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FLOODING STRESS

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Varietal effects on methane intensity of paddy fields under different irrigation management

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Abstract

Alternate wetting and drying irrigation (AWD) has been shown to decrease water use and trace gas emissions from paddy fields. Whereas genotypic water use shows little variation, 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 has been shown to affect genotypic yields and high-yielding varieties suffer the greatest loss when grown under AWD. The 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 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 reduce methane emissions but may compromise farmers' income if such varieties perform less well than the current standard. Methane emissions and rice yields were determined in field trials over two consecutive winter/spring seasons with continuously flooded and AWD irrigation treatments for 20 lowland rice varieties in the Mekong Delta of Vietnam. Based on the results, this paper investigates the magnitude of methane savings through varietal choice for both AWD and continuous flooding in relation to genotypic yields and explores potential options for compensating farmers' mitigation efforts.

KEYWORDS
AWD, carbon footprint, farmers compensation, greenhouse gases, lowland rice

Key points

- AWD reduces methane emissions with little yield penalty by about 60% across all varieties.
- Difference in varietal methane emissions are by a factor of about 100 larger under continuous flooding than under AWD conditions.

- Selecting the lowest emitting and highest yielding genotype constitutes a mitigation potential of about 40%.
- To incentivize farmers to change crop management, a climate premium mechanism should be developed.

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 (Bouman et al., 2007; Fairhurst & Dobermann, 2002), 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 (Singh et al., 1999; Wassmann et al., 1994), 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 (Johnson et al., 2023; Sander et al., 2017; Setyanto et al., 2018). 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%–45% between the highest and the lowest emitters. However, within a similar range of variability, the difference in methane emissions 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. In order to assess the mitigation potential of selecting low emitting varieties, we investigated the methane productivity (seasonal methane emissions per seasonal yield) under two contrasting irrigation methods 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 conditions

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 December 2019 to 14 March 2020, cumulatively, 22.1 mm and during the second season, 8 December 2020 to 11 March 2021, 74.7 mm of rain were recorded. Within the same timeframe mean temperatures were 26.0 ± 2.8°C with 17.5 ± 1.3 mol m^{-2} day^{-1} of solar radiation in the first season, and 25.5 ± 2.8°C with 16.7 ± 2.3 mol m^{-2} day^{-1}

of solar radiation in the second season. The soil was a clay loam with a CEC of 13.9 meq/100 g 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 mS cm^{-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 split-plot design with three replications as randomized blocks in the same experimental field. The splits were by irrigation treatment and the constituent plots of each split were the 20 varieties. With 20 rice cultivars, two irrigation treatments (CF, AWD), and three replications, overall, there were 120 plots each with a dimension of 4 m × 5 m 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 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 1 m 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 × 46 cm) was inserted about 10 cm into the top soil surrounding four rice hills planted at 20 cm × 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 (Systat Software Inc.).

In addition, data were analysed 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 × 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 ($p < .05$) between the treatments. On average 348 L m^{-2} with a standard error of 29 L m^{-2} were applied to the continuous flooding treatment whereas to the AWD 216 ± 29 L m^{-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 and 398 kg ha^{-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 kg ha^{-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 and 167 kg ha^{-1} which is less than half the variation in emissions under CF. Whereas for all varieties AWD significantly ($p < .05$) reduced seasonal methane emissions, differences in emissions between varieties were not statistically significant at $p < .05$ for either irrigation treatment.

Seasonal yields varied between 5263 kg ha^{-1} (OM 2517) and 7880 kg ha^{-1} (GKG 35) under CF irrigation and under AWD between 4990 kg ha^{-1} (ST24) and 7353 kg ha^{-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 ($p < .05$) between the two parameters under CF irrigation, indicating that higher yields lead to higher methane emissions. Under AWD this correlation is not

