2019). This Tier 1 default value was computed by averaging all available field records at that time and refers to baseline crop management, specifically continuous flooding without organic manure.

In Vietnam, the GHG inventory in the latest National Communication is based on nationally determined EFs (Tier 2) that are converted to CO_2e by using GWPs of 25 for CH_4 and 298 for N_2O, respectively. According to the official figures submitted to the UNFCCC (MONRE 2019), CH_4 emissions from rice production (irrigated and rainfed) accounts for 44.29 Mt CO_2e. This high value makes rice the second largest GHG source in the national economy (after "energy industry") and by far the most important source (49.3%) within the agriculture sector (MONRE 2019). Although the GHG inventory does not provide data for specific regions at sub-national scale, it can be assumed that the MRD with more than 50% of the national rice area also contributes a major share of this emission.

Given the intensive rice production and the variations in bio-physical conditions (soil and hydrological feature), the geographic characterization of GHG emissions will require multiple-site measurements to account for the differences among the rice-growing environments. In the case of Vietnam in general and the MRD in particular, the GHG measurements have to consider both regional and seasonal factors -- called for disaggregation in the IPCC guidelines -- instead of blanket EFs to improve the reliability of emissions estimates.

In contrast, N_2O emissions, the GHG inventory in the National Communication only provides an aggregate figure for all land uses and no specific value for rice production. The direct N_2O emissions from all agricultural soils account for 13.4 Mt CO_2e which is roughly a third of the CH_4 emissions from rice alone. Although rice land shares 82% of the cultivated land area in Vietnam, the relative share in N_2O emissions from rice production will be smaller than this figure because the IPCC emission factor used for N_2O from upland crops (0.01) is considerably higher than for wetland rice production (0.003 for continuous flooding and 0.005 for frequent drainage).

As shown above in equation 1, the IPCC approach for calculating CH_4 emissions at national scale requires disaggregated data on rice area. Although the data acquisition of this ‘activity data’ was beyond the scope of this dissertation, it seems adequate to set the improvements in disaggregated emission factor in the context of other uncertainties in calculating CH_4 emission at national scale. In principle, this ‘activity data’ can be adopted from national statistics that typically list the area grown for different crops per province and season, e.g. the statistics compiled by the General Statistics Office (GSO) for Vietnamese rice production. However, these statistics do not provide any data on the crucial factors that affect CH_4 emissions, particularly water management practices, organic amendments and straw treatment. These conditions do not only vary from location to location, but can even differ for specific season as a function of water availability, duration of fallow periods, etc. As shown in a recent study for Vietnamese rice production based on simulation models, the insufficient information on activity data presents the key uncertainty for CH_4 emission estimates at national scale (Butterbach-Bahl et al. 2022). The uncertainties in water management information will also affect the N_2O estimates at national scale, although the overall data availability is better than for CH_4 because the consumption of synthetic fertilizers is captured in national statistics.

4. The role of water management in reducing emissions from rice production in the MRD

In contrast to many other developing countries, the Vietnamese government has already paid special attention to the agricultural sector in assessing potential mitigation options which is reflected in ambitious goals in the Nationally Determined Contributions (NDCs) submitted to the UNFCCC (MONRE 2022). In the case of rice production, water saving strategies were identified as the key option to reduce CH_4 emissions. Other crop management practices such as split application of fertilizer and residue recycling have also been tested in field measurements, but to date, the practice of AWD stands out as the most promising and mature approach (Wassmann et al., 2019). From the government side, AWD has also been the core innovation in government projects and programs promoting the sustainable development of rice in the MRD with the aim of reducing water consumption for irrigation. Despite its co-benefits in terms of resource efficiency, however, AWD has not yet been adopted at a larger scale. This can be partly attributed to limited incentives for farmers to change their irrigation practice, labour demanding and yield penalty. Saving irrigation water could potentially help coping with water scarcity (Sander et al., 2017), but does not always translate into immediate financial returns for farmers given the free access or non-volumetric pricing schemes of irrigation water. Thus, AWD should be introduced to farmers as an integral part of advanced technology packages – including well-selected varieties – rather than being promoted as a stand-alone approach.

5. Varietal selection: Evidence and mechanisms of rice plants affecting emissions

Several field studies have reported differences in GHG emissions due to the use of different rice varieties (Win et al. 2021, Das and Baruah 2008, Setyanto et al. 2004, Wang et al. 2016, Wang et al. 1997, Oo et al. 2016, Singh et al. 1997, Khosa et al. 2010...). Based on the current mechanistic understanding, the main impact pathways of rice plants on emissions are through

- the duration of plant maturity resulting in either short or long flooding periods and thus, low or high seasonal fluxes of CH_4, respectively, even if daily emission rates remain unaffected (Wassmann et al. 2000)
- the aerenchyma development, which determines the diffusion rate of gases through the rice plants, e.g. oxygen moving downward and CH_4 upward (Aulakh et al. 2000, Kim et al. 2018)
- production of root exudates which provide substrate for methanogenic microbes (Lu et al. 2000) and organic C as an energy source for denitrifiers.
- regulation of carbon allocation to the grain ('carbon sink') resulting in a similar impact mechanism as root exudation and probably even expressed indirectly through changes in exudation (Yu et al. 2013).

So far, the only mitigation strategy based on varietal selection is the introduction of varieties with short plant duration in fields previously planted with long-duration varieties. Wassmann et al. (2000) compared seasonal emissions in a field experiment in Indonesia, the new variety with a short duration (110 d) had a proportionally lower seasonal emission as compared to the traditional variety with a duration of 140 d. This straight-forward concept is also reflected in the IPCC methodology for GHG inventories (IPCC 2019) that multiplies daily emission rates by the days from planting to harvest. In many regions with intensive rice cultivation, season lengths have been reduced by new varieties to less than 100 d (e.g. as short as 90 d in the

Vietnamese Mekong Delta). Nevertheless, it seems a rarely acknowledged fact that the prevailing development of rice production systems toward shorter season length – facilitated through breeding of new rice varieties – has reduced emissions at a global scale.

Several research projects have investigated the particular functions of aerenchyma properties on GHG emissions from rice and also considered external factors that influence ontogenetic development. In spite of a wealth of new information on the mechanistic basis of CH_4 emissions, it is still not possible to classify low-emitting vs. high-emitting varieties based on this functional trait. However, as of now, it is not clear whether the restrictions on gas transport by less permeable aerenchyma will increase or decrease CH_4 emissions. Both effects could be justified by the antagonistic mechanisms of stimulating oxidation vs. constraining upward flux of CH_4. Varietal differences in terms of aerenchyma diffusivity have been reported under controlled conditions (culture solution) but these differentiations could not be replicated under field conditions. Obviously, the expression of this functional trait under field conditions is affected by pronounced Genotype-by-Environment-by-Management interaction. Aerenchyma development is stimulated by low redox-potentials in the soil, a factor that is known to exhibit strong spatial and temporal variations.

Root exudation in rice was studied in many projects including a set of experiments aiming at understanding its influence on CH_4 emission. Low root exudation reduces the pool of methanogenic substrate in the soil but also limits the loss of assimilates for the plant. Thus, breeding for plants with low root exudation will also result in synergies for increased yield potentials. Root exudation, however, shows a similar variability under field conditions as aerenchyma development, so that proper crop management will be needed to achieve the desired mitigation effect. The exact mechanisms determining root exudation are not well understood, although nutrient deficiency, such as phosphorus deficiency, has been identified as a driver of high exudation rates (Lu et al. 2000).

The role of carbon allocation to the grain for GHG emissions was originally derived from statistical analysis of an inverse relationship between CH_4 emissions and yields alongside with a clipping experiment (van der Gon et al., 2000). In this experiment, the carbon sink mechanism has been inhibited by cutting off the spikelets, so that more carbon was available for methanogen leading to higher emissions. This relationship between high carbon sink and low CH_4 emissions appears straight-forward for below-ground biomass whereas the actual recycling rate of above-ground biomass into the soil will depend on the respective straw management and will not be that evident.

Recently, this concept of increasing the carbon sink has gained specific attention through an experiment with GMO rice. Su et al. (2005) have introgressed a gene from barley into rice plants that showed higher rice starch and less CH_4 emissions. The authors of this study postulated that a higher carbon sink in the plant will translate into less root exudation, although direct proof of this mechanism has not been shown as of now. While more starch allocation in the grain is obviously a favourable feature, it remains to be seen if this GMO study will have any practical implications on GHG mitigation. Any transgenic rice will need an enormous lead time before such plants may be grown in farmers' fields – even if the results on plant performance observed in tightly controlled greenhouses will prove to be transferrable to field conditions.

In addition to the direct impact pathways, the suitability of different rice varieties for mitigation can also indirectly be affected through their plasticity to cope with changing crop management. The shift from CF to AWD significantly alters a wide range of bio-physical factors in the rhizosphere (Norton et al. 2017). Thus, it seems reasonable to assume that distinct rice varieties differ in their development of roots and aerenchyma that will in the next step modify CH_4 emission rates. Moreover, fertilization also has to be considered because of its impacts on root exudation (see above) and plant vigour in general.

Moreover, the selection of varieties could also affect emissions of N_2O, a GHG with has higher radiative forcing (GWP = 265) as compared to CH_4 (GWP = 28). Generally speaking, the swift plant uptake of ammonia, the dominant form of nitrogen in flooded soils, will limit the microbial turnover rates of nitrification as a source of N_2O ("whole in the pipe model"). The same applies to the plant uptake of nitrate that will become available under AWD and can also result in N_2O emissions through denitrification. Moreover, a recent publication has postulated that the carbon allocation to the grain will also reduce N_2O emissions. The underlying hypothesis for this finding is that a higher carbon sink will reduce the plant carbon pool that could potentially be released to the soil in form of root exudation. In turn, this lack of organic substrate will decline the soil organic carbon pool and thus, energy supply for the bacteria producing N_2O. The principles of site-specific nutrient management will prevent any excessive nitrogen concentration in the soil while it should be noted that the nutrient demand is a function of space and time – and ultimately also of variety selection

6. Research context and objectives

The research topic of the presented studies derives from the broader context of the current GHG inventory roles as well as future mitigation scenarios. Conceptually, these studies are placed at the interface of field measurements and the extrapolation of field data to larger scales. As a common denominator, the empirical data is evaluated with the aim of quantifying both baseline emissions as well as potential mitigation impacts at the scale of the MRD or the entire Vietnam.

The individual studies improve the knowledge base on GHG emissions from rice production

- in width – by compiling multiple sites in coherent data bases; and
- in depth – by adding detailed information on the interaction of rice variety and water management.

The compilation of measurement sites reflects a vigorous attempt to measure EFs across different regions and cropping seasons. To the best of my knowledge, the density of the measurement network at the national appears unmatched for any crop or country worldwide. While the studies in chapters 2 and 3 capitalize on field data provided by cooperating research groups, the main task in these studies was the consolidation of previously scattered and heterogenous data sets within coherent presentations and data evaluations.

Regarding the newly implemented field measurements used in chapter 4 (Vo et al. 2023) and 5 (Asch et al. 2023), their innovative feature lies in the focus on rice varieties that are considered for their stand-alone impacts as well as their interaction with water management. It should be noted, the dimension of this field layout with 120 plots clearly exceeded the typical sizes of other field studies on GHG emissions that can be found in the literature.

The specific objectives of the individual studies under this dissertation can be grouped into two clusters:

The first cluster of objectives relates to the assessment of GHG emissions in Vietnamese rice production with emphasizing on the MRD:

- To determine EFs for both CH_4 and N_2O in the MRD
- To disaggregate these EFs for different rice growing regions and seasons;
- To assemble a database on baseline emissions for the forthcoming GHG assessments in the National Communications (IPCC Tier 2 approach)
- To assess the impact of AWD in form of a scaling factor that could be used to identify low-emitting varieties for future mitigation projects.
- To set the newly obtained values for both EF and SF into the context of the existing IPCC defaults used in the current GHG inventory

The second cluster of objectives was the selection of rice varieties effecting GHG emissions and its mitigation potential:

- To quantify GHG emission potentials of 20 different rice varieties

- To assess the interactive impacts of varieties and different water management on CH_4 and N_2O emissions
- To determine the SFs of the tested rice varieties
- To explore the effect of low-emitting varieties on emission at the provincial scale as well as for potential mitigation projects in the context of carbon crediting

References

Asch, F., Johnson, K., Vo, T.B.T., Sander, O., Duong, V.N, Wassmann, R. (2023). Varietal effects on methane productivity of paddy fields under different irrigation management. [Manuscript submitted for publication]. Journal of Agronomy and Crop Science.

Aulakh M.S., Bodenbender, J., Wassmann, R, Rennenberg, H. Methane transport capacity of rice plants, II. Variations among different rice cultivars and relationship with morphological characteristics. NutrCycling Agroecosyst. 2000; 58: 367–375.

Butterbach-Bahl, K., Kraus, D., Kiese, R., Mai, V. T., Nguyen, T., Sander, B. O., Wassmann, R., & Werner, C. (2022). Activity data on crop management define uncertainty of CH_4 and N_2O emission estimates from rice: A case study of vietnam. Journal of Plant Nutrition and Soil Science, 185, 793– 806. https://doi.org/10.1002/jpln.202200382

Das, K., & Baruah, K. K. (2008). Methane Emission Associated with Anatomical and Morphological Characteristics of Rice (Oryza sativa) Plant. Physiologia Plantarum, 134, 303-312. https://doi.org/10.1111/j.1399-3054.2008.01137.x

Fukagawa, N.K., Ziska, L.H. Rice: Importance for Global Nutrition. J Nutr Sci Vitaminol (Tokyo). 2019;65(Supplement):S2-S3. doi: 10.3177/jnsv.65.S2. PMID: 31619630.

GSO (General Statistics Office of Viet Nam) 2021. Planted Area and Production of Paddy. Available online: https://www.gso.gov.vn/default_en.aspx?tabid=778 (accessed March 2023)

IPCC (Intergovernmental Panel on Climate Change) 2006: Agriculture, forestry and other land use. In 2006 IPCC guidelines for national green- house gas inventories, Eds Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K, Institute for Global Environmental Studies (IGES), Hayama, Japan

IPCC (Intergovernmental Panel on Climate Change) 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge and New York: Cambridge University Press)

IPCC (Intergovernmental Panel on Climate Change) 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535

IPCC (Intergovernmental Panel on Climate Change) 2019. Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S., Eds.; IPCC: Geneva, Switzerland, 2019.

IPCC (Intergovernmental Panel on Climate Change) 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P.

Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

Khosa, M.K., Sidhu, B.S., Benbi, D.K. Effect of organic materials and rice cultivars on methane emission from rice field. J Environ Biol., 2010; 31: 281–285.pmid:21046997

Kim, W., Bui, L.T., Chun, J., McClung, A.M., & Barnaby, J.Y. (2018). Correlation between Methane (CH_4) Emissions and Root Aerenchyma of Rice Varieties. Plant Breeding and Biotechnology.

Lu, Y., Wassmann, R., Neue, H.U., Huang, C., Bueno, C.S. Methanogenic responses to exogenous substrates in anaerobic rice soils, Soil Biology and Biochemistry, Volume 32, Issues 11–12, 2000, Pages 1683-1690, ISSN 0038-0717. https://doi.org/10.1016/S0038-0717(00)00085-7.

MONRE - Ministry of Natural Resources and Environment (2019). Vietnam's 3rd National Communication for the United Nations Framework Convention on Climate Change. https://unfccc.int/documents/192805

MONRE - Ministry Of Natural Resources And Environment, 2022. Nationally Determined Contribution (updated in 2022)file:///C:/Users/RW/Downloads/Viet%2520Nam_NDC_2022_Eng.pdf.

Norton, G.J., Travis, A.J., Danku, J.M.C.; Salt, D.E., Hossain, M., Islam, Md. R., Price, A.H. (2017). Biomass and elemental concentrations of 22 rice cultivars grown under alternate wetting and drying conditions at three field sites in Bangladesh. Food and Energy Security, (), –. doi:10.1002/fes3.110

Oo, A.Z., Win, KT.., Motobayashi, T. and Bellingrath-Kimura, S.D. Effect of cattle manure amendment and rice cultivars on methane emission from paddy ricesoil under continuously flooded conditions. J. Environmental Biology, 2016; 37(5): 1029–1036.

Preston, N., Clayton, H. 2003: Rice-shrimp farming in the Mekong Delta: biophysical and socioeconomic issues. ACIAR Technical Reports No. 52e, 5

Sander, B.O., Wassmann, R., Palao L.K., Nelson, A. (2017). Climate-based suitability assessment for alternate wetting and drying water management in the Philippines: a novel approach for mapping methane mitigation potential in rice production, Carbon Management, 8:4, 331-342, DOI: 10.1080/17583004.2017.1362945

Setyanto, P., Rosenani, A.B., Boer, R., Fauziah, C.I. and Khanif, M.J. The effect of rice cultivars on methane emission from irrigated rice field. Indonesian J AgricSci., 2004; 5: 20–31.

Singh, S., Kumar, S., Jain, M.C. Methane emission from two Indian soils planted with different rice cultivars. Biol Fert Soils. 1997; 25: 285–289.

Su, J., Hu, C., Yan, X., Jin, Y., Chen, Z., Guan, Q., Wang, Y., Zhong, D., Jansson, C., Wang, F., Schnürer, A., Sun, C. Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice. Nature. 2015 Jul 30;523(7562):602-6. doi: 10.1038/nature14673. Epub 2015 Jul 22. PMID: 26200336.

Van den Berg, M. Hof, A.F. van Vliet, J., van Vuuren, D.P. 2015. Impact of the choice of emission metric on greenhouse gas abatement and costs. Environ. Res. Lett. 10 (2015) 024001 doi:10.1088/1748-9326/10/2/024001

Van der Gon, H. D. (2000). Changes in CH4 emission from rice fields from 1960 to 1990s: 1. Impacts of modern rice technology. Global Biogeochemical Cycles, 14(1), 61-72.

Vo, T. B. T., Johnson, K., Wassmann, R., Sander, B.O., Asch, F (2023). Varietal effects on greenhouse gas emissions from rice production systems under different water management in the Vietnamese Mekong Delta [Manuscript submitted for publication]. Journal of Agronomy and Crop Science.

Vo, T.B.T., Wassmann, R., Tirol-Padre, A., Cao, V.P., MacDonald, B., Espaldon, M.V.O. and Sander. B.O. 2018. “Methane Emission from Rice Cultivation in Different Agro-Ecological Zones of the Mekong River Delta: Seasonal Patterns and Emission Factors for Baseline Water Management.” Soil Science and Plant Nutrition 64 (1): 47–58. https://DOI: 10.1080/00380768.2017.1413926

Vo, T.B.T.; Wassmann, R.; Mai, V.T.; Vu, D.Q.; Bui, T.P.L.; Vu, T.H.; Dinh, Q.H.; Yen, B.T.; Asch, F.; Sander, B.O. Correction: Vo, T.B.T., et al. Methane Emission Factors from Vietnamese Rice Production: Pooling Data of 36 Field Sites for Meta-analysis. Climate 2020, 8, 74. Climate 2020, 8, 113. https://doi.org/10.3390/cli8100113

Wang, B., Neue, H.U., Samonte, H.P. Effect of cultivar difference (‘IR72’, ‘IR65598’ and ‘Dular’) on methane emission. Agric Ecosyst Environ., 1997; 62: 31–40.

Wang, W., Lai, D.Y.F., Wang, C., Tong, C., Zeng, C. Effects of inorganic amendments, rice cultivars and cultivation methods on greenhouse gas emissions andrice productivity in a subtropical paddy field. Ecological Engineering 2016; 95: 770–778.

Wassmann, R., Jagadish, S.V.K., Sumfleth, K., Pathak, H., Howell, G., Ismail, A., Serraj, R., Redoña, E., Singh, RK.. and Heuer, S. 2009. Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. Advances in Agronomy 102, 91-133

Wassmann, R., Neue, H.U., Lantin, R.S. (2000) Characterization of methane emissions from rice fields in Asia. 1. Comparison among field sites in five countries. Nutrient Cycling Agroecosystems 58: 1-12

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, T.M. Corton and Y. Lu (2000) Characterization of methane emissions in Asia III: Mitigation options and future research needs. Nutrient Cycling in Agroecosystems 58: 23-36, 2000, 2000 Kluwer Academic Publishers, The Netherlands.

Wassmann, R., Phong, N.D., Tho, T.Q., Hoanh, T.T., Khoi, N.H., Hien, N.X., Vo, T.B.T., Tuong, T.P. High-Resolution Mapping of Flood and Salinity Risks for Rice Production in the Vietnamese Mekong Delta. *Field Crops Res.* **2019**, *236*, 111–120. Kim, W., Bui, L.T., Chun, J., McClung, A.M., & Barnaby, J.Y. (2018). Correlation between Methane (CH_4) Emissions and Root Aerenchyma of Rice Varieties. Plant Breeding and Biotechnology.

Win, E.PO., Kyaw Kyaw Win, Sonoko D. Bellingrath-Kimura, Aung Zaw Oo. 2021. Influence of rice varieties, organic manure and water management on greenhouse gas emissions from paddy rice soils. https://doi.org/10.1371/journal.pone.0253755

Yu, J., Wang, L.L., Yan, X.J., Tian, Y.L., Deng, A.X., Zhang, W.J. Super rice cropping will enhance rice yield and reduce CH_4 emission: a case study in Nanjing, China. Rice Sci., 2013; 20: 427–433.

CHAPTER 2

METHANE EMISSION FROM RICE CULTIVATION IN DIFFERENT AGRO-ECOLOGICAL ZONES OF THE MEKONG RIVER DELTA: SEASONAL PATTERNS AND EMISSION FACTORS FOR BASELINE WATER MANAGEMENT

Vo et al. 2018[2]

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Supplementary data of this chapter can be found in Appendix 1, page 129 or accessed at https://www.tandfonline.com/doi/suppl/10.1080/00380768.2017.1413926

Abstract

This study comprises a set of methane emission measurements in rice fields located in the four agro ecological zones of the Mekong River Delta (MRD), namely the zones with (i) alluvial soils, (ii) salinity intrusion, (iii) deep flood, and (iv) acid sulfate soils. These zones have very distinct bio-physical conditions and cropping cycles that will affect methane emissions in various forms. Our study includes comprehensive mapping of these zones as well as an overview of rice statistics (activity data) at provincial level for each cropping season. Emission data were obtained by the closed chamber method. The available data set comprises 7 sites with 15 cropping seasons. Mean emission rates showed large variations ranging from 0.31 to 9.14 kg CH_4 ha^{-1} d^{-1}. Statistical analysis resulted in weighted means for all zones that we use as zone-specific CH_4 emission factors (EF_z) in the context of the IPCC Tier 2 approach. The lowest EF_z was computed for the saline accounting for 1.14 kg CH_4 ha^{-1} d^{-1} (confidence interval: 0.60–2.14). The EF_z values of the alluvial and acid sulfate zones were 2.39 kg CH_4 ha^{-1} d^{-1} (2.19–4.13) and 2.78 kg CH_4 ha^{-1} d^{-1} (2.65–3.76), respectively, which indicated that they were not different from each other derived from their confidence intervals. The deep flood zone, however, required a season-specific, assessment of EF_z because emission in the autumn–winter cropping season, corresponding to the wet period, was significantly higher (9.14 kg CH_4 ha^{-1} d^{-1} (7.08–11.2)) than the other seasons (2.24 kg CH_4 ha^{-1} d^{-1} (1.59–3.47)). Although these emission factors correspond to baseline water management and do not capture the diversity of farmers' practices, we see the availability of zone-specific data as an important step for a more detailed assessment of Business as Usual emissions as well as possible mitigation potentials in one of the most important rice growing regions of the world.

Key words: Greenhouse gas; alluvial soil; acid sulfate soil; salinity; flooding

1. Introduction

The Mekong River Delta (MRD) is popularly known as the ‘Rice Bowl’ of Vietnam. With a harvested area of 4.25 Mha, this region produces more than 25 million tons of rice yearly accounting for 56% of the Vietnamese rice production (GSO; data for 2014). Rice production forms the backbone of the economy of the delta and represents primary livelihood for 60% of the 17 million inhabitants of the Mekong Delta (Kaekoenen 2008). Also at national scale, rice from the MRD is an important commodity by ensuring a large surplus pro duction that can be used for exports. Overall, Vietnam is the third-largest rice-exporting country with annual exports reaching 4.5 million tons (Nathan 2016). The MRD is an ecologically very diverse region that comprises 13 provinces that differ largely in terms of cropping intensity at different seasons (Fig. 1). Rice in MRD is grown in different cropping cycles ranging from single to triple crops per year as shown in Fig. 2 jointly with the periods of salinity and deep flood risks. Rice production represents a large methane source (CH_4) within the Viet Nam’s GHG budget, but the quantification of the CH_4 source strength can only be given with a high range of uncertainty. It must be noted that rice production is also a source of other GHGs such as N_2O, but those emissions are typically low (Sander et al. 2014). The GHG inventory in the most recent National Communication of Vietnam, based on the global default emission rates, concluded that rice production accounts for 1.78 Mt CO_2eq at national scale, equivalent to 57.5% of the GHG emissions from agriculture or 26.1% of all GHG sources (MONRE 2010). These values were revised in 2014 (MONRE 2014) and it was estimated that rice accounts for 50.5% of emissions from agriculture and 18.1% of all GHG emissions in Vietnam. However, these national GHG inventories do not provide data for specific regions at subnational scale, so there is no direct quote on the specific GHG contribution of the MRD. This region accounts for 54.4% of the total rice area in Vietnam (GSO for data 2014) and – as a first approximation – its GHG contribution will be in a similar range. The MRD forms a highly diverse region in terms of soil constraints (acidity and salinity) and hydrological features (flooding, availability, and quality) that directly impact on the rice-growing conditions and GHG emissions at any given location and season (Fig. 1).

In this regard, the MRD is similar to other Asian mega- deltas which have very intensive rice production tailored to deltaic bio-physical conditions. The deltaic rice production systems are characterized by very specific hydrological conditions as compared to other rice-growing environments (Wassmann *et al*. 2009), so that the application of default emission factors may be erroneous. However, there are only few studies published on methane emissions of rice grown in such environments (Pandey Nguyen et al. 2014; Arai et al. 2015; Vu et al. 2015; Nguyen et al. 2016; Tariq et al. 2017; Tirol-Padre et al. 2017).

The objectives of our study were (1) to assess the spatial and seasonal variability of CH_4 emissions under conventional rice cultivation over a wide range of rice environments in the MRD and (2) to determine zone-specific emission factors on CH_4 emissions as a basis for future upscaling.

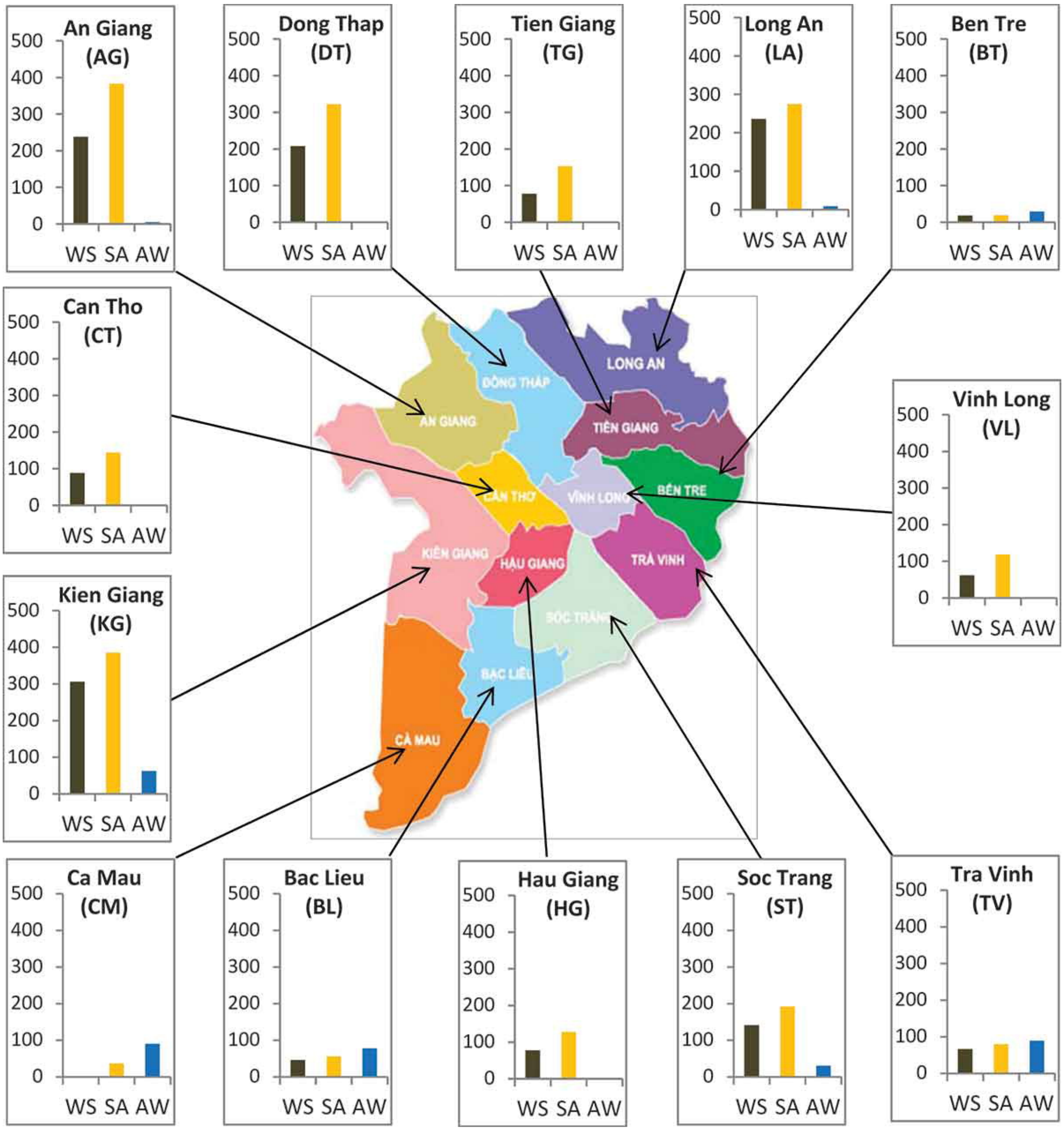


Figure 1. Maps of the MRD provinces alongside with diagrams of rice area per season and province (in ‘000 ha), statistics data for the year 2014 obtained from GSO (http://www.gso.gov.vn)

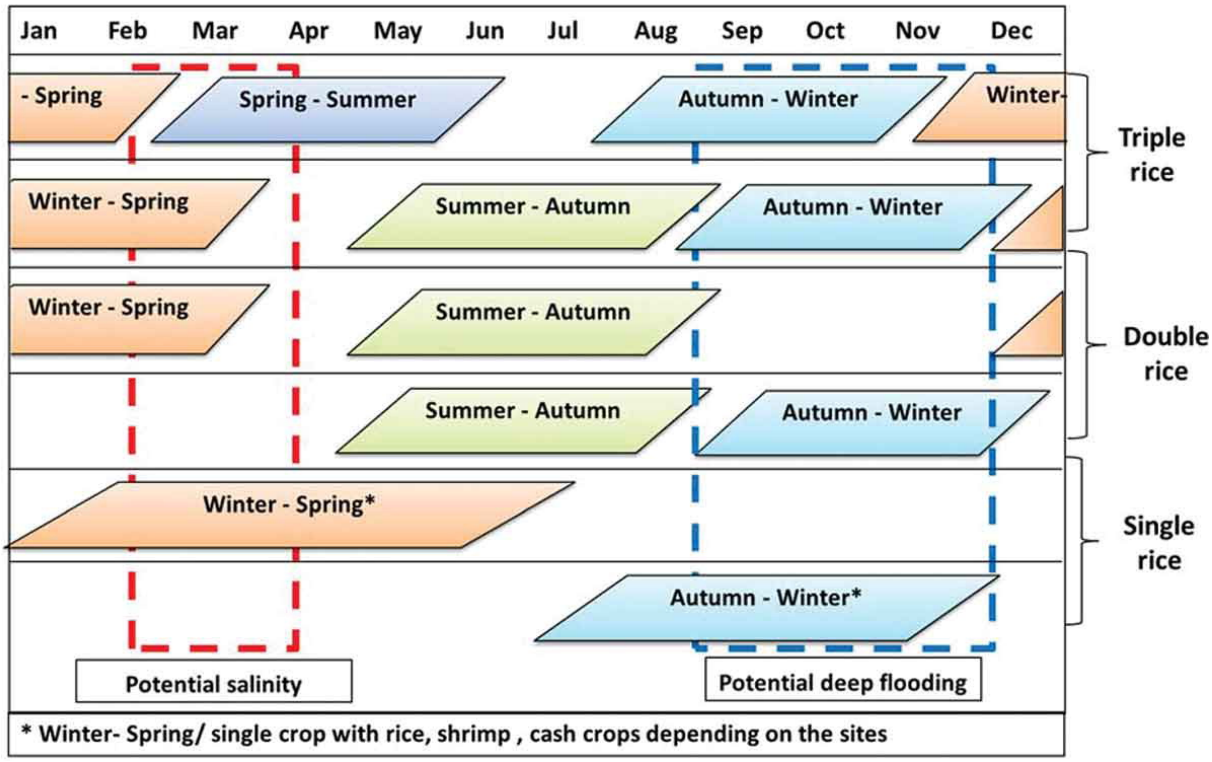


Figure 2. Simplified rice cropping calendar in MRD.

2. Materials and methods

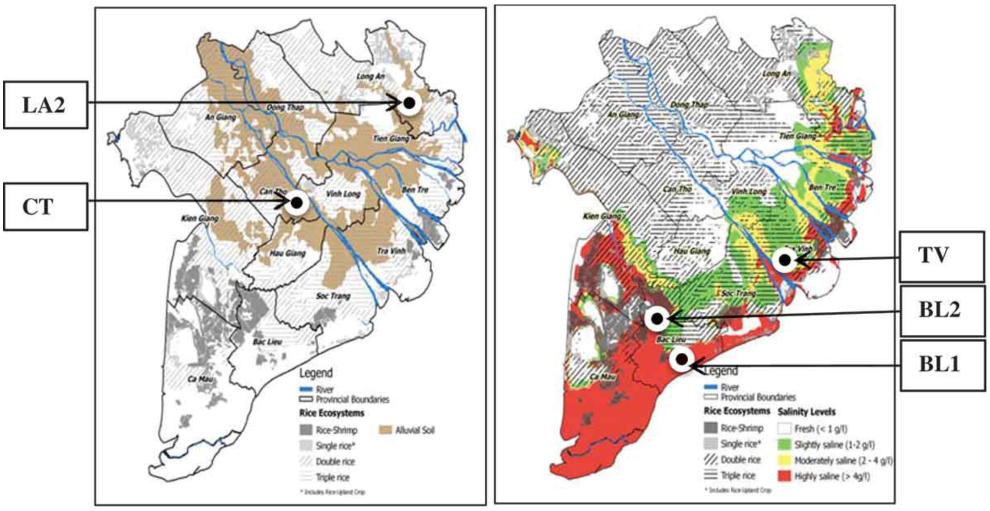
2.1. Agro-ecological zones of the MRD with relevance to the CH_4 budget

2.1.1. Alluvial zone

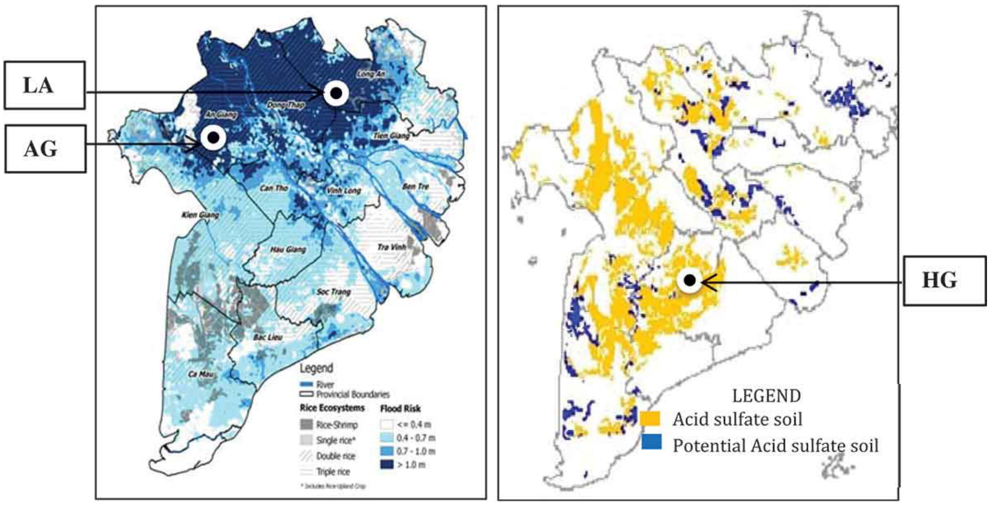
This zone basically comprises the bulk of the favorable rice fields along the river branches (Fig. 3). Land use is very intense with wo to three rice crops per year. Only years with extreme climatic conditions will exert adverse impacts on rice productions, e.g., El Niño years associated with droughts and high salinity intrusion as observed in 2016. Conversely, the alluvial area can be affected by floods in years with high river discharge and rainfall as has happened in the year 2000. As a response to this flood disasters in the past, the government has provided large investments for flood protection that have prevented flash floods in the alluvial zone during recent years – even in years with higher water levels.

