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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

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ABSTRACT

Greenhouse gas (GHG) mitigation strategies are often constrained by rice farmers' preferences, therefore an assessment of mitigation strategies taking farmers' constraints into consideration, are important for their possible adoption. The field experiments were conducted for two continuous rice-growing seasons in northern Vietnam, to evaluate the effectiveness of drainage patterns on methane (CH_4) and nitrous oxide (N_2O) emissions under farmers' variable conditions. Two improved drainage practices (pre-planting plus midseason [PM] drainage and early-season plus midseason [EM] drainage) were compared with local practices of water management (midseason drainage [M] and conventional continuous flooding (control) [C]) with full residue [F] and reduced residue [R] (local practice of residue management) incorporation. The GHG mitigation potential of water regimes was tested in two water management systems (efficient field water management [EWM] system and inefficient field water management [IWM] system). In EWM system, EM resulted an average 14% and 55% reduction in CH_4 emissions compared to M with R and F respectively. The EM lowered the CH_4 emissions by 67% and 43% compared to C in the EWM and IWM respectively. The EM and PM resulted in higher N_2O emissions compared to M (25–36%) and C (42–43%) in both systems. The contribution of increased N_2O emissions with EM and PM to global warming potential (GWP) was negligible. EM reduced the GWP by 42% compared to C with F in the IWM system, and by 20–52%, 30–62% and 66% compared to M, PM and C respectively in the EWM system. Furthermore, greenhouse gas intensity (GHGI) reduced by 22–72% in the EWM than in IWM. This study demonstrates that efficient field water management system has a positive impact on over-all GHG mitigation potential of drainage practices in farmers' field conditions.

1. Introduction

Paddy fields are a major source of agricultural methane (CH_4) emissions, contributing about 20–40 Tg CH_4 $year^{-1}$ and thus accounting for nearly 20% of anthropogenic global CH_4 emissions (Yan et al., 2009). CH_4 production and emissions from paddy fields depend on the availability of organic carbon and anaerobic soil conditions (Sass et al., 1991). Emission of another major greenhouse gas (GHG), nitrous oxide (N_2O), from rice fields is associated with soil water and nitrogen status (Wang et al., 2011; Skinner et al., 2014), but globally rice production is not an important source of N_2O emissions due to often highly anaerobic paddy conditions, in which complete reduction of N_2O into N_2 occurs (Granli and Bøckman, 1994).

Rice farmers are often constrained in their options for sustainable management of rice straw (for animal feed, composting, biogas and biochar *etc.*) due to practical infeasibility, lack of incentives and expensive labor (Haider, 2013). In the Red River Delta, rice-cropping systems are based on an intensive double rice-crop rotation. So, farmers have very little flexibility to shift harvest and planting times for sustainable residue management. Ultimately, farmers burn rice residues in the open fields for fast cleaning and land preparation (Truc et al., 2012). Open burning of rice residues results in loss of major nutrients

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and emission of toxic gases such as carbon monoxide, hydrocarbons, volatile organic compounds and inhalable particles (Pathak and Wassmann, 2007; Romasanta et al., 2017). Residue burning is becoming increasingly restricted in Vietnam (Hai and Tuyet, 2010). Therefore, farmers have to dispose of rice straw by incorporating it into the soil due to the lack of alternative residue management options.

Incorporation of rice residues in paddy fields leads 50–60% increase in CH_4 emissions (Wang et al., 2012). The CH_4 emissions from crop residues are more concentrated in the early incorporation stage, due to readily available carbon (Watanabe et al., 1999). Therefore, it is becoming important to modify the farmers' conventional water management practices to reduce CH_4 emissions from added rice residues. Soil drainage in the early stage of residue incorporation has been found to lower the CH_4 emissions by 45–74% (Tariq et al., 2017). Wang et al. (2012) found 60% reduction in CH_4 emissions with midseason drainage from residue amended paddy fields in South China. Pandey et al. (2014) found 64% less global warming potential (GWP) with Alternate wetting and drying (AWD) from organic amended paddy fields in northern Vietnam. Triol-Padre et al. (2017) recorded a 21–38% reduction in CH_4 emissions with a 4% increase in rice grain yield with AWD compared to continuous flooding in the delta lowland of Central Vietnam. Despite the benefits of reduced GHG emissions and increased rice yield from improved water management practices, farmers often face practical and technical constraints in implementing these systems (Ly et al., 2013; Searchinger et al., 2014).

The mitigation and yield potential of improved water management practices has been quite extensively tested and studied under controlled conditions on research farms and in greenhouses. However, little is known about the actual performance of improved water management practices to mitigate GHG emissions in farmers' variable field conditions (Searchinger et al., 2014). The design and testing of improved water management practices on farmers' field conditions allow to identify the mitigation potential and adoption capacity of improved drainage practices in less efficiently controlled farmers' systems.