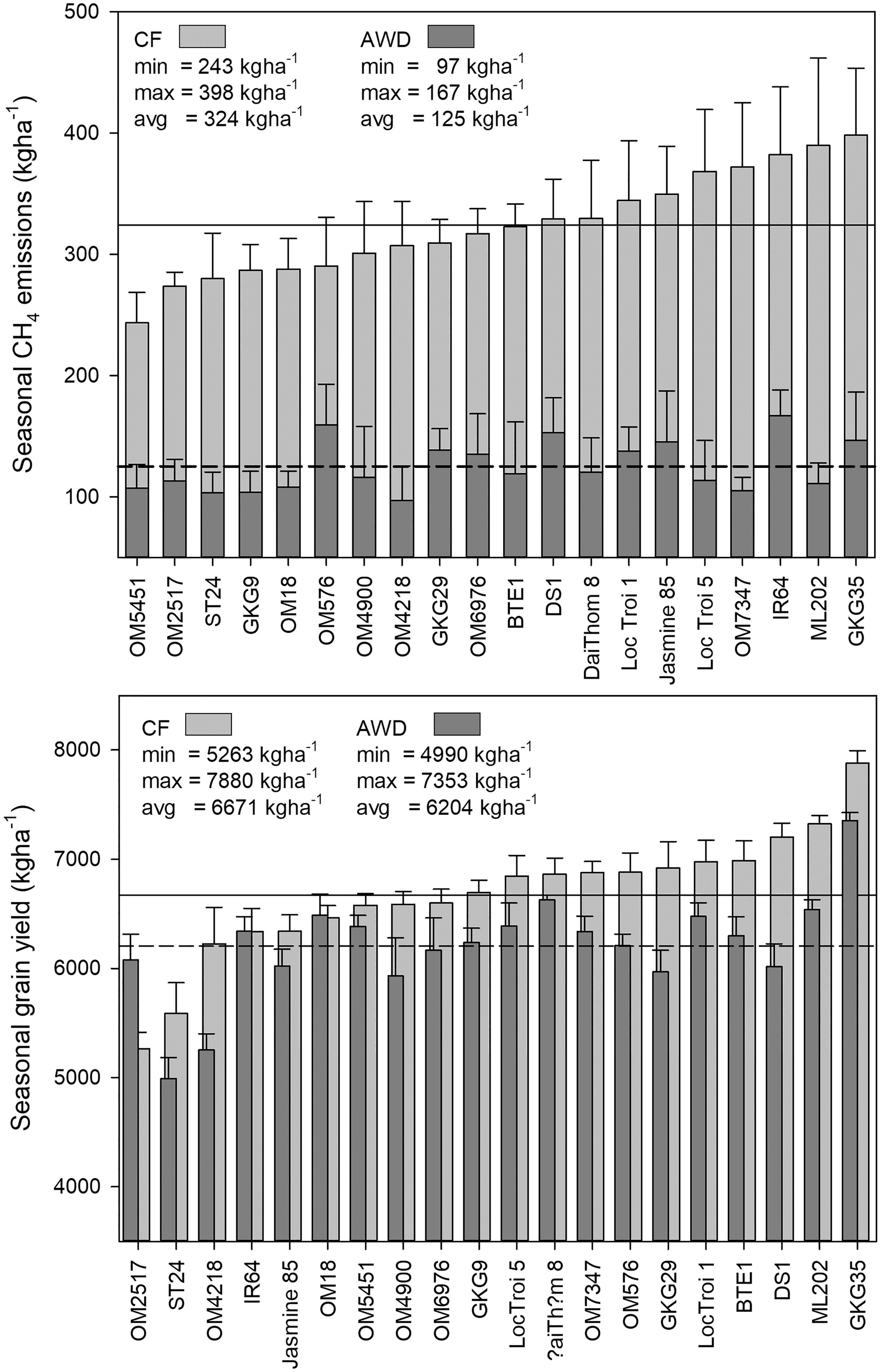

FIGURE 1 Seasonal methane emissions and seasonal grain yield for 20 lowland rice varieties grown over two winter–spring seasons (Dec–Mar) in a field trial in the Vietnam Mekong Delta under continuous flooding (CF) and alternate wetting and drying (AWD) irrigation treatments. Solid horizontal lines indicate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

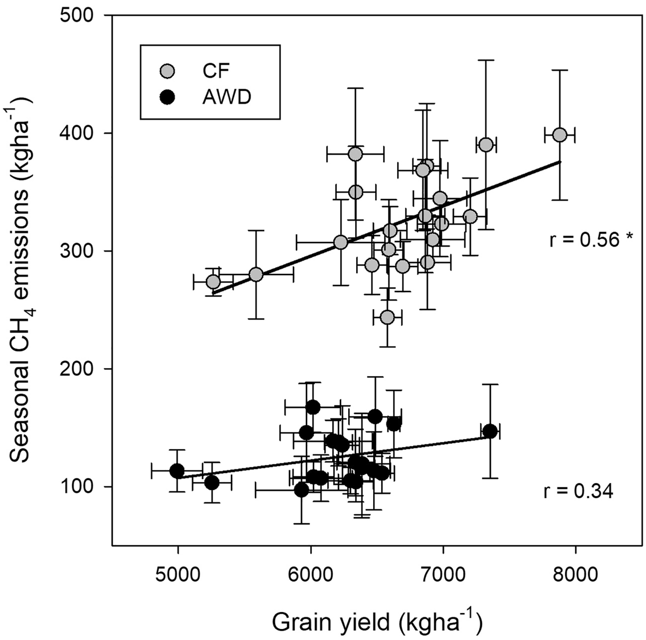

FIGURE 2 Regression of seasonal grain yield versus seasonal methane emissions of 20 lowland rice varieties subjected to two irrigation treatments (continuous flooding—CF; alternate wetting and drying—AWD) averaged over two consecutive winter seasons (Dec–Mar) in the Vietnam Mekong Delta.