2.1.2. Saline zone

In the dry season (winter–spring crop (WS)), salinity intrusion is a major impediment for rice production along the entire coastal belt with few exceptions, smaller areas with prevailing freshwater conditions on the west coast and Ca Mau peninsular (Fig. 3). Salinity is effectively absent during the high- water season (autumn–winter crop (AW)), so that this forms the main rice season in most parts of the saline zone (Fig. 1). The area classified as saline zone comprises very diverse rice-growing environments with different degrees of salinity problems over space and time. Newly constructed sluices are now shielding larger parts of the coastal belt from salinity intrusion. However, salinity protection can be in sufficient in especially dry years, e.g., in the El Nino event of 2016, when salinity intrusion reaches far inland.



Alluvial zone Saline zone



Deep flood zone Acid sulfate zone

Figure 3. Maps of alluvial, saline, deep flood, and acid sulfate zone alongside with measurement sites. Redrawn from the following sources: Nguyen et al. (2017) for alluvial; CLUES project for saline and deep flood; Soil and Fertilizer Research Institute (SFRI), Hanoi for acid sulfate soil; maps drawn by Jorrel Khalil Aunario (IRRI GIS lab).

2.1.3. Deep flood zone

Almost the entire northern part of the delta is characterized by deep flood during the wet season (AW) lasting from September to November (Fig. 3). However, large parts in this region are protected from flash floods by dykes, so that the water level in the canals is higher than in the soil. The dykes in the flood-prone areas have recently been elevated above the water level of the disastrous flooding of the year 2000. In the wet season, water levels in the canals typically are higher than soil levels. Heavy rainfall then causes 'stagnant flooding' in these fields because the water cannot be drained fast enough.

2.1.4. Acid sulfate zone

About 1.6 Mha of the soils of the MRD are classified as acid sulfate soils (Duong *et al*. 2010) that are generally characterized by pH < 4 (Attanandana and Vacharotayan 1986). As can be seen in Fig. 3, this soil type dominates the western part, but smaller areas can be found throughout the delta. However, the conditions for growing rice have drastically changed in many locations within the acid sulfate zone. While soil acidity impaired high-yielding rice systems, the acidity of the topsoil has been washed out over years of rice cultivation. Farmer can now control the soil at pH levels of >4 by keeping the soils continuously flooded. In turn, this allows fairly high rice yields of 4–5 Mg/ha in this zone.

2.2. Site and soil characteristics

The CH_4 fluxes were measured from independent experimental field trials that are widely scattered among the delta (Fig. 1). Measurements at the sites CT, AG, BL1, BL2, and HG were part of the CLUES project[1] ('Climate change affecting land use in the Mekong Delta: Adaptation of rice-based cropping systems'). The sites TV and LA1 were part of a collaboration by Cuu Long Delta Rice Research Institute (CLRRI) with a local GIZ2 project (Dill et al. 2014) while LA2 was part of a collaboration by IRRI and Nong Lam University. The soil data given in Table 1 stems from sampling in January 2016 and subsequent analysis at the CLRRI lab using standard methods (Vo et al. 2010; Tat et al. 2016).

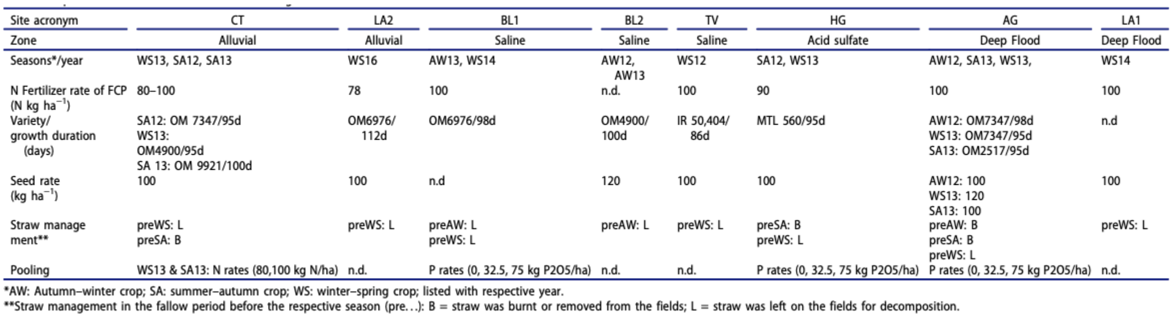
Table 1. Characterization of measurement sites

Acronym	CT	LA2	BL1	BL2	TV	HG	AG	LA1
Zone	*Alluvial*	Alluvial	Saline	Saline	Saline	Acid sulfate	Deep Flood	Deep Flood
Province	Can Tho	Long An	Bac Lieu	Bac Lieu	Tra Vinh	Hau Giang	An Giang	Long An
District	Thoi Lai	Tan An	Hoa Binh	Phuoc Long	Tieu Can	Hoa An	Tri Ton	Tan Thanh
Long/ Lat	9°59′57″N 105°39′40″E	10° 32′ 0″ N, 106° 25′ 0″ E	9°17′6″N 105°39′12″ E	9°25′18″N 105°27′32″E	9°48′41″N 106°11′46″ E	9°46′23″N 105°38′19″ E	10°25′N 105°0′E	10° 36′ 0″ N, 106° 6′ 0″ E
Soil texture	Clay	Clay	Silty Clay	Clay	n.d	Clay	Clay	n.d
Total OC (%)	2.20	4.90	1.51	2.72	n.d	4.27	3.07	n.d
Total N (%)	0.11	0.20	0.08	0.11	n.d	0.28	0.17	n.d
Available P (mg kg^{-1})	5.40	20.42	13.00	8.50	n.d.	27.33	9.17	n.d.
Active Fe (%)	2.47	n.d.	1.58	1.49	n.d.	1.60	1.98	n.d.
pH	4.90	5.40	5.92	5.79	n.d.	4.63	4.82	n.d.
EC (mS cm^{-1})	0.37	n.d.	1.44	2.10	n.d.	1.36	0.33	n.d.

2.3. Field layout and management

Each field treatment had three replicate plots. All field experiments were conducted with randomized complete block design to compare different treatments, although we have now only used CH_4 emissions data obtained from baseline management in this study. This comprises in all cases fields under the continuous flooding and direct seeding. In terms of straw management, our experiment followed farmers' practices that vary with seasons and sites (see Table 2). The fallow periods before the SA crop are typically very dry and farmers prefer to burn the straw while other fallow periods are in some cases too wet for straw burning. As shown in Table 2, we have used locally grown rice varieties and fertilizer applications according to typical practices of farmers in the respective zone. In some cases, however, our GHG measurements were part of agronomic experiments assessing different application rates of N and P. Since these trials did not show any significant differences in emissions, we have pooled those data as mentioned in Table 2.

Table 2. Experimental details of baseline water management at all sites and season.



Site acronym	CT	LA2	BL1	BL2	TV	HG	AG	LA1
Zone	Alluvial	Alluvial	Saline	Saline	Saline	Acid sulfate	Deep Flood	Deep Flood
Seasons*/year	WS13, SA12, SA13	WS16	AW13, WS14	AW12, AW13	WS12	SA12, WS13	AW12, SA13, WS13,	WS14
N Fertilizer rate of FCP (N kg ha^{-1})	80–100	78	100	n.d.	100	90	100	100
Variety/ growth duration (days)	SA12: OM 7347/95d WS13: OM4900/95d SA 13: OM 9921/100d	OM6976/ 112d	OM6976/98d	OM4900/ 100d	IR 50,404/ 86d	MTL 560/95d	AW12: OM7347/98d WS13: OM7347/95d SA13: OM2517/95d	n.d
Seed rate (kg ha^{-1})	100	100	n.d	120	100	100	AW12: 100 WS13: 120 SA13: 100	100
Straw manage ment**	preWS: L preSA: B	preWS: L	preAW: L preWS: L	preAW: L	preWS: L	preSA: B preWS: L	preAW: B preSA: B preWS: L	preWS: L
Pooling	WS13 & SA13: N rates (80,100 kg N/ha)	n.d.	P rates (0, 32.5, 75 kg P2O5/ha)	n.d.	n.d.	P rates (0, 32.5, 75 kg P2O5/ha)	P rates (0, 32.5, 75 kg P2O5/ha)	n.d.

*AW: Autumn–winter crop; SA: summer–autumn crop; WS: winter–spring crop; listed with respective year.

**Straw management in the fallow period before the respective season (pre…): B = straw was burnt or removed from the fields; L = straw was left on the fields for decomposition.

2.4. Gas sampling and CH_4 analysis

CH_4 fluxes were measured using the static chamber method, as described in Tirol-Padre et al. (2017). In all the sites, a plastic base with a diameter of 50 cm was inserted about 10 cm into the soil in thre replicate blocks for each treatment. These bases were installed at least a day before sample collection. The gas collection chambers, fabricated from a plastic pail with a height of 70 cm (120 L volume), were equipped with a sampling port, thermometer, and a battery-operated fan installed inside the chamber. Gas samples were collected at 0, 10, 20, and 30 min after chamber closure.

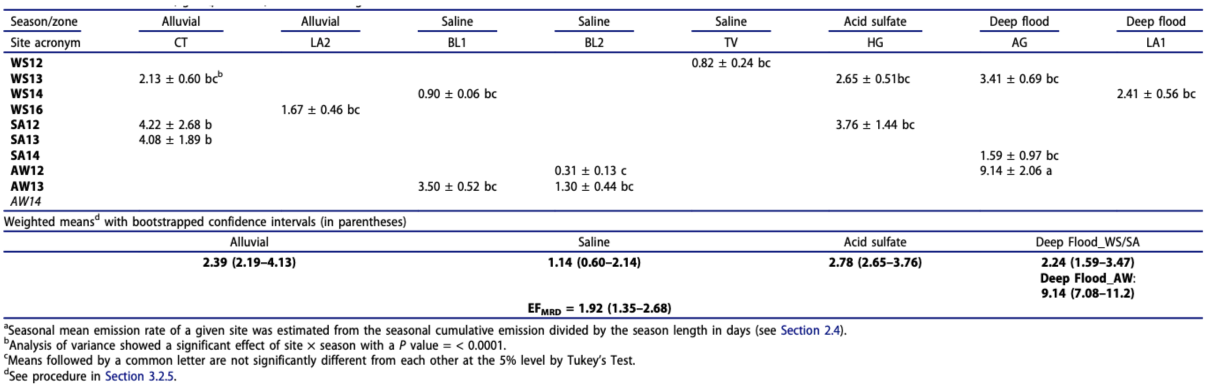
The gas samples were analyzed at the CLRRI lab except for those from the site LA2 that were analyzed at Hue University. Both GHG labs have compatible instrumentation and procedures. A gas chromatograph (8610C, SRI Instruments, CA, USA) equipped with a flame ionization detector was used to determine the CH_4 concentration in the gas samples. The column for the analysis of CH_4 was packed with Porapak Q (50–80 mesh) and the carrier gas was nitrogen (N_2).

2.5. Calculation of emission rates and statistical analysis

CH4 emission rates were computed based on the ideal gas law, using chamber air temperature values measured at the time of sampling. For calculating the total CH_4 emitted for a sampling interval, the measurements taken in the morning were assumed to represent daily average flux rates. It was further assumed that flux changes between two consecutive sampling days as well as between sowing and the first sampling and the last sampling and harvest are linear. The emission rates on the day of sowing and harvest were set to ‘0.’

The seasonal cumulative emission was calculated as the sum of the daily emissions from sowing to harvest. The seasonal mean emission rate of a given site (Table 3) was estimated from the seasonal cumulative emission divided by the season length in days. Analysis of variance (ANOVA) was performed with the SAS mixed procedure (SAS software ver. 9.4, SAS Institute Inc., Cary, NC, USA) on each data set with different N or P fertilizer treatments to test if these treatments had a significant effect on the mean CH_4 emissions rates. Since ANOVA results did not show significant ($P < 0.05$) treatment effects, the CH_4 emission rates from all the N or P treatments in each block were pooled in calculating the seasonal means at a given site (Table 3). To assess the variability of seasonal CH_4 emission rates measured in eight sites, ANOVA was performed by the SAS mixed procedure (SAS software ver. 9.4, SAS Institute Inc., Cary, NC, USA) with comparison of means by Tukey test each. For each zone, a weighted mean CH_4 emission rate across seasons with bootstrapped confidence intervals was estimated using Metawin (ver.2.1; Rosenberg *et al.* 2000).

Table 3. Average emission rates (kg CH_4 ha^{-1} d^{-1}) of all sites



Season/zone	Alluvial	Alluvial	Saline	Saline	Saline	Acid sulfate	Deep flood	Deep flood
Site acronym	CT	LA2	BL1	BL2	TV	HG	AG	LA1
WS12					0.82 ± 0.24 bc			
WS13	2.13 ± 0.60 bc[b]					2.65 ± 0.51bc	3.41 ± 0.69 bc	
WS14			0.90 ± 0.06 bc					2.41 ± 0.56 bc
WS16		1.67 ± 0.46 bc						
SA12	4.22 ± 2.68 b					3.76 ± 1.44 bc		
SA13	4.08 ± 1.89 b							
SA14							1.59 ± 0.97 bc	
AW12				0.31 ± 0.13 c			9.14 ± 2.06 a	
AW13			3.50 ± 0.52 bc	1.30 ± 0.44 bc				
AW14								

Weighted means[d] with bootstrapped confidence intervals (in parentheses)

Alluvial	Saline	Acid sulfate	Deep Flood_WS/SA
2.39 (2.19–4.13)	**1.14 (0.60–2.14)**	**2.78 (2.65–3.76)**	**2.24 (1.59–3.47)** **Deep Flood_AW:** **9.14 (7.08–11.2)**

EF_{MRD} = 1.92 (1.35–2.68)

[a] Seasonal mean emission rate of a given site was estimated from the seasonal cumulative emission divided by the season length in days (see Section 2.4).
[b] Analysis of variance showed a significant effect of site × season with a P value = < 0.0001.
[c] Means followed by a common letter are not significantly different from each other at the 5% level by Tukey's Test.
[d] See procedure in Section 3.2.5.

3. Results

3.1. Soil parameters of measurement sites

Soil textures in the study sites varied from clay to silty clay. Soil available P displayed a 59.7% CV among the study sites followed by total N (46.8%), total organic C (40.9%), and active iron (22.3%). These soil properties are known to affect CH_4 emissions in various forms, although there is up to now no clear-cut correlation established. The picture on site variability is much more complicated for the dynamic soil factors of EC and pH that are superimposed by pronounced seasonal cycle. The figures given in Table 1 have been obtained by sampling in January which corresponds to the transition phase from wet to dry season. In totality among all sites, soil EC showed the largest variability among the soil properties measured, with a coefficient of variation of 67.8%.

3.2. Spatial and seasonal variations in emissions

3.2.1. Alluvial zone

In our study, the alluvial rice environments are represented by the sites CT and LA2 (Fig. 3) with two emission charts for each of the two main seasons in this zone (WS and SA) as shown in Fig. 4 supplemented by climate data in Figure S1. Emission records were at low or moderately high level in this zone. Only few individual data points are <100 and only one >1000 mg CH_4 m^{-2} d^{-1} (Fig. 4). There is no distinct seasonal cycle that can be derived from these charts. Seasonal means range from 1.67 of LA2-WS16 to 4.22 kg CH_4 ha^{-1} d^{-1} of CT-SA12 (Table 3).

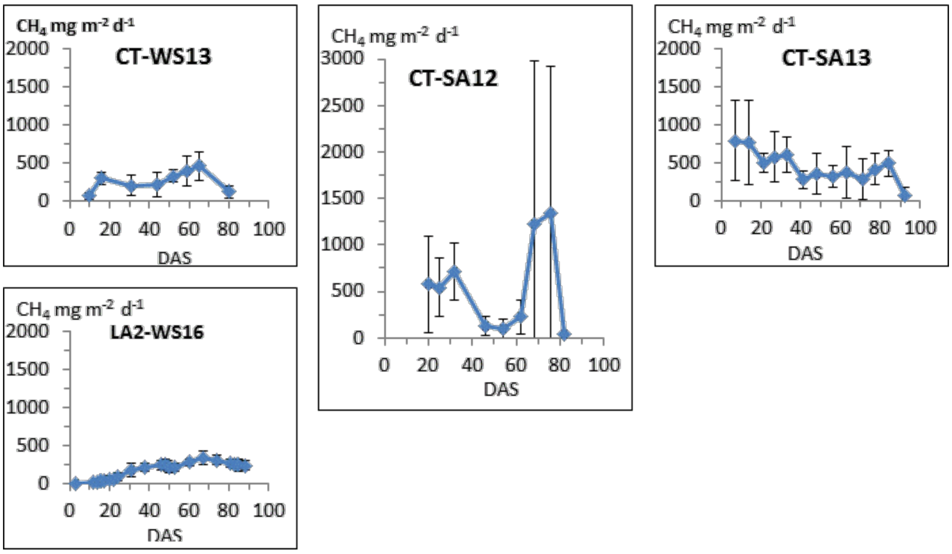


Figure 4. Emission rates obtained in alluvial zone per site and season; for climate data, see Supplement Figure S1.

3.2.2. Saline zone

Our measurements in the saline zone comprise three sites in the provinces BL and TV (Fig. 3) with three season charts for AW and two season charts for WS (Fig. 5). The database for TV has been re-calculated resulting in slightly higher mean values than the one given in Dill *et al.* (2014) (which corresponded to 0.57 kg ha^{-1} d^{-1}). The wet season (AW) is by far the most important crop in the saline zone followed by WS and SA (Fig. 3). Emission rates are generally at very low level (≤1.3 kg CH_4 ha^{-1} d^{-1}) except for AW season in BL1 (3.5 kg CH_4 ha^{-1} d^{-1}). The low values at BL2 and TV can be attributed to the inhibition of methane formation by salinity because these sites are exposed to high salinity levels during the drier periods of the year. For the site BL2, we obtained EC > 2 mS cm^{-1} in the January samples and for the site TV we can refer to verbal information from farmers on prevailing salinity problems at that site. The AW season recorded at BL2 coincides with the point of lowest salinity intrusion, but remaining salinity in the soil and emissions appears to impair CH_4 emissions (Fig. 5). The SA season recorded in TV encompasses a period of heavy salinity intrusion, so that emissions are generally very low. Data from the site BL1 encompass one season with relatively high (AW) and one with low (WS) emissions. Apparently, this site had better salinity protection in the AW season which is also corroborated by the EC measurement (< 2 mS/cm recorded in January). We also measured EC values on each sampling day at BL1 and these records show very low salinity levels in the initial 30-day period of the AW season while only the latter stages are affected by EC >2 mS/cm (data not shown).

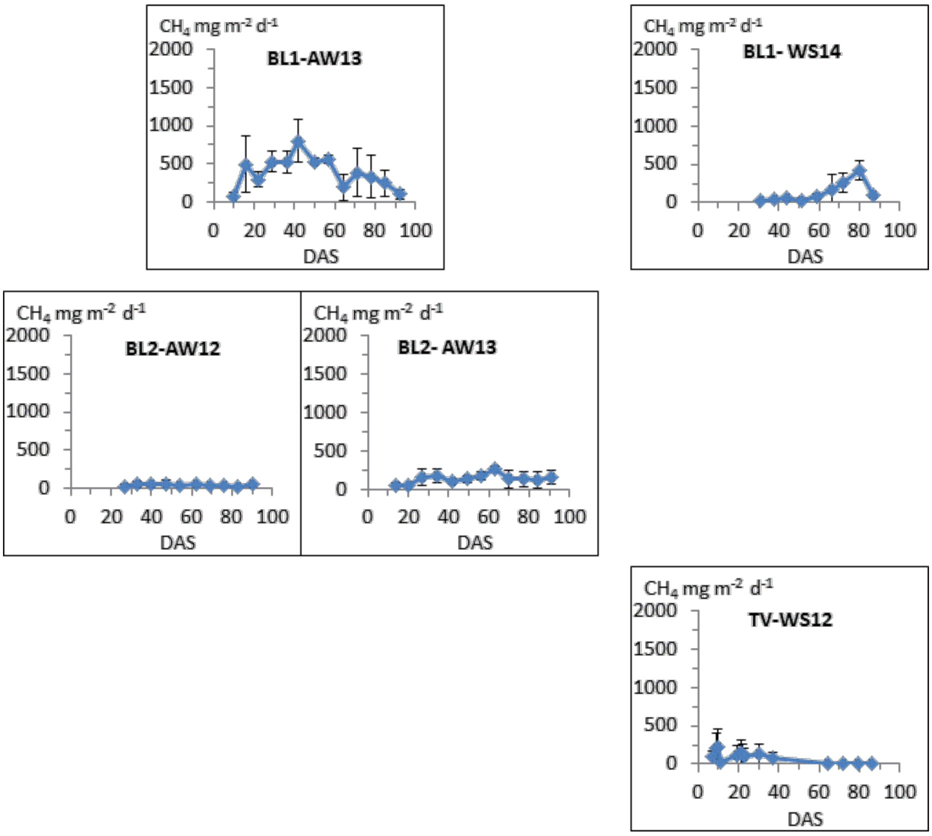


Figure 5. Emission rates obtained in saline zone per site and season; for climate data, see Supplement Figure S2.

3.2.3. Deep flood zone

This zone is represented by one site in An Giang Province (Fig. 3). The AW crop is characterized by very wet conditions that typically start even before seeding. As a consequence, CH_4 emissions are very high in this season (Fig. 6). The mean emission AG during the AW crop (9.14 kg CH_4 ha^{-1} d^{-1}) was two to five times higher than those from any other given site and season of this study. In the WS season, emissions at the AG site are still high during the earlier plant stages, but they decrease with the retreat of the water during the later stages (Fig. 6). The mean emission rates in the WS season (3.41 kg CH4 ha^{-1} d^{-1} at AG and 2.41 at LA1) were in a similar range as the alluvial zone while the mean of the SA season (1.59 kg CH_4 ha^{-1} d^{-1} at AG) was lower than those.

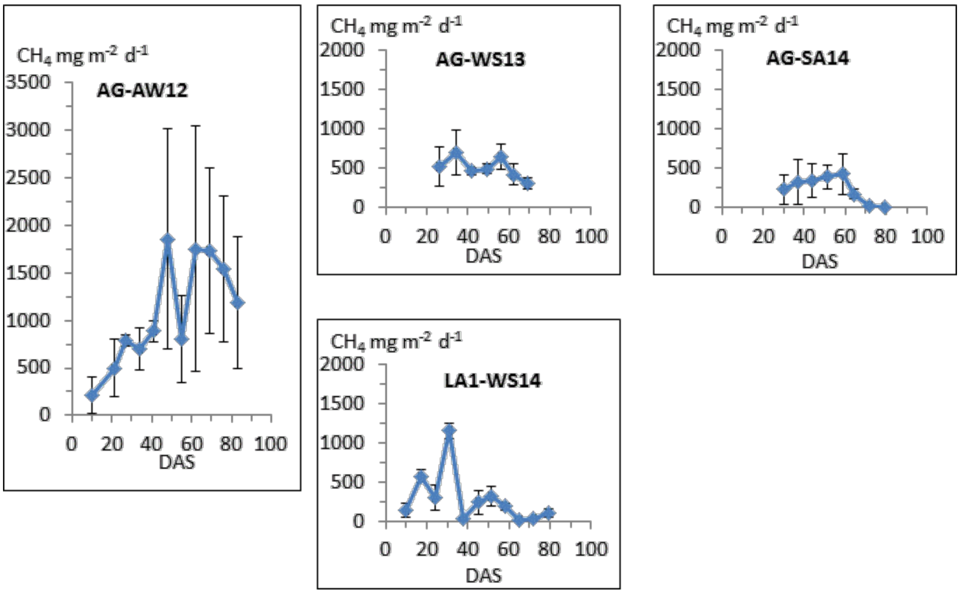


Figure 6. Emission rates obtained in deep flood zone per site and season; for climate data, see Supplement Figure S3

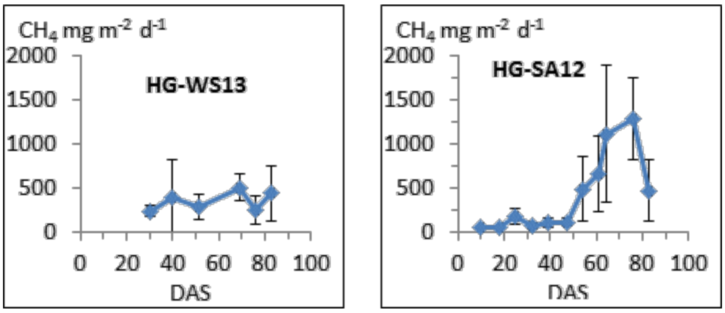


Figure 7. Emission rates obtained in acid sulfate zone per site and season; for climate data, see Supplement Figure S4

3.2.4. Acid sulfate zone

The zone is represented by one site in the Hau Giang Province (Fig. 3) where rice production encompasses two cropping seasons WS and SA (Fig. 1). Emission rates in WS were fairly stable at moderately high level while these patterns of the SA crop show a pronounced peak during the latter stages. In both seasons, mean values were moderately high (2.65 and 3.76 kg CH_4 ha^{-1} d^{-1}) and in a similar range as emissions in the alluvial sites. Even though classified as acid sulfate soil, the soil in Hau Giang had consistently pH >4.5. In addition to the soil sample in January (pH = 4.63), we also recorded pH values during the observed seasons WS 13 and SA 12. Average pH values were 4.92 in WS and 4.68 in SA, respectively.

3.2.5. Assessing emission factors for different zones and the entire MRD

Statistical analysis resulted in weighted means for all zones (using Metawin ver.2.1 to indicate bootstrapped confidence intervals (Rosenberg *et al.* 2000)). These weighted means were used as zone-specific CH_4 emission factors (EF_z) in the context of the IPCC Tier 2 approach. ANOVA showed significant ($P < 0.0001$) differences among seasonal CH_4 emissions from different sites as shown in Table 3. The lowest EF_z was computed for the saline accounting for 1.14 kg CH_4 ha^{-1} d^{-1} (confidence interval: 0.60–2.14). The EF_z values of the alluvial and acid sulfate zones were 2.39 kg CH_4 ha^{-1} d^{-1} (2.19–4.13) and 2.78 kg CH_4 ha^{-1} d^{-1} (2.65– 3.76), respectively, which indicated that they were not different from each other derived from their confidence intervals. The deep flood zone, however, required a season-specific assessment because mean comparison by Tukey test showed that the CH_4 emission rate from AG-AW12 (deep flood) was different (much higher) from all the other crops. This high value coincides with continuous heavy rain during AW resulting in 1020 mm rain (Figure S3) as well as organic inputs from decomposed straw (Table 2). Thus, we assigned two different EF_z values for the deep flood zone, namely EF_z_AW (9.14 kg CH_4 ha^{-1} d^{-1} (7.08–11.2)) and EF_z_WS/SA (2.24 kg CH_4 ha^{-1} d^{-1} (1.59–3.47)).

4. Discussion

4.1. Zonal differentiation and seasonal patterns

In totality, the database provides a good overview of CH_4 emissions in rice production systems of the MRD assuming continuous flooding, i.e., baseline water management as defined in the IPCC methodology. Given the size and variability within the delta, it seems unrealistic to aim at a fully exhaustive database of ample field measurements covering the entire range of environmental factors and their spatio- temporal modifications. Nevertheless, the documented emission patterns encompass the major seasons in the four distinct agro-ecological zones.

In our study, the mean emissions rates per season ranged from 0.31 to 9.14 kg CH_4 ha^{-1} d^{-1} (Table 3). All emission charts have been displayed in Figs. 4–7 while the respective climate data has been displayed in the Supplemental material (Figures S1–S4). In two data sets (CT-SA12, AG-AW12), the individual records are attached to high variability in the latter stages. We attribute this to bubble ebullition which is typically higher in the second half of the season (Wassmann *et al.* 1996).

There is only one published study available on methane emissions in the MRD, but that focuses on straw burning and mushroom production (Arai *et al.* 2015), so the reported values cannot be taken as a reference for our study. Moreover, there are few studies from other deltas of Vietnam available such as the Red River Delta in North Vietnam (Pandey Nguyen *et al.* 2014; Nguyen *et al.* 2016; Vu *et al.* 2015; Tariq *et al.* 2017) and the Vu Gia/Thu Bon delta in Central Vietnam (Tirol-Padre *et al.* 2017) which reported values ranging from 104 to 696 kg CH_4 ha^{-1} per season. Although these data sets will not be directly applicable to the MRD because the hydrological conditions are very distinct in the different deltas of Vietnam, most of the seasonal emissions we obtained from the MRD are within the range that has been reported in North and Central Vietnam except for some very low emissions in the saline soils and the very high in the deep flood zone.

The lowest emission rates were obtained in the saline zone at BL2, namely the site with the highest EC value (Table 1). The adverse effect of salinity on microbial methane production is known for a long time (Koyama *et al.* 1970) and attributed to the sulfate content of sea water. Methanogens have to compete with sulfate-reducing bacteria for hydrogen (Neue 1993). Denier Van Der Gon and Neue (1995) showed that an increase in the salt content of pore water to an electrical conductivity of 4 mS cm^{-1} led to a 25% reduction in the methane emission rate compared with a control plot. In laboratory incubations, the addition of salt progressively decreased methane emission in relation with low microbial activities and populations as reflected by decreased microbial biomass C and low soil microbial populations, including methanogens (Pattnaik *et al.* 2000). In our measurements, CH_4 emissions at BL1 were significantly higher than the other sites during WS. This is an indication of protection from salinity intrusion that can be attributed to recent infrastructure development, namely newly built sluices in the coastal zone. On the other hand, there are many locations in the coastal belt that show this type of protection, so this value should not be seen as an exceptional case.

In the deep flood zone, the AW crop that coincides with the wet season is marked by much higher emission rates than any other of our measurements. This finding may look surprising given that all our field measurements were done under continuous flooding. In the deep flood zone, however, flooding of the soils typically starts in the fallow period before seeding of the AW crop. Due to high water levels in the surrounding canals and water bodies, any rainfall event will directly translate into flooding of the field. Prolonged flooding is known to increase methane emission rates, which was first shown in field experiments in China (Cai *et al.* 2000). This finding has been taken up in the IPCC methodology by introducing a specific scaling factor to account for the differences in water regime in the pre-season before the cultivation period (IPCC 2006, p. 5.50). In our case, flooding during the fallow period can be seen as one reason for the high emission levels in the AW season in the deep flood zone, but can hardly explain the emission peak in the second half of the season (Fig. 6). We attribute the high emission rates at latter stages to the absence of irrigation events in the wet season. When ambient water levels are higher than in the rice fields, percolation will be extremely low. During the other seasons with lower water levels and lesser rainfall, farmers have to irrigate the fields regularly which corresponds to exchanging the entire water column in the field for several times over the season. This leads to inputs of oxygen dissolved in the irrigation water. Methane production in the soil is extremely sensitive to – even small – oxygen inputs so that the emission rates will be lower than in a soil that is largely cut off from such inputs. Numerous studies have reported a significant decrease of CH_4 emission in rice fields through single or periodic aeration which inhibit the activity of CH_4-producing archaea (Jiao et al. 2007; Itoh et al. 2011; Minamikawa et al. 2014; Sander et al. 2014; Yagi et al. 1996)

The findings from the site mapped within the acid sulfate zone also need considerations regarding the validity of this classification. While acid sulfate soils are generally characterized by pH < 4 (Attanandana and Vacharotayan 1986), the soil pH at HG was consistently >4. These moderately high pH values can be attributed to continuous cropping over recent years that has leached out acidity from the topsoil. Given this soil amelioration, the question has to be raised if this soil located in the acid sulfate zone can actually still be labeled as acid sulfate soil. Even if we assume that acidity levels may be more pronounced in the AW season (which is not present in HG province), it seems unlikely that this will have a greater impact of the overall emissions from the area with acid sulfate soils.

These conditions of an ‘improved’ acid sulfate soil can plausibly explain the fairly high emission rates observed at the site HG. There is ample evidence that soil acidity will largely constrain emissions (Yao *et al.* 1999). While the optimum pH of CH_4 production is near neutrality, a small reduction in soil pH could decrease CH_4 emissions due to the combined effect of inhibiting activity of methanogens and increasing soil Eh (Wang *et al.* 1993).

Fig. 8 provides a comprehensive picture of the CH_4 emissions cumulated over a given season. As all seasons had a similar length of around 100 days, the displayed results basically reflect the emission rates shown in Table 3. This graphic presentation effectively highlights the different degrees of variability in the different zone. Variations of seasonal emission rates were very high in the deep flood and in the saline zone. As discussed earlier, these two zones are characterized by very variable bio-physical conditions in space and time. Infrastructure development has generally improved growing conditions for rice, but also resulted in a highly dynamic mosaic-like structure of rice-growing environments. In contrast, emission rates in the alluvial and acid sulfate zone seem to be less variable ranging within low to moderately high level.

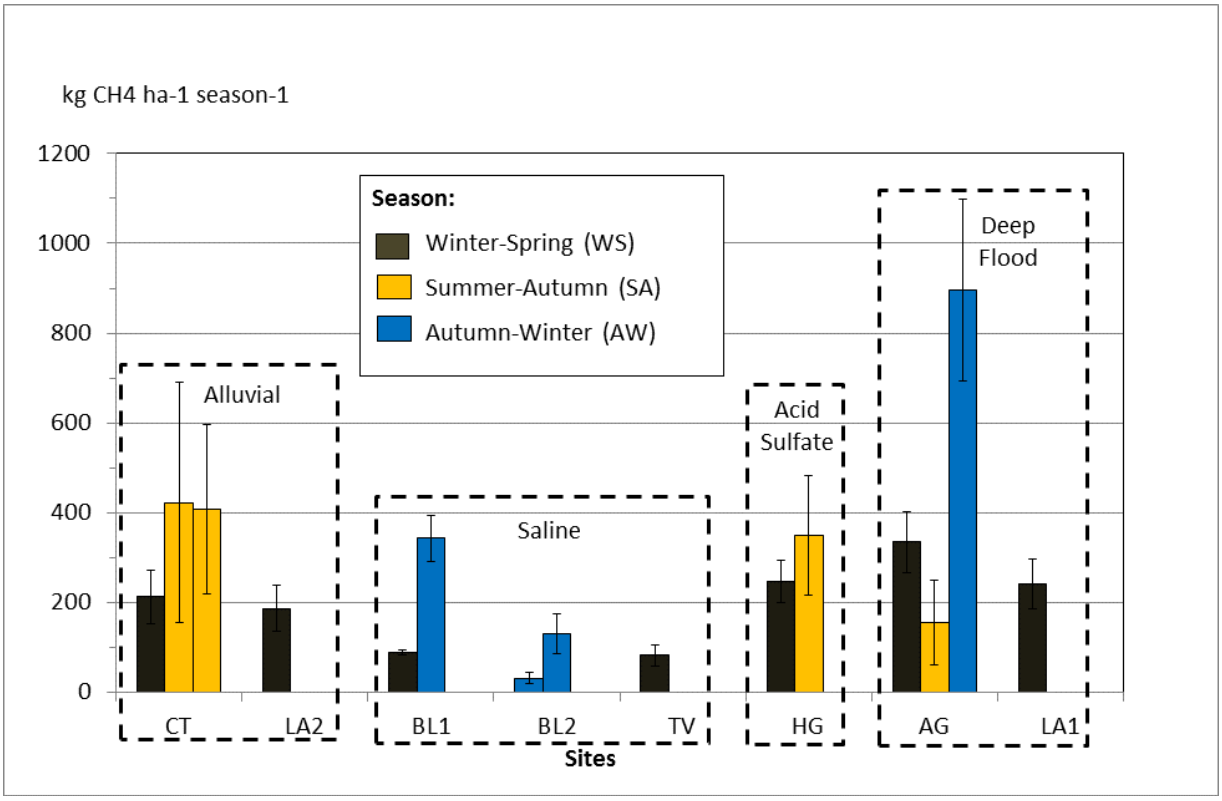


Figure 8. Cumulated emission rates per season for all sites and seasons

4.2. Relevance of results for upscaling with IPCC approach

The IPCC guidelines from 2006 provide clearly defined formulae on using EF and SF for emission upscaling, but they are relatively vague on the exact modalities for the requested disaggregation of these factors. Equation 5.1 (IPCC 2006, p. 5.45) represents the basic formula for overall emissions by multiplication of specific emission factors with the respective season length and area. In terms of disaggregation, these EFs should 'represent different ecosystems, water regimes, type and amount of organic amendments, and other conditions under which CH_4 emissions from rice may vary' (IPCC 2006, p. 5.45). When we apply Equation 5.1 to the conditions of the MRD rice production and different agro-ecological zones, the formula can be phrased as follows:

$CH_{4\ MRD} = \sum (EF_z \times t_z \times A_z \times 10^{-3})$

where:

$CH_{4\ MRD}$ = annual methane emissions from rice cultivation (in Mg CH_4 year^{-1}),

EF_z = daily emission factor (in kg ha^{-1} d^{-1}) for each agro- ecological zone,

t_z = cultivation period (in days) of rice for each agro-ecolo- gical zone,

A_z = annual harvested area (in ha) of rice for each agro- ecological zone, and

z = agro-ecological zone.

Thus, we have used our data set for computing EF_z values in Table 3. Then, we have averaged all EF_z values and calculated an overall EF_{MRD} for the entire delta. For this purpose, we have used the weighted mean (see method discussed earlier) as EF_{MRD} that accounts to 1.92 kg CH_4 ha^{-1} d^{-1} with confidence limits from 1.41 to 2.68. Unlike the arithmetic mean, the weighted mean takes precision of the measured emissions into consideration as values are weighted based on respective variance. Values with high variance are given less weight as compared to those with low variance. This emission factor is 48% higher than the global default value given by IPCC (2006) which is 1.30 kg CH_4 ha^{-1} d^{-1}, but below the upper margin of the error range of the IPCC guidelines which is given as
2.20 kg CH_4 ha^{-1} d^{-1}.