It is very important to consider the diversity and constraints of rice farmers' in residue and water management to test the efficiency and possible implementation of improved water management practices on farmers' fields. This study was conducted in the fields of different farm households with the following objectives: i) to assess the effectiveness of drainage practices at reducing the total GHGs (combined methane and nitrous oxide emissions) with residue incorporation, ii) to determine the mitigation potential of drainage practices under water management systems with an efficient and inefficient water control in farmers' fields.

2. Material and methods

2.1. Site description

The study site is in An Luong village, An Lam commune, Nam Sach district, Hai Duong province, 80 km east of Hanoi in northern Vietnam (21° 0.298′N, 106° 21.254′E) in the Red River Delta (Fig. S1). The typical cropping system in this area is spring rice followed by summer rice, and then winter fallow or onion/vegetables. The ministry of agriculture started the AWD project in An Luong village in 2013 with the aim of implementing AWD practices. The project area covers 15 ha of the village's 90 ha of paddy fields, and has an adequate infrastructure for efficient field water control. In the remaining paddy area, field water control is inefficient due to poorly developed field canals. The climate in the area is humid sub-tropical with annual precipitation of 2029 mm, and maximum rainfall occurring during the months of May, July and August (Fig. S2). The mean monthly temperature varies from 16 °C (February) to 30 °C (June–July) (Fig. S2). The soil in the area is generally classified as alluvial, with poor soil structure and low fertility.

2.2. Experimental design and field management

The two-rice cropping season field trials were conducted on 24 farm fields of households in two water management systems. Twelve fields were in the system with an efficient field water management [EWM], and twelve fields were in the system with an inefficient field water management [IWM]. In the EWM system, water drainage is easier and more applicable due to presence of proper infrastructure to fill and drain water in the fields and cooperate management. In the IWM system, water control is not as efficient due to the lack of a specific infrastructure and individual management by farmers. The fields usually remain saturated during the drainage period in the IWM system. In the winter season, farmers grow onion/vegetables in EWM system, and leave fields fallow in IWM system. The detail on field management in EWM and IWM systems is given in the Supplementary data.

Water and residue treatments were designed in line with the participatory approach (Vereijken, 1997; Le Bellec et al., 2012), bearing in mind the farmers' practices and constraints (Tariq, forthcoming). Four water treatments were applied: i) conventional continuous flooding (control) [C], ii) midseason drainage [M], iii) pre-planting plus midseason drainage [PM], and iv) early-season plus midseason drainage [EM]. The water treatments were replicated three times as one treatment replicate per household in both the EWM and IWM systems (Fig. 1a). Two residue treatments were applied: i) full residue incorporation [F] and ii) reduced residue incorporation [R] (farmers' practice of partial residue burning and incorporation). Residue treatments were applied on each main field plot of the household by dividing it into two subplots of 50 m^2, with residue treatments randomly distributed on subplots. The C water treatments only receive F residue treatments.

In the C water treatments, the plots were continuously flooded with water from mid-January to mid-September, and only drained for 10 days before harvesting (Fig. 1b). During flooding periods, water table was 3 to 6 cm and 7 to 10 cm above the ground surface in spring and summer season respectively. In the M water treatments, irrigation was stopped at the end of the tillering stage in both seasons. During spring season, irrigation was stopped at 48 days after transplanting (DAT) and re-flooded at 59 DAT. During the summer season, irrigation was stopped at 35 DAT and re-flooded at 45 DAT. In the PM water treatments, water was drained out from fields for five days before transplanting (*i.e.* during land preparation) in both seasons. In the pre-planting drainage, fields were not fully dried but saturated in spring season, and water table lowered to 2 cm below the ground surface in summer season. In the EM water treatments, fields were drained from 15 to 21 DAT in both seasons. In the spring season, water was drained out from the field, but in the summer season fields were allowed to drain by natural evapotranspiration. Both the PM and EM treatments follow the M treatment in both seasons. In M and EM treatments, water table goes below the ground surface up to 4–6 cm in spring and 8–10 cm in summer. In F residue treatments, all the residues left after removing the rice grains were incorporated into the soil. While in R residue treatments, the residues were incorporated according to farmers' practices in both seasons (Table S1). The residues were applied at the rate of 5.5 t ha^{-1} in F residue treatments in both EWM and IWM systems in both seasons. In EWM system, 4.0 t ha^{-1} residue was applied in R treatments in both seasons. In IWM system, residue was applied at the rate of 3.5 t ha^{-1} in spring season, and 4.0 t ha^{-1} in summer season. The rate of incorporated residues was estimated by taking the residue samples per m^2. The straw sampling and analysis is explained in the following section.