TABLE 1 Mean water and methane productivity under continuous flooded (CF) and alternate wetting and drying (AWD) 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	17.8cd	27.1fg	27.8	60.3
Jasmine 85	18.1d	27.1fg	24.4	55.2
OM7347	17.1bcd	25.1bcde	16.7	54.1
Loc Troi 5	16.6bcd	25.1bcde	17.5	53.8
ML202	16.6bc	23.8b	17.0	53.3
OM2517	21.5e	32.7i	22.7	52.0
GKG 35	14.7a	22.2a	20.0	50.5
ST 24	20.5e	30.6h	19.7	50.1
Loc Troi 1	17.4bcd	24.7bc	22.2	49.4
OM4218	18.1d	27.5g	16.4	49.3
OM6976	17.3bcd	26.3efg	21.7	48.1
Dai Thom 8	17.0bcd	25.1bcde	19.0	48.0
BTE 1	16.8bcd	24.6bc	18.7	46.2
DS 1	16.3b	24.4bc	23.1	45.7
OM4900	16.9bcd	26.4efg	18.2	45.7
GKG 29	17.4bcd	24.8bcd	22.5	44.7
OM18	17.8cd	26.7fg	18.0	44.6
GKG 9	17.0bcd	25.8cdef	16.4	42.9
OM576	16.6bc	25.1bcde	24.6	42.2
OM5451	17.6bcd	26.3defg	17.6	37.0

Note: Letters indicate groupings of a post-hoc Tukey test at $p < .05$. Values sharing the same letter are not signifcantly different.

significant and the slope is weak. In both cases, variation in methane emissions among varieties was largest in the range of 6000–7000 $kg\,ha^{-1}$ seasonal grain yield.

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 kilogram 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.

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

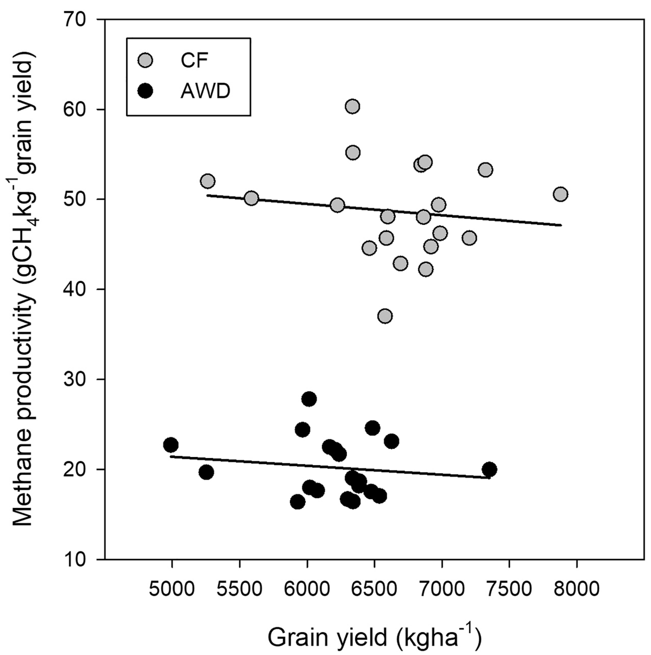

FIGURE 3 Relationship between seasonal grain yield and methane productivity for 20 lowland rice varieties grown under continuous flooding (CF) or alternate wetting and drying (AWD) for two consecutive winter seasons (Dec–Mar) in a field trial in the Vietnam Mekong Delta.