In terms of constraints in our approach, one could argue that the computation of EF_{MRD} still has an arbitrary element because it is based on the available measurements rather that a stratified sampling strategy. However, this possible criticism is applicable to all studies that have so far used emission factors for upscaling. The global default value of IPCC (2006) as well as the country-specific emission factors embedded in the various National Communications have been derived by averaging available emission rates for the geographic domain. At the same time, we recognize that any emission factor database will inherently require updating once more data becomes available. Thus, we regard the reported values as being tentative. EF_z and EF_{MRD} values may soon have to be updated by integrating new measurements into the MRD emission database.

Due to high spatio-temporal heterogeneity and the limited number of available measurements, we also recognize that EF values presented in our study are attached to considerable uncertainties. The number of recorded seasons is smaller than in some other GHG studies for individual sites including those in this special issue. This is – under given limitation of financial and logistic resources – a direct consequence of the objectives of our study that gave priority to spatial coverage at the expense of continued observation. Moreover, the term ‘baseline water management’ may need some elaboration. Field managers have been instructed at all sites to maintain a minimum water level of a few centimeters and thus to ensure that the soil will not fall dry. Insofar, we feel that we can call this ‘baseline water management’ even though the records of water levels are not available.

Likewise, the focus on CH_4 emissions without N_2O measurement could be seen as a possible uncertainty in terms of total GHG emissions. The reason for exclusion of N_2O is attributed to technical limitations in the lab system. We have, however, estimated the range of N_2O emissions by using the IPCC approach vis-à-vis a CH_{4MRD} value of 1.92 kg CH_4 ha^{-1} d^{-1}

accounting for 5.4 Mg CO_2eq. Given an average fertilizer rate of 100 kg N ha^{-1} $season^{-1}$ and the IPCC emission factor for N_2O from flooded rice fields (=0.3% of applied N), this input corresponds to 0.09 Mg CO_2eq or less than 2% of the CH_4 emissions. Moreover, there will be smaller CO_2 emissions stemming from farm operations, but those will only marginally affect overall magnitude and patterns of GHG emissions.

These EF values will allow future use of the IPCC formula for improved upscaling of emissions for the entire MRD. At this point, however, we refrain from this upscaling, because our data set is confined to continuous flooding and does not take into account the variability in management practices. As we recognize that continuous flooding is not the ubiquitous water management practice at any season throughout the delta, the upscaling for the entire delta derived from baseline EFs only would be pre-mature.

Ideally, the EFs obtained in our study should be applied for extrapolation jointly with detailed activity data on management practices in the different parts of the delta. Future surveys on farmers' management practices are needed to estimate the percentages of continuous flooding vs. other water management practices over space and time. This 'Business-as-Usual' assessment was beyond the scope of this study. Irrespective of this constraint, we see the availability of zone-specific emission data as an important step for a more detailed assessment of BAU emissions as well as possible mitigation potentials in one of the most important rice-growing regions of the world, but still we see our data as an important step to acquire a better assessment of GHG emissions in one to other major rice-growing regions of the world.

Notes

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References

Arai H, Hosen Y, Nguyen PHV, Truong TN, Nguyen HC, Inubushi K 2015: Greenhouse gas emissions from rice straw burning and straw-mush- room cultivation in a triple rice cropping system in the Mekong Delta. *Soil Sci. Plant Nutr.*, 61, 719–735. 10.1080/00380768.2015.1041862

Attanandana MG, Vacharotayan S 1986: Acid sulfate soils. Their characteristics, genesis, amelioration and utilization. *Southeast Asian Stud.*, 24, 154.

Cai ZC, Tsuruta H, Minami K 2000: Methane emission from rice paddy fields in China: I. measurements and influencing factors. *J. Geophys. Res.*, 105, 17231–17242. 10.1029/2000JD900014

Denier van der Gon HAC, Neue HU 1995: Soil parameters controlling methane emission from rice paddies. *Stud. Environ. Sci.*, 65, 607–610.

Dill J, Deichert G, Le TNT eds. 2014: Promoting the System of Rice Intensification: lessons Learned from Trà Vinh Province, Viet Nam, Infoagro website. 25 http://infoagro.net/archivos_Infoagro/Regatta/bib lioteca/VN-GIZreportonLesson.pdf

Duong TN, Ngo NH, Le VP, Vo QM, Le QT 2010: Some morphological characteristics of acid sulphate soils in the Mekong Delta. *Can. Tho Univ. J. Sci.*, 14, 243–249.

GSO (General Statistics Office of Viet Nam). http://www.gso.gov.vn/ Default_en.aspx?tabid=766

IPCC (Intergovernmental Panel on Climate Change) 2006: Agriculture, forestry and other land use. *In* 2006 IPCC guidelines for national green- house gas inventories, Eds Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K, Institute for Global Environmental Studies (IGES), Hayama, Japan

Itoh M, Sudo S, Mori S, et al. 2011: Mitigation of methane emissions from paddy fields by prolonging midseason drainage. Agric. Ecosyst. Environ., 141, 359–372. 10.1016/j.agee.2011.03.019

Jiao Z, Hou A, Shi Y, Huang G, Wang Y, Chen X 2007: Water management influencing methane and nitrous oxide emissions from rice field in relation to soil redox and microbial community. *Comm. Soil Sci. Plant Anal.*, 1(37), 1889–1903

Kaekoenen M 2008: Mekong delta at the crossroads: more control or adaptation? *Ambio*,20537,-212. 10.1579/0044-7447(2008)37[205 MDATCM]2.0.CO;2

Koyama T, Hishida M, Tomino T 1970: Influence of sea salts on the soil methabolism. 11. On the gaseous metabolism. *Soil Sci. PlantNutr.*, 16, 81–86.

Minamikawa K, Fumoto T, Itoh M, Hayano M, Sudo S, Yagi K 2014: Potential of prolonged midseason drainage for reducing methane emission from rice paddies in Japan: a long-term simulation using the DNDC-Rice model. *Biol. Fertil. Soils*, 50, 879–880. 10.1007/s00374-014-0909-8

MONRE 2010 Vietnam's Second National Communication of Vietnam to the United Nations Framework Convention on Climate Change, 152pp. Hanoi

MONRE (Ministry of Natural Resources and Environment) 2014: Initial Biennial Updated Report of Viet Nam to the UNFCCC, 94 pp. Hanoi

Nathan C 2016: The January 2016 Rice Outlook No. (RCS-16A), In USDA's World Agricultural Supply and Demand Estimates Report 24, USDA Economic Research Service (ERS) Publications.

Neue HU 1993: Methane emission from rice fields: wetland rice fields may make a major contribution to global warming. *BioScience*, 43(7), 466– 473. 10.2307/1311906

Nguyen PM, Haghverdi A, De Pue J, Botula YD, Le KV, Waegeman W 2017: Comparison of statistical regression and data-mining techniques in estimating soil water retention of tropical delta soils. *Biosystems Eng.*, 153, 12–27. 10.1016/j.biosystemseng.2016.10.013

Nguyen TT, Bui TPL, Trinh MV, Nguyen HS 2016: Effect of water regimes and organic matter strategies on mitigating green house gas emission from rice cultivation and co-benefits in agriculture in Vietnam. *Int. J. Environ. Sci. Dev.*, 7, 85–90. 10.7763/IJESD.2016.V7.746

Pandey Nguyen A, Mai VT, Vu DQ, Bui TPL, Mai TLA, Jensen LS, De Neergaard A 2014: Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice fields in Vietnam. *Agric. Ecosyst. Environ.*, 196, 137–146. 10.1016/j.agee.2014.06.010

Pattnaik P, Mishra SR, Bharati K, Mohanty SR, Sethunathan N, Adhya TK2000: Influence of salinity on methanogenesis and associated micro-flora in tropical rice soils. *Microbiol. Res.*, 155, 5013(00)80035-X-220. 10.1016/S0944-5013(00)80035-X

Rosenberg M, Adams DC, Gurevitch J 2000: Statistical software for meta- analysis, version 2.1 release 5.1. Sinauer associates Inc., Sunderland, MA, USA. SAS Institute Inc. 2004: SAS/STAT ® 9.1 User's Guide. Cary, NC: SAS Institute Inc.

Sander BO, Wassmann R, Siopongco JDLC 2014: Water-saving techniques: potential, adoption and empirical evidence for mitigating greenhouse gas emissions from rice production, Hoanh CT, Smakhtin V, Johnston T Eds, Climate Change and Agricultural Water Management in Developing Countries. 193–207. CABI Climate Change Series, CABI Publishing, Wallingford.

Tariq A, Vu QD, Jensen LS, Tourdonnet S, Sander BO, Wassmann R, Van Mai T, Neergaard A 2017: Mitigating CH_4 and N_2O emissions from intensive rice production systems in northern Vietnam: efficiency of drainage patterns in combination with rice residue incorporation. *Agric. Ecosyst. Environ.*, 249, 101–111. 10.1016/j.agee.2017.08.011

Tat AT, Le VD, Vo TG, Nguyen TBT, Trang NLC, Dao LKD 2016: Efficiency of organic and lime compost in rice yield improvement and adverse effect of saline soils under greenhouse conditions. *Can. Tho Univ. J. Sci.*, 4, 84– 93

Tirol-Padre A, Tran DH, Hoang TN, Duong VH, Tran TN, Le VA, Ngo DM, Wassmann R, Sander BO 2017: Measuring GHG emissions from rice production in Quang Nam province (Central Vietnam): emission factor for different landscape and water management practices, Alexandra N, Lars R eds, Land Use and Climate Change Interactions in Central Vietnam. 103–122. Springer Nature, Singapore.

Vo TG, Tran BL, Chau TAT 2010: Improving soil fertility and yield of paddy rice on lost cultivation floor soil in Chau Thanh district, Tra Vinh province. *Can. Tho Univ. J. Sci.*, 16b, 107–116.

Vu QD, De Neergaard A, Toan DT, Quan QH, Ly P, Tien MT, Stoumann Jensen L 2015: Manure, biogas digestate and crop residue management affects methane gas emissions from rice paddy fields on Vietnamese smallholder livestock farms. *Nutr. Cycl. Agroecosyst.*, 103, 329–346. 10.1007/s10705-015-9746-x

Wang ZP, DeLaune RD, Patrick WH, Masscheleyn PH 1993: Soil redox and pH effects on methane production in a flooded rice soil. *Soil Sci. Soc. Am. J.*, 57, 382–385. 10.2136/sssaj1993.03615995005700020016x

Wassmann R, Jagadish SVK, Sumfleth K, Pathak H, Howell G, Ismail A, Serraj R, Redoña E, Singh RK and Heuer S 2009: Regional vulnerability of climate change impacts on Asian rice production and scope for adaptation. *Advances in Agronomy,* **102**, 91-133

Yagi K, Tsuruta H, Kanda K, Minami K 1996: Effect of water management on methane emission from a Japanese paddy field: automated methane monitoring. *Global Biogeochem. Cycles*, 10, 255-267. 10.1029/96GB00517

Wassmann R, Neue HU, Alberto MCR, Lantin RS, Bueno C, Llenaresas D, Arah JRM, Papen H, Seiler W, Rennenberg H 1996: Fluxes and pools of methane in wetland rice soils with

Yagi K, Tsuruta H, Kanda K, Minami K 1996: Effect of water management on methane emission from a Japanese rice paddy field: automated methane monitoring. *Global Biogeochem. Cycles*, 10, 255–267. 10.1029/96GB00517

Yao H, Ronrad H, Wassmann R, Neue HU 1999: Effect of soil characteristics on sequential reduction and methane production in sixteen rice paddy soils from China, the Philippines, and Italy. *Biogeochemistry*, 47, 267– 293. 10.1023/A:1006186420644

CHAPTER 3

METHANE EMISSION FACTORS FROM VIETNAMESE RICE PRODUCTION: POOLING DATA OF 36 FIELD SITES FOR META-ANALYSIS

Vo et al. 2020[3]

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Supplementary data of this chapter can be found in Appendix 2, page 133 or accessed at http://www.mdpi.com/2225-1154/8/6/74/s1

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).

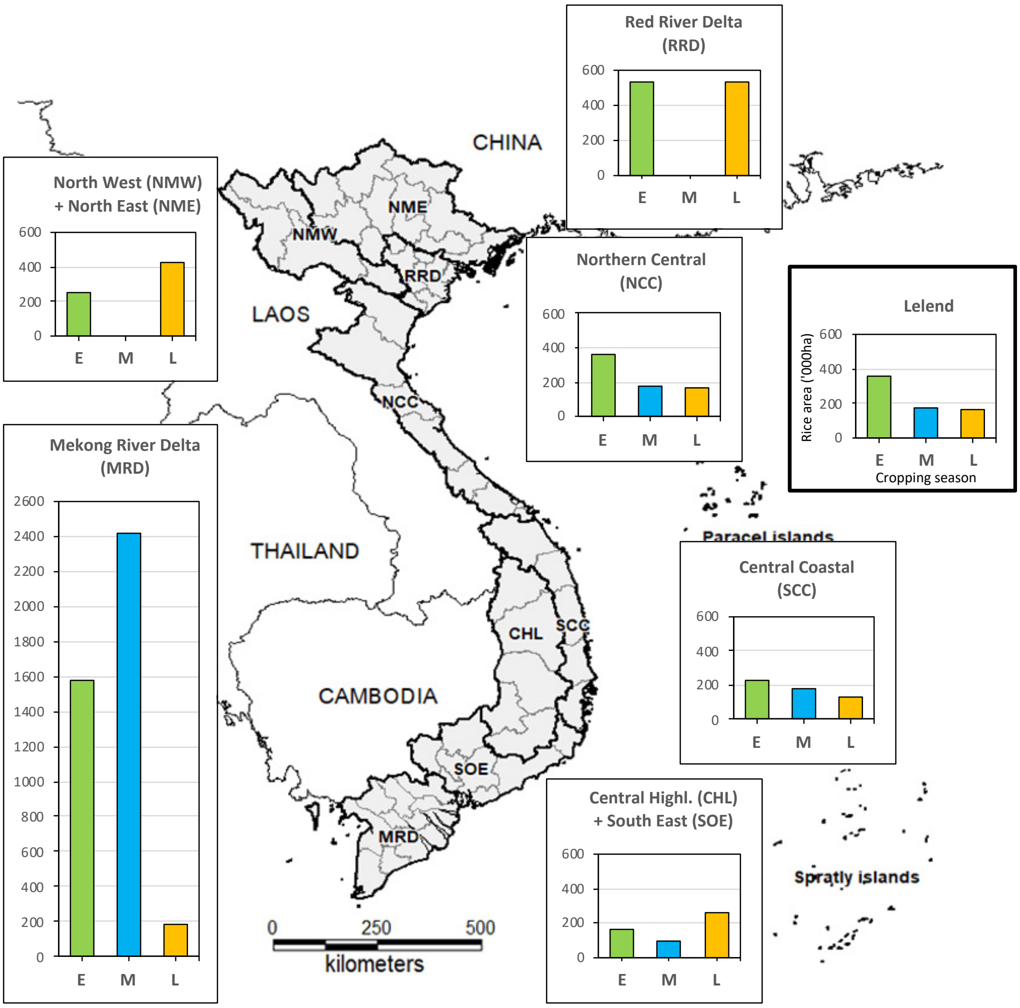

Figure 1. Distribution of rice area (in thousand ha) per region/agro-ecological zones (AEZ) and season in 2017 according to the General Statistics Office (GSO) [1]; rice crops in the early year (E), mid-year (M) and late-year (L) seasons are named spring, autumn

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 8610C) and for the sites S5–S13 at the laboratory of the Cuu Long Rice Research Institute (CLRRI) (GC: SRI 8610C). 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.

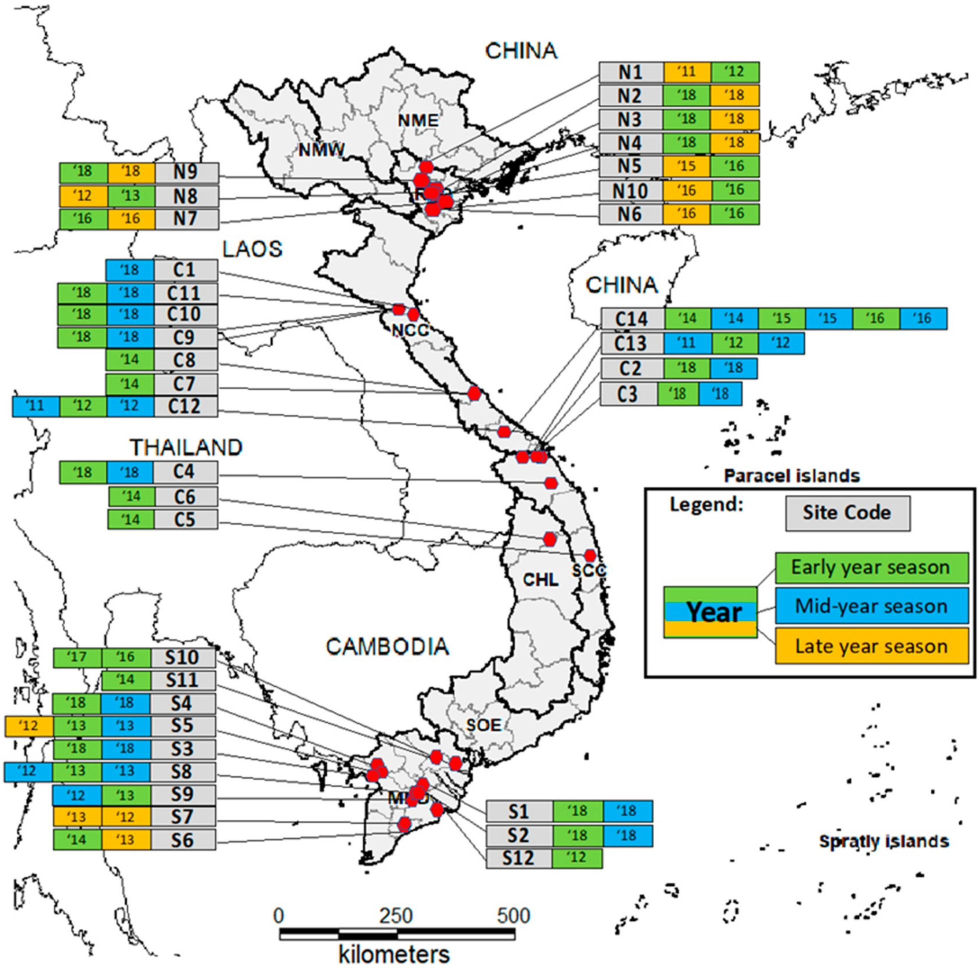

Figure 2. Overview of field sites and recorded seasons.

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.

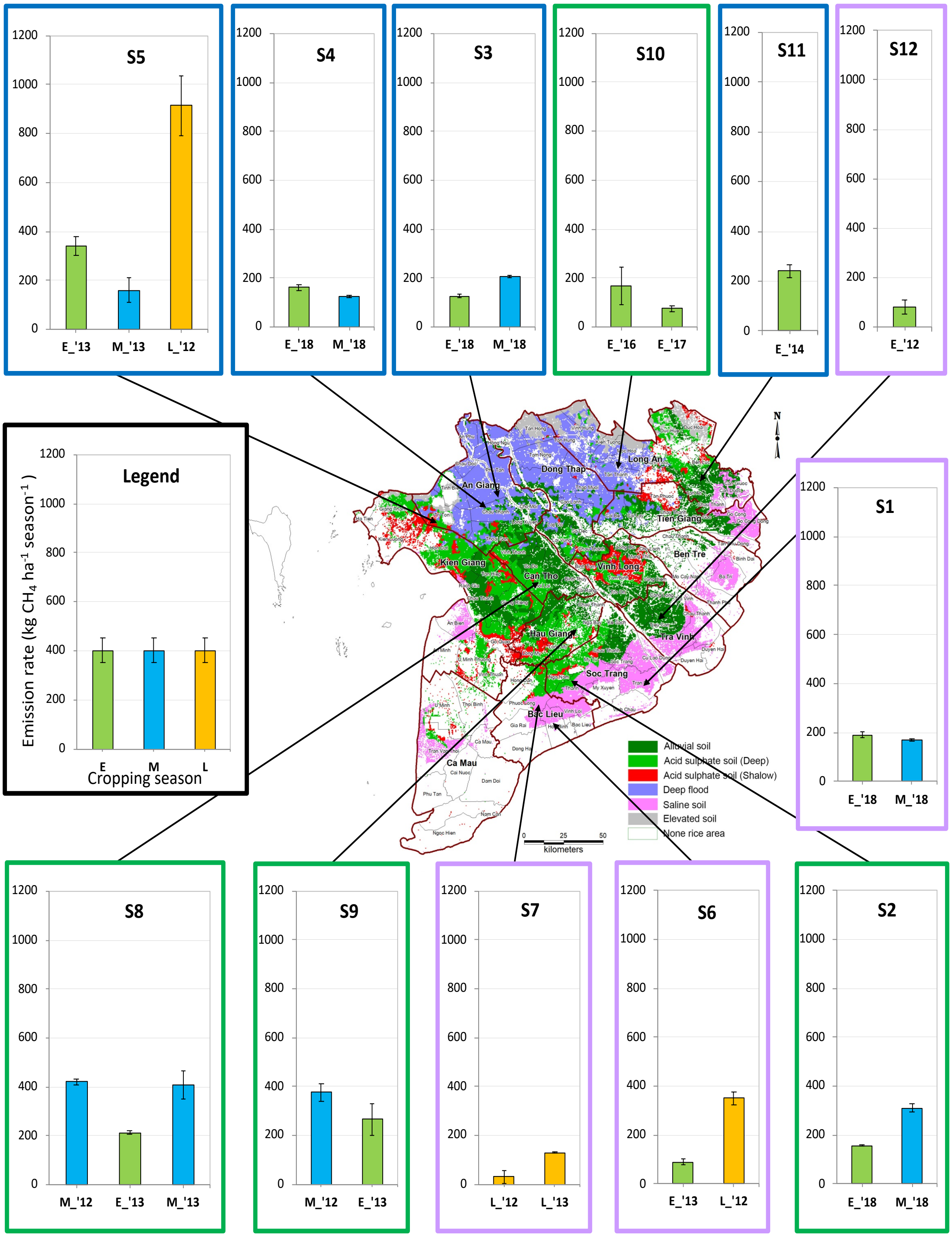

Figure 3. Seasonal emission rates in field experiments in South Vietnam with field sites marked in a map adopted from Wassmann et al. [20], colored frames indicate alluvial (green), deep flood (blue) and saline (magenta) zones; rice crops in the early year (E), mid-year (M) and late-year (L) seasons 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.

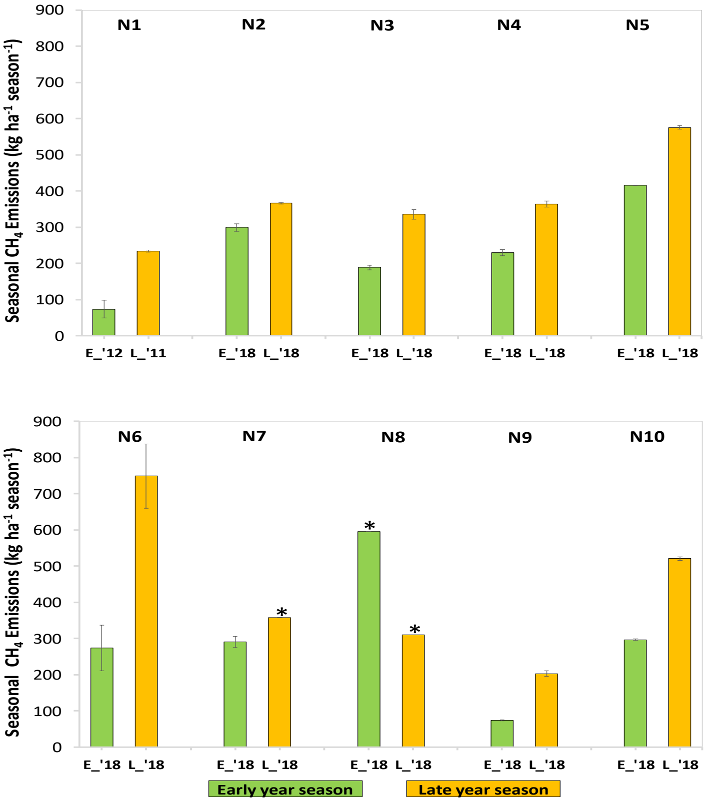

Figure 4. Seasonal CH_4 emission rates (kg ha−1 season−1) of field measurements in North Vietnam; standard errors among three replicates shown as error bars or marked by asterisks if not available. Crops are shown in sequential order which does not always correspond to the chronological order shown in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

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.

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.

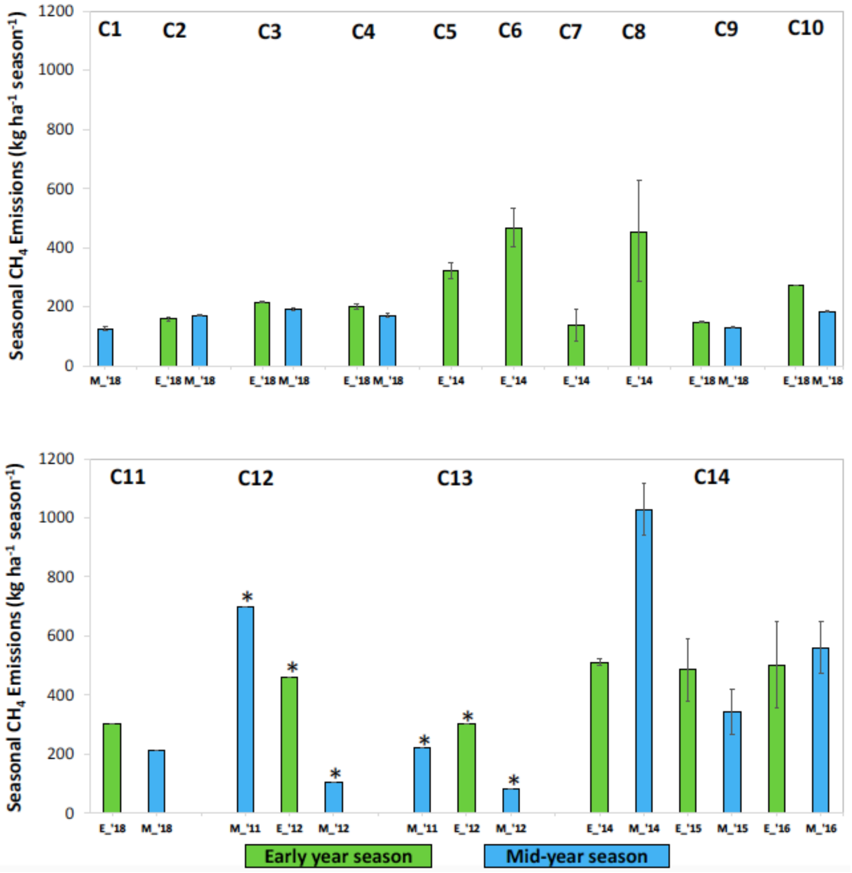

Figure 5. Seasonal emission rates of field measurements in Central Vietnam; standard errors among three replicates shown as error bars or marked by asterisks if not available. Crops are shown in sequential order which does not always correspond to the chronological order shown in Figure 2.

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 $\mathrm{CH_4}$ emission factor ($\mathrm{kg\ ha^{-1}\ d^{-1}}$)**							**Seasonal $\mathrm{CH_4}$ emissions ($\mathrm{kg\ ha^{-1}\ season^{-1}}$)**		
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	13	107	3.097 ± 2.218	0.398**	2.54	10.720	5.92	0.900	0.92	321 ± 237	1110	93
C-mid	16											
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).

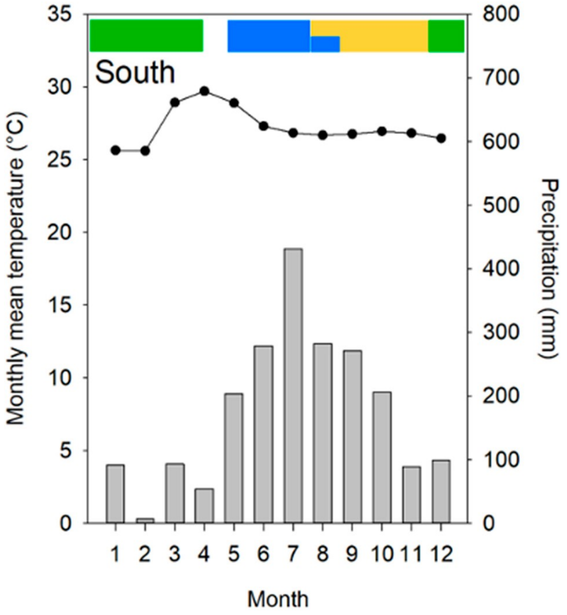

Figure 6. Time windows of cropping seasons in the Mekong River Delta (MRD) (E—green, M—blue, L—gold) shown with rainfall/temperature data (values from 2018 at Soc Trang).

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 is similar to the EFs previously used by the Ministry of Natural Resources and

Environment (MONRE) in the Central region, slightly lower in the North region and much higher in the South region. 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} $season^{-1}$ 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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Conflicts of Interest:

The authors declare no conflict of interest.

References

1. General Statistics Office of Viet Nam. (2020) Planted Area and Production of Paddy. Available online: https://www.gso.gov.vn/default_en.aspx?tabid=778 (accessed on 19 March 2020).
2. World's Top Exports. Available online: http://www.worldstopexports.com/rice-exports-country/ (accessed on 5 May 2020).
3. Intergovernmental Panel on Climate Change. *IPCC 2014: Climate Change 2014: Mitigation of Climate Change*; Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014.
4. Wassmann, R. *Environmental Footprints of Modernization Trends in Rice Production Systems of Southeast Asia. Oxford Research Encyclopedia of Environmental Science*; Oxford University Press: Oxford, UK, 2019.
5. MONRE—Ministry of Natural Resources and Environment. *The Third National Communication of Vietnam to the United Nations Framework Convention on Climate Change*; MONRE: Hanoi, Vietnam, 2019; p. 124. ISBN 978-604-952-383-0.
6. Carlson, K.M.; Gerber, J.S.; Mueller, N.D.; Herrero, M.; MacDonald, G.K.; Brauman, K.A.; Havlík, P.; O'Connell, C.S.; Johnson, J.A.; Saatchi, S.; et al. Greenhouse Gas Emissions Intensity of Global Croplands. *Nat. Clim. Chang.* **2016**, *7*, 63–68. [CrossRef]
7. FAO. AQUASTAT Core Database. Food and Agriculture Organization of the United Nations. 2020. Available online: http://www.fao.org/nr/water/aquastat/data/query/index.html (accessed on 19 March 2020).
8. Abidoye, B.; Truong, T.; Kurukulasuriya, P.; Mendelsohn, R.; Tomova, M.; Dobias, R. *Economics of Climate Change Adaptation: Agriculture Sector Analysis for Viet Nam*; USAID: Washington, DC, USA, 2016.
9. Minderhoud, P.S.J.; Coumou, L.; Erkens, G.; Middelkoop, H.; Stouthamer, E. Mekong delta much lower than previously assumed in sea-level rise impact assessments. *Nat. Commun.* **2019**, *10*, 3847. [CrossRef] [PubMed]

10. Sander, B.O.; Wassmann, R. Common Practices for Manual Greenhouse Gas Sampling in Rice Production: A Literature Study on Sampling Modalities of the Closed Chamber Method. *Greenh. Gas Meas. Manag.* **2014**, *4*, 1–13. [CrossRef]
11. Rochette, P.; Eriksen-Hamel, N.S. Chamber measurements of soil nitrous oxide flux: Are absolute values reliable. *Soil Sci. Soc. Am. J.* **2008**, *72*, 331–342. [CrossRef]
12. Ma, J.; Ma, E.; Xu, H.; Yagi, K.; Cai, Z. Wheat straw management affects CH4 and N2O emissions from rice fields. *Soil Biol. Biochem.* **2009**, *41*, 1022–1028. [CrossRef]
13. Lindau, C.W.; Bollich, P.K.; Delaune, R.D.; Patrick, W.H.; Law, V.J. Effect of Urea Fertilizer and Environmental Factors on CH4 Emissions from a Louisiana, USA Rice Field. *Plant Soil* **1991**, *136*, 195–203. [CrossRef]
14. Vu, D.Q.; de Neergaard, A.; Tran, T.D.; Hoang, Q.Q.; Ly, P.; Tran, T.M.; Jensen, L.S. Manure, biogas
digestate and crop residue management affects methane gas emissions from rice paddy fields on Vietnamese smallholder livestock farms. *Nutr. Cycl. Agroecosyst.* **2015**, *103*, 329–346. [CrossRef]
15. Vu, D.Q.; Mai, V.T.; Bui, T.P.L.; Tran, T.A.; Bui, V.M.; Nguyen, H.S.; Ha, M.T.; Nguyen, H.M.; Nguyen, T.T.; Dang, M.A.; et al. Assessment of economic, ecological efficiency and resistant ability to unfavorable climate condition of System of rice intensification (SRI) in comparison with conventional rice cultivation in Binh Dinh province. *J. Vietnam Agric. Sci. Technol.* **2018**, *6*, 27–33.
16. Tariq, A.; Vu, D.Q.; Jensen, L.S.; Tourdonnet, S.; Sander, B.O.; Wassmann, R.; Trinh, M.V.; Neergaard, A. Mitigating CH4 and N2O emissions from intensive rice production systems in northern Vietnam: Efficiency of drainage patterns in combination with rice residue incorporation. *Agric. Ecosyst. Environ.* **2017**, *249*, 101–111. [CrossRef]
17. Tirol-Padre, A.; Tran, D.H.; Hoang, T.N.; Duong, V.H.; Tran, T.N.; Le, V.A.; Ngo, D.M.; Wassmann, R.; Sander, B.O. Measuring GHG emissions from rice production in Quang Nam province (Central Vietnam): Emission factor for different landscape and water management practices. In *Land Use and Climate Change Interactions in Central Vietnam*; Alexandra, N., Lars, R., Eds.; Springer: Singapore, 2017; pp. 103–122.
18. Vo, T.B.T.; Wassmann, R.; Tirol-Padre, A.; Cao, V.P.; MacDonald, B.; Espaldon, M.V.O.; Sander, B.O. Methane emission from rice cultivation in different agro-ecological zones of the Mekong River Delta: Seasonal patterns and emission factors for baseline water management. *Soil Sci. Plant Nutr.* **2017**, *64*, 47–58. [CrossRef]
19. Smith, K.A.; Conen, F. Measurement of trace gas, I: Gas analysis, chamber methods and related procedures. In *Smith Soil and Environmental Analysis. Modern Instrumental Techniques*, 3rd ed.; Smith, K.A., Cresser, M.S., Eds.; Marcel Dekker: New York, NY, USA, 2004.
20. Wassmann, R.; Phong, N.D.; Tho, T.Q.; Hoanh, T.T.; Khoi, N.H.; Hien, N.X.; Vo, T.B.T.; Tuong, T.P. High-Resolution Mapping of Flood and Salinity Risks for Rice Production in the Vietnamese Mekong Delta. *Field Crops Res.* **2019**, *236*, 111–120. [CrossRef]
21. Minh, H.V.T.; Avtar, R.; Mohan, G.; Misra, P.; Kurasaki, M. Monitoring and Mapping of Rice Cropping Pattern in Flooding Area in the Vietnamese Mekong Delta Using Sentinel-1A Data: A Case of An Giang Province. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 211. [CrossRef]
22. Bartlett, K.B.; Bartlett, D.S.; Harriss, R.C.; Sebacher, D.I. Methane emissions along a salt marsh salinity gradient. *Biogeochemistry* **1987**, *4*, 183–202. [CrossRef]
23. Van der Gon, H.A.D.; van Bodegom, P.M.; Wassmann, R.; Lantin, R.S.; Metra-Corton, T.M. Sulfate-containing amendments to reduce methane emissions from rice fields: Mechanisms, effectiveness and costs. *Mitig. Adapt. Strat. Glob. Chang.* **2001**, *6*, 71–89. [CrossRef]

24. Tan Yen, B.; Nguyen, T.Y.; Tung, T.L.; Amjath-Babu, T.S.; Sebastian, L. Development of a participatory approach for mapping climate risks and adaptive interventions (CS-MAP) in Vietnam's Mekong River Delta. *Clim. Risk Manag.* **2019**, *24*, 59–70. [CrossRef]
25. Tan Yen, B.; Quyen, N.H.; Duong, T.H.; Van Kham, D.; Amjath-Babu, T.S.; Sebastian, L. Modeling ENSO impact on rice production in the Mekong River Delta. *PLoS ONE* **2019**, *14*, e0223884. [CrossRef] [PubMed]
26. Hoa, L.T.V.; Shigeko, S.; Nhan, N.H.; Cong, T.T. Infrastructure Effects on Floods in the Mekong River Delta in Vietnam. *Hydrol. Process.* **2008**, *22*, 1359–1372. [CrossRef]
27. IPCC—Intergovernmental Panel on Climate Change. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Studies (IGES): Hayama, Japan, 1996.
28. IPCC. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*; Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., Emmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., Meijer, J., et al., Eds.; IPCC: Hayama, Japan, 2000.
29. IPCC—Intergovernmental Panel on Climate Change. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Studies (IGES): Hayama, Japan, 2006.
30. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S., Eds.; IPCC: Geneva, Switzerland, 2019.
31. Tran, D.H.; Hoang, T.N.; Tokida, T.; Tirol-Padre, A.; Minamikawa, K. Impacts of alternate wetting and drying on greenhouse gas emission from paddy field in Central Vietnam. *Soil Sci. Plant Nutr.* **2018**, *64*, 14–22. [CrossRef]
32. Oo, A.Z.; Nguyen, L.; Win, K.T.; Cadisch, G.; Bellingrath-Kimura, S.D. Toposequential variation in methane emissions from double-cropping paddy rice in Northwest Vietnam. *Geoderma* **2013**, *209–210*, 41–49. [CrossRef]
33. Richards, M.; Metzel, R.; Chirinda, N.; Ly, P.; Nyamadzawo, G.; Vu, Q.D.; De Neergaard, A.; Oelofse, M.; Wollenberg, E.; Keller, E.; et al. Limits of agricultural greenhouse gas calculators to predict soil N_2O and CH_4 fluxes in tropical agriculture. *Sci. Rep.* **2016**, *6*, 26279. [CrossRef] [PubMed]
34. DMHCC—Department of Meteorology Hydrology and Climate Change of Ministry of National Resources and Environment (MONRE). Report on MONRE-JICA project "Strengthening capacity development for national GHG inventory in Vietnam". 2014. Available online: http://www.monre.gov.vn/English/Pages/ Vietnam--Japan-strengthen-national-greenhouse-gas-inventory.aspx (accessed on 19 March 2020).
35. MONRE—Ministry of Natural Resources and Environment. *Initial Biennial Updated Report of Viet Nam to the UNFCCC*; MONRE: Hanoi, Vietnam, 2014; p. 94.