All plots were tilled twice with a rotavator and a 20-cm deep plough before transplanting. Twenty-day-old seedlings were transplanted with a spacing of 20 × 20 cm and with 3–4 seedlings per hill. Farmers applied the nutrients in the form of urea, single super phosphate, potassium chloride and NPK (10-5-10) fertilizers. The rate of fertilizer application is presented in Table 1. In the spring season, all P and 40%

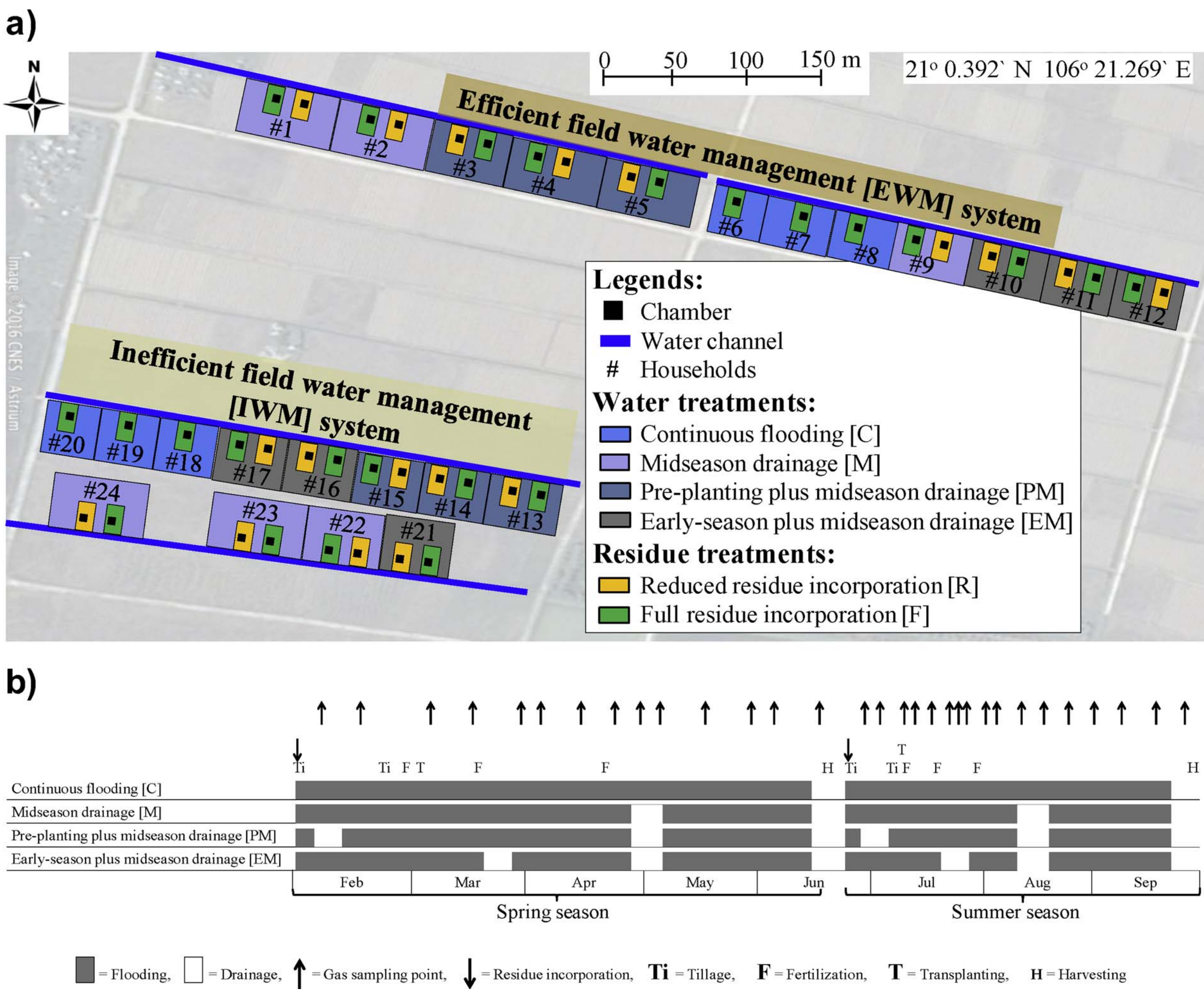

Fig. 1. Layout of treatments in the farmers' fields (a); timing of gas sampling, water regimes and crop management (b) in the spring and summer seasons.

Table 1
The properties of incorporated rice straw and amounts of mineral nutrients applied in efficient field water management [EWM] system and inefficient field water management [IWM] system in spring and summer rice seasons. Values represent the means of households in each system with standard deviations in brackets, n = 12. The upper-case letters reflect a significant difference ($p < 0.05$) between the two systems.

	Spring season		Summer season	
	EWM	IWM	EWM	IWM
Properties of rice straw				
Total C (g kg^{-1})	329.3 (40)^B	390.6 (47)^A	389.2 (4)	394.1 (8)
Total N (g kg^{-1})	9.5 (2)^A	6.8 (2)^B	7.8 (1)	8.2 (1)
C:N ratio	37 (14)^B	63 (22)^A	50 (5)	48 (6)
Dry matter contents (%)	32.5 (3)	30.2 (4)	29.8 (2)	29.7 (3)
Nutrient applied				
N (kg ha^{-1})	132 (26)	139 (24)	138 (16)	140 (16)
P (kg ha^{-1})	14 (11)	12 (10)	12 (6)	12 (8)
K (kg ha^{-1})	52 (12)	42 (14)	89 (19)	88 (19)

N were applied as a basal dose, 30% N and 50% K at 12 DAT, and the remaining 30% N and 50% K at 40 DAT. In the summer season, all P and K and 50% of N were applied at 4 DAT, and the remaining 50% N was applied in two doses at 14 and 25 DAT.