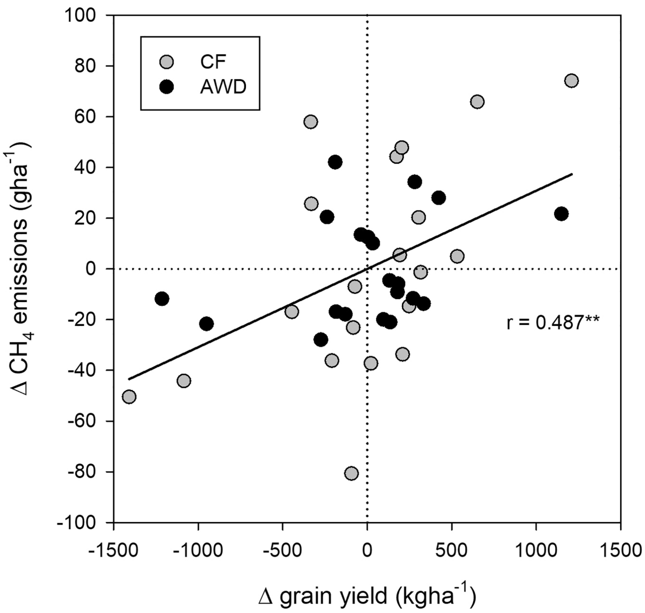

FIGURE 4 Seasonal varietal yield shown as differences to the varietal mean as related to seasonal varietal methane emissions shown as differences to the varietal mean for 20 lowland rice varieties grown under two irrigation managements (continuous flooding—CF and alternate wetting and drying—AWD). **Significant at $p < .01$.

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 kg ha^{-1}, particularly under CF where the highest methane productivity is 37 g kg^{-1} and the lowest 60 g kg^{-1}, constituting a reduction potential by genotype selection of about 40%.

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 ($p < .01$) for both irrigation treatments following the same function.

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 GHG) 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 & 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 (Singh et al., 1999; Wassmann et al., 1994), 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 (Bharali et al., 2017; Huang et al., 2018; Win et al., 2022).

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 t ha^{-1} independent of the irrigation management, indicating a relatively wide range of genotype × 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 (Figure 1), mean seasonal methane emissions were strongly reduced under AWD (Figure 1) and varietal differences in seasonal methane emissions under AWD were rather small (Figure 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 kg ha^{-1} (Figures 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 $p < .05$. 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 (Qin 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 Figure 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 4500 and 6500 kg ha^{-1} with seasonal methane emissions of up to 210 kg ha^{-1}. Although this yield level is about 1000 kg below the highest yields recorded in this study, methane emissions were about 30 kg ha^{-1} lower than the lowest emitting variety in this study which yielded on average a comparable 6800 kg ha^{-1}. For the varietal spectrum in the VMD, methane productivity was relatively stable of about 50 and 20 g kg^{-1} under CF and AWD, respectively (Figure 3). For reasons unknown, largest variations in methane productivity were observed in the seasonal grain yield range of 6000–7000 kg ha^{-1} (Figure 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 Qin 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 (Figure 4). If compared to differences in yield, a positive correlation exists between yield increase and methane emission increase (Figure 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 recognized 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, for example 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 CH_4 emissions of the VMD correspond to 24.6 Mt CO_2e which accounts for to 55.5% of the total CH_4 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

TABLE 2 Rice area of the MRD provinces and percentage of low/no suitability for implementation of AWD in three harvesting rice seasons.

Province	D–M Area (1000 ha)	D–M LS (%)	A–J Area (1000 ha)	A–J LS (%)	A–D Area (1000 ha)	A–D LS (%)	All seasons Area (1000 ha)	All seasons 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	1957	26.2	1154	37.9	1421	76.7	4532	45.0

Abbreviations: AWD, Alternate wetting and drying; A–D, August–December; A–J, April–July; D–M, December–March; LS, low or no suitability for AWD implementation.

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.

	Scenario 1: 25% reduction in CH_4 for the entire rice area of the VMD (1000 t CO_2e)				Scenario 2: 25% reduction in CH_4 in low/no suitability for AWD area of the VMD (1000 t 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	2655	1565	1927	6147	696	592	1477	2767

Note: 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.
Abbreviations: A–D, August–December; A–J, April–July; D–M, December–March.

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°C target of the Paris Agreement.

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 3 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.

Moreover, the data displayed in Tables 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, for example 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 $ 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 155 and 309 $, 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.

AUTHOR CONTRIBUTIONS

F. Asch: Conceptualization; funding acquisition; supervision; project administration; writing – review and editing; writing – original draft; visualization. **K. Johnson:** Conceptualization; methodology; data curation; formal analysis; funding acquisition; investigation; writing – review and editing. **T.B.T. Vo:** Conceptualization; methodology; data curation; formal analysis; investigation; funding acquisition; writing – review and editing. **B.O. Sander:** Conceptualization; methodology; supervision; resources; funding acquisition; writing – review and editing; validation. **V.N Duong:** Conceptualization; supervision; resources. **R. Wassmann:** Conceptualization; methodology; supervision; formal analysis; writing – review and editing; resources; validation.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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