CHAPTER 4

VARIETAL EFFECTS ON GREENHOUSE GAS EMISSIONS FROM RICE PRODUCTION SYSTEMS UNDER DIFFERENT WATER MANAGEMENT IN THE VIETNAMESE MEKONG DELTA

Vo et al. 2023[4]

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Abstract

Rice production accounts for 15 % of the national Greenhouse Gas (GHG) emissions and Vietnam aims at reducing emissions from rice production by changing farming practices. Little is known about varietal dependent GHG emissions and the potential for mitigation through the selection of different rice varieties is still poorly understood. A two-year field screening of 20 rice varieties under Continuous Flooding (CF) and Alternate Wetting and Drying (AWD) irrigation was conducted in the Mekong Delta, Vietnam, employing the closed chamber method for assessing greenhouse gas emissions. The results confirmed that varietal variation was largest for CH_4 emissions under CF. Across varietal spectrum, CH_4 emissions were more important than N_2O (accounts for less than 2 % of the CO_2e) with the lowest emitting variety showing 243 kg CH_4 ha^{-1} and highest emitting variety showing 398 kg CH_4 ha^{-1} emissions as compare to 0.07 kg N_2O ha^{-1} and 0.76 kg N_2O ha^{-1} emissions, respectively. Under AWD, CH_4 emissions were generally strongly reduced with the varietal effect being of minor importance. Compared with IPCC default values, the data set from the two seasons yielded higher Emission Factors under CF (2.92 and 3.00 kg ha^{-1} d^{-1}) as well as lower Scaling Factors of AWD (0.41 and 0.38). In the context of future mitigation programs in the Mekong Delta, the dry season allows good control of the water table, so varietal selection could maximize the mitigation effect of AWD that is either newly introduced or practiced in some locations already. In the wet seasons when AWD cannot be implemented, selecting low emitting cultivars appears to be the only practical mitigation strategy in many locations.

Keywords

Mitigation, Drought Stress, CH_4, N_2O, seasonal patterns

1. Introduction

Rice production forms the backbone of food supply in Vietnam and has high economic significance as a source of income for smallholder farmers as well as the trade balance of the country. The area of rice production in Vietnam comprises 7.3 million ha (GSO 2020) which makes Vietnam the 6th largest rice producer worldwide. Irrigated rice is the predominant environment in the two Vietnamese mega-deltas, namely the Mekong Delta, which accounts for 55% of all Vietnamese rice production, and the Red River Delta with 18% (GSO 2020). The tropical monsoon climate encompasses distinct rainy months as well as a relatively dry period from November to April. The delta comprises a complex water infrastructure with over 10,000 km of canals and 20,000 km of dykes which provides irrigation to 90% of the cropland (Nguyen et al., 2020). However, rising sea levels as well as the expansion of highly profitable shrimp farming and subsequent changes in irrigation regimes have led to increasing risk of salinity in coastal rice production systems (Wassmann et al., 2019).

Although population growth is slowing in most Asian countries, the demand for rice is projected to increase globally until at least 2035 (Zeigler, 2008). Trends in consumer behavior with regards to environmentally sustainable production of food are especially important for rice production which is associated with high emissions of methane and – to a lesser extent – nitrous oxide. CH_4 is generated in flooded soils as a result of anaerobic decomposition of organic material. For rice-growing countries such as Vietnam, this is the source of a major share of its national greenhouse gas budget. The agriculture sector comprises 27.9 % of the total Greenhouse Gas emissions of which almost half (13.8% of the total) is attributed to rice production (MONRE 2019).

Therefore, the required increase in rice production will rely on adopting technology innovations, site-specific production strategies, and improved varieties (Becker and Angulo, 2019). Compared to rice grown under continuous flooding, CH_4 emissions can substantially be reduced by allowing the field to dry periodically throughout the season, a practice part of the irrigation technology, alternate wetting and drying (AWD). On average, the reduction in emission is 45% according to the IPCC guidelines (IPCC 2019). As a trade-off this practice typically entails increased emissions of another greenhouse gas, namely N_2O, but net emissions in terms of CO_2e was shown to be beneficial for mitigation in the vast majority of field measurements (Jiang et a. 2019). As a signatory of the Paris agreement, Vietnam has reaffirmed "the goal of limiting global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees."

Whereas existing mitigation efforts and plans by the government have focused on adjusted water management such as AWD, the private sector is primarily concerned about marketable rice varieties.

To date the effectiveness of AWD in mitigating GHG emissions from rice production has been well-investigated and described (Schneider and Asch, 2020, Uno et al. 2021, Arai 2022). However, during the intense southeast Asian rainy seasons, precipitation is often too high for an effective and economically viable water saving irrigation. Therefore, during the rainy season high GHG emissions from rice production systems seem unavoidable although little is known on the mitigation potential of individual rice varieties. In this study we investigate the option of selecting specific, high-yielding but low-emitting rice varieties as a potential mitigation strategy for the rainy season and an addition to AWD during the dry season. The specific objectives of our study were:

- To quantify the baseline emissions of 20 selected rice varieties under typical growing conditions in the Vietnam Mekong Delta
- To assess the interactive effects of varieties and two different water management practices on greenhouse gas emissions to provide the field data for assessing viable mitigation strategies.
- To determine the Emission Factors and Scaling Factors as needed in the National Communications (IPCC Tier 2 approach).

2. Materials and Methods

2.1. Experimental site and field design

A field experiment was conducted during the Winter-Spring seasons of 2019-20 (S1) and 2020-21 (S2) covering the periods from December to March. The experimental site was provided by the Loc Troi Group (LTG) and was located in Dinh Thanh commune, Thoai Son district, An Giang province, Vietnam and is characterized by a tropical climate with an annual rainfall of 1415 mm and an average temperature of 27.4 °C. Weather data was extracted from a weather station located next to the experimental fields indicating similar temperature ranges in both seasons with averages of 26.5°C and 25.8°C in S1 and S2, respectively (Figure 1). Total precipitation was 23mm and 89 mm in S1 and S2, respectively. This pronounced inter-annual difference was caused by several high-rainfall events throughout S2 whereas rainfall events were more sporadic and short-lived in the course of S1 (Figure 1).

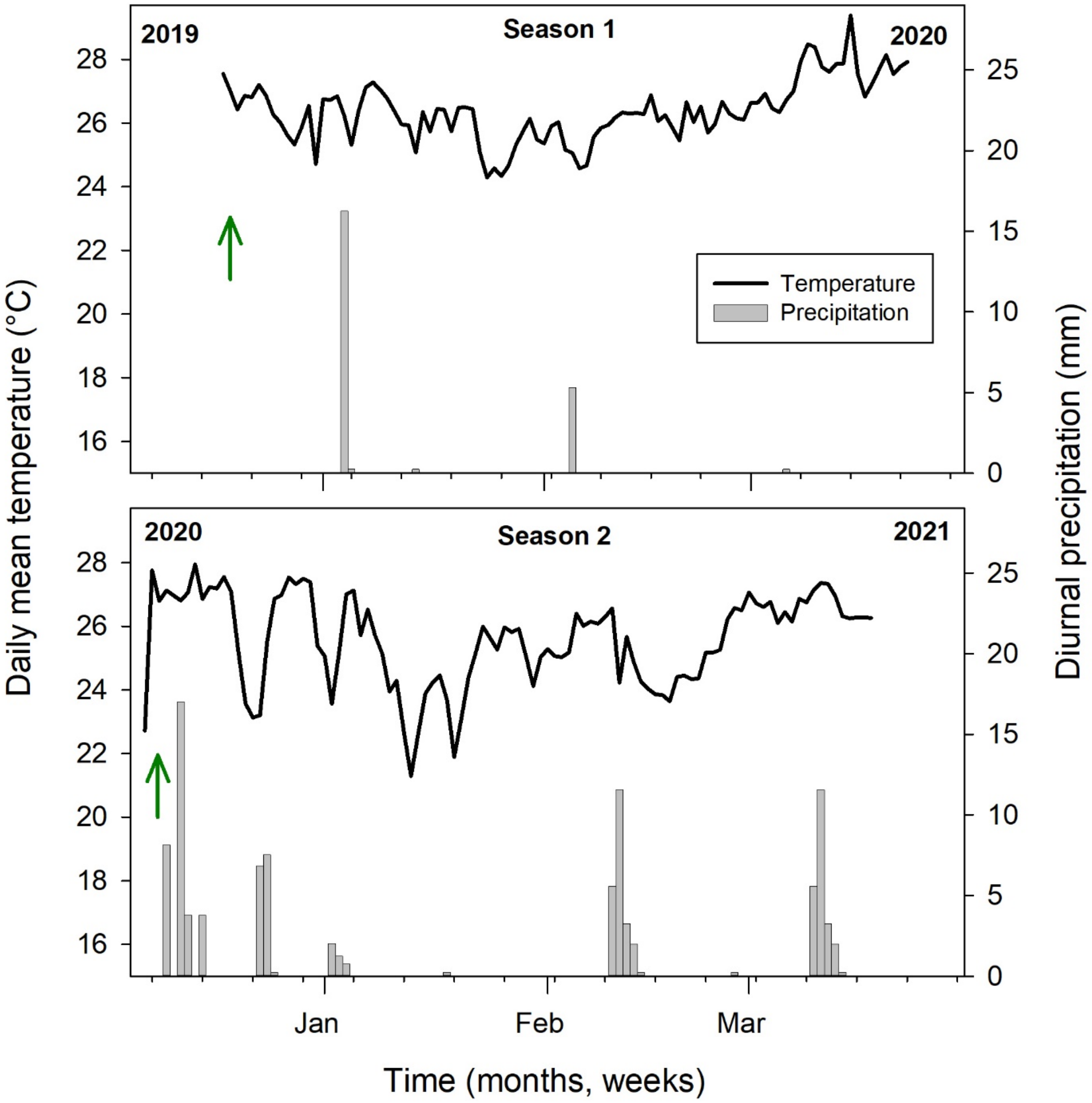

Figure 1. Rainfall and temperature at the experimental site during the two observation periods. The arrows indicate transplanting.

While the soil properties are given in Table 3.1, Table 2 shows the sequence of field operations which corresponded to the typical practices in the research area. Crop management followed the conventional practice of the LTG (Table 2) including cropping calendar, fertilizer and pesticide application. Rice straw was burnt in the first season, whereas it was taken out of the field for other purposes in the second season. The stubbles (30-40 cm height) were partly burnt and incorporated into the soil less than four weeks before the season started.

Table 1. Soil properties of the experimental site. Soil data analysis procedure follow the Vietnamse standards; soil data provided by Loc Troi Group.

Properties	**Results**	**Unit**
Coordinates	10°18’44.9 N 105°19’08.3 E	
Soil texture	Clay	
pH	5.2	
Electrical conductivity (EC)	0.4	
Total Organic Carbon (OC)	3.92	%
Total Nitrogen (total N)	0.37	%
Total Phosphorus (total P)	93.86	mg kg^{-1}
Potassium (K)	141.03	mg kg^{-1}
Calcium oxide (CaO)	232	mg g^{-100}
Magnesium oxide (MgO)	161	mg g^{-100}
Potassium oxide (K_2O)	28.2	mg g^{-100}
Phosphorus pentoxide (P_2O_5)	3.7	mg g^{-100}
Nitrate-nitrogen (NO_3-N)	0	mg g^{-100}
Cation exchange capacity (CEC)	13.9	meq g^{-100}
Silicon dioxide (SiO_2)	15	mg g^{-100}
Humus	390	%

Table 2: Field management practices in the 2 seasons 2019-2020 and 2020-2021 (DAT: days after transplanting)

Practice	**Season 1 - 2019-2020**		**Season 2 - 2020-2021**	
Rice straw management (previous season)	Burnt		Taken out of the field	
Stubble management (previous season)	Burnt and incorporated (< 4 weeks)		Burnt and incorporated (< 4 weeks)	
Height of incorporated stubbles	30 - 40 cm		30 - 40 cm	
Seeding date	05.12.2019		27.11.2020	
Transplanting dates	18 - 20.12.2019		08 - 09.12.2020	
Starting gas sampling	6 DAT		8 DAT	
Inorganic fertilizer application (kg ha^{-1})	90 N - 40 P_2O_5 - 40 K_2O		90 N - 40 P_2O_5 - 40 K_2O	
1st application (30 % N + 40 % P_2O_5 + 20 % K_2O)	3 DAT		9 DAT	
2nd application (40 % N + 50 % P_2O_5 + 30 % K_2O)	14 DAT		16 DAT	
3rd application (30 % N + 10 % P_2O_5 + 50 % K_2O)	35 DAT		39 DAT	
Harvest dates	DAT	Variety	DAT	Variety
	89	OM18, OM2517, OM4218, OM5451	95	OM18, OM2517, OM4218, OM5451, GKG9, ML202
	92	Dai Thom 8, GKG9, IR64, ML202	98	Dai Thom 8, GKG29, IR64, Loc Troi 1, Loc Troi 5,
	96	GKG29, GKG35, Loc Troi 1, OM7347, OM6976,	100	GKG35, Jasmine 85, OM4900, OM7347, ST24
	99	BTE1, DS1, Loc Troi 5, Jasmine 85, OM4900, ST24	108	BTE1, DS1, OM576

The field experiment comprised 120 plots of 4 x 5 m each separated by bunds and ditches (Figure 2a,b,c). Plots with different water treatments (see below) were lined by plastic sheets to prevent lateral water seepage between the plots. The field layout corresponded to a randomized complete block design with two water management treatments, namely Continuous Flooding (CF) and Alternate Wetting and Drying (AWD) as the main experimental factor. The sub-factor of the field design comprises 20 different rice varieties that were planted in 3 replicate plots per water management. The varieties are listed and have been characterized in terms of their agronomic features by Johnson et al. 2023.

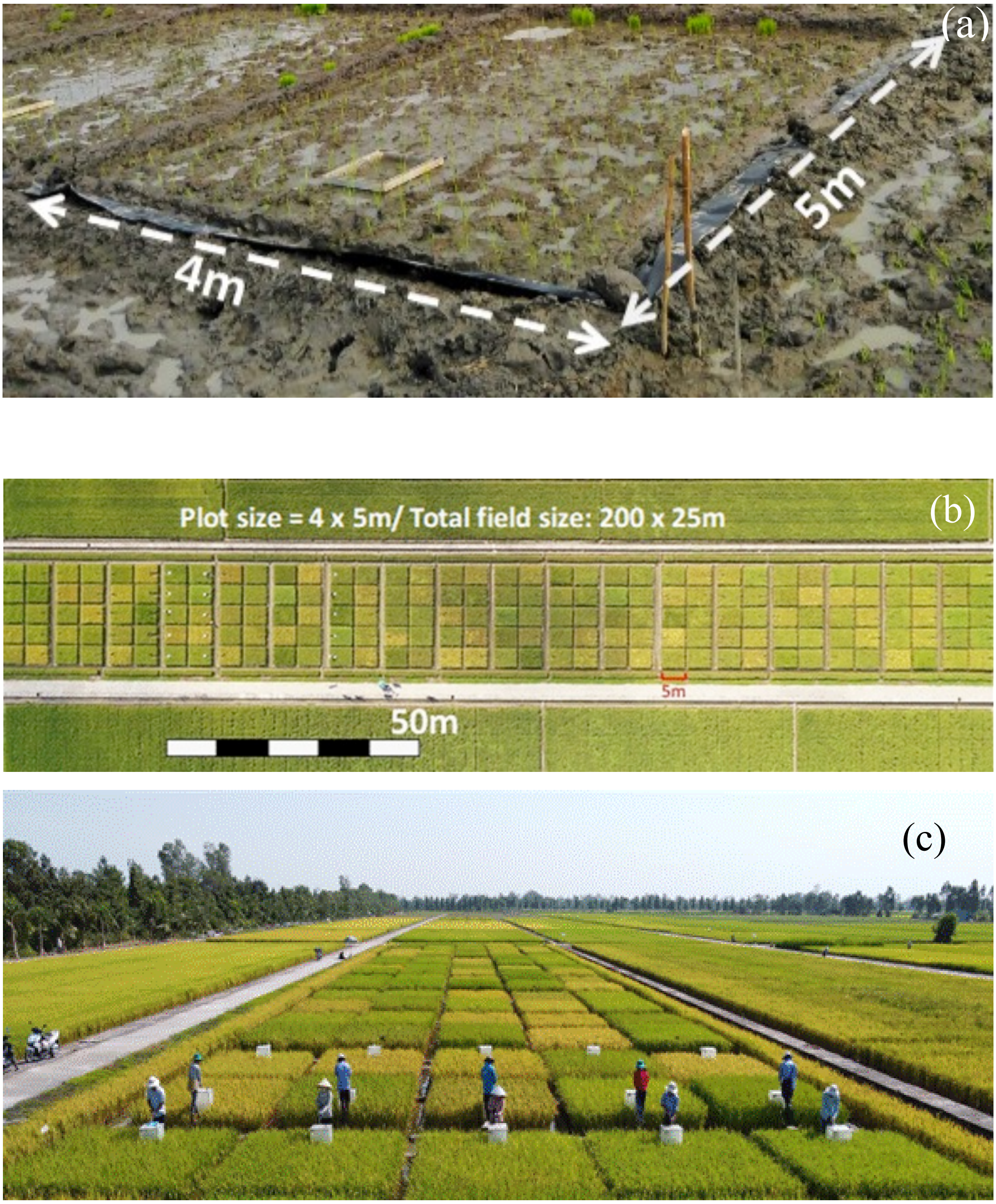

Figure 2a-c. Photos of field experiment at the farm of Loc Troi Group in An Giang Province, Vietnam; (a) plots before transplanting lined with plastic sheets (along the dotted lines) to prevent lateral water flow; (b) an aerial image of entire field showing 4 chambers each placed in the 6th, 7th and 11th row and (c) aerial view of the sampling procedure.

2.2. Water management

Water in the field was controlled by tapping irrigation water from an open canal. In every plot, water level gauges were inserted into the soil at 4 points and kept for the whole season to ensure measuring at the same positions. The surface water level was manually recorded with a ruler on every regular GHG sampling date at the respective sampling plot plus the level before and after every irrigation event, which were scheduled twice a week according to the regular irrigation plan at the research station. The AWD plots were equipped with PVC tubes to monitor the level of water below the soil surface.

In the CF plots, surface water was maintained at the level of 1-5 cm above the soil surface. In line with the IPCC definitions for baseline management, the plots were kept flooded except for terminal drainage of about 1 week without floodwater in preparation for harvest. In the AWD plots, water levels were monitored using perforated PVC tubes (Lampayan et al., 2015). Irrigation was stopped in given intervals allowing the water level to decline due to evapotranspiration. At the threshold water level of -15 cm below the soil surface the fields were re-irrigated to a ponded water layer of 5 cm. This practice was incorporated into the concept of ‘safe AWD’ to prevent eventual drought stress for the plant (IRRI 2023).

2.3. GHG field sampling and lab analysis

CH_4 and N_2O fluxes were measured using the closed chamber method as described in Tirol-Padre et al. (2017). In all plots, a square metal base with a diameter of 46 cm was inserted about 10 cm into the soil covering a soil area with four rice hills planted at 20 x 20 cm spacing (Figure 3). Steel bases were placed in each plot before transplanting and remained in the field throughout the season. To minimize physical disturbance and subsequent CH_4 ebullition during the sampling procedure as well as to avoid any border effects, bases were inserted at one-meter distance from the plot bund. In every plot, a connecting boardwalk (wooden blank) with removable metal frames was temporarily placed on four wooden poles to allow a stable positioning during sampling. The gas collection chambers, constructed of transparent plexiglass with a height of 96 cm and a length and width of 46 cm, were equipped with a sampling port, a thermometer, and a battery-operated fan to circulate the air in the headspace of the closed chamber (Figure 3a,b).

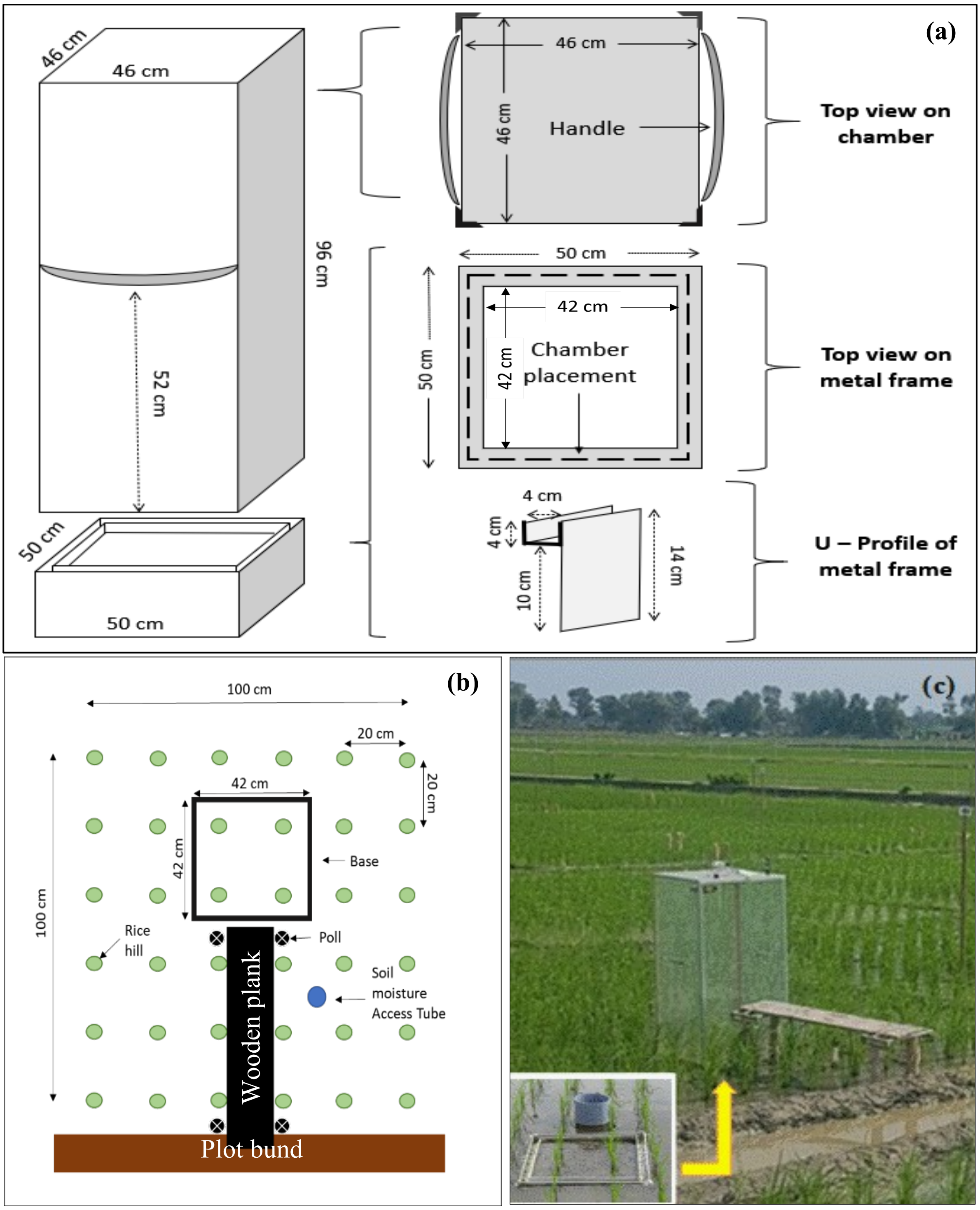

Figure 3a-c. Design and placements of closed chambers (a) design of chamber and base. (b) schematic drawing of field placement, (c) photo of actual sampling point setup

At each sampling event, chambers were placed for 30 minutes on the metal base. The trenches of the bases were filled with water to ensure an airtight enclosure of the soil/ water surface and the rice plants (Figure 3c). Gas samples from inside the chamber were retrieved at 0, 15, and

30 minutes after chamber placement. Gas sampling was implemented in weekly intervals over the whole growing period. While samples were collected from 8:00 to 12:00 in the routine sampling for assessing seasonal emissions, we also conducted sporadic measurements on diurnal patterns of hourly emission rates (data not shown), namely five varieties in S1 (3 measurements) and two varieies in S2 (2 measurements). To optimize labor requirements, these hourly emission rates over one 24-h cycle were aggregated to one value and used as a daily emission rate for the respective variety and given week within the assessment of seasonal emission rates in this study (see calculation procedures below). Since the field experiment included varieties differing in phenology (Table 2), the number of varieties sampled was reduced during the last weeks of both observation periods.

Gas samples from the enclosed chamber headspace were retrieved using a 60 mL syringe fitted with a stopcock attached via a valve to the gas sampling port at the chamber headspace. The gas samples were immediately inserted into pre-evacuated vacuum glass vials with a butyl rubber septum and covered by an aluminum cap. Individual steps of sampling, analysis and data evaluation procedure included the following steps: a) samples were stored in pre-evacuated vials and shipped to the IRRI lab in the Philippines (> 9000 samples in total); b) chemical analysis of CH_4- and N_2O-concentrations through gas chromatography (Model: SRI 8610C); c) hourly emission rates were derived from the temporal increase (slope) of concentrations (incl. QA/QC procedure of linearity); d) average of 3 replicate flux rates were considered as weekly emission record in further data evaluation.

2.4. Data evaluation and quality control

Hourly emission rates of CH_4 (mg CH_4 m^{-2} h^{-1}) and N_2O (µg N_2O m^{-2} h^{-1}) were calculated according to Minamikawa et al. (2015). The measurements taken in the morning were assumed to represent daily average flux rates representing a weekly interval. The evaluation of emission rates was done at three levels: (i) hourly emission rates as intermediate data that is not shown in the paper, (ii) daily emission rates derived from the replicate measurements of one variety in a given week, and (iii) seasonal emission rates calculated by multiplying the daily emission rates with the number of days of the cultivation period. For the conversion from daily to seasonal emission rates, it was assumed that flux changes between two consecutive sampling days are linear, so that seasonal emission rates also represent the cumulative emission over one season.. The daily emission rates on the day of sowing and harvest were set to “0”. The seasonal emission was calculated as the sum of the daily emissions from transplanting to harvest by applying the trapezoidal integration method described by Minamikawa et al. (2015).

The seasonal emission rates are used as the basic metric for intercomparison of seasons and varieties as well as for references to the national GHG inventory (MONRE 2019). The individual values of daily emission rates are embedded in the diagrams whereas the mean daily emission rate over a given season is used for the comparison with the default values of the IPCC guidelines (IPCC 2019).

Calculated fluxes were included when the coefficient of determination (R^2) of the linear regression of gas concentration over time was at least 0.976 and with a $p < 0.01$ (Minamikawa et al. 2015). In our study, the CH_4 fluxes show a high rate of acceptable values (about 55 % met the required R^2 of Minamikawa et al. (2015)), therefore, CH_4 emission data were presented without correction as postulated by Parkin et al. 2012 (cited in Minamikawa et al. 2015). In contrast, of the seasonal N_2O emission rates only about 10 % passed the required R^2 value including negative linearity, in this case data were set to zero for the interpolation and integration. The data was used to determine the Emission Factor (EF), Scaling Factor (SF), and area-scaled Global Warming Potential (GWP) of each variety.

Finally, seasonal emission rates of CH_4 and N_2O per variety were averaged over both seasons and converted to CO_2e with the commonly used GWP-values of CH_4 (28) and N_2O (265) given in the 5th IPCC assessment report (IPCC 2014) for a time horizon of 100 years. Analysis of variance (ANOVA) was performed in order to evaluate the effects of water management and variety on CH_4 emission rates and their interactions if the factors differed significantly (by p-value).

3. Results

3.1. Water management and rice growth duration

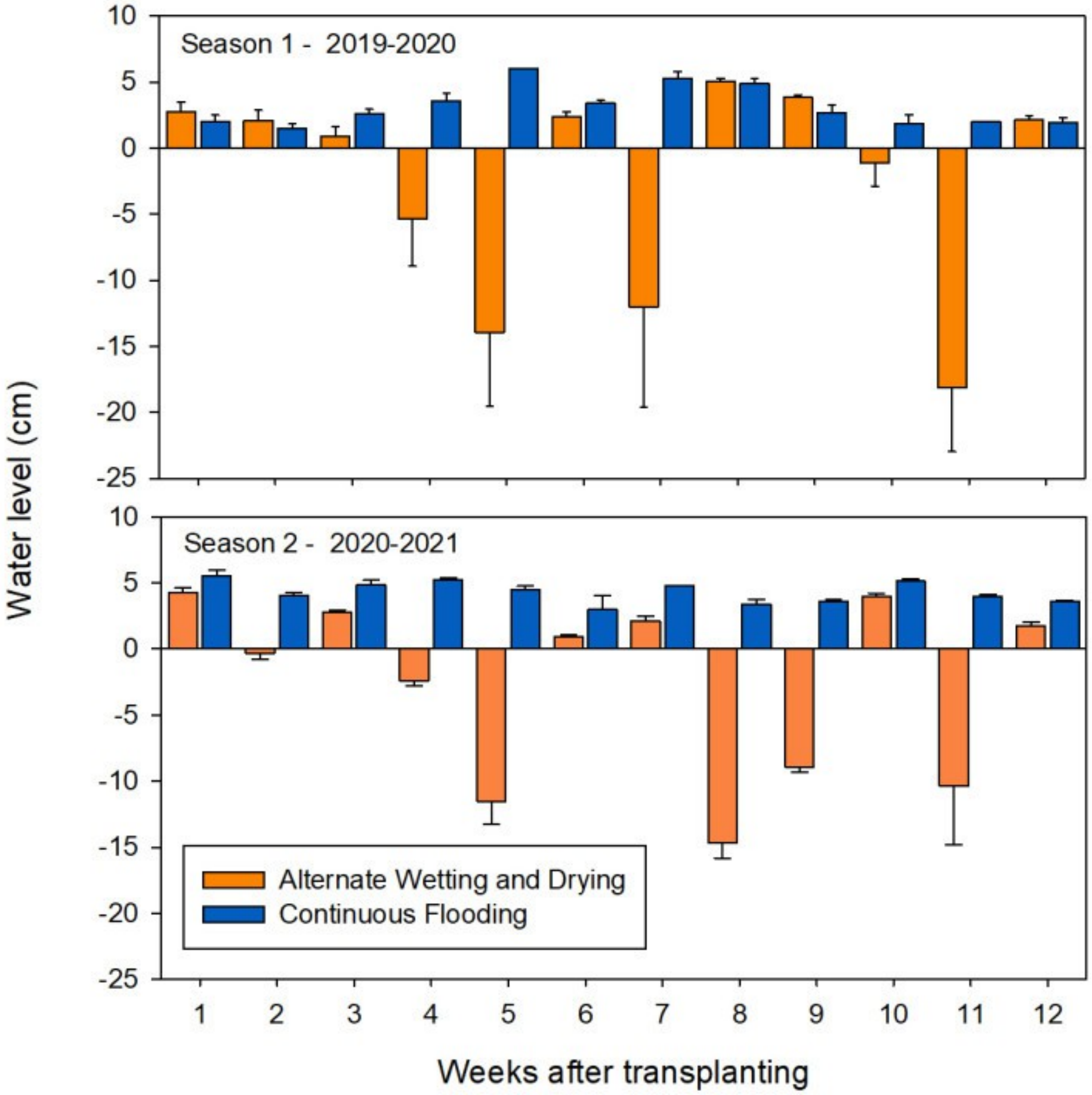

Figure 4. Patterns of plot water levels summarized across varieties measured by water level gauges and PVC tubes in the season 2019/2020 (upper graph) and the 2020/2021 (lower graph), respectively.

Figure 4 illustrates the seasonal water level dynamics for CF and AWD as measured in the plots during the two cultivation periods. Water levels were efficiently controlled throughout the two seasons with minor differences in seasonal irrigation management. In the first season, water levels in the AWD plots declined to less than -20 cm below the soil surface, whereas in the second season maximum depletion was to -15 cm. The stronger depletion in the first season may be attributed to imperfect construction of plot bunds that were initially not yet compacted enough to prevent cracks and holes. This shortcoming was resolved in the second season by making the bunds wider. Moreover, the first season had lower rainfall which probably also contributed to the inter-annual differences in water levels.

Seasons also differed in planting duration, which was in most cases delayed in the second season (Table S1). This may have been due a) seedlings being two days younger at transplanting in the second season and the season was markedly cooler (Figure 1), which likely extended the growth period in the fields; and b) surplus water from higher rainfall in the second season.

3.2. Seasonal emission patterns

The seasonal emission patterns are available for all 20 varieties for both treatments and both GHG species. CH_4 emission shows similar among all varieties and seasons, the differences between CF and AWD were noticeable starting 25 and 35 days after transplanting (DAT) when water levels were periodically below the soil surface in S1 and S2, respectively (Figure 5). In the remaining cultivation periods, daily emission rates of AWD were consistently lower than those of CF. Given the high level of daily emission rates, the graphs of CF showed some fluctuation whereas emission from AWD remained within a very low range. The results of ANOVA showed significant differences of treatment and variety on daily CH_4 emission rate averaged over the season ($p<0.0001$ and $p<0.001$ respectively). However, the effect of season on cumulative emission rates was not significant. The variations in N_2O emissions appeared rather irregular during both seasons. Water management does not show any discernable effect based on the seasonal patterns although this observation will not exclude differences in terms of the seasonal emissions. While N fertilizer application did not trigger N_2O peaks, some varieties showed high N_2O emission during the terminal stage of the season when the field was drained for harvest (Figure 6). The average daily N_2O emission rate varied significantly with variety and season ($p<0.0001$) but not treatment.