2.3. Soil and straw sampling and analysis

Soil samples were collected before the spring season. Three random samples were taken from the plot of each household at 0–20 cm depth with a soil core, thoroughly mixed and one composite sample was prepared for each household. Soil samples were analyzed for pH (1 M KCL), bulk density, organic carbon, total N, total P, total K and soil texture (sand, silt and clay) at the Institute for Agricultural Environment in Hanoi, Vietnam. Soil pH was analyzed with a pH meter (Hanna Hi 8424, Italy), organic C was determined with the Walkley–Black method (Walkley and Black, 1934), and total N was analyzed using the Kjeldahl method. Total P and K were determined after digestion with concentrated sulphuric acid and nitric acid (1:1; v:v). Soil texture analysis was performed using the hydrometer method. Soil chemical and physical properties are listed in Table 2.

Straw samples were collected before the spring and summer season.

Table 2
Properties of soil in efficient field water management [EWM] system and inefficient field water management [IWM] system. Data represent the means of households in each system with standard deviations in brackets, n = 12. The upper-case letters reflect a significant difference ($p < 0.05$) between the two systems.

	EWM	IWM
$pH_{(KCL)}$	5.14 (0.17)	5.16 (0.17)
Bulk density (g cm^{-3})	1.20 (0.06)	1.16 (0.05)
Organic C (g kg^{-1})	9.11 (1.83)^B	13.0 (0.85)^A
Total N (g kg^{-1})	0.69 (0.37)^B	1.06 (0.37)^A
Total P (g kg^{-1})	0.80 (0.29)^A	0.47 (0.06)^B
Total K (g kg^{-1})	4.55 (0.67)^B	7.84 (0.70)^A
Sand (%)	51.03 (0.60)^A	32.95 (2.28)^B
Silt (%)	38.29 (0.87^B	45.19 (1.13)^A
Clay (%)	10.69 (1.06)^B	21.87 (2.25)^A

The straw samples were dried naturally in the sun for two weeks and then put in the oven at 60 °C for 48 h to constant weight. The total carbon and nitrogen contents in the straw samples were analyzed using an elemental micro-analyzer (vario MICRO cube, Elementar, Germany). The properties of the straw incorporated in the spring and summer seasons are shown in Table 1.

2.4. Gas sampling and analysis

The CH_4 and N_2O sampling campaign was carried out from 6 February 2016 to 27 September 2016 for a total of 31 sampling dates, divided into the spring season (14 samples from 6 February to 14 June) and the summer season (17 samples from 29 June to 27 September). Sampling frequency was intensified in line with the water treatments (drainage periods, flooding) and fertilization period, when the high fluxes were expected (Fig. 1b). All gas samples were taken between 8.30am and 11.30am. Gas samples were collected using the vented, static closed chamber method following the recommendations of Rochette and Eriksen-Hamel (2008). The stainless-steel base chambers (40 cm long, 36 cm wide and 35 cm high) with a groove on the top were inserted into the soil up to a depth of 10 cm. Two holes were provided in the opposite walls of the base chamber to maintain water equilibrium. The holes were sealed with a rubber stopper one hour before gas sampling. Bamboo bridges were installed to access the chambers without disturbance. During the gas sampling, rectangular Plexiglas top chambers (90 cm high) were fitted on the groove of the base chamber by means of a water seal. The top chambers were equipped with a gas sampling tube connected with a three-way stopcock, two small battery-driven fans to ensure sufficient mixing of the air inside the chamber, and a digital thermometer. A pressure vent valve (4 m long and 1.5 mm internal diameter) was installed in the top chamber according to Lindau et al. (1991), to maintain gas pressure equilibrium during sampling. The gas sampling tubes were flushed five to seven times with chamber air before the gas samples were collected. The gas samples were collected with 50 ml propylene syringes at 0, 10, 20 and 30 min after chamber closure. Immediately after collection, the gas samples were injected into 3-ml evacuated vials closed with butyl rubber septa (12.5 mm diameter, Exetainer Labco Ltd, UK). After gas sampling, the vials were shipped immediately to the Department of Plant and Environmental Sciences at the University of Copenhagen in Denmark for analysis.

The CH_4 and N_2O concentrations in the collected samples were measured simultaneously by a gas chromatograph (Bruker 450-GC 2011) equipped with a flame ionization detector and electron capture detector. CH_4 was determined by a flame ionization detector at 300 °C, and N_2O was determined by electron capture detector at 350 °C. Helium (99.99%) and argon (99.99%) were used as carrier gases for CH_4 and N_2O respectively at a flow rate of 60 ml min^{-1}. The oven temperature was set at 50 °C. The fluxes of CH_4 and N_2O were calculated according to Smith and Conen (2004) for linear or nonlinear development of headspace concentration. The cumulative emissions of CH_4 and N_2O for each season were sequentially measured by trapezoid formula from the emissions between each two-adjacent interval (Ly et al., 2015). The global warming potential (GWP) was calculated over the 100-year time scale by using IPCC GWP factors 28 and 265 to convert CH_4 and N_2O into CO_2 equivalents without the inclusion of climate-carbon feedback (Myhre et al., 2013). Greenhouse gas intensity (GHGI) is GWP relative to rice yield and this was also calculated by dividing GWP by rice grain yield. The uncalibrated N_2O emission factor (EF) was estimated as a percentage amount of N emitted as N_2O-N per unit of N applied by farmers without subtracting the background (control) N_2O-N emission (Zou et al., 2005). There was no treatment with zero fertilizer application, since experiments were conducted on farmers' fields.

2.5. Additional measurements

Rice grain yields were calculated at the end of each season by harvesting and manually threshing three 1-m^2 areas from each treatment. To determine the dry matter contents of rice grains, 200 g of rice grains were oven-dried at 80 °C to constant weight.

2.6. Statistical analysis

The cumulative fluxes of CH_4 and N_2O emissions, GWP, rice grain yield and GHGI were determined by a linear mixed effect model with random effects of households using the R software package (R Version 3.3.0) for both spring and summer separately. The linear mixed model consisted of the fixed effect of the water management systems (EWM and IWM), water treatments (PM, EM, M and C), and straw treatments (F and R). The statistical models were validated by residual and normal quantile plots. All responses except CH_4 in the spring season were analyzed on their natural scale, and CH_4 in the spring season was square-root transformed to achieve variance homogeneity. To avoid large variability in observations, one-way ANOVA was also performed to test the significance of water treatments within each residue treatment. The treatments mean comparison was considered significant at $p < 0.05$ level using the Tukey-Kramer test.

3. Results

3.1. Methane emissions

The CH_4 fluxes were higher in the summer than the spring season (Fig. 2). In the spring season, CH_4 fluxes reached their maximum in the middle of the season. While, in the summer season, higher CH_4 fluxes were observed early in the season. The higher CH_4 fluxes were observed in IWM system compared to EWM system under C treatment in the spring season, however there was no difference in summer season. The highest CH_4 fluxes were observed in the F compared to the R under C, M and PM treatments (Fig. 2a–c). In the EM, the R and F showed similar CH_4 fluxes (Fig. 2d). The CH_4 fluxes were reduced following the mid-season drainage in M, PM and EM treatments and then increased after the fields were re-flooded. The pre-planting drainage in PM showed no effect on CH_4 fluxes under either water management system in either season. The early-season drainage in EM lowered the CH_4 fluxes from the F under both water management systems in both seasons.

Total accumulated CH_4 emissions were significantly ($p < 0.05$) lower in the EWM system than in the IWM system under C treatment in spring season (Table 3). Significantly ($p < 0.05$) higher CH_4 emissions were observed in the IWM system compared to the EWM system under EM treatment in both seasons. The EM significantly ($p < 0.05$) reduced CH_4 emissions compared to the M, PM and C treatments with F treatment under both water management systems in both seasons. While, with R treatment, EM significantly ($p < 0.05$) reduced CH_4 emissions only in the EWM system in the spring season. The F resulted in significantly ($p < 0.05$) higher CH_4 emissions than R under PM in both seasons, and under M in the summer season.

3.2. Nitrous oxide emissions

Higher peaks of N_2O fluxes were observed in the spring than in the summer season (Fig. 3). The highest peaks of N_2O fluxes generally coincided with fertilization and drainage events. The initial high peaks (5–10 mg N_2O m^{-2} day^{-1}) in the C, M and PM treatments corresponded to the fertilization in both seasons (Fig. 3a–c). The initial high peaks in the EM corresponded to early-season drainage in both seasons (Fig. 3d). The following high N_2O peaks in the C, PM and EM treatments occurred in connection with the fertilization in both seasons. In M water regime second high N_2O peak was observed during midseason drainage in the summer season (Fig. 3b). The exceptionally high peaks