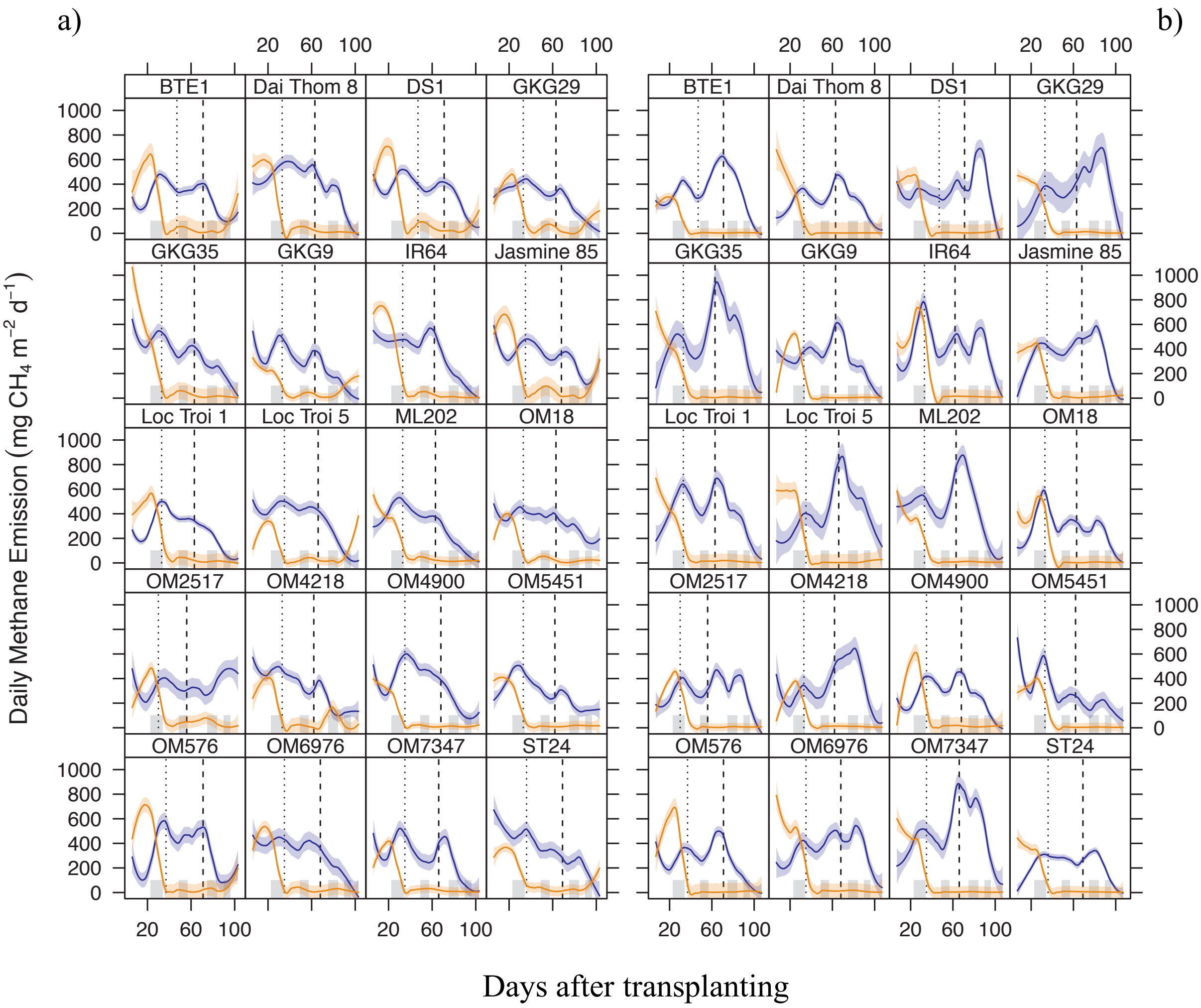

Figure 5a-b: Daily CH_4 emission rates from 20 rice varieties; a) the first season (2019-2020), and the b) the second season (2020-2021). The lines are loess regressions (locally estimated scatterplot smoothing) for all replicates by variety with an alpha of 0.3. The shaded band around each line represents standard error. Line color indicates irrigation treatment: blue, AWD, and orange, CF. The grey blocks on the x-axis represent the duration of a drying event related to the implementation of AWD. The dotted vertical line represents panicle initiation (P.I.), and the dashed vertical lines, flowering.

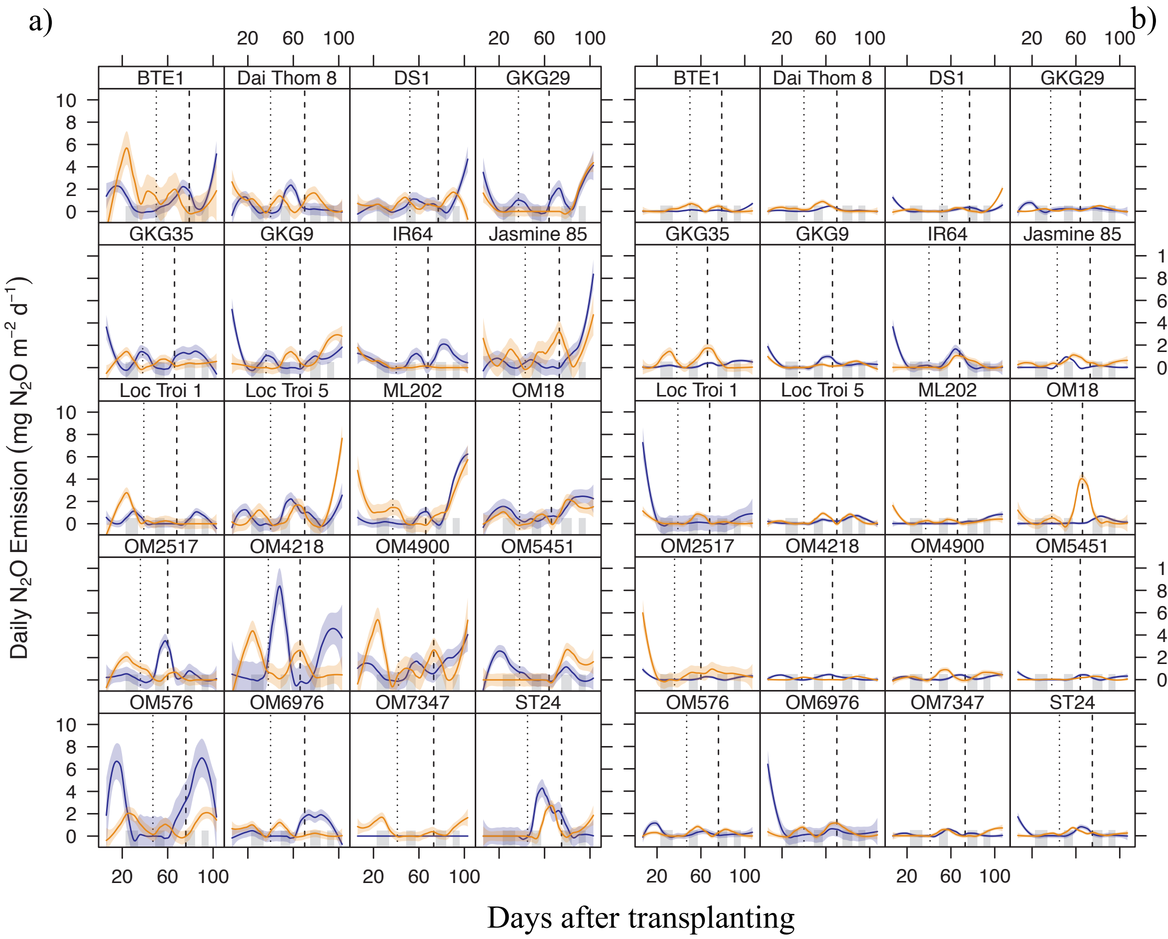

Figure 6a-b: Daily N_2O emission rates from 20 rice varieties; a) the first season (2019-2020), and the b) the second season (2020-2021). The lines are loess regressions (locally estimated scatterplot smoothing) for all replicates by variety with an alpha of 0.3. The shaded band around each line represents standard error. Line color indicates irrigation treatment: blue, AWD, and orange, CF. The grey blocks on the x-axis represent the duration of a drying event related to the implementation of AWD. The dotted vertical line represents panicle initiation (P.I.), and the dashed vertical lines, flowering.

3.3. Comparison of seasonal emissions

The seasonal emissions show in Figure 7 that CH_4 emissions under CF are at least twice as high as under AWD in both seasons. In the first season, the cumulative CH_4 emission rates had a mean value across all varieties of 315 kg ha^{-1} for CF (ranging from 257 to 416 kg ha^{-1}) and 130 kg ha^{-1} for AWD (ranging from 86 to182 kg ha^{-1}). In the second season the mean of the cumulative CH_4 emission rates for CF was 332 kg ha^{-1} (ranging from 222 to 478 kg $ha^{-1}$and for AWD mean CH_4 emission rate was 120 kg ha^{-1} (ranging from 78 to 158). In comparison to CF, the cumulative CH_4 emission rates under AWD in the 2 seasons were significantly reduced by 59 and 64 %, respectively. Despite large differences between varieties, seasonal emissions were not significantly different between varieties, though treatment effects were significant ($p<0.001$).

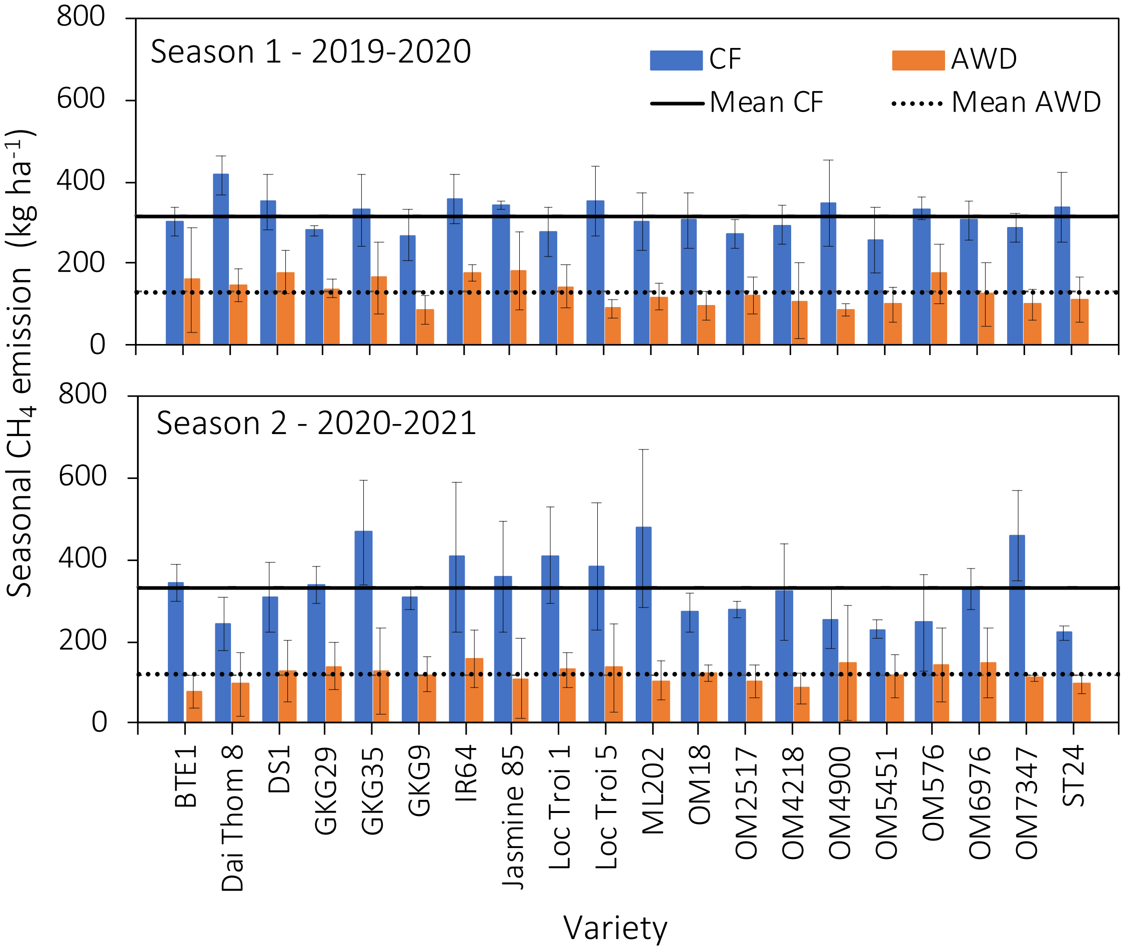

Figure 7. Seasonal CH_4 of 20 rice varieties in the 2019-2020 (upper graph) and the 2020-2021(lower graph), respectively. CF = Continuoues Flooding; AWD = Alternated Wetting and Drying; Error bars = standard deviation.

The seasonal N_2O emissions (Figure 8) reflect the generally low emission levels throughout both seasons. On average, seasonal emissions of N_2O were 0.71 kg ha^{-1} (ranging from 0.2 to 1.35 kg ha^{-1}) in S1 and 0.24 kg ha^{-1} (ranging from 0.04 to 0.58 kg ha^{-1}) in S2, across all varieties. Total N_2O emission in S1 was 3 times greater than that in S2 (Figure 8), due to the due to the lower level of water in AWD plots in the first season. However, the irrigation treatment did not lead to any reduction in N_2O emission rate. Moreover, the N_2O emission rates of certain varieties differed strongly between S1 and S2 (Figure 8) and there were some strong variations among the replications in both seasons. These discrepancies go along with high standard deviations caused by individual extremes of high N_2O emission rates, namely BTE1, Jasmine 85, OM4218, OM4900 and OM576 in S1 as well as Loc Troi 1 and OM6976 in S2. Although treatment effects were significant ($p<0.001$), differences in varietal seasonal N_2O emissions were not significantly different.

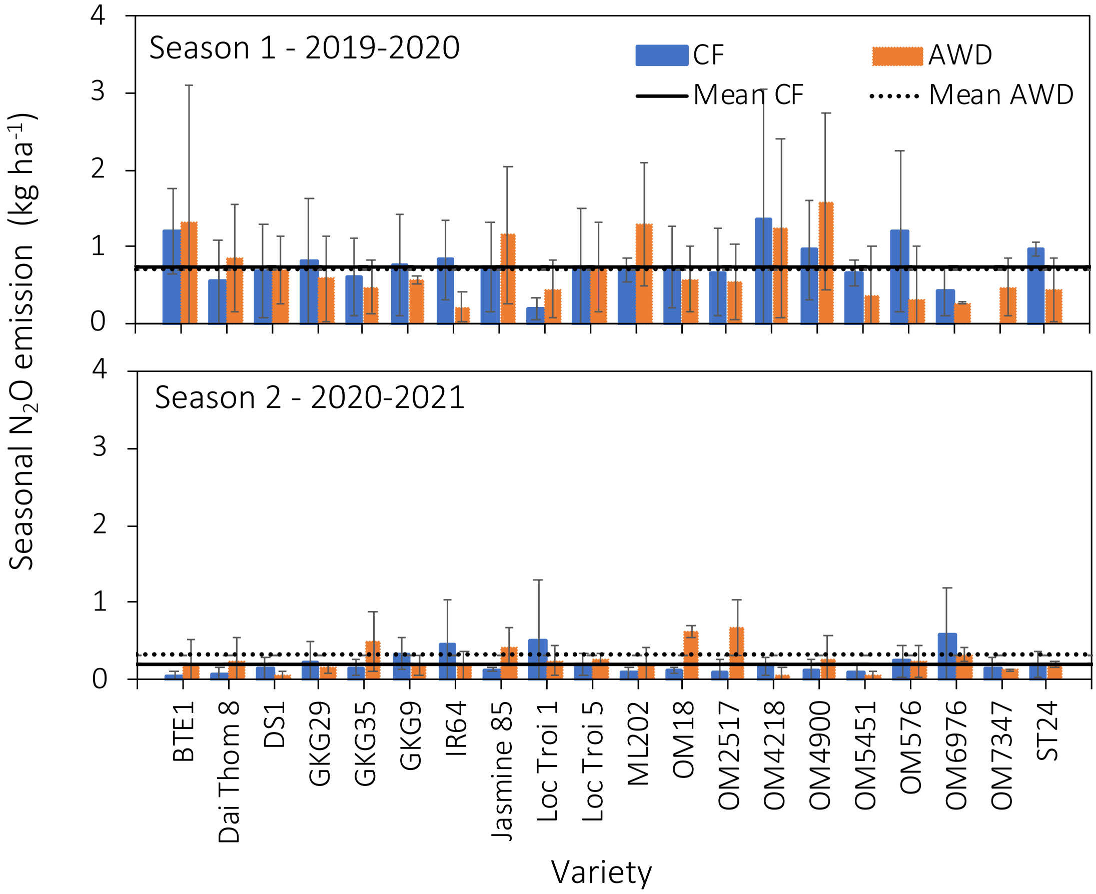

Figure 8. Seasonal N_2O of 20 rice varieties in the 2019/2020 (upper graph) and the 2020/2021(lower graph), respectively. CF = Continuous Flooding; AWD = Alternated Wetting and Drying; Error bars = standard deviation.

3.4. Variety dependent emissions under given and changing water management

Strong varietal effects on GHG emissions were found in the CF treatment where emissions of the highest emitting variety were factor 1.6 and 2.1 higher than those of the lowest emitters in S1 and S2, respectively. Referenced to the average of all varieties, the seasonal emission rates range from a reduction of 59 kg CH_4 ha^{-1} (19 %) for the lowest emitting variety to an increment of 100 kg CH_4 ha^{-1} (32 %) of the highest emitting variety in S1. These figures were similar in S2, namely 110 kg CH_4 ha^{-1} (33%) and 150 kg CH_4 ha^{-1} (44 %) (Table S1). Despite all the variations inherent in this data set, the results for CF indicate a sizable mitigation potential by variety selection in the range of 19 % and 44 %. As for AWD, however, the CH_4 seasonal emission rates show a converging trend across different varieties. In part, this can be attributed to generally low emission levels that translate into small differences in absolute terms ranging from 130 and 120 kg CH_4 ha^{-1} for S1 and S2, respectively. Even in relative terms, the variations of 59 and 64 % were lower than for CF. Likewise, for the N_2O emissions, the results do not allow recommending a specific variety. Daily N_2O emission rates were generally low under both CF and AWD which was superimposed by large variations from season to season.

In order to assess the magnitude of the individual varietal mitigation potential under the two irrigation management methods, we calculated the difference (delta) between the individual, seasonal varietal emissions and the mean seasonal emissions across all varieties and plotted these for the two irrigation methods. Figure 9 comprises the 4 charts with the delta CF values plotted against the x-axis and delta AWD values against y-axis for CH_4 and N_2O in both seasons. The delta values reflect the different magnitudes of absolute emissions under CF and AWD, i.e. Figure 9a show data of CH_4 for season 1, delta CF varied from -59 (±20) to 100 (± 22) kg ha^{-1} while the delta AWD values varied from -45 (± 16) to 51 (± 45) kg ha^{-1} whereas that of delta value from season 2 (Figure 9b) ranged from -111 (± 16) to 145 (± 89) and -42 (± 3) to 38 (± 37) for CF and AWD, respectively. The CH_4 data clearly shows the seasonal effect on varietal emissions but for CF the range is similar in both seasons, even though, probably due to differences in temperature the varietal range was larger, and thus also the mitigation potential in the second season where AWD are almost evenly scattered around zero and the distribution of the delta CF values is skewed, i.e. the positive values stretch over a larger range than the negative values. For N_2O, Figure 9 c,d show a large range of emissions between two seasons, particularly, varietal differences are more apparent in the first than in the second season but deltas are very small and irrigation treatment has only minor effect on the emissions.

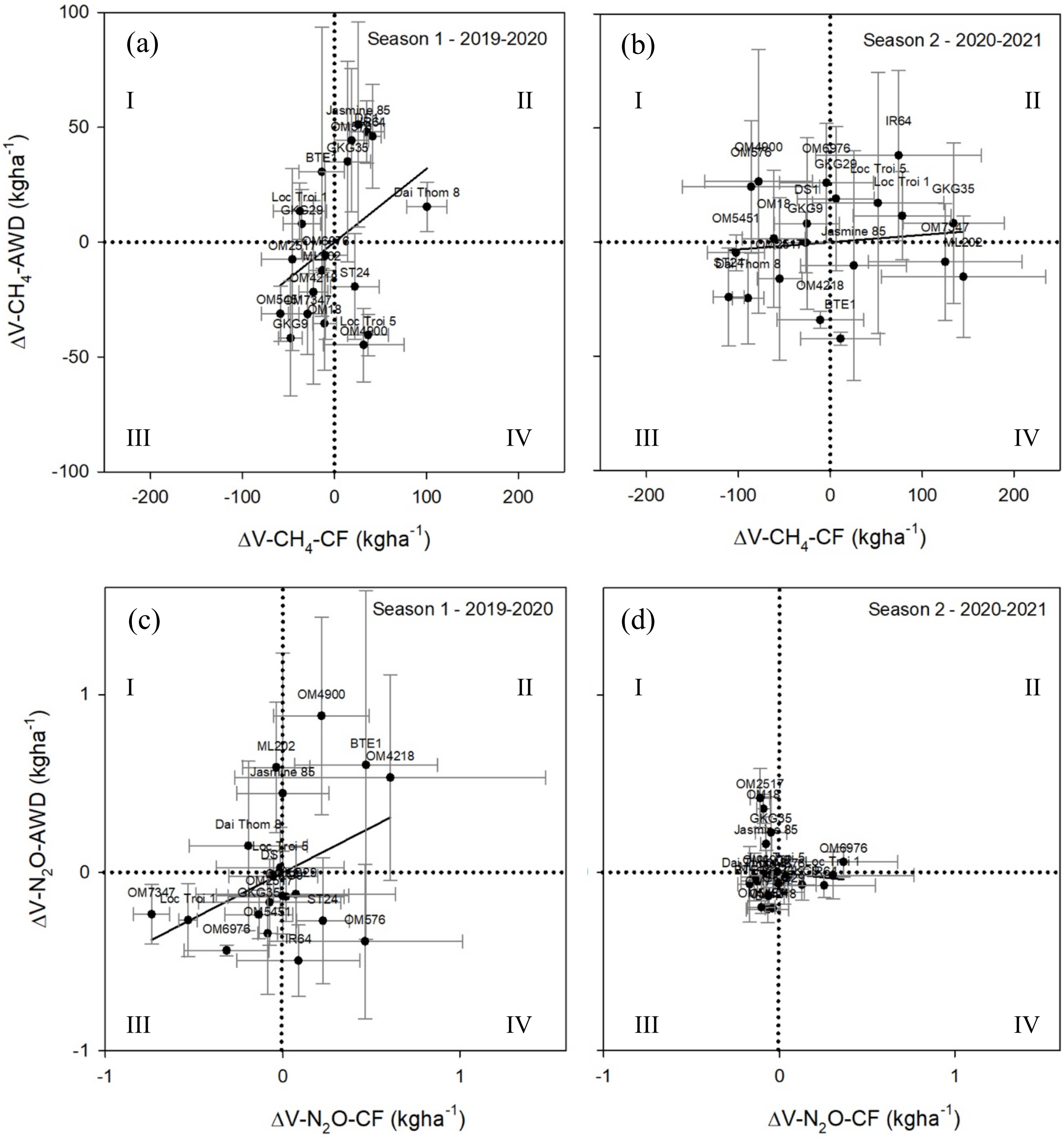

Figure 9 a-d. Delta variety (ΔV) of Continuous Flooding (CF) and Alternated Wetting and Drying (AWD) of CH_4 and N_2O (kg ha-1) values of 20 varieties from two seasons. Greek numbers indicate the chart quarters.

The two zero dotted lines in each graph create four clusters in the chart corresponding to different priorities in variety selection. The varieties in the lower left cluster (III) can be assigned highest priority for future mitigation projects due to their above average mitigation effect for both CF and AWD. The varieties in the upper left quarter (I) could be considered as second priority because they reduce emissions as long as the CF water management will be maintained. The varieties in the lower right quarter (IV) would in principle qualify for mitigation projects that switch from CF to AWD, but varietal emissions vary in a smaller range than GHG emissions reductions achieved by AWD. Finally, the cluster of varieties in the upper right quarter (II) should not be considered in future mitigation efforts.

However, the database allows conclusions on the interactive nature of variety selection and water management. The chart in Figure 10 depicts the baseline emissions as the x-axis with the respective net mitigation as the y-axis to allow easy identification of the most promising varieties for mitigation. The net mitigation potential in the season ranged between 135 (OM576) and 270 (OM7347) kg ha^{-1}. The largest reductions through AWD in those varieties with high baseline emissions are shown in the orange circles, whereas, low-emitting varieties AWD had smaller effects than those with green arrows. To maximize net mitigation potential, varieties should be selected according to season

Scaling factors varied between 0.29 and 0.55. Small AWD effects in low-emitting varieties resulted in the highest scaling factors. Given the underlying equation of calculating scaling factors, however, the resulting data points project an inverse image as in Figure 10 is that the most promising varieties are plotted in the lower right corner. This clearly indicates that scaling factors alone are not sufficient to describe the varietal effect on seasonal emissions, but have to be seen against the backdrop of high vs low baseline emissions and that varieties should be annually low emitting with a small scaling factor.

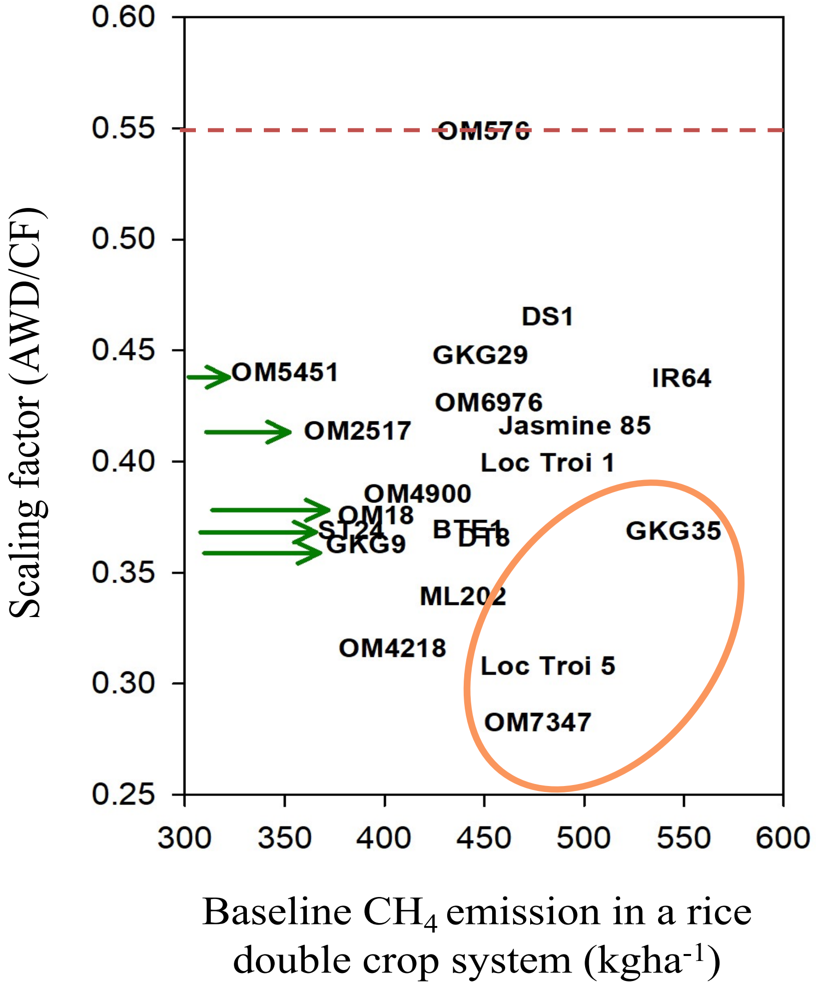

Figure 10: Varietal scaling factor for 20 rice varieties. Green arrows indicate the 5 lowest emitters. Orange circle includes high emitters with strong AWD reduction potential; Dashed line indicates the Scaling factor (AWD/CF) according to IPCC. Data show the means over two seasons.

3.5. Global Warming Potentials

Figure 11 shows the CH_4 and N_2O emissions per variety averaged over both seasons and converted to CO_2e with the GWP-values of 28 and 265, respectively, that were adopted from the 5th IPCC Assessment Report (IPCC, 2014). It should be noted that these values vary from the GWP used in Vietnam's National Communication (i.e. 25 for CH_4 and 298 for N_2O) adopted from the 4th Assessment report (MONRE 2019). The varieties were plotted in ascending order of the GWP which highlights the predominant role of CH_4 vs N_2O – even for those varieties with high GWP. Particularly, 98 % and 99 % contributed by CH_4 in S1 and S2, respectively. Across all varieties, the reduction potential of AWD was above the IPCC default

(40 %) ranging from 57% and 63% in seasons 1 and 2, respectively. In terms of CH_4 contribution, the relative share was 75.3 % CH_4 from CF and 24.7 % from AWD treatment in the 1st season. Similarly, the share was 69.9 % and 30.1 % in the 2nd season and that results in a significant variation in an overall GWP observed between water management in each season.

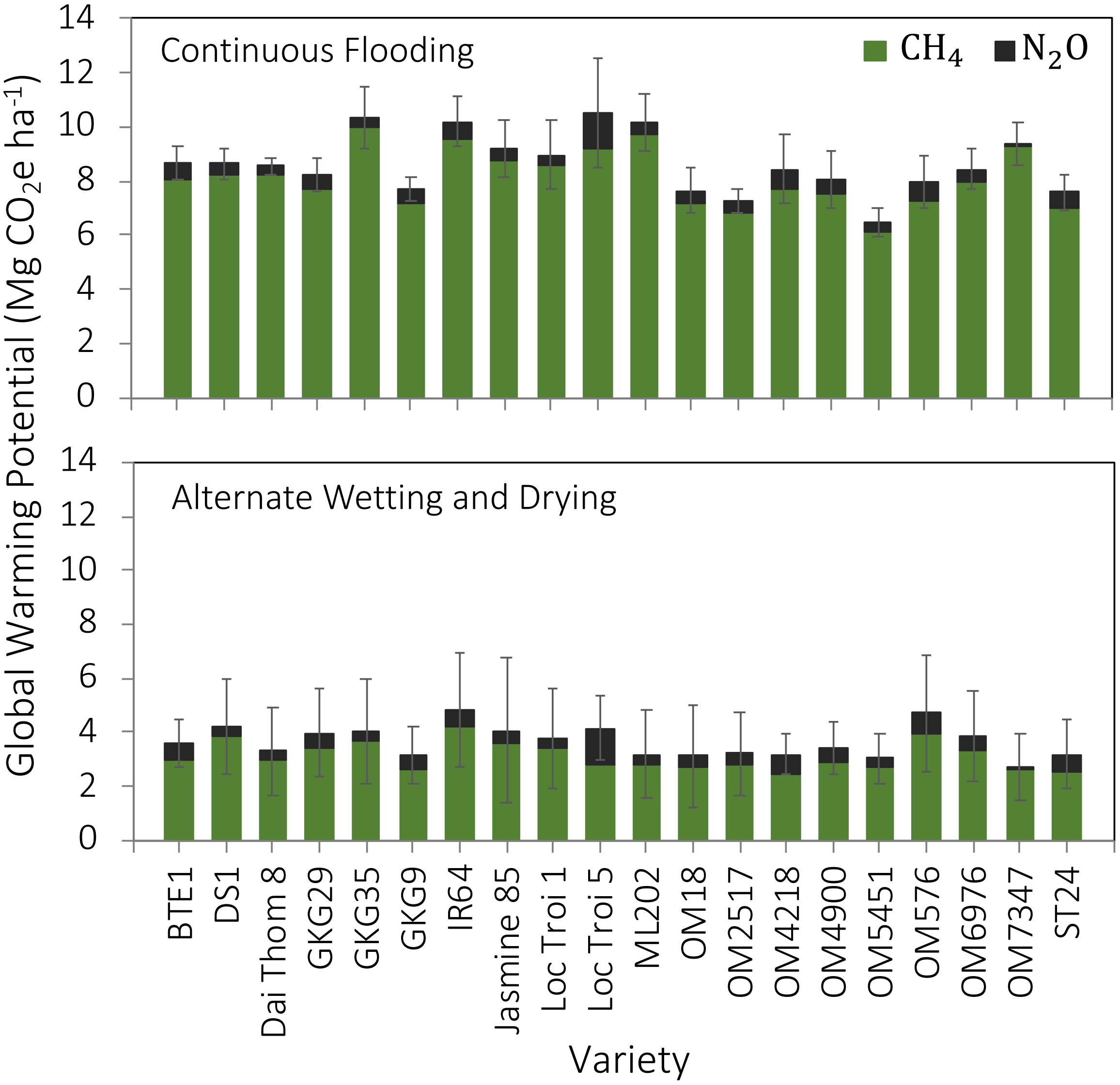

Figure 11. Seasonal Global Warming Potential of 20 rice varieties under Continuous Flooding (upper graph) and Alternate Wetting and Drying (lower graph) based on aggregated emissions of CH_4 (GWP_{CH4} = 28) and N_2O (GWP_{N2O} = 265). The bars show the means over two seasons and the error bars show the standard deviations of the aggregated emissions

4. Discussion

4.1. Literature data on rice varieties

In the current study, 19 lowland rice varieties from Vietnam and one international check variety (IR64 from the Philippines) were investigated for their greenhouse gas emissions during two consecutive dry seasons under two irrigation managements in the Vietnam Mekong Delta. The aim was to elucidate the mitigation potential for greenhouse gas emissions via a) irrigation management and b) selection of low emitting varieties. Whereas the body of literature describing the mitigation potential of AWD for CH_4 emissions is comprehensive, the mitigation potential originating from selecting suited low-emitting varieties for the rainy season has hardly been investigated. Two meta-analyses addressed this issue: Zhang et al (2014) compared the GWP measured in 27 publications from field studies in China that included 120 data points while the meta-analysis by Jiang et al. (2017) comprised 17 field studies from 6 Asian countries covering 79 varieties in total. However, these meta-analyses only marginally dealt with field studies from southeast Asia. We compiled a list of field studies that were not included in these two meta-analyses.

As shown in Table 3, several field studies have reported substantial effects of rice varieties on GHG emissions, especially CH_4. Based on the present mechanistic understanding, the main impact of rice plants on emissions seems to be through the duration to maturity resulting in different lengths of periods of ponded water layers. In a field experiment in Indonesia, Wassmann et al. (2000) showed that seasonal emissions of an early maturing (110 d) variety were proportionally lower than the traditional variety with a duration of 140 d. This is also reflected in the IPCC methodology for GHG inventories (IPCC 2019) that multiplies daily emission rates with the days from planting to harvest. In this respect, the prevailing breeding of new, early maturing rice varieties – has contributed to reducing emissions from rice production systems at the global scale. However, when looking closer into a set of varieties less contrasting than landraces vs. improved varieties or short duration (<90d) vs long duration (>130 d), as in the current study, where the duration to maturity varied among the varieties at maximum by 18-21 days in the respective seasons (data showed in Johnson et al. 2023), these patterns do not hold. We showed that under continuous flooding the emissions of the highest emitting variety are factor 1.6 and 2.15 higher than those of the lowest emitters in season 1 and season 2, respectively. The varieties emitting consistently lower than average, OM18, OM5451, OM2517, and GKG 9, were with on average 83.5 (S1) and 87.5 (S2) days to maturity indeed among the varieties with the shortest duration. However, the varieties that showed strongly above average emissions in both seasons, LocTroi 5, Jasmine 5 and IR64, had on average 88.5 (S1) and 94 (S2) days to maturity which were 11.3 % (S1) and 6.3 % (S2) shorter durations than the respective longest durations observed. The varieties with the longest durations in both seasons, BTE 1 and DS1, had seasonal emissions at the genotypic average level. The remaining varieties showed no consistent emission pattern across seasons.

An earlier study in India (Das and Baruah, 2008) found lower CH_4 emissions from improved varieties than from traditional varieties. In another study, Baruah et al. 2010 examined ten popularly grown rice varieties in India and confirmed that CH_4 emissions were higher in the traditional varieties than in improved high yielding varieties. This was attributed to the profuse vegetative growth in the traditional variety since CH_4 emissions showed significant positive correlations with leaf area, leaf number, tiller number, and root dry weight. The current study underlines the large variation among genotypes. Here, only improved, high-yielding varieties were included and with few exceptions seasonal emissions were lower than the improved, semi-dwarf international check IR64.

Table 4. Comparison with literature data on rice varieties

Study	Number of varieties	Country	Observed differences
Arianti et al. (2022)	3	Indonesia	Varied among varieties in CH_4 emission
Wang et al. (2021)	4	China	Rice variety was among the most important factors affecting CH_4 emission and GWP whereas N_2O mainly related to N-fertilizer
Bhattacharyya et al. (2019)	7	India	Significant variation in CH_4 emission among varieties; low emission found in short growth-duration varieties
Bharali et al. (2017)	6	India	Significant differences in photosynthetic rate among varieties, which were found to influence CH_4 emission
Baruah et al. (2010)	10	India	CH_4 emissions were higher in the traditional varieties than in improved high yielding varieties CH_4, N_2O had significant positive correlation with leaf area, leaf numbers, tiller numbers, root dry weight.
Khosa et al. (2010)	3	India	Significant variation in CH_4 emission among varieties
Gogoi et al. (2008)	10	India	Traditional varieties showed higher CH_4 emission rate; Positive correlation between CH_4 and leaf numbers, tiller numbers, leaf area index
Butterbach-Bahl et al. (2007)	2	Italy	Different in emission in the field and a significantly higher gas transport capacity between 2 varieties
Kerdchoechuen, 2005	4	Thailand	CH_4 emission rate significantly differed with varieties
Setyanto et al. (2004)	3	Indonesia	Rice varieties showed different ability in emitting CH_4 in flooded soil
Aulakh et al. (2002)	22	Asia	Rice varieties widely differ in methane transport capacity

Wassmann et al. (2002)	19	Philippines	Varietal effect is not a major determinant factor for CH_4 emissions
Liou et al. (2003)	2	Taiwan	GHG emission depends on type of N fertilizer and rice varieties
Shin et al. (2000)	8	Korea	Rice varieties did not influence the CH_4 seasonal patterns but the total amount of CH_4 emitted
Subadiyasa et al. (1997)	3	Indonesia	No distinction between an improved variety and improved varieties
Lindau et al. (1995)	6	USA	Rice variety had a significant effect on the emission in Louisiana flooded plots

4.2. Comparison with IPCC default values

4.2.1. CH_4 emission factor

Figure 12 shows the results of the comparison of emission factors of CH_4 across all varieties averaged for both seasons. The values for given varieties ranged from 2.52 (OM5451) to 3.96 kg ha^{-1} $season^{-1}$ (ML202). 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}. The Emission Factors of this study were also higher in comparison to previously published data for baseline emissions of continuously flooded rice field in the Mekong River Delta (Vo et al, 2018 and Vo et al, 2020). Regarding the possible impact of the cultivation period, OM5451 was in the earliest harvest group of both seasons whereas ML202 did not belong to the latest harvest group. The new 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) whereas the average cultivation period of the selected 20 cultivars was 95-100 days depending on the growing condition. Nevertheless, when looking closer into the groups of low and high-emission varieties, the early-maturing varieties such as OM5451, OM2517 tend to have low EF whereas GKG35, OM7347 were late-maturing and had high emission in both seasons.

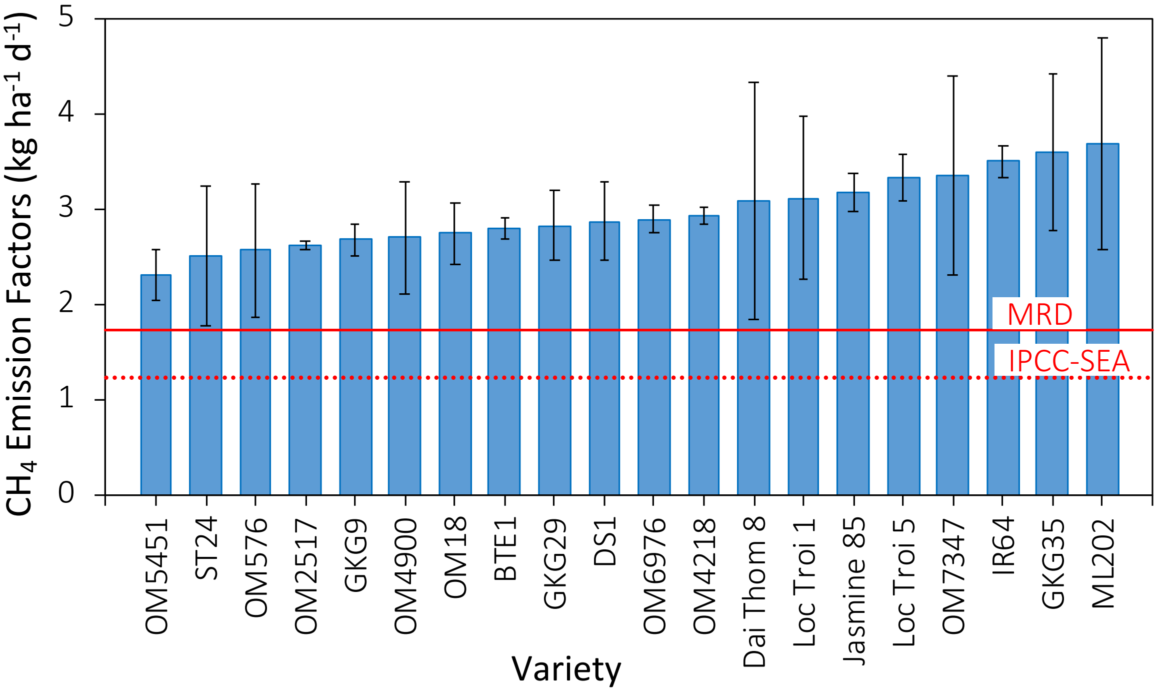

Figure 12. Emission Factors of 20 varieties plotted against the IPCC value for Southeasth Asia (IPCC-SEA) and a literature value for the Mekong River Delta; The bars show the means over two seasons and the error bars show the standard deviations of the aggregated emissions

4.2.2. CH_4 scaling factor for AWD

While CH_4 emissions of AWD ranged from 0.76 - 1.68 and 0.65 - 1.41 kg ha^{-1} d^{-1} in the first and second seasons, Figure 10 reveals the AWD Scaling Factors (corresponding to the ratio between CF and AWD) had average values of 0.41 and 0.38 in S1 and S2, respectively, which are considerably lower than the default value (0.55) given by IPCC (2019). This indicates that the shift from CF to AWD entailed higher emission savings in our field experiments as predicted through the IPCC defaults (Figure 10a). As compared to mitigation assessment following the IPCC defaults, the net emission impact derived from this study will considerably be higher because the lower AWD/ CF ratio will further be amplified by higher background levels under CF as compared to the IPCC values (see above).

4.2.3. N_2O emission factor

According to the data provided in table S1, the averages N_2O emissions was 0.47 kg N_2O ha^{-1} for continuous flooding. To allow comparison with the IPCC default value, these rates have to be converted to the amount of N emitted (44 % of the amount of N_2O) and be set in relation to a synthetic fertilizer application rate of 90 kg N ha^{-1}. In turn, the relative amount of applied N that was emitted as N_2O was 0.14 %. The percentage is in a lower range to the IPCC default (0.3 %) given for flooded rice fields (IPCC 2019).

As for AWD, however, the refined IPCC guidelines of 2019 introduced a separate value, namely 0.5 % of the applied N fertilizer, to account for the empirical findings of slightly enhanced N_2O emissions under frequent drainage. Our data also showed similar level of N_2O emissions in AWD across the seasons by 0.49 kg N_2O ha^{-1}. In terms of Emission Factors, our data indicate 0.24% which is again lower than the given IPCC value. However, the standard deviation is too high (Figure 8) for given a solid confirmation of the magnitude of the IPCC Emission Factor for AWD vs CF.

5. Conclusion

To the best of our knowledge, this study represents the first systematic screening of the interaction of rice variety selection and water management on GHG emissions. Since rice varieties often have been selected to perform best in a specific production environment, special adaptations, such as varietal greenhouse gas emissions are best tested within the target environment in the genetic diversity that is present in the system. The 20 varieties that have been screened in this study represent a good section through the genetic diversity of rice in the Vietnamese Mekong Delta and although not transferable to rice in general, this study offers several generic take-home messages on the role of varietal emissions within mitigation efforts in rice production.

Varietal variation was largest for CH_4 emissions under CF. Under AWD CH_4 emissions were generally strongly reduced with the varietal effect being of minor importance. For both irrigation methods, N_2O emissions played a minor role and varietal effects were small. Therefore, if AWD can be implemented, choice of variety is of minor importance since for all varieties, the scaling factors. On the other hand, if AWD cannot be implemented which is the case of lacking drainage capacities or in periods with strong rainfall, field will stay flooded most of the season, choice of variety can be a game changer for CH_4 emissions.

In addition, shifting from CF to AWD often does not agree with the farmers' preferences in the adoption of technological changes. The relative ease of interventions in seed distribution to farmers – either supplied by local governments or accessed from the private sector -- is a well-established fact derived from numerous development projects whereas rice farmers are generally more reluctant to change water management. Thus, the proper selection of varieties should be factored into mitigation efforts -- either as an additional measure to maximize the AWD effect during the dry season or as a stand-alone mitigation option in locations or seasons where mitigation through AWD is not possible.

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References

Arai, H. (2022). Increased rice yield and reduced greenhouse gas emissions through alternate wetting and drying in a triple-cropped rice field in the Mekong Delta. Science of The Total Environment, 842, 156958.

Arianti, F.D.; Pertiwi, M.D.; Triastono, J.; Purwaningsih, H.; Minarsih, S.; Kristamtini; Hindarwati, Y.; Jauhari, S.; Sahara, D.; Nurwahyuni, E. (2022) Study of Organic Fertilizers and Rice Varieties on Rice Production and Methane Emissions in Nutrient-Poor Irrigated Rice Fields. Sustainability 2022, 14, 5919. https:// doi.org/10.339

Aulakh M.S., Wassmann R., Rennenberg H. (2002). Methane transport capacity of twenty-two rice cultivars from five major Asian rice-growing countries, 91(1-3), 59–71. doi:10.1016/s0167-8809(01)00260-2

Baruah, K.K., Gogoi, B. & Gogoi, P. Plant physiological and soil characteristics associated with methane and nitrous oxide emission from rice paddy. Physiol Mol Biol Plants 16, 79–91 (2010). https://doi.org/10.1007/s12298-010-0010-1

Becker, M., & Angulo, C. (2019). The evolution of lowland rice-based production systems in Asia: Historic trends, determinants of change, future perspective. Advances in Agronomy. doi:10.1016/bs.agron.2019.04.003

Bharali, Ashmita; Baruah, Kushal K.; Gogoi, Nirmali (2017). Potential option for mitigating methane emission from tropical paddy rice through selection of suitable rice varieties. Crop and Pasture Science, 68(5), 421–. doi:10.1071/CP16228

Bhattacharyya P., Dash P.K., Swain C.K., Padhy S.R., Roy, K.S., Neogi S., Berliner J., Adak T., Pokhare S.S., Baig M.J., Mohapatra T. Mechanism of plant mediated methane emission in tropical lowland rice, Science of The Total Environment, Volume 651, Part 1, 2019, Pages 84-92, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2018.09.141.

Butterbach-Bahl, K., Papen H., Rennenberg, H. (1997). Impact of gas transport through rice cultivars on methane emission from rice paddy fields. 20(9), 1175–1183. doi:10.1046/j.1365-3040.1997.d01-142.x

Das K. and Baruah K K. Association between contrasting methane emissions of two rice (Oryza sativa L.) cultivars from the irrigated agroecosystem of northeast India and their growth and photosynthetic characteristics. Acta Physiological Plantarum, 2008; 30: 569–578.

Gogoi N., Baruah K. K., Prabhat K. Gupta (2008). Selection of rice genotypes for lower methane emission. 28(2), 181–186. doi:10.1051/agro:2008005

GSO-General Statistics Office of Viet Nam. (2020) Planted Area and Production of Paddy. Available online: https://www.gso.gov.vn/default_en.aspx?tabid=778 (latest update 8/1/2022)

IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S., Eds.; IPCC: Geneva, Switzerland, 2019.

IPCC- Intergovernmental Panel on Climate Change 2014: Annex II: Glossary [Mach, K.J., S. Planton and C. von Stechow (eds.)]. In: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, pp. 117-130.

IRRI – International Rice Research Institute (2023) Rice Knowledge Bank. Accessed on 15 March 2023 at http://www.knowledgebank.irri.org/training/fact-sheets/water-management/saving-water-alternate-wetting-drying-awd

Jiang, Y., Carrijo, D., Huang, S., Chen, J. I., Balaine, N., Zhang, W., ... & Linquist, B. (2019). Water management to mitigate the global warming potential of rice systems: A global meta-analysis. Field Crops Research, 234, 47-54.

Jiang, Y., van Groenigen, K. J., Huang, S., Hungate, B. A., van Kessel, C., Hu, S., … Zhang, W. (2017). Higher yields and lower methane emissions with new rice cultivars. Global Change Biology, 23(11), 4728–4738. doi:10.1111/gcb.13737

Johnson, K., Vo, T.B.T., Duong, V.N., Asch, F.2023. Effects of alternate wetting and drying irrigation on rice phenology and yield. Agronomy and Crop Science. Submitted.

Kerdchoechuen O. (2005). Methane emission in four rice varieties as related to sugars and organic acids of roots and root exudates and biomass yield, 108(2), 155–163. doi:10.1016/j.agee.2005.01.004

Khosa MK, Sidhu BS, Benbi DK. Effect of organic materials and rice cultivars on methane emission from rice field. J Environ Biol., 2010; 31: 281–285.pmid:21046997

Lampayan, R.M., Samoy-Pascual, K.C., Sibayan, E.B. et al. Effects of alternate wetting and drying (AWD) threshold level and plant seedling age on crop performance, water input, and water productivity of transplanted rice in Central Luzon, Philippines. Paddy Water Environ 13, 215–227 (2015). https://doi.org/10.1007/s10333-014-0423-5

Lindau, C.W., Bollich, P.K., & Delaune, R.D. (1995). Effect of rice variety on methane emission from Louisiana rice. Agriculture, Ecosystems & Environment, 54, 109-114. DOI:10.1016/0167-8809(95)00587-I

Liou, R.M., Huang, S., Lin, C., & Chen, S. (2003). Methane Emission from Fields with Three Various Rice Straw Treatments in Taiwan Paddy Soils. Journal of Environmental Science and Health, Part B, 38, 511 - 527. DOI:10.1081/PFC-120021670

Minamikawa, K., Tokida, T., Sudo, S., Padre, A., Yagi, K. (2015) Guidelines for measuring CH_4 and N_2O emissions from rice paddies by a manually operated closed chamber method. National Institute for Agro-Environmental Sciences, Tsukuba, Japan.

MONRE -- Ministry of Natural Resources and Environment (2019). Vietnam’s 3rd National Communication for the United Nations Framework Convention on Climate Change. https://unfccc.int/documents/192805

Nguyen, V.K., Nguyen, H.H. and Cramb, R. 2020 Trends in Rice-Based Farming Systems in the Mekong Delta in Cramb, R. (Ed.). (2020). White Gold: The Commercialisation of Rice Farming in the Lower Mekong Basin. Pp. 347 – 374. doi:10.1007/978-981-15-0998-8

Padre, A., & Tran, D.H., Hoang, T.N., Duong, H., Tran, N., Le Van, A., Ngo, M., Wassmann, R., Sander, B.O. (2017). Measuring GHG Emissions from Rice Production in Quang Nam Province (Central Vietnam): Emission Factors for Different Landscapes and Water Management Practices. 10.1007/978-981-10-2624-9_7.

Schneider, P. and Asch. F. 2020. Rice production and food security in Asian Mega deltas—A review on characteristics, vulnerabilities and agricultural adaptation options to cope with climate change J Agro Crop Sci. 2020;206:491–503. DOI: 10.1111/jac.12415

Setyanto P, Rosenani AB, Boer R, Fauziah CI and Khanif MJ. The effect of rice cultivars on methane emission from irrigated rice field. Indonesian J AgricSci., 2004; 5: 20–31.

Shin, YK., Yun, SH. Varietal Differences in Methane Emission from Korean Rice Cultivars. Nutrient Cycling in Agroecosystems 58, 315–319 (2000). https://doi.org/10.1023/A:1009819324897

Subadiyasa, N., Arya, N., Kimura, M. (1997). Methane emissions from paddy fields in Bali Island, Indonesia. Soil Science and Plant Nutrition, 43(2), 387–394. doi:10.1080/00380768.1997.10414762

Uno, K., Ishido, K., Nguyen Xuan, L., Nguyen Huu, C., Minamikawa, K. (2021). Multiple drainage can deliver higher rice yield and lower methane emission in paddy fields in An Giang Province, Vietnam. Paddy and Water Environment, 19, 623-634.

Vo, T.B.T., Wassmann, R., Tirol-Padre, A., Cao, V.P., MacDonald, B., Espaldon, M.V.O. and Sander. B.O. 2018. "Methane Emission from Rice Cultivation in Different Agro-Ecological Zones of the Mekong River Delta: Seasonal Patterns and Emission Factors for Baseline Water Management." Soil Science and Plant Nutrition 64 (1): 47–58. https://DOI: 10.1080/00380768.2017.1413926

Vo, T.B.T.; Wassmann, R.; Mai, V.T.; Vu, D.Q.; Bui, T.P.L.; Vu, T.H.; Dinh, Q.H.; Yen, B.T.; Asch, F.; Sander, B.O. Correction: Vo, T.B.T., et al. Methane Emission Factors from Vietnamese Rice Production: Pooling Data of 36 Field Sites for Meta-analysis. Climate 2020, 8, 74. Climate 2020, 8, 113. https://doi.org/10.3390/cli8100113

Wang, ZH., Wang, LH., Liang, H. et al. Methane and nitrous oxide emission characteristics of high-yielding rice field. Environ Sci Pollut Res 28, 15021–15031 (2021). https://doi.org/10.1007/s11356-020-11641-y

Wassmann R., Aulakh M.S., Lantin R.S., Rennenberg H., Aduna J.B. (2002). Methane emission patterns from rice fields planted to several rice cultivars for nine seasons. , 64(1-2), 111–124. doi:10.1023/a:1021171303510

Wassmann R., Gonsalves J., Sprang P., Yen B.T., Villanueva J., Nelakhom P., Okumo B. (2022) Climate Smart Villages in Southeast Asia: The pivotal role of Seed Systems in rice-based landscapes. Asian Journal of Agriculture and Development

Wassmann R., Lantin R.S., Neue H.U., Buendia L.V., Corton T.M. and Lu Y. (2000) Characterization of methane emissions in Asia III: Mitigation options and future research needs. Nutrient Cycling in Agroecosystems 58: 23-36, 2000, 2000 Kluwer Academic Publishers, The Netherlands.

Wassmann R., Ngo D.P., Tran Q.T., Chu T.H., Nguyen H.K., Nguyen X. H, Vo T.B.T., Tuong T.P. High-resolution mapping of flood and salinity risks for rice production in the Vietnamese Mekong Delta, Field Crops Research, Volume 236, 2019, Pages 111-120, ISSN 0378-4290, https://doi.org/10.1016/j.fcr.2019.03.007.

Yamaguchi T., Tuan L. M., Minamikawa K., & Yokoyama S. (2019). Assessment of the relationship between adoption of a knowledge-intensive water-saving technique and irrigation conditions in the Mekong Delta of Vietnam. Agricultural Water Management, 212, 162–171. doi:10.1016/j.agwat.2018.08.041

Supplementary material

Table S1. Seasonal CH_4 and N_2O emissions as affected by water management and rice variety, grain yield as affected by water management; *CS = Croping season; W= Water management; V= Variet*y; ^{i} days to maturity caculated from date of seeding; ^{ii} cultivationperiod calculated from dates of seedling to harvest; $^{\&}$ varieties with one - day different between CF and AWD

Variety	Season 1 (2019-2020)						Season 2 (2020-2021)					
	CH_4 (kg CH_4 ha^{-1})		N_2O (kg N_2O ha^{-1})		Days to maturity^{i}	Cultivation period (days)^{ii}	CH_4 (kg CH_4 ha^{-1})		N_2O (kg N_2O ha^{-1})		Days to maturity^{i}	Cultivation period (days)^{ii}
	CF	AWD	CF	AWD			CF	AWD	CF	AWD		
BTE1	302.1	160.9	1.2	1.3	94	112	343.6	77.5	0.0	0.2	101	120
Dai Thom 8	416.2	145.7	0.5	0.9	86	112	243.0	95.3	0.1	0.2	92	120
DS1	351.2	178.2	0.7	0.7	100	105	307.1	128.0	0.1	0.1	101	110
GKG29	280.5	138.2	0.8	0.6	85	110	338.5	139.0	0.2	0.2	87	110
GKG35	330.1	165.3	0.6	0.5	87	110	466.5	128.2	0.2	0.5	89$^{\&}$	112
GKG9	268.2	88.5	0.8	0.6	84	105	305.6	119.6	0.3	0.2	89	110
IR64	357.3	176.4	0.8	0.2	86	105	406.9	157.9	0.5	0.2	96	112
Jas.85	341.7	181.5	0.7	1.2	91	112	357.9	109.6	0.1	0.4	95	107
Loc Troi 1	278.2	143.8	0.2	0.4	86	110	410.7	131.4	0.5	0.2	91	110
Loc Troi 5	352.5	89.8	0.7	0.7	89	112	384.4	137.0	0.2	0.3	93	110
ML202	302.5	118.0	0.7	1.3	86	105	477.5	104.7	0.1	0.2	89	107
OM18	305.0	94.8	0.7	0.6	86	102	271.0	121.5	0.1	0.6	89	107
OM2517	270.2	122.8	0.7	0.5	79	102	277.2	103.7	0.1	0.7	83	107
OM4218	293.0	108.5	1.3	1.2	85	102	321.4	85.7	0.2	0.1	89	107
OM4900	347.6	85.5	1.0	1.6	91	112	254.3	146.4	0.1	0.3	94	112
OM5451	257.1	99.1	0.7	0.4	85$^{\&}$	102	229.9	115.2	0.1	0.1	89	107
OM576	334.5	174.6	1.2	0.3	98	110	246.4	144.1	0.2	0.2	100$^{\&}$	120
OM6976	306.1	124.5	0.4	0.3	91	110	328.3	145.9	0.6	0.3	94	110
OM7347	286.6	99.0	0.0	0.5	89	110	457.3	111.2	0.1	0.1	92	112
ST24	338.0	110.9	1.0	0.4	92	112	221.9	95.7	0.2	0.2	97	112
CS. mean	223.0		0.7		89	108	229.7		0.2		92	111
W. Means	315.9	130.3	0.7	0.7			332.5	119.9	0.2	0.3		
P-value												
W	***		0.9				***		0.8			
V	0.1		0.3				0.1		0.6			
W x V	0.8		0.9				0.2		0.5			

$*p < 0.05$, $**p < 0.01$, $***p < 0.001$, respectively

CHAPTER 5

VARIETAL EFFECTS ON METHANE PRODUCTIVITY OF PADDY FIELDS UNDER DIFFERENT IRRIGATION MANAGEMENT

Asch et al. 2023[5]

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[5] This chapter is submitted and under review: Asch, F., Johnson, K., Vo, T.B.T., Sander, B.O., Duong, V.N, Wassmann, R. (2023). Varietal effects on methane productivity of paddy fields under different irrigation management. [Manuscript submitted for publication]. Journal of Agronomy and Crop Science.

Contribution of the candidate: Theoretical background and design of the study: 25%; Data collection: 40%; Data analysis: 30%; Paper writing: 10%

Abstract

Alternate wetting and drying (AWD) irrigation has been shown to decrease irrigation water use in and trace gas emissions from paddy fields. Whereas genotypic water use shows little variation in irrigated lowland rice, it has been shown that rice varieties differ in the magnitude of their methane emissions. Management and variety related emission factors have been proposed for modelling the impact of paddy production on climate change, however, the magnitude of a potential reduction in greenhouse gas emissions by changing varieties has not yet been fully assessed. AWD irrigation has been shown to affect genotypic yields and high yielding varieties suffer the greatest loss when grown under AWD irrigation. Highest yielding varieties may not have the highest methane emissions, thus, a potential yield loss could be compensated by a larger reduction in methane emissions. However, AWD irrigation, can only be implemented under full control of irrigation water, leaving the rainy seasons with little scope to reduce methane emissions from paddy fields. Employing low emitting varieties during the rainy season may be an option to substantially reduce methane emissions but may compromise farmers income if such varieties perform less well than the current standard. This paper investigates the magnitude of methane savings through varietal choice for both AWD and continuous flooding irrigation management in its relation to genotypic yields and explores potential options for compensating farmers mitigation efforts.

Keywords: AWD, carbon footprint, farmers compensation, greenhouse gases, lowland rice

1. Introduction

A global staple, rice cultivation accounts for around 11% of arable land worldwide (Khush, 2005). The vast majority of rice is produced in irrigated (paddy) systems (Fairhurst & Doberman, 2002; Bouman et al., 2007), which require significant water resources, estimated to be 24-30% of global freshwater resources (Bouman et al., 2007), and a leading source of potent greenhouse gases (GHG) (Yan et al., 2009), methane (CH_4) (Saunois et al., 2020) and nitrous oxide (N_2O) (Zou et al., 2007). This poses a problem for rice producing countries, such as Vietnam, that are looking to both mitigate the effects of climate change, such as less predictable rainfall, and reduce GHG emissions.

Both methane and nitrous oxide are by-products of the anaerobic degradation of organic matter and root exudates by methanogens and methanotrophs found in paddy soils (Wassmann & Aulakh, 2000). The rate of methane formation depends on redox potential, pH, and temperature (Minami, 1994). It reaches the atmosphere by a combination of diffusion from the water's surface, ebullition from the soil, and the aerenchyma of the rice plant (Minami, 1994). Of the three pathways, the greatest flux, up to 90% of CH_4 released, is through the aerenchyma (Wassmann & Aulakh, 2000).

The degree of methane emission is determined by seasonal effects (Vo et al., 2018), fertilizer management (Wassmann et al., 1994; Singh et al., 1999), soil texture (Wang et al., 1993), phenological stage (Wassmann & Aulakh, 2000), and rice variety (Kerdchoechuen, 2005).

The International Rice Research Institute (IRRI) has developed water saving irrigation technologies, such as alternate wetting and drying (AWD) that through periodic drying reduce water requirements (Schneider et al., 2019) and, thus, pumping costs (Lampayan et al., 2015) while reducing methane emissions with little yield penalty (Sander et al., 2017; Setyanto et al., 2018; Johnson et al., 2023). Thus, combining AWD with adapted fertilizer management minimizes methane emissions at minimal costs for the farmer.

Under fully flooded conditions, unavoidable during the rainy seasons in the major Asian rice production systems, fertilizer management and planting density may be the only controllable factors influencing methane emissions from paddy fields. The effect of rice varieties under such conditions on methane emissions have been controversially reported to date. Whereas Kerdchoechuen (2005) reports substantial differences in methane emissions among four Thai rice varieties grown in sand in a pot experiment, Wassmann et al. (2002) report only small varietal differences as compared to other influencing factors such as season and fertilizer management. Recently, Vo et al (2023) have shown that, in a set of 20 Vietnamese rice varieties, seasonal methane emissions vary in the range of 40 to 45% between the highest and the lowest emitters and this difference is by a factor of about 100 larger under continuous flooding than under AWD conditions. If brought to scale for e.g. the entire VMD, this difference could impact methane emissions from lowland rice production systems substantially. However, low emitting cultivars may not be farmers favourite varieties and may not be as high yielding as stronger emitting varieties. Thus, the farmer may face an economical loss when trying to mitigate methane emissions. Therefore, varietal choice should be based on a minimal methane emission per kg of yield combined with a minimal loss of yield. Comprehensive studies on the potential impact of such an approach are scarce to date. We investigated the methane productivity (seasonal methane emissions per seasonal yield) in a set of lowland rice varieties widely used in the Vietnamese Mekong delta based on summarized data from Vo et al. (2023) and Johnson et al. (2023) of a field trial conducted over the course of two consecutive winter-spring seasons.

2. Materials and Methods

Over the course of two successive winter-spring seasons (December-March), we conducted a field experiment at the Vietnam Mekong Delta (VMD) Loc Troi Group’s (LTG) Agricultural Research Station, Bình Đức, Long Xuyên, An Giang Province, Vietnam (10°18’44.9 N 105°19’08.3 E). Rice varieties widely grown in the VMD, comprising of nineteen short-duration (~90 days to maturity), high-yielding, indica or tropical japonica cultivars were grown and one international check variety (IR64) were included in the trials. Seeds were sourced from LTG, Cuu Long Delta Rice Research Institute as well as local seed sellers. Further details on each variety are given in Johnson et al. (2023).

2.1. Field onditions

Rainfall, solar radiation, and temperature were recorded in 15 min intervals by a weather station positioned next to the field trials. In the first season, from transplanting to when the last variety reached maturity, 18/12/2019 to 14/03/2020, cumulatively, 22.1 mm and during the second season, 8/12/2020 to 11/03/2021, 74.7 mm of rain were recorded. Within the same timeframe mean temperatures were 26±2.8 ˚C with 17.5±1.3 $molm^{-2}day^{-1}$ of solar radiation in the first season, and 25.5±2.8 ˚C with 16.7±2.3 $molm^{-2}day^{-1}$ of solar radiation in the second season. The soil was a clay loam with a CEC of 13.9 meq/100g and about 3.9% organic matter content. The pH of the irrigation water in the plots was about 5.2, with an EC of 0.4 $mScm^{-1}$. Fertilizer was applied according to best practice at LTG, for details see Johnson et al. (2023) and Vo et al. (2023).

2.2. Experimental design and treatments

The field trials were setup in a randomized complete block design with three replications in the same experimental field. The blocks were by irrigation treatment, replicated three times, and the constituent plots of each block were of each variety. With 20 rice cultivars, two irrigation treatments (CF, AWD), and three replications, overall, there were 120 plots each with a dimension of 4m x 5m each. Water supply was fully controlled by irrigation from a nearby surface freshwater source.

Two irrigation treatments were established: continuous flooding (CF) with a ponded water layer of 5-10 cm and alternate wetting and drying (AWD) in which the plots were irrigated to a 10 cm ponded water layer and then allowed to dry out to a water level of 10-15 cm below the surface before being re-irrigated to the original ponded water layer to start a new cycle of drying. The water level for the AWD treatment was monitored in each plot using an open-ended PVC tube set 1m from the bund within the plot. It was perforated to allow water to enter from the surrounding soil (Lampayan et al., 2015). The perched water table was regularly measured with a meter stick manually inserted into the tube and in the CF treatment by placing the meter stick at the soil level 1 m from the bund.

2.3. Yield determination and methane measurements

Yield was determined by variety, replication, and treatment. Yield was calculated from the dry (14% moisture content) grain harvest of 13 hills by 13 hills, equivalent to an area of 6.67 m^2, from the center of the experimental plot.

CH_4 emissions were measured with the closed chamber method as described in Tirol-Padre et al. (2017). In all plots, a square metal base (46 cm x 46 cm) was inserted about 10 cm into the top soil surrounding four rice hills planted at 20 x 20 cm spacing. Gas was sampled at weekly intervals. The three replicates were averaged to determine the weekly emissions. The seasonal average emissions were calculated from transplanting to harvest for each variety and treatment. For more details on the collection and processing of the methane emissions during this field experiment, refer to Vo et al. (2023).

2.4. Data treatment

Data were processed with Microsoft Excel V 2019. All data shown were averaged across two seasons. T-tests for mean comparison were performed with MS Excel. For data presented in figures, data were plotted, means and standard errors calculated, and regression analyses performed with SigmaPlot 12.5 (Sysstat Software Inc.).

In addition, data were analyzed using a linear mixed-effects model based on the lme4 package (1.1-28; Bates et al., 2015) in R (R Core Team, 2022). The fixed effects were the irrigation treatment (AWD, CF), and variety (1-20), whereas the random effects were replication (1-3) and treatment block (treatment x replication). To quantify differences between varieties and treatments, a post-hoc Tukey test was performed. The post-hoc pairwise comparisons were used to generate marginal means using the emmeans package (1.7.2; Lenth, 2022).

3. Results

3.1. Water use in CF and AWD

Water supplied by irrigation between transplanting and harvest differed significantly ($p<0.05$) between the treatments. On average 348 Lm^{-2} with a standard error of 29 Lm^{-2} were applied to the continuous flooding treatment whereas to the AWD 216 ± 29 Lm^{-2} were applied, corresponding to a reduction in water use by 38% on average.

3.2. Varietal methane emissions and yield

Figure 1 shows the seasonal methane emissions (a) for all varieties and the two irrigation treatments and the respective yields obtained (b) as means over two consecutive winter seasons. Mean seasonal methane emissions in the CF irrigation treatment varied among all varieties between 243 $kgha^{-1}$ and 398 $kgha^{-1}$, on average, constituting about 50% variation relative to the mean across all varieties. Under AWD methane emissions on average across all varieties were about 200 $kgha^{-1}$ lower than under CF irrigation, which is a about 30% stronger reduction in emissions than the difference between the lowest (OM5451) and highest emitting variety (GKG35) under CF. Under AWD varieties varied in methane emissions between 97 $kgha^{-1}$ and 167 kg ha^{-1} which is less than half the variation in emissions under CF. Whereas for all varieties AWD significantly ($p<0.05$) reduced seasonal methane emissions, differences in emissions between varieties were not statistically significant at $p<0.05$ for either irrigation treatment.

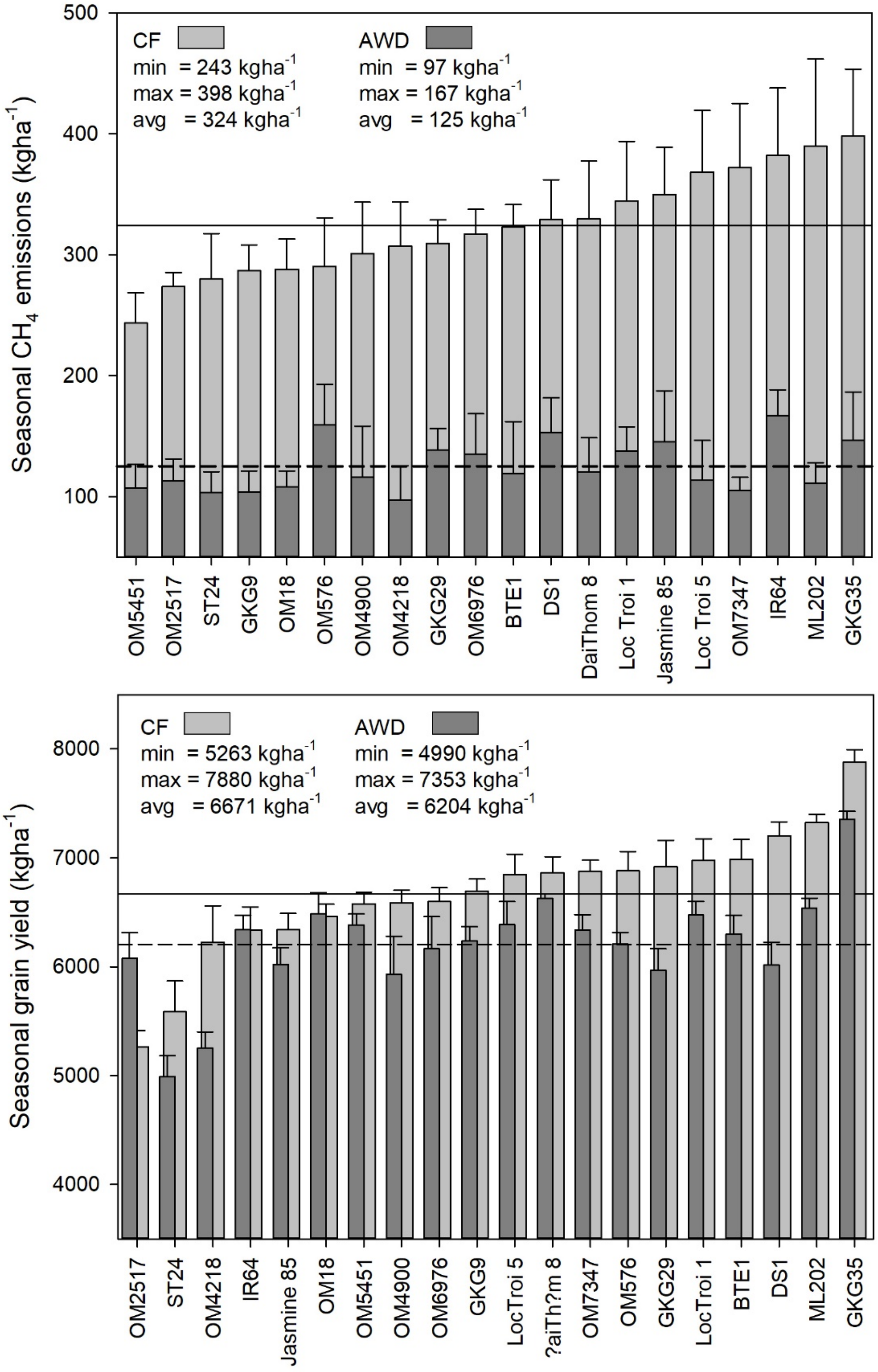

Figure 1: Seasonal methane emissions and seasonal grain yield for 20 lowland rice varieties grown over two winter-spring seasons (Dec-Mar) in a field trial in the Vietnam Mekong Delta under continuous flooding (CF) and alternate wetting and drying (AWD) irrigation treatments. Solid horizontal lines indicate means across all varieties under CF and dashed horizontal lines indicate means across all varieties under AWD.

Seasonal yields varied between 5263 kgha^{-1} (OM 2517) and 7880 kgha^{-1} (GKG 35) under CF irrigation and under AWD between 4990 kgha^{-1} (ST24) and 7353 kgha^{-1} (GKG 35) and were significantly different among varieties. Across all varieties, yields under AWD were significantly lower by about 8% as compared to CF.

Regressing seasonal yields against seasonal methane emissions (Figure 2) revealed a significant positive correlation ($p<0.05$) between the two parameters under CF irrigation, indicating that higher yields lead to higher methane emissions. Under AWD this correlation is not significant and the slope is weak. In both cases variation in methane emissions among varieties is largest in the range of 6000 to 7000 kgha^{-1} seasonal grain yield.

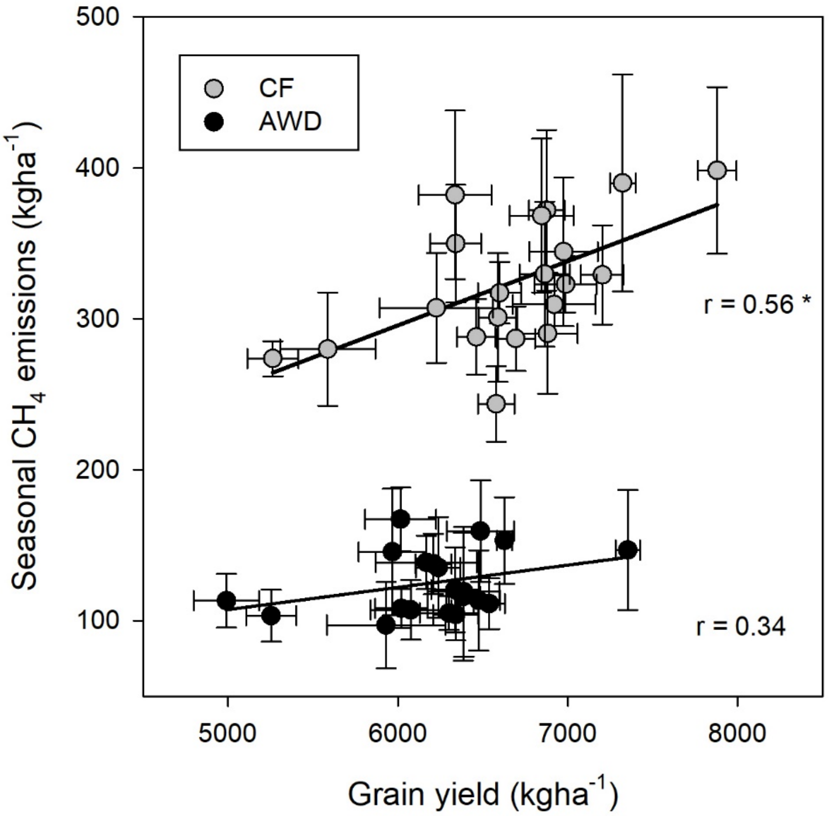

Figure 2: Regression of seasonal grain yield versus seasonal methane emissions of 20 lowland rice varieties subjected to two irrigation treatments (continuous flooding – CF; alternate wetting and drying – AWD) averaged over two consecutive winter seasons (Dec-Mar) in the Vietnam Mekong Delta.