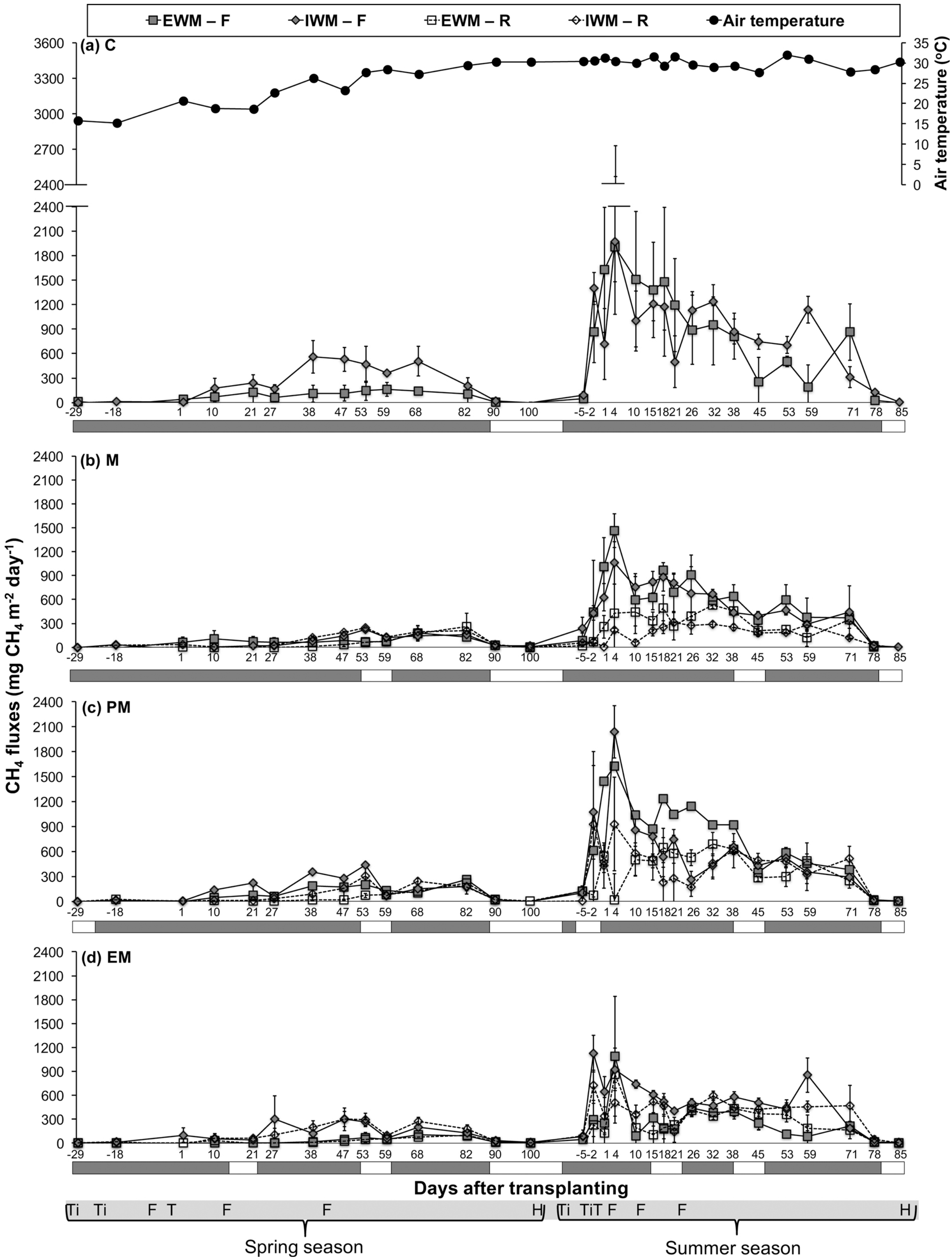

Fig. 2. Seasonal variation in CH_4 fluxes (mg CH_4 m^{-2} day^{-1}) over two rice seasons as a function of the efficient field water management [EWM] system and inefficient field water management [IWM] system with four water treatments; continuous flooding [C], midseason drainage [M], pre-planting plus midseason drainage [PM], and early-season plus midseason drainage [EM], and two residue amendments; full residue incorporation [F] and reduced residue incorporation [R]. Values represent the mean of three replicates/households ± standard error. Water regime indicated below each figure: grey represents flooded and white represents drained periods. The abbreviations below the figure represent the field management events: Ti (tillage), T (transplanting), F (fertilization) and H (harvesting).

Table 3

Cumulative CH_4 and N_2O emissions, and N_2O emission factor (EF) in spring and summer rice seasons under efficient field water management [EWM] system and inefficient field water management [IWM] system with four water treatments; continuous flooding [C], midseason drainage [M], pre-planting plus midseason drainage [PM], and early-season plus midseason drainage [EM], and two residue amendments; full residue incorporation [F] and reduced residue incorporation [R]. Values represent the mean of three replicates/households (± standard error). The upper-case letters reflect a significant difference ($p < 0.05$) between residue amendments collectively in both systems within each water regimes; lower case letters indicate a significant difference ($p < 0.05$) between water regimes in each residue amendment separately.

		Spring season			Summer season		
		CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})	N_2O-EF (% N input)	CH_4 (kg ha^{-1})	N_2O (kg ha^{-1})	N_2O-EF (% N input)
EWM-R	M	90.7 (±40)$^{a\ BC}$	1.3 (±0.4)^{A}	1.5 (±0.4)$^{b\ A}$	252.3 (±69)^{BC}	0.5 (±0.4)	0.6 (±0.5)^{AB}
	PM	59.1 (±13)$^{c\ AB}$	1.7 (±0.7)	2.8 (±1.3)$^{a\ A}$	328.9 (±69)^{B}	0.5 (±0.4)	0.7 (±0.4)
	EM	34.6 (±5)$^{b\ B}$	2.0 (±0.4)^{A}	2.3 (±0.5)$^{a\ A}$	236.6 (±36)^{B}	0.4 (±0.1)	0.5 (±0.1)
EWM-F	M	92.1 (±54)$^{ab\ C}$	1.2 (±0.3)^{A}	1.7 (±0.5)^{A}	486.5 (±131)$^{b\ AB}$	0.1 (±0.0)	0.1 (±0.0)$^{b\ B}$
	PM	107.2 (±30)$^{ab\ B}$	1.8 (±0.3)	2.4 (±0.2)^{AB}	627.4 (±96)$^{ab\ A}$	0.7 (±0.2)	0.8 (±0.1)^{a}
	EM	36.1 (±16)$^{b\ B}$	2.0 (±0.4)^{A}	2.3 (±0.4)^{A}	222.6 (±64)$^{c\ B}$	0.6 (±0.2)	0.7 (±0.2)^{a}
	C	129.6 (±82)$^{a\ B}$	1.1 (±0.6)^{A}	1.5 (±0.7)^{A}	698.5 (±310)$^{a\ A}$	0.3 (±0.1)	0.3 (±0.2)^{ab}
IWM-R	M	108.6 (±12)^{A}	0.4 (±0.3)^{B}	0.4 (±0.3)$^{b\ B}$	148.4 (±20)$^{b\ C}$	0.8 (±0.6)	0.9 (±0.6)^{A}
	PM	98.4 (±7)^{B}	1.3 (±0.1)	1.1 (±0.1)$^{ab\ C}$	379.5 (±9)$^{a\ B}$	0.7 (±0.3)	0.8 (±0.3)
	EM	123.9 (±27)^{A}	1.1 (±0.2)^{B}	1.4 (±0.3)$^{a\ AB}$	355.8 (±60)$^{a\ A}$	0.5 (±0.2)	0.6 (±0.3)
IWM-F	M	88.4 (±8)$^{b\ AB}$	0.7 (±0.2)^{B}	0.9 (±0.3)^{AB}	447.5 (±0.88)$^{ab\ A}$	0.7 (±0.4)	0.7 (±0.4)^{AB}
	PM	154.3 (±48)$^{ab\ A}$	1.4 (±0.5)	1.4 (±0.6)^{BC}	472.8 (±126)$^{ab\ AB}$	0.5 (±0.4)	0.5 (±0.4)
	EM	134.9 (±54)$^{b\ A}$	0.7 (±0.3)^{B}	0.8 (±0.4)^{B}	448.1 (±36)$^{b\ A}$	0.7 (±0.2)	0.9 (±0.2)
	C	273.9 (±63)$^{a\ A}$	0.6 (±0.2)^{B}	0.8 (±0.4)^{B}	749.1 (±89)$^{a\ A}$	0.4 (±0.1)	0.5 (±0.1)

of N_2O at 21, 27 and 47 DAT in spring season were caused by one very high N_2O flux in one of the three replicates. The N_2O fluxes were not consistent due to variability in fertilization between households (Table 1).

Significantly ($p < 0.05$) higher N_2O emissions were observed in the EWM system as compared to the IWM system only in the spring season (Table 3). The N_2O emissions were not significantly ($p < 0.05$) different between treatments in summer season. The proportion of applied N emitted as N_2O-N was significantly ($p < 0.05$) higher in the EWM (1.5% to 2.8% of N applied) system compared to the IWM (0.4% to 1.4% of N applied) system in spring season (Table 3). In the summer season, N_2O-EF was not significantly ($p < 0.05$) different between the water and residue treatments, and EF values fall below the 1%. The PM and EM treatments resulted in significantly ($p < 0.05$) higher N_2O emission factor compared to M with R treatment under both systems in spring season, and with F treatment under EWM system in summer season.

3.3. Global warming potential (GWP)

GWP was calculated for CH_4 and N_2O emissions in both seasons (Table 4). GWP was significantly lower ($p < 0.05$) in the EWM system as compared IWM system under EM treatment in both seasons. The EM treatment significantly ($p < 0.05$) lowered the GWP compared to the C, M and PM treatments with F residues in the EWM system. The C treatment significantly ($p < 0.05$) increased the GWP compared to M, PM and EM under both systems in both seasons. The F treatment resulted in significantly ($p < 0.05$) higher GWP compared to R in M and PM, but showed non-significant ($p < 0.05$) difference in EM under both systems in both seasons.

3.4. Rice grain yield and greenhouse gas intensity (GHGI)

The farmers' rice grain yield was higher in the spring season compared to the summer season (Table 4). A significantly ($p < 0.05$) higher grain yield was observed in EWM system compared to the IWM system in both seasons.

Greenhouse gas intensity (GHGI), *i.e.* yield-scaled GWP was higher in the summer than in the spring season (Table 4). A significantly ($p < 0.05$) higher GHGI was observed in all water and residue treatments under IWM system compared to the EWM system in both seasons, with exception of M with R in summer season. The EM significantly ($p < 0.05$) lowered the GHGI compared to C with F under both water management systems in both seasons.