3.3. Water and methane productivity

Varietal water and methane productivity are shown in Table 1. In both cases smaller values indicate a yield advantage over resource use. Water use differed between the irrigation treatments but could not be measured at plot level, thus, genotypic water use could not be determined. Since yields differed significantly among the varieties (Figure 1), water productivity did as well (Table 1). For methane, varietal specific seasonal emissions were determined (Figure 1) and via division by the respective grain yield, methane productivity was calculated (Table 1). Methane productivity was highest under AWD where the reductions in methane emissions were relatively larger than the yield penalty due to the increase in water productivity. Under CF methane productivity was reduced on average by factor 2.4 relative to AWD. Under AWD, the variety with the highest methane emissions per kg of grain yield and, thus, lowest methane productivity, was IR64, and the highest methane productivity was observed in GKG 9, whereas under CF, IR64 showed the lowest and OM5451 the highest methane productivity.

Table 1: Mean Water and methane productivity under continuous flooded (CF) and alternate wetting and drying irrigation for two consecutive winter-spring seasons in the Vietnam Mekong Delta.

	Water Productivity ($L\ kg^{-1}$)		Methane productivity ($g\ kg^{-1}$)	
Variety	AWD	CF	AWD	CF
IR64	17.8 cd	27.1 fg	27.8	60.3
Jasmine 85	18.1 d	27.1 fg	24.4	55.2
OM7347	17.1 bcd	25.1 bcde	16.7	54.1
Loc Troi 5	16.6 bcd	25.1 bcde	17.5	53.8
ML202	16.6 bc	23.8 b	17.0	53.3
OM2517	21.5 e	32.7 i	22.7	52.0
GKG 35	14.7 a	22.2 a	20.0	50.5
ST 24	20.5 e	30.6 h	19.7	50.1
Loc Troi 1	17.4 bcd	24.7 bc	22.2	49.4
OM4218	18.1 d	27.5 g	16.4	49.3
OM6976	17.3 bcd	26.3 efg	21.7	48.1
Dai Thom 8	17.0 bcd	25.1 bcde	19.0	48.0

BTE 1	16.8 bcd	24.6 bc	18.7	46.2
DS 1	16.3 b	24.4 bc	23.1	45.7
OM4900	16.9 bcd	26.4 efg	18.2	45.7
GKG 29	17.4 bcd	24.8 bcd	22.5	44.7
OM18	17.8 cd	26.7 fg	18.0	44.6
GKG 9	17.0 bcd	25.8 cdef	16.4	42.9
OM576	16.6 bc	25.1 bcde	24.6	42.2
OM5451	17.6 bcd	26.3 defg	17.6	37.0

Regressing seasonal grain yield against methane productivity (Figure 3) shows a weak, statistically non-significant, negative correlation under both irrigation treatments indicating that methane costs per unit yield are similar between the varieties under the same treatment. However, similar to the seasonal methane emissions (Figure 2) strong genotypic variation exists for methane productivity in the grain yield range of 6000-7000 kgha^{-1}, particularly under CF where the highest methane productivity is 37 gkg^{-1} and the lowest 60 gkg^{-1}, constituting a difference of about 40%.

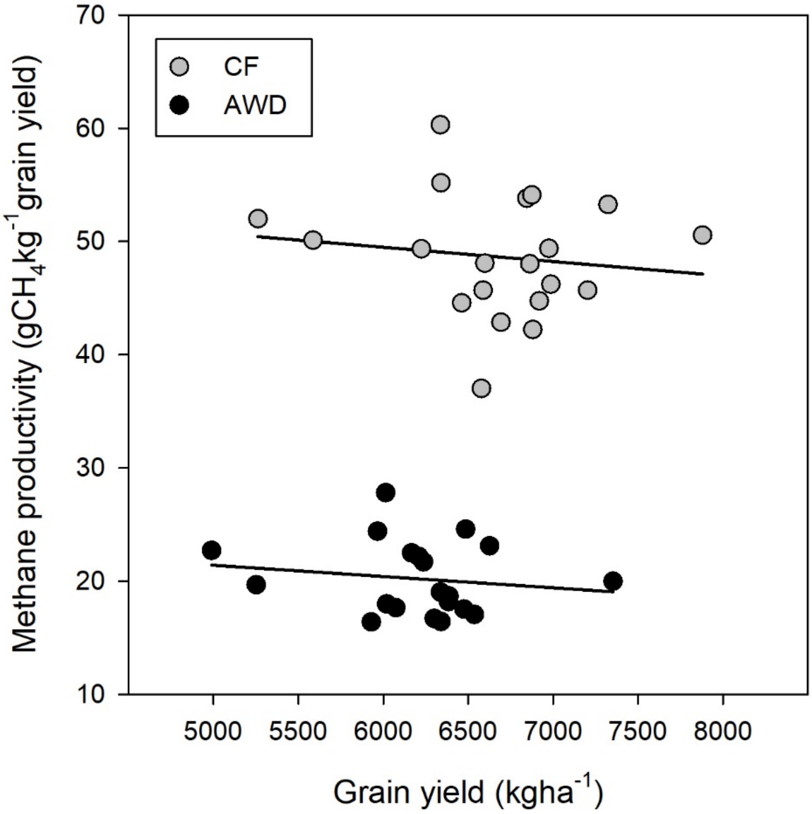

Figure 3: Relationship between seasonal grain yield and methane productivity for 20 lowland rice varieties grown under continuous flooding (CF) or alternate wetting and drying (AWD) for two consecutive winter seasons (Dec-Mar) in a field trial in the Vietnam Mekong Delta.

The aim for selecting a variety for production under continuous flooding should be: minimizing methane emissions while maximizing yield. Thus, in Figure 4 we regressed the differences in methane emissions between the individual variety and the varietal mean versus the differences in individual grain yield and the varietal mean grain yield. The figure shows a significant positive correlation between the two deltas ($p<0.01$) for both irrigation treatments following the same function.

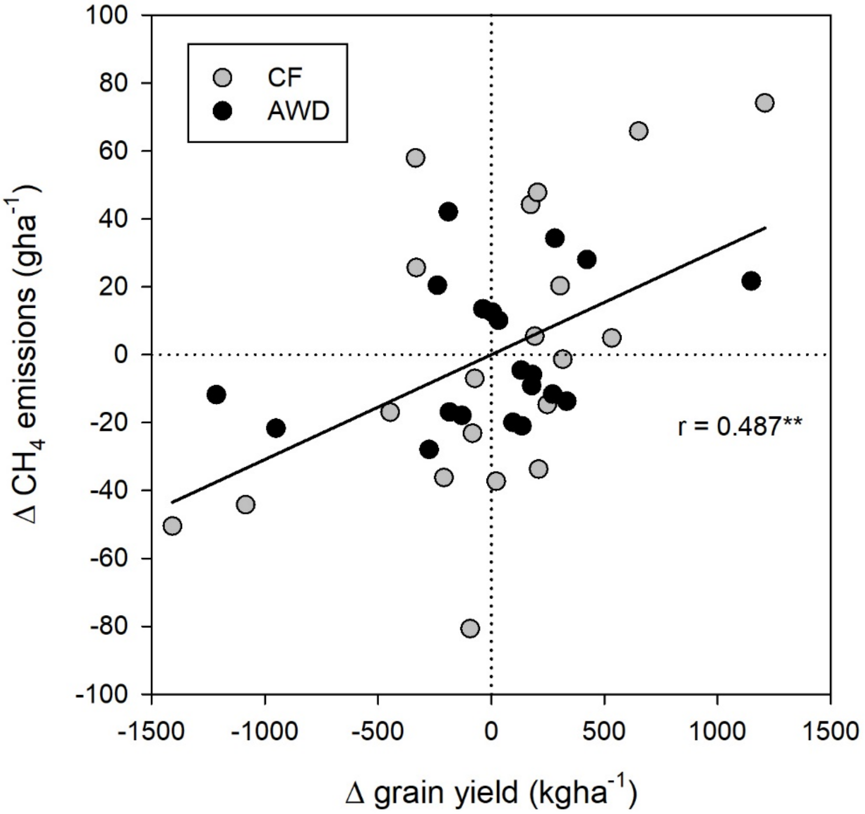

Figure 4: Seasonal varietal yield shown as differences to the varietal mean as related to seasonal varietal methane emissions shown as differences to the varietal mean for 20 lowland rice varieties grown under two irrigation managements (continuous flooding – CF and alternate wetting and drying – AWD). ** = significant at $p<0.01$.

The variety with the largest reduction in methane emissions as compared to the varietal mean with the smallest yield penalty as compared to the varietal mean was OM5451.

4. Discussion

Alternate wetting and drying irrigation was originally invented to reduce water use in rice production systems and soon turned out to be a major mitigation technology for methane (and other greenhouse gases) emissions from rice production systems (Chidthaisong et al., 2018; Sander et al., 2020) with no or little impact on rice yields (Arai et al., 2021; Carrijo et al. 2018; Johnson et al., 2023). Albeit being an effective way of reducing greenhouse gas emissions, AWD requires complete control over irrigation and drainage of rice fields (Schneider et al., 2019), which is not always available in areas that are mainly producing rainfed lowland rice such as the major river deltas of Asia (Schneider and Asch, 2020) including the VMD. As, therefore, in two out of three seasons AWD may not be applicable, alternatives for mitigating greenhouse gas emissions from paddy fields need to be developed. Since methane is by far the most important greenhouse gas emitted from rice fields (Sass et al.,1999), we will concentrate on the actual methane emissions in this paper and not on the global warming potential which is more important in calculating national or global carbon or GHG budgets (Vo et al., 2020; Yan et al., 2009). In addition to crop management options such as fertilizer dosing and application strategies (Wassmann et al., 1994, Singh et al., 1999), soil amendment with organic matter such as rice straw (Wassmann et al., 2002) or plastic mulch (Fawibe et al., 2019), choosing a low emitting rice variety adapted to the local conditions has been put forward as an important factor in reducing methane emission from rice fields (Win et al., 2022; Huang et al., 2018, Bharali et al., 2017).

The present study is a supplement to two earlier studies focussing on varietal greenhouse gas emissions and global warming potential of lowland rice production in the VMD (Vo et al., 2023) and genotypic traits related to AWD induced yield penalties of lowland rice varieties grown in the VMD during the dry season (Johnson et al. 2023). Across two consecutive winter-spring seasons yields in varietal spectrum studied here varied by about 2.5 tha^{-1} independent of the irrigation management, indicating a relatively wide range of genotype x environment interactions in the yield building processes as indicated earlier for water saving technologies in Sahelian environments by Stuerz et al. (2014). Whereas the mean yield penalty inflicted by the AWD irrigation treatment was relatively small (Fig.1), mean seasonal methane emissions were strongly reduced under AWD (Fig.1) and varietal differences in seasonal methane emissions under AWD were rather small (Fig.2). In contrast, the varietal variation in seasonal grain yield under CF was in the same range as under AWD, seasonal methane emissions, however, varied at a much larger scale, showing a maximal difference of 155 kgha^{-1}. (Fig. 1 and 2). Due to a relatively large interannual variation, a relatively high soil organic matter content, and a relatively high fertilizer input CH_4 emissions in general were relatively high as compared to other studies (e.g. Bharali et al., 2017; Qin et al., 2015) and differences between the varieties were not statistically significant at the desired probability level of $p<0.05$. Nonetheless, the absolute differences between the lowest and highest emitter in the current study were about 23 times larger than the mean seasonal varietal emissions reported from a low input system in India (Bharali et al., 2017) and about 15% larger than the highest emitting variety in a study with 9 cultivars from a high input system in China (Quin et al., 2015). This indicates that there is substantial potential for mitigating CH_4 emissions from rice fields during the rainy seasons in south east Asia via selecting a low emitting variety.

We have shown in Fig. 2 that there is a significant and positive correlation between yield and seasonal CH_4 emissions, implying that the much-needed increase in rice production for future food security (Samal et al., 2022) comes unavoidably at the cost of further accelerating climate change. In a recent study, Huang et al. (2018) found significant variation in a set of 50 varieties to propose selecting high yielding but low emitting varieties for the adaption of production systems. In their varietal spectrum exceptionally high yielding varieties were not included but yields varied between 4,500 and 6,500 $kgha^{-1}$ with seasonal methane emissions of up to 210 $kgha^{-1}$. Although this yield level is about 1,000kg below the highest yields recorded in this study, methane emissions were about 30$kgha^{-1}$ lower than the lowest emitting variety in this study which yielded on average a comparable 6,800 $kgha^{-1}$. For the varietal spectrum in the VMD, methane productivity was relatively stable of about 50 and 20 gkg^{-1} under CF and AWD, respectively (Fig.3). For reasons unknown, largest variations in methane productivity were observed in the seasonal grain yield range of 6000-7000 $kgha^{-1}$ (Fig. 3) under both irrigation treatments with the variability being twice as large under CF as compared to AWD confirming the importance of varietal choice under CF as pointed out by Quin et al. (2015). The effect of irrigation treatment on the varietal mitigation potential for methane emissions becomes less important when seasonal emissions are considered as the difference to the seasonal varietal mean (Fig.4). If compared to differences in yield, a positive correlation exists between yield increase and methane emission increase (Fig. 4) Here, both irrigation treatments share the same function. Since the aim of varietal selection for such a production system should be maximal yields with minimal methane emissions (Huang et al., 2018) suitable varieties for the VMD can be found in the lower part of the graph close to the vertical zero line as those combine average yields of the VMD with below average methane emissions.

4.1 Varietal mitigation potential and farmers incentives in the VMD.

As a signatory of the Paris Agreement, Vietnam committed – just like almost all other countries of the world -- to lower greenhouse gas emissions within its own capability. With the global goal to slow down if not reverse the climate change induced temperature increase, Vietnam specified mitigation targets in their Nationally Determined Contribution submitted to the UN Framework Convention on Climate Change, namely 9% compared to BAU by 2030 as unconditional reduction and 27% reduction pending on international support. One of the high emitting sectors is agriculture comprising 27.9% of total emissions of which almost half (13.8% of the total) is attributed to rice production (MONRE 2019). Since emission reduction needs to be balanced against food security of a still growing global population, technologies have to be developed that maintain food security while reducing the emission load on the planet. For AWD this potential is clearly recognised with some site-specific scaling factors still under discussion (Vo et al. 2023). For systems in which AWD cannot or will not be practised, on the other hand, additional management options have been proposed such as fertilizer management or soil organic matter management, but the mitigation effect of selecting low emitting varieties has not received much attention until to now.

As for the Mekong Delta, the possible scaling of AWD and its inherent mitigation potential were recently assessed in an in-depth study in form of a suitability assessment (Yen et al. 2023). This GIS-based study also clarified that a sizable portion of the MRD rice area (45%) is lowly suitable or totally unsuitable for AWD, so the ambitious mitigation targets of Vietnam cannot be achieved with an exclusive focus on AWD. In our study based on field data from Vo et al. 2023, we showed that rice varieties substantially differ in the amount of methane they emit, and when related to yield, different varieties emerge as low emitters. For example, per unit yield, GKG 9 produces the lowest amount of methane under AWD, but under CF it is OM5451. Depending on location, water availability, and water quality, rice is produced in the VMD either as single crop, double-cropped or triple cropped, leading to a large variation of area under rice, depending on the season.

Table 3 comprises area data from Vietnam's General Statistics Office (GSO 2017) for all provinces of the VMD broken up into the three rice growing seasons found in this region. The VMD has a total rice area of about 4.5 Mha corresponding to 57.8% of the Vietnamese rice area. Table 3 also shows the results adopted from the suitability assessment by Yen et al. (2023) which is based on a methodology described in Nelson et al (2015). While this approach indicates the climatic suitability and does not – in its current version – consider the infrastructural requirements of the irrigation scheme, the percentages given in Table 2 highlight the differences across growing seasons and provinces. In the dry season (December – March), the areas with low/ no suitability for AWD implementation are generally low, e.g. less than 10% in Can Tho and An Giang. The coastal provinces of Ca Mau and Bac Lieu have relatively high percentages of low/ no suitability areas, but then they have a small rice area in this season. The season from April to July has the lowest rice area and shows intermediate results in terms of the percentage of low/ no suitability rice area. The latter varies from less than 20% (An Giang, Dong Thap) to almost 100% (Bac Lieu). The wet season (August – December) covers less than the dry season but shows by far the highest percentages of low/ no suitability area for AWD application. While the provincial percentages are generally higher than 50%, the only exception is Dong Thap with 25% of low/ no suitability area. As for the entire MRD, the seasonal percentages of low/ no suitability area vary from 26.2% (D-M) to 37.9% (A-J) and 76.7% (A-D) whereas the overall percentage for all seasons is 45.0%.

Table 3 shows the mitigation potential of the MRD provinces assuming the adoption of low-emitting varieties (corr. to 25% reduction) based on the emission factor for the VMD used in the most recent official GHG inventory as part of Vietnam's 3rd National Communication (MONRE 2019). These tabulated data should be seen against the backdrop that the annual CH4 emissions of the VMD correspond to 24.6 Mt CO_2e which accounts for to 55.5 % of the total CH4 emissions from Vietnamese rice production (44.3 Mt CO_2e per year). While these official figures were provided by the Vietnamese government to the UNFCCC, it should be noted that they have certain assumptions, namely (i) a baseline of continuously flooding and (ii) that the GWP of CH_4 is 25. Given the promotion of AWD in recent government programs such as VnSAT, the first assumption may not be valid any more for 100% of the rice area. As for the GWP of CH_4, this value of 25 was adopted from the 4th Assessment Report of IPCC (IPCC 2007) whereas the most recent 6th Assessment Report (IPCC 2021) gives a value of 27 for non-fossil CH_4 emissions. It should further be noted that both GWP values refer to a 100-year horizon whereas CH_4 has a GWP of 78 over a 20-year horizon (IPCC 2021) which underpins the significance and urgency of reducing CH_4 emissions to meet the 1.5/ 2°C target of the Paris Agreement.

Table 2: Rice area of the MRD provinces and percentage of low/ no suitability for implementation of AWD in three harvesting rice seasons. (D-M = December - March; A-J =

April - July; A-D = August - December). LS = low or no suitability for AWD implementation.

Province	D-M		A-J		A-D		All Seasons	
	Area (1000ha)	*LS (%)*	*Area (1000ha)*	*LS (%)*	*Area (1000ha)*	*LS (%)*	*Area (1000ha)*	*LS (%)*
Long An	277	21.7	147	21.3	162	72.8	585	35.8
Dong Thap	259	16.1	183	18.2	165	25.0	607	19.2
An Giang	281	7.0	249	13.7	203	65.1	732	25.4
Tien Giang	97	25.6	27	22.6	67	50.2	191	33.8
Kien Giang	311	27.8	111	48.7	268	97.8	689	58.4
Vinh Long	101	32.1	74	34.8	58	96.9	233	49.0
Ben Tre	35	62.8	11	48.8	31	75.1	77	65.8
Can Tho	112	2.9	46	9.7	36	88.1	194	20.2
Tra Vinh	103	28.1	88	72.0	87	80.3	278	58.3
Hau Giang	106	19.6	82	78.2	70	100.0	259	60.0
Soc Trang	184	55.5	112	82.4	168	87.3	464	73.5
Bac Lieu	57	74.8	20	99.9	69	99.9	146	90.1
Ca Mau	34	81.9	7	56.5	37	97.6	78	87.2
Seasonal total	**1,957**	**26.2**	**1,154**	**37.9**	**1,421**	**76.7**	**4,532**	**45.0**

The mitigation potential of selecting low-emitting varieties was assessed in two scenarios (Table 3). Scenario 1 assumes a delta-wide adoption of low-emitting varieties across all provinces and growing seasons. This data is shown in Table 4 to provide a reference for the more distinguishing Scenario 2 which focuses on the variety adoption in the areas with low / no suitability for AWD. The underlying assumption of Scenario 2 is that – under limited financial resources - it will be more efficient for a future mitigation project based on rice variety selection to focus on those areas where AWD will be difficult or impossible to implement. In the areas with high and moderate suitability for AWD, the changes in water management will be more efficient and also diminish any add-on impact by variety selection. But even this targeted dissemination of varieties in Scenario 2 corresponds to 11.3% reduction of the total baseline emissions of the MRD.

Table 3: Mitigation potential of the MRD provinces assuming adoption of low-emitting varieties (corr. to 25% reduction) in the entire MRD (Scenario 1) and confined to the area

classified with low suitability/ unsuitable for AWD (Scenario 2) in three harvesting rice seasons (D-M = December - March; A-J = April - July; A-D = August - December). GHG calculations based on GWP (25) and the emission factor (217 kg CO_2e ha^{-1} $season^{-1}$) used in MONRE (2019) for South Vietnam.

	Scenario 1: 25% reduction in CH_4 for the entire rice area of the VMD (1000t CO_2e)				**Scenario 2: 25% reduction in CH_4 in low / no suitability for AWD area of the VMD (1000t CO_2e)**			
Province	*D-M*	*A-J*	*A-D*	**All seasons**	*D-M*	*A-J*	*A-D*	**All seasons**
Long An	375	199	220	794	82	42	160	284
Dong Thap	352	245	224	824	57	45	56	158
An Giang	381	338	275	993	27	46	179	252
Tien Giang	131	36	91	258	34	8	46	87
Kien Giang	422	150	363	935	117	73	355	546
Vinh Long	137	100	78	315	44	35	76	155
Ben Tre	47	15	42	105	30	7	32	69
Can Tho	152	62	48	263	5	6	42	53
Tra Vinh	140	119	119	377	39	86	95	220
Hau Giang	145	111	95	351	28	87	95	211
Soc Trang	250	152	228	629	139	125	199	462
Bac Lieu	78	27	94	198	58	27	94	179
Ca Mau	46	9	51	106	38	5	49	92
Seasonal total	2,655	1,565	1,927	6,147	696	592	1,477	2,767

Moreover, the data displayed in Table 2 and 3 can be used to prioritize an eventual mitigation campaign to disseminate low-emitting varieties in space and time. While the dry season represents the most efficient time window for variety selection across all provinces (Table 2), the mitigation impacts of this strategy will largely vary from province to province (Table 3). In Scenario 2, only two provinces (Kien Giang and Soc Trang) account for 36.4% of the total mitigation potential.

In order to incentivize farmers to change management of the rice crop and maybe even face a certain yield penalty (Johnson et al., 2023) a compensation mechanism should be developed. We tried to simply estimate the economic importance of the achievable reduction of GHG emission in the VMD using existing data on compensation schemes. Assuming that these mitigation scenarios could be monetized in the voluntary carbon market, we used current CO_2 prices available on the internet to provide an approximation of potential payments. This approach encompassed the following steps:

1.) The emission factor of 217 kg CH_4 ha^{-1} $season^{-1}$ used in Vietnam's Third National Communications for the Mekong River Delta corresponds to 5.425 t CO_2e ha_{-1} $season_{-1}$ (with GWP = 25).

2.) The price given per t CO_2e varies in a wide range depending on different data sources, e.g. Source A: 3.5 $/ t CO_2e for “nature-based solutions” (https://carboncredits.com/carbon-prices-today) or Source B: 7 $/ t CO_2e for CH_4 reduction through livestock (https://8billiontrees.com/carbon-offsets-credits/new-buyers-market-guide/carbon-credit-pricing)

3.) These prices translate into the following amounts for the adoption of low-emitting varieties corresponding to 25% reduction in GHG emissions: Source A: 4.75 $ ha^{-1} $season^{-1}$, Source B: 9.5 $ ha^{-1} $season^{-1}$.

Assuming a typical profit of 1000 USD per ha and season for rice farming in the MRD (Berg et al. 2017), the incremental income from carbon trading would be 2.5% and 5%, respectively. Given an average farm size of 2 ha (Berg et al. 2017) and triple cropping, the absolute amounts translate into 154.5 and 309 USD, respectively. It seems obvious that these amounts are probably too low to trigger a behavioural change among the rice farmers and should be taken under consideration when trying to convince the rice farming community to participate in the efforts of climate change mitigation. Based on these simplified calculations and by considering additional transaction costs, the direct payment of carbon credits to farmers appears as an inefficient strategy for increasing livelihoods. However, if these payments are aggregated at larger scale -- either for entire cooperatives or by integrating individual farms – eventual payments for carbon credits could become an add-on in support of rural development such as investing in irrigation facilities.

5. Conclusion

Varietal choice was shown to affect methane emissions in the range of 40-45% under continuous flooding under both irrigation treatments. AWD had, nonetheless, the larger effect, however in seasons or systems in which AWD is not possible choosing a high yielding but low emitting variety over a high emitting variety contributes strongly (about 25% on average) to the effort of mitigating methane emissions from rice fields. If farmers could earn additional income through such efforts, the effect could be permanent. To date, compensation schemes already in existence would probably not generate sufficient additional income to trigger a change in farmers management practices.

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References

Arai, H., Hosen, Y., Chiem, N. H., & Inubushi, K. (2021). Alternate wetting and drying enhanced the yield of a triple-cropping rice paddy of the Mekong Delta. *Soil Science and Plant Nutrition, 67(4)*, 493–506. https://doi.org/10.1080/00380768.2021.1929463

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. Journal of Statistical Software, 67(1). https://doi.org/10.18637/jss.v067.i01

Berg, H., Ekman Söderholm, A., Söderström, A.-S., & Tam, N. T. (2016). Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. Sustainability Science, 12(1), 137–154. https://doi:10.1007/s11625-016-0409-x

Bharali, A., Baruah, K. K., & Gogoi, N. (2017). Potential option for mitigating methane emission from tropical paddy rice through selection of suitable rice varieties. Crop and Pasture Science, 68 (5), 421-433. https://doi.org/10.1071/CP16228

Bouman, B. A. M., Humphreys, E., Tuong, T. P., & Barker, R. (2007). Rice and Water. In *Advances in Agronomy* (Vol. 92, pp. 187–237). Elsevier. https://doi.org/10.1016/S0065-2113(04)92004-4

Carrijo, D. R., Akbar, N., Reis, A. F. B., Li, C., Gaudin, A. C. M., Parikh, S. J., Green, P. G., & Linquist, B. A. (2018). Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. *Field Crops Research*, 222, 101–110. https://doi.org/10.1016/j.fcr.2018.02.026

Chidthaisong, A., Cha-un, N., Rossopa, B., Buddaboon, C., Kunuthai, C., Sriphirom, P., Towprayoon, S., Tokida, T., Padre, A. T., & Minamikawa, K. (2018). Evaluating the effects of alternate wetting and drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand. *Soil Science and Plant Nutrition*, *64*(1), 31–38. https://doi.org/10.1080/00380768.2017.1399044

Fairhurst, T. H., & Dobermann, A. (2002). Rice in the Global Food Supply. *Better Crops International*, *16* (Special Supplement), 3–6.

Fawibe, O.O., Honda, K., Taguchi, Y., Park, S. &, Isoda, A. (2019). Greenhouse gas emissions from rice field cultivation with drip irrigation and plastic film mulch. Nutrient Cycling in Agroecosystems 113, 51–62. https://doi.org/10.1007/s10705-018-9961-3

GSO-- Government Statistics Office 2017. Statistic data on agriculture, forestry and fishery. Retrieved from https://www.gso.gov.vn/en/agriculture-forestry-and-fishery/

Huang, N.-R., Liang, K.-M., Zhong, X.-H., Pan, J.-F., Liu, Y.-Z., Peng, B.-L., Fu, Y.-Q., Hu, X.-Y., Tian, K., & Kong, Q.-N. (2018). Screening for and evaluation of rice (*Oryza sativa*) varieties with low methane emission and high yield in South China. Journal of Agro-Environment Science, 37 (12), 2854-2863. https://doi.org/10.11654/jaes.2018-0125

IPCC (Intergovernmental Panel on Climate Change) 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge and New York. https://www.ipcc.ch/assessment-report/ar4/

IPCC (Intergovernmental Panel on Climate Change) 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York. https://www.ipcc.ch/assessment-report/ar6/

Johnson, K., Vo, T.B.T., Duong, V.N., & Asch, F. (2023). Effects of alternate wetting and drying irrigation on rice phenology and yield. *Journal of Agronomy and Crop Science*, submitted.

Kerdchoechuen, O. (2005). Methane emission in four rice varieties as related to sugars and organic acids of roots and root exudates and biomass yield. *Agriculture, Ecosystems & Environment*, *108*(2), 155–163. https://doi.org/10.1016/j.agee.2005.01.004

Khush, G. S. (2005). What it will take to Feed 5.0 Billion Rice consumers in 2030. *Plant Molecular Biology*, *59*(1), 1–6. https://doi.org/10.1007/s11103-005-2159-5

Lampayan, R. M., Rejesus, R. M., Singleton, G. R., & Bouman, B. A. M. (2015). Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. *Field Crops Research*, *170*, 95–108. https://doi.org/10.1016/j.fcr.2014.10.013

Lenth, R. (2022). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.7.2. https://CRAN.R-project.org/package=emmeans

Minami, K. (1994). Methane from rice production. *Fertilizer Research*, *37*(3), 167–179. https://doi.org/10.1007/BF00748935

MONRE -- Ministry of Natural Resources and Environment (2019). Vietnam's 3rd National Communication for the United Nations Framework Convention on Climate Change. https://unfccc.int/documents/192805.

Nelson, A., Wassmann, R., Sander, B.O., Palao, L.K. (2015). Climate-Determined Suitability of the Water Saving Technology "Alternate Wetting and Drying" in Rice Systems: A Scalable Methodology demonstrated for a Province in the Philippines. PLOS ONE 10: Article Number: e0145268.

Qin, X., Li, Y., Wang, H., Li, J., Wan, Y., Gao, Q., Liao, Y., & Fan, M. (2015). Effect of rice cultivars on yield-scaled methane emissions in a double rice field in South China. Journal of Integrative Environmental Sciences, 12, 47-66. https://doi.org/10.1080/1943815X.2015.1118388

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Samal, P., Babu, S. C., Mondal, B., & Mishra, S. N. (2022). The global rice agriculture towards 2050: An inter-continental perspective. Outlook on Agriculture, 51(2), 164–172. https://doi.org/10.1177/00307270221088338

Sander, B. O., Wassmann, R., Palao, L. K., & Nelson, A. (2017). Climate-based suitability assessment for alternate wetting and drying water management in the Philippines: A novel approach for mapping methane mitigation potential in rice production. *Carbon Management*, *8*(4), 331–342. https://doi.org/10.1080/17583004.2017.1362945

Sander, B. O., Schneider, P., Romasanta, R., Samoy-Pascual, K., Sibayan, E. B., Asis, C. A., & Wassmann, R. (2020). Potential of Alternate Wetting and Drying Irrigation Practices for the Mitigation of GHG Emissions from Rice Fields: Two Cases in Central Luzon (Philippines). *Agriculture*, *10*(8), 350. https://doi.org/10.3390/agriculture10080350

Sass, R. L., Fischer, F.M., Ding, A., & Huang, Y. (1999). Exchange of methane from rice fields: National, regional, and global budgets, Journal of Geophysical Research 104(D21), 26,943 – 26,952. https://doi.org/10.1029/1999JD900081

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., … Zhuang, Q. (2020). The Global Methane Budget 2000–2017. *Earth System Science Data*, *12*(3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020

Schneider, P. & Asch, F. (2020). Rice production and food security in Asian Mega deltas—A review on characteristics, vulnerabilities and agricultural adaptation options to cope with climate change. *Journal of Agronomy and Crop Science 206*, 491-503. https://doi.org/10.1111/jac.12415.

Schneider, P., Sander, B. O., Wassmann, R., & Asch, F. (2019). Potential and versatility of WEAP model (Water Evaluation and Planning System) for hydrological assessments of AWD (Alternate Wetting and Drying) in irrigated rice. *Agricultural Water Management*, *224*, 105559. https://doi.org/10.1016/j.agwat.2019.03.030

Setyanto, P., Pramono, A., Adriany, T. A., Susilawati, H. L., Tokida, T., Padre, A. T., & Minamikawa, K. (2018). Alternate wetting and drying reduces methane emission from a rice paddy in Central Java, Indonesia without yield loss. *Soil Science and Plant Nutrition*, *64*(1), 23–30. https://doi.org/10.1080/00380768.2017.1409600

Singh, S., Singh, J. S., & Kashyap, A. K. (1999). Methane Flux from irrigated rice fields in relation to crop growth and N-fertilization. *Soil Biology and Biochemistry*, *31*, 1219–1228. https://doi.org/10.1016/S0038-0717(99)00027-9

Stuerz, S., Sow, A., Muller, B., Manneh, B., & Asch, F. (2014). Yield components in response to thermal environment and irrigation system in lowland rice in the Sahel. Field Crops Research 163, 47-54. https://doi.org/10.1016/j.fcr.2014.04.004

Tirol-Padre, A., Tran, D. H., Hoang, T. N., Hau, D. V., Ngan, T. T., An, L. V., Minh, N. D., Wassmann, R., & Sander, B. O. (2017). Measuring GHG Emissions from Rice Production in Quang Nam Province (Central Vietnam): Emission Factors for Different Landscapes and Water Management Practices. In A. Nauditt & L. Ribbe (Eds.), *Land Use and Climate Change Interactions in Central Vietnam* (pp. 103–121). Springer Singapore. https://doi.org/10.1007/978-981-10-2624-9_7

Vo, T.B.T., Wassmann, R., Mai, V.T., Vu, D.Q., Bui, T.P.L., Vu, T.H., Dinh, Q.H., Yen, B.T., Asch, F., & Sander, B.O. (2020). Methane Emission Factors from Vietnamese Rice Production: Pooling Data of 36 Field Sites for Meta-analysis. Climate 8 (6), 74. https://doi.org/10.3390/cli8060074.

Vo, T. B. T., Wassmann, R., Tirol-Padre, A., Cao, V. P., MacDonald, B., Espaldon, M. V. O., & Sander, B. O. (2018). Methane emission from rice cultivation in different agro-ecological zones of the Mekong river delta: Seasonal patterns and emission factors for baseline water management. *Soil Science and Plant Nutrition*, *64*(1), 47–58. https://doi.org/10.1080/00380768.2017.1413926

Vo, T.B.T., Wassmann, R., Sander, B. O., & Asch, F. (2023). Varietal effects on greenhouse gas emissions from rice production systems under different water management in the Vietnamese Mekong delta. *Journal of Agronomy and Crop Science*, submitted.

Wang, Z. P., Lindau, C. W., Delaune, R. D., & Patrick, W. H. (1993). Methane emission and entrapment in flooded rice soils as affected by soil properties. *Biology and Fertility of Soils*, *16*(3), 163–168. https://doi.org/10.1007/BF00361401

Wassmann, R., Neue, H. U., Lantin, R. S., Aduna, J. B., Alberto, M. C. R., Andales, M. J., Tan, M. J., van der Gon, H. A. C. D., Hoffmann, H., Papen, H., Rennenberg, H., & Seiler, W. (1994). Temporal patterns of methane emissions from wetland rice fields treated by different modes of N application. *Journal of Geophysical Research*, *99*(D8), 16457. https://doi.org/10.1029/94JD00017

Wassmann, R., & Aulakh, M. S. (2000). The role of rice plants in regulating mechanisms of methane missions. *Biology and Fertility of Soils*, *31*(1), 20–29. https://doi.org/10.1007/s003740050619

Wassmann, R., Aulakh, M. S., Lantin, R. S., Rennenberg, H., & Aduna, J. B. (2002). Methane emission patterns from rice fields planted to several rice cultivars for nine seasons. *Nutrient Cycling in Agroecosystems*, *64*, 111–124. https://doi.org/10.1023/a:1021171303510

Win, E. P., Bellingrath-Kimura, S. D., Oo, A. Z., & Park, K. I. (2022). Effect of rice cultivars, organic manures, and water management on methane emissions and grain yield. Physiologia Plantarum, 174 (4), art. no. e13747. https://doi.org/10.1111/ppl.13747

Yan, X., Akiyama, H., Yagi, K., & Akimoto, H. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines: METHANE EMISSION FROM GLOBAL RICE FIELDS. *Global Biogeochemical Cycles*, *23*(2), n/a-n/a. https://doi.org/10.1029/2008GB003299

Yen, B.T., Hue, N.T., Wassmann, R., Sander, B.O. (2023) Mapping potential scaling areas for the intermittent irrigation practices in rice production of Vietnam. Agriculture, Ecosystems & Environment, submitted

Zou, J., Huang, Y., Zheng, X., & Wang, Y. (2007). Quantifying direct N2O emissions in paddy fields during rice growing season in mainland China: Dependence on water regime. *Atmospheric Environment*, *41*(37), 8030–8042. https://doi.org/10.1016/j.atmosenv.2007.06.049

CHAPTER 6

GENERAL DISCUSSION

The relevance of the results in this dissertation can be derived in the context of the forthcoming reporting commitments at the national scale (Dinesh et al. 2017). In preparation for the Conference of the Parties - COP21 in Paris, all countries submitted Intended Nationally Determined Contributions (INDC) in 2015 that have then been transformed into Nationally Determined Contributions (NDC) when the Paris Agreement has been ratified. While this process was important to achieve a broad consensus at the international level, the fulfillment of these pledges will require specific plans as to what mitigation can be accomplished and how those achievements will be quantified. While the mitigation plans will be defined in the form of Nationally Appropriate Mitigation Actions (NAMA), the quantification is supposed to form part of a broader Measurement, Reporting, Verification (MRV) framework. However, the present concepts on NAMAs and MRVs in Vietnam as well as other rice-growing countries are still very vague (Boos et al. 2015). Considerably, this can be attributed to the lack of advanced calculation tools which are indispensable for systematic planning on mitigation efforts and keeping track of GHG impacts.

Assessing our results across all individual studies of this dissertation, that can be extracted the following take-home messages:

Message 1) The database on disaggregated EFs for the Vietnamese rice production is remarkably large as compared to other crops and countries, however, it is still very small in relation to the variability in cropping systems

The publication in Chapter 2 (Vo et al. 2018) and Chapter 3 (Vo et al. 2020) comprises data from 4 sub-zones in the MRD and 36 stations with 73 cropping seasons from the whole Vietnam, respectively. Although this presentation summarized the available measurements as of 2020, there have been several measurement campaigns conducted in the meantime including the measurements presented in Chapter 4 (Vo et al. 2023). The study of EFs in the MRD represents the first kind of the different sub-zones in the MRD. The MRD comprises more than 50% of Vietnamese rice production and more than 5% of ASEAN rice production (GSO, 2020; Wailes and Chavez, 2012). Simply by its size, any GHG assessment for this area will affect the overall GHG inventory for the country and Southeast Asia. The study also elaborates on the possible integration of this data into the national reporting commitments and possible project development for mitigation in rice production.

Message 2) The Tier 2 assessment with disaggregated EFs should be seen as a process that is constantly fluid due to new incoming data – as opposed to a static calculation procedure

Due to the increasing interest in carbon financing, it can even be expected that these efforts become more abundant in the future. The newly generated EFs with zonal and seasonal integration for CH_4 emission from Vietnamese rice production are generally higher than IPCC Tier 1 defaults for global as well as Southeast Asian rice production. While this finding speaks in favor of the Tier 2 approach, it should be noted that any compilation of EFs will automatically need updating as soon as new emission data has been generated. Since the available data on N_2O emissions from Vietnamese rice production is still very limited, also this information could be compiled given a future Tier 2 approach for N_2O emissions.

Message 3) AWD was (yet again) identified as the most efficient mitigation strategy in the MRD

The new field measurements in chapter 4 (Vo et al. 2023) support previous results on the strong mitigation potential of AWD in Vietnam as a whole and in MRD in particular. In comparison to the IPCC defaults as well as the EFs previously used by MONRE, the experiment yielded higher EFs and lower SFs for CH_4. The combined effect of these two factors leads to a stronger mitigation effect whenever AWD is implemented. This finding, however, should not be confused with the question of AWD suitability across the rice-growing area which was beyond the scope of this dissertation.

Although there is no well-documented survey across the entire delta, there is plenty of anecdotal evidence that a sizable number of farmers have already adopted water-saving practices. AWD has been an integral part of the crop management recommendations under the technology programs “3 Reductions – 3 Gains” and “1 Must Do – 5 Reductions”. The trend toward water-saving irrigation practices in the MRD will accelerate in the foreseeable future under aggravating climate change impacts. While sea level rise is the underlying effect pathway in this delta, its effect will encompass positive as well as negative on the availability of fresh water for irrigation depending on location and season. Superimposed on the rising sea water levels are more and more extremes in the discharge of the MRD that could already be observed in recent years leading to an unprecedented scarcity of freshwater suited for irrigation.

Message 4) Variety selection can be seen as an important mitigation strategy – in particular if implemented a supplementary approach to AWD.

Given the large number of rice varieties scattered in different rice-growing regions, it is understood that the screening of 20 varieties is by no means comprehensive at the national scale. Moreover, other rice-growing countries have developed their rice varieties in recent decades as discussed in chapter 4, so the specific information on the tested varieties will have limited implications there. Irrespective of this caveat, there are several generic take-home messages on the role of varietal selection within mitigation efforts in rice production. As outlined in chapter 4 (Vo et al. 2023), varietal selection may be exploited for well-planned mitigation efforts -- either as a complementary option to AWD or as a stand-alone approach. The latter will be applicable as long as AWD is impractical but could also address the other end of the scale when the farmers are already applying a baseline water management (CF) that is comparable to AWD.

The main advantage of variety selection is the relative ease of disseminating improved seeds to farmers – as compared to convincing them to change the water management. These distinctive features will have to be taken into account for any technology-based mitigation program in the MRD. Seeds of low-emitting varieties can either be supplied by seed centers that are operated at the provincial level or accessed from the private sector. As has been shown in numerous development projects, farmers in Vietnam and other rice-growing countries are typically very receptive to the introduction of new seeds (Nguyen 2020, Wassmann et al. 2022). On the other hand, Johnson et al. 2023 shows that there is a potential of minor yield losses when these varieties are cultivated under AWD and that the high-yielding varieties suffer the greatest loss. However, the highest-yielding varieties may not have the highest CH_4 emissions. As long as yield losses are compensated for, farmers could cultivate the low-emitting varieties during the rainy seasons as a means to reduce CH_4 emissions. Although the additional income (5-10%) calculated by Asch et al. 2023 (chapter 5) might not be considered as an attractive benefit to farmers to put efforts into mitigation, the adoption of low-emitting varieties could be driven by institutions involved in rural development, e.g. providing free access to seeds. In totally, as outlined in chapter 4 and 5, the proper selection of varieties should be factored into future mitigation efforts -- either as an additional measurement to maximize the AWD effect during the dry season or as a stand-alone mitigation option in locations or seasons where mitigation through AWD is not possible.

Message 5) While the disaggregated EFs represent incremental progress in national GHG calculations, the real breakthrough in enhancing the accuracy of these estimates will rely on a systematic database of disaggregated activity data

As shown above, in equation 1, the EFs have to be multiplied with area data that should ideally be at the same level of disaggregation. At this point, however, the national GHG inventories have is based on assumptions, e.g. adopting the IPCC baseline practice (continuous flooding, no organic amendments) as the Business-as-Usual for the entire country. Similar to emission factors, the accuracy of activity data can be improved through disaggregation over space and time. In turn, the harvested area will have to be divided into sub-units (e.g., specific zones) comprising similar features of crop management. Despite several farm surveys (Berg and Tam 2018, Stuart e al. 2018, Duyen et al. 2018) in specific regions including the MRD, the available data on crop management practices is very fragmented. This applies to both the geographic coverage of farm survey data as well as the coherence of the methodologies and questionnaires applied in different studies.

A structured and regularly updated database on crop management practices, e.g. at the district level, would greatly benefit both the current Tier 2 approach as well as any future attempt in moving toward Tier 3. Such a database could become the core of a country-wide MRV system that will greatly improve the international standing of Vietnam given potential carbon financing. The MRV system could also be applied for product labeling of GHG footprints – either required through regulation or voluntarily by retailers – will also stimulate more GHG assessments along the rice value chain, especially in rice-exporting countries like Vietnam.

References

Berg, H., and Tam, N. T. (2018). Decreased use of pesticides for increased yields of rice and fish-options for sustainable food production in the Mekong Delta. Science of the Total Environment, 619, 319-327.

Boos, D, Broecke, H, Dorr T, von Luepke H, Sharma S. (2015) How are INDCs and NAMAs linked? Discussion paper published by GIZ and UNEP DTU. https://www.giz.de/en/downloads_els/indcnama.pdf

Dinesh D, Campbell B, Wollenberg L, Bonilla-Findji O, Solomon D, Sebastian L, Huyer S. A step forward for agriculture at the UN climate talks – Koronivia Joint Work on Agriculture (2017) https://ccafscgiarorg/ blog/step-forward-agriculture-un-climate-talks-% E2%80%93-koronivia-joint-work-agriculture#WpN0E4

Duyen, T. N. L., Sander, B. O., & Wassmann, R. (2018). Gender and climate-smart agriculture: A case study in Tra Hat village, Bac Lieu province, Vietnam. Gender Dimension, 105.

Eric J. Wailes and Eddie C. Chavez (2012). ASEAN and Global Rice Situation and Outlook. No. 22 | August 2012. ADB Sustainable Development Working Paper Series. https://www.adb.org/sites/default/files/publication/29969/adb-wp-22-asean-global-rice-situation.pdf.

General Statistics Office of Viet Nam. (2020) Planted Area and Production of Paddy. Available online: https://www.gso.gov.vn/default_en.aspx?tabid=778 (accessed on 19 March 2020).

Stuart, A. M., Devkota, K. P., Sato, T., Pame, A. R. P., Balingbing, C., Phung, N. T. M., ... & Singleton, G. R. (2018). On-farm assessment of different rice crop management practices in the Mekong Delta, Vietnam, using sustainability performance indicators. Field Crops Research, 229, 103-114.

CHAPTER 7

CONCLUSIONS AND OUTLOOK

From the viewpoint of future GHG assessments, I deem our studies a timely contribution toward more evidence-based GHG inventories and mitigation planning in Vietnam. The growing demand for improved GHG calculations is illustrated in Table 1 of this chapter. In principle, these different applications could best be addressed by using biogeochemical models (Tier 3). At present, these simulation models are not sufficiently user-friendly and require expert knowledge for regional validation that exceeds the capabilities for setting up an MRV system in developing countries like Vietnam. Thus, it can be assumed that the official emission calculations will at least in the foreseeable future rely on the IPCC Tier 2 approach and thus, on disaggregated EFs.

Table 1: Overview of growing demand for GHG calculation schemes distinguishing context and time horizon of the scenario

Scenario	Project context	Subnational/ national context
Ex ante	• Quantifying GHG emissions as required for the development of mitigation proposals, thereby using and comparing Tier1, Tier 2 and Tier 3 approaches • Integrating GHG data into broader Environmental Impact Assessments in development projects	• Prioritizing mitigation options and target regions for NAMAs/ NDCs • Assessing GHG scenarios within regional development plans
Status quo	• Designing and operating efficient MRV systems for mitigation and development projects	• Substantiating GHG inventories on rice in National Communications • Complying with short-term requests from policy makers for specific GHG calculations • Training on GHG footprint calculations for rice traders (exported as well as domestic rice supply)
Ex post	• Reporting on GHG impacts caused by completed projects	• Documenting GHG mitigation as part of NDC reporting

Apart from all messages extracted from our findings, there was the underlying pattern that CH_4 emissions certainly exceed N_2O emissions from rice production and play a crucial role in the national GHG balance. The relative significance of CH_4 vs CO_2 and N_2O emissions is further amplified by choosing the GWP-values with a 20-year time horizon as opposed to the conventional metric of 100 years. If the context is a country’s contribution to the Paris target, then GWP_{20} should be the obvious choice. The divergence by a factor of 2.9 between these values provides a strong rationale for prioritizing mitigation projects in rice (and cattle husbandry) at this point. These GHG sources dominated by CH_4 emissions will provide more tangible benefits to curtail the global temperature increase in the coming decades while CO_2 and N_2O mitigations have to be seen in the context of the long-term objectives of GHG mitigation. In the realm of climate policy, this notion has already been reflected in the large momentum of the Global Methane Pledge which was initiated in 2021 by the EU and USA. In the meantime, this policy initiative has more than 100 signatories including Vietnam and many other rice-growing countries.

In addition to the policy relevance, our results also point to possible improvements in the IPCC Tier 2 approach. The IPCC guidelines request for disaggregation of the EFs, but there is no such provision for the SFs. In the past, the uniform use of a default SF for water management may have been justified by data scarcity, but this situation is gradually changing due to an increase in field measurements that encompass AWD as one of the treatments. It seems obvious that comparative measurements, namely different plots in one field as described in chapter 4 (Vo et al. 2023), will be more indicative to determine the realistic impacts of this irrigation practice. In turn, future versions of the IPCC guidelines should explicitly encourage the use of national or sub-national SF_w values in GHG calculations whenever those will be available.

Moreover, future guidelines should also be more specific on how to consider varietal differences. The 2019 refinement of the IPCC guidelines introduced a new scaling factor (SF_r) to account for the effects of rice varieties as long as such data is available. Although there is no elaboration on the calculation procedure in the guidelines, this concept inherently requires the existence of a baseline rice variety to meet the condition of $SF_r = 1$. Strictly speaking, the EF of a given region will not only require specific management practices but also implies that the rice variety has to be defined for baseline management. Conceptually, this can be done by a reference variety which should be the most popular variety in a given region. This new aspect of baseline setting may in the future become more prominent when more emission data will become available for different varieties.

References

Nguyen, L. (2020). Land rights and technology adoption: Improved rice varieties in Vietnam. The Journal of Development Studies, 56(8), 1489-1507.

Wassmann R., Gonsalves J., Sprang P., Yen B.T., Villanueva J., Nelakhom P., Okumo B. (2022) Climate Smart Villages in Southeast Asia: The pivotal role of Seed Systems in rice-based landscapes. Asian Journal of Agriculture and Development 19 (1362-2022-707), 1-24.

APPENDICES

Appendix 1: Supplementary material for chapter 2

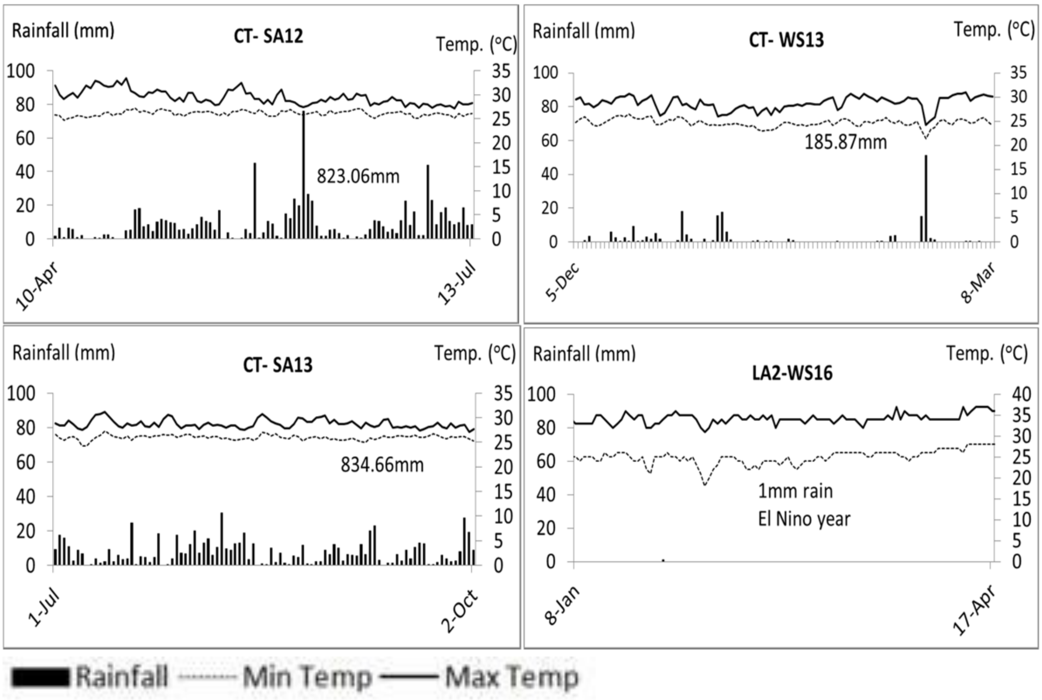

Figure S1. Climate data including total rainfall during observation period per site and season in alluvial zone. Source: NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from the Website at http://www.esrl.noaa.gov/psd/

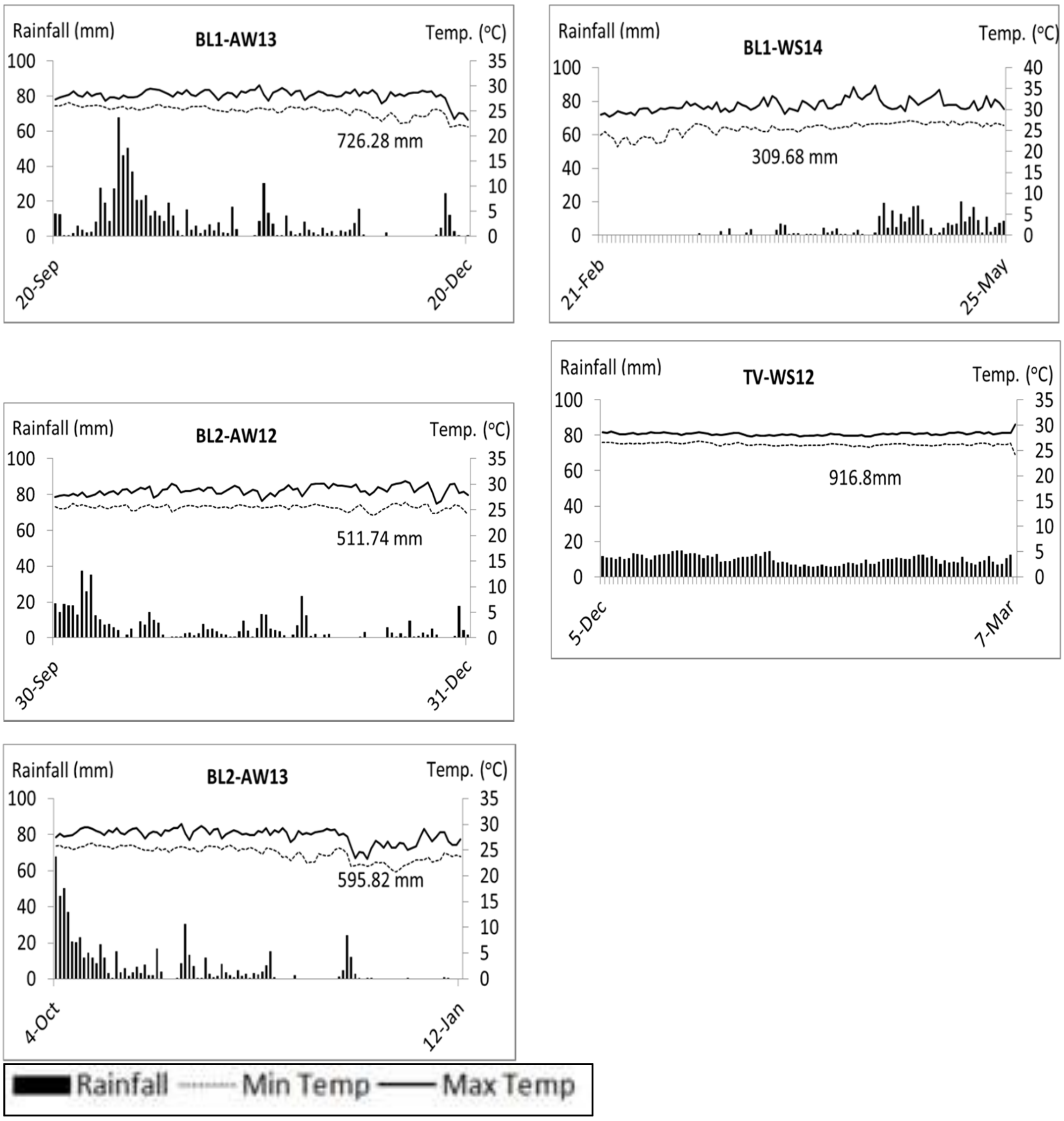

Figure S2. Climate data including total rainfall during observation period per site and season in saline zone. Source: see Figure S1

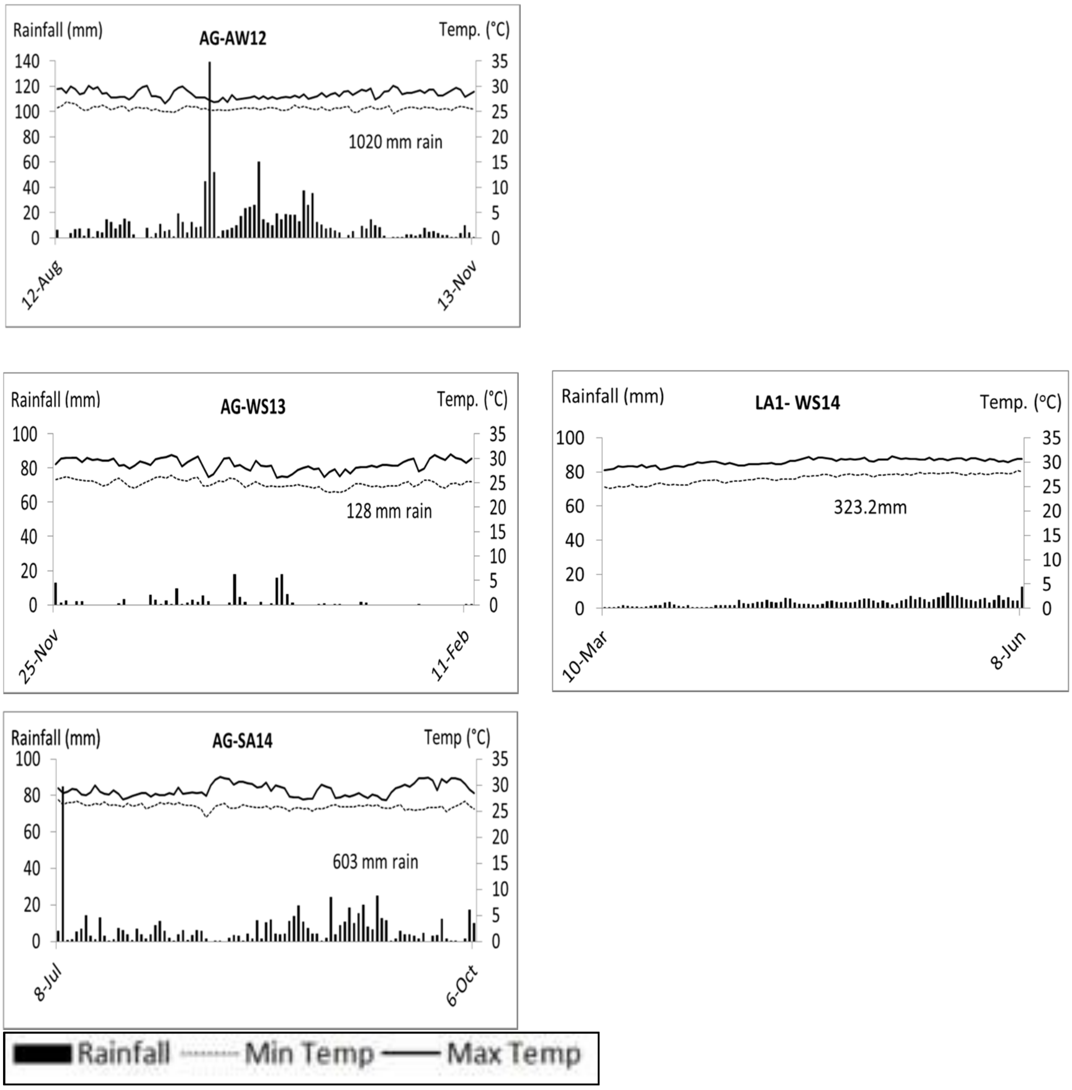

Figure S3. Climate data including total rainfall during observation period per site and season in deep zone. Source: see Figure 1

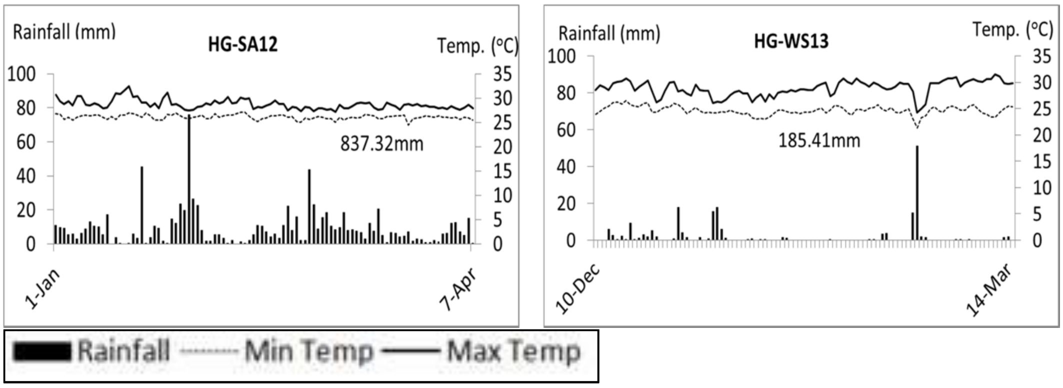

Figure S4. Climate data including total rainfall during observation period per site and season in acid sulfate zone. Source: see Figure

Appendix 2: Supplementary material for chapter 3

Table S1. Site characterization of the Northern sites. For site locations refer to Figure 3; nd = not determined; Not yet publ. = not yet published

Site	Commune	Province	Lat	Long	Publication
N1	Luong Phong	Bac Giang	21° 20' 32.28" N	106° 0' 50.76" E	[14]
N2	Binh Minh	Thai Binh	20°24'26.85"N	106°26'56.57"E	Not yet publ.
N3	Nguyen Xa	Thai Binh	20°24'23.00"N	106°16'57.76"E	Not yet publ.
N4	Tay Phong	Thai Binh	20°21'37.25"N	106°30'58.42"E	Not yet publ.
N5	Hai Phuc	Nam Dinh	20°13′58,56″N	106°15′32,58″E	Not yet publ.
N6	An Lam	Hai Duong	21°0'11.8512"E	106° 21' 6.4332" N	[16]
N7	Thinh Long	Nam Dinh	20° 3'8.05"N	106°13'27.92"E	[37]
N8	Vinh Quynh	Ha Noi	20°55’603’’ N	105°050’544’’E	[39]
N9	Bac Phu	Ha Noi	21°16'21.08"N	105°53'34.46"E	Not yet publ.
N10	Rang Dong	Nam Dinh	19°59'37.03"N	106° 8'20.49"E	[37]

Table S2. Site characterization of the Central sites. For site locations refer to Figure 3; Not yet publ. = not yet published

Site	Commune	Province	Lat	Long	Publication
C1	Nghi Thach	Nghe An	18°46'26.92"N	105°42'35.87" E	Not yet publ.
C2	Đai Minh	Quang Nam	15°51'13.60"N	108° 4'12.14"E	Not yet publ.
C3	Đai Minh	Quang Nam	15°51'9.38"N	108° 4'5.25"E	Not yet publ.
C4	Binh An	Quang Nam	15°38'44.05"N	108°25'23.27" E	Not yet publ.
C5	Phuoc Son	Binh Dinh	13°52'33.7"N	109°12'19.1"E	[15]
C6	Tay Vinh	Binh Dinh	13° 55' 35.16" N	109° 0' 48.46" E	Not yet publ.
C7	An Thuy	Quang Binh	17° 14' 19.51" N	106° 42' 49.87" E	Not yet publ.
C8	Xuan Ninh	Quang Binh	106° 37' 47.262" E	106° 37' 47.26" E	Not yet publ.
C9	Nam Hung	Nghe An	18°44'37.17"N	105°26'41.16" E	Not yet publ.
C10	Nam Hung	Nghe An	18°44'43.60"N	105°26'37.18" E	Not yet publ.
C11	Nam Hung	Nghe An	18°45'19.91"N	105°26'0.32"E	Not yet publ.
C12	Nam Phuoc	Quang Nam	150 50’ 56.3”N	1080 16’ 37.1”E	[17]
C13	Dai Quang	Quang Nam	150 53’ 20.9”N	108003’ 23.2”E	[17]
C14	Huong An	Thua Thien Hue	16°28′16″N	107°31′26″E	[31]

Table S3. Site characterization of the Southern sites. For site locations refer to Figure 3; Not yet publ. = not yet published

Site	Commune	Province	Lat	Long	Publication
S1	Tran De	Soc Trang	9°26'49.93"N	106° 9'49.03"E	Not yet publ.
S2	Nga Nam	Soc Trang	9°31'19.81"N	105°39'56.20"E	Not yet publ.
S3	Chau Thanh	An Giang	10°26'32.23"N	105°19'38.98"E	Not yet publ.
S4	Chau Thanh	An Giang	10°27'40.45"N	105°16'29.73"E	Not yet publ.
S5	Tri Ton	An Giang	10°25′N	105°0′E	[18]
S6	Hoa Binh	Bac Lieu	9°17′6″N	105°39′12″E	[18]
S7	Phuoc Long	Bac Lieu	9°25′18″N	105°27′32″E	[18]
S8	Thoi Lai	Can Tho	9°59′57″N	105°39′40″E	[18]
S9	Hoa An	Hau Giang	9°46′23″N	105°38′19″E	[18]
S10	Tan An	Long An	10° 32′ 0″ N	106° 25′ 0″ E	[18]
S11	Tan Thanh	Long An	10° 36′ 0″ N	106° 6′ 0″ E	[18]
S12	Tieu Can	Tra Vinh	9°48′41″N	106°11′46″E	[18]

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

Site	Crop rotation	Season[6] and year	Seeding month	Harvesting month	Variety	Residue manage-ment	Seasonal CH_4 emission rate ($kg\ ha^{-1}\ season^{-1}$)
N1	2x rice/	E_'12	Feb	May	Khang dan 18	Removed	74
	Transpl.	L_'11	Jul	Sep	Khang dan 18	Removed	234
N2	2x rice/	E_'18	Jan	Jun	BC15	Removed	299
	Transpl.	L_'18	Jun	Oct	BC15	Removed	367
N3	2x rice/	E_'18	Jan	Jun	BT7	Compost	189
	Transpl..	L_'18	Jun	Oct	BT7	Compost	336
N4	2x rice/	E_'18	Feb	Jun	DS1	Compost	230
	Transpl.	L_'18	Jun	Oct	DS1	Compost	364
N5	2x rice/	E_'18	Feb	Jun	TX111	Removed	416
	Transpl.	L_'18	Jun	Oct	TX111	Burnt	576
N6	2x rice/	E_'18	Feb	June	Tam X.	Incorpor.	274
	Transpl.	L_'18	July	Oct	Bac Thom 7	Incorpor.	749
N7	2x rice/	E_'18	Feb	Jun	TX111	Removed	291
	Transpl.	L_'18	Jun	Oct	TX111*	Removed	358
N8	2x rice/	E_'18	Feb	Jun	Khang dan 18	Removed	311
	Transpl.	L_'18	Jun	Oct	Khang dan 18	Removed	595
N9	2x rice/	E_'18	Feb	Jun	BC15	Removed	74
	Transpl.	L_'18	Jun	Oct	BC15	Removed	203
N10	2x rice/	E_'18	Feb	Jun	TX111	Incorpor.	297
	Transpl.	L_'18	Jun	Oct	TX111	Burnt	521

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[6] Local names: E = vụ Xuân; L = vụ Mùa

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

Site	Crop rotation	Season[7] and year	Seeding month	Harvesting month	Variety	Residue manage-ment	Seasonal CH_4 emission rate (kg ha^{-1} season^{-1})
C1	1x rice/ Transpl.	M_'18	Aug	Nov	Thiên Ưu	Removed	125
C2	2x rice/ Dir. Seed.	E_'18	Dec	Apr	HT1	Removed	157
		M_'18	Jun	Sep	HT1	Removed	171
C3	2x rice/ Dir. Seed.	E_'18	Dec	Apr	HT1	n.d.	214
		M_'18	Jun	Sep	HT1	Removed	191
C4	2x rice/ Dir. Seed.	E_'18	Dec	Apr	HT1	n.d.	200
		M_'18	Jun	Sep	HT1	n.d.	171
C5	1x rice/ Dir. Seed.	E_'14	Dec	Apr	VNTA2	n.d.	323
C6	1x rice/ Dir. Seed.	E_'14	Dec	Apr	CT16	n.d.	468
C7	1x rice/ Dir. Seed.	E_'14	Jan	May	P6	n.d.	136
C8	2x rice/ Dir. Seed.	E_'14	Jan	May	P6	n.d.	454
C9	2x rice/ Transpl.	E_'18	Jan	May	Thiên Ưu	n.d.	148
		M_'18	May	Sep	Thiên Ưu	n.d.	130
C10	2x rice/ Transpl.	E_'18	Jan	May	Thiên Ưu	Removed	273
		M_'18	May	Sep	Thiên Ưu	Removed	184
C11	2x rice/ Transpl.	E_'18	Jan	May	Thiên Ưu	Removed	302
		M_'18	May	Sep	Thiên Ưu	Removed	213
C12	2x rice/ Dir. Seed.	M_'11	May	Sep	HT1	Removed	696
		E_'12	Dec	Apr	HT1	Removed	461
		M_'12	May	Sep	HT1	Removed	103
C13	2x rice/ Dir. Seed.	M_'11	May	Sep	HT1	Removed	224
		E_'12	Dec	Apr	HT1	Removed	304
		M_'12	May	Sep	HT1	Removed	83
C14	2x rice/ Dir. Seed.	E_'14	Jan	May	HT1	Removed	511
		M_'14	May	Sep	HT1	Removed	1029
		E_'15	Jan	May	HT1	Removed	485
		M_'15	May	Aug	HT1	Removed	343
		E_'16	Jan	May	HT1	Removed	502
		M_'16	Jun	Sep	HT1	Removed	560

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[7] Local names: E = vụ Đông Xuân; M= vụ Hè Thu

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

Site	Crop rotation	Season[8] and year	Seeding month	Harvest-ing month	Variety	Residue manage-ment	Seasonal CH_4 emission rate (kg ha^{-1} season^{-1})
S1	2x rice/ Dir. Seed.	E_'18	Nov	Feb	OM4900	Removed	191
		M_'18	Jul	Oct	OM4900	Removed	170
S2	2x rice/ Dir. Seed.	E_'18	Jan	Apr	RVT	Removed	158
		M_'18	May	Aug	RVT	Removed	311
S3	3x rice/ Dir. Seed.	E_'18	Dec	Apr	Đài Thơm 8	Removed	126
		M_'18	May	Aug	Đài Thơm 8	Removed	208
S4	2x rice/ Dir. Seed.	E_'18	Dec	Apr	OM5451	n.d	161
		M_'18	May	Aug	OM5451	n.d	126
S5	3x rice/ Dir. Seed.	E_'13	Nov	Mar	OM7347	Burnt	341
		M_'13	May	Aug	OM2517	Burnt	159
		L_'12	Aug	Nov	OM7346	Incorpor.	914
S6	3x rice/ Dir. Seed.	E_'13	Jan	Apr	OM6977	Incorpor.	90
		L_'12	Sep	Dec	OM6976	Incorpor.	350
S7	3x rice/ Dir. Seed.	L_'12	Oct	Jan	OM4900	Incorpor.	31
		L_'13	Oct	Jan	OM4900	Incorpor.	130
S8	2x rice Dir. Seed.	M_'12	May	Aug	OM7347	Incorpor.	422
		E_'13	Nov	Feb	OM7347	Burnt	213
		M_'13	May	Aug	OM7347	Burnt	408
S9	3x rice/ Dir. Seed.	M_'12	May	Aug	OM9921	Burnt	376
		E_'13	Dec	Mar	OM9921	Incorpor.	265
S10	3x rice/ Dir. Seed.	E_'16	Jan	May	OM6976	Burnt	167
		E_'17	Nov	Feb	OM6976	Burnt	75
S11	3x rice/ Dir. Seed.	E_'14	Feb	May	MTL 560	Burnt	241
S12	2x rice/ Dir. Seed.	E_'12	Dec	Mar	IR50404	Removed	82

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[8] Local season names: E = vụ Đông Xuân, M = vụ Hè Thu; L = vụ Thu Đông

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)

	Standard error	**p***
Compare S to A	0.94	0.14
Compare S to F	0.91	0.24
Compare A to F	0.88	0.71

* 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 zones are statistically different)

Correction[9]

Correction: Vo, T.B.T, et al. Methane Emission Factors from Vietnamese Rice Production: Pooling Data of 36 Field Sites for Meta-analysis. *Climate* 2020, *8, 74*

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The authors wish to make the following corrections to this paper [1]:

Change in Main Body Paragraphs (see below)

The authors would like to apologize for any inconvenience caused to the readers by these changes.

References

Vo, T.B.T.; Wassmann, R.; Mai, V.T.; Vu, D.Q.; Bui, T.P.L.; Vu, T.H.; Dinh, Q.H.; Yen, B.T.; Asch, F.; Sander, B.O. Methane Emission Factors from Vietnamese Rice Production: Pooling Data of 36 Field Sites for Meta-Analysis. *Climate* **2020**, *8*, 74.

4.1 Change in Main Body Paragraphs

The authors are sorry to report that on page 17, the unit of CH_4 emissions is given in [kg ha^{-1} yr^{-1}] but should be in [kg ha^{-1} $season^{-1}$]. This mistake also has implications on the conclusion on page 16 that "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." Consequently, the authors wish to make the following corrections to the paper:

1) Correct the units used on page 17 to [kg ha-1 season-1], i.e. "As of now, Vietnam's GHG inventories have been based on IPCC Tier 2 guidelines using EFs derived from a capacity

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[9] The corection of this study is resulted from mis-communication.

development program in 2014 [34], namely CH_4 emissions of 375 kg ha-1 season-1 in the North region, 336 in the Central region and 217 in the South region of Vietnam.”

2) Correct the conclusion on page 16 to “The new data is similar to the EFs previously used by the Ministry of Natural Resources and Environment (MONRE) in the Central region, slightly lower in the North region and much higher in the South region.”

There are two additional mistakes in this article [1].
1) On page 4, the model number of the gas chromatograph used is stated as “(GC: SRI 861 oC)” but should be “(GC: SRI 8610C)” in two instances on the same page.
2) On page 14, the formula (2) is given as “EFi—EFc · SFw · SFp · SFo · SFs · SFv “ but should be “EFi = EFc · SFw · SFp · SFo · SFs · SFv”.

These changes have no material impact on the conclusions of our paper. We apologize for any inconvenience caused to the readers.