3.5. Soil and straw characteristics

The IWM system was slightly low lying, and therefore had more of the fine particulate sediments from the floodplain (Table 2). This also explained why total C, N and K was higher in the IWM system than in the EWM system. Total P contents was higher in the soils under EWM system than IWM system. This is attributed to high P fertilization and retention due to three crops rotation (spring rice-summer rice-winter vegetable) in EWM system than two crops rotation (spring rice-summer

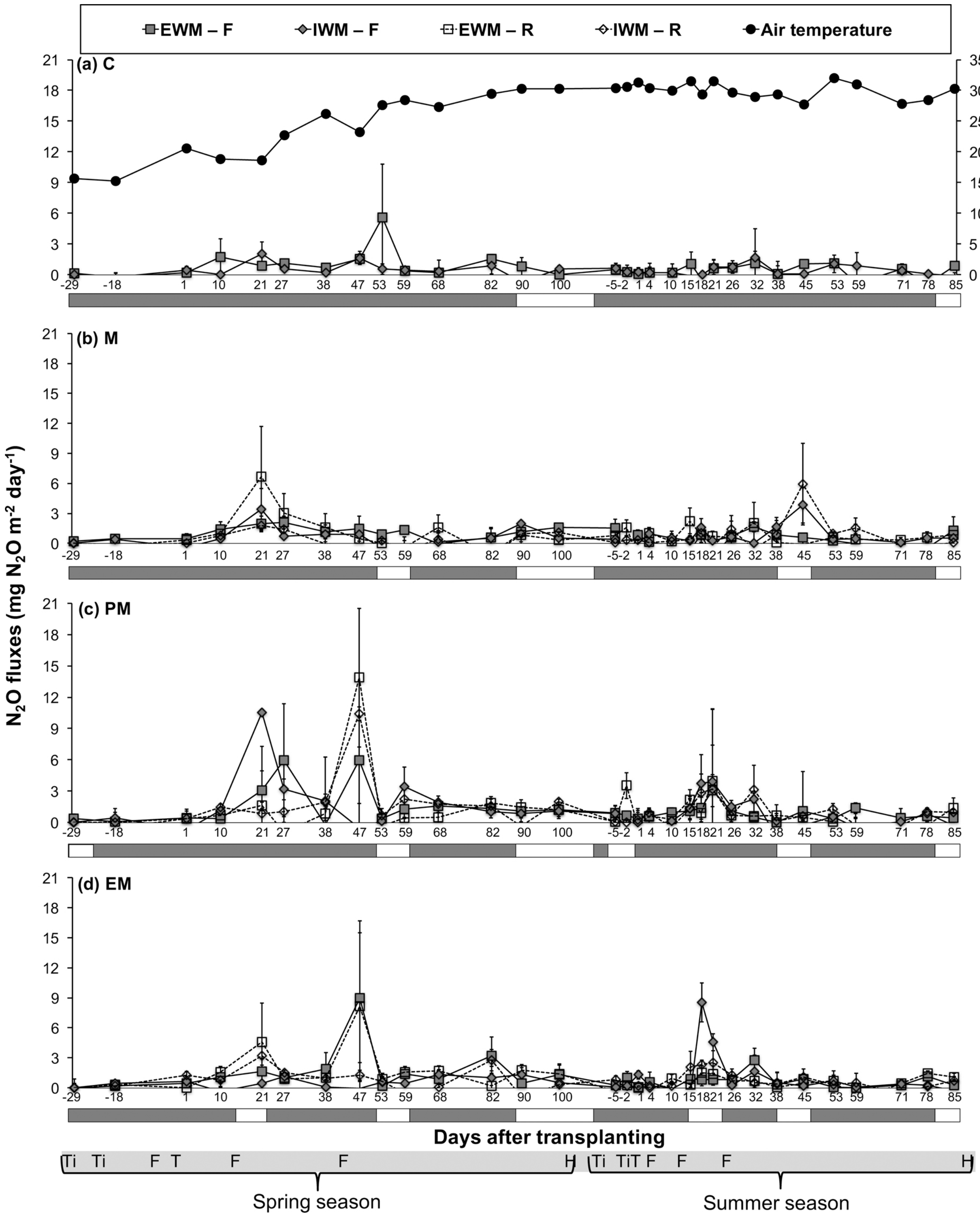

Fig. 3. Seasonal variation in N_2O fluxes (mg N_2O m^{-2} day^{-1}) over two rice seasons as a function of the efficient field water management [EWM] system and inefficient field water management [IWM] system with four water treatments; continuous flooding [C], midseason drainage [M], pre-planting plus midseason drainage [PM], and early-season plus midseason drainage [EM], and two residue amendments; full residue incorporation [F] and reduced residue incorporation [R]. Values represent the mean of three replicates/households ± standard error. Water regime is indicated below each figure: grey represents flooded and white represents drained periods. The abbreviations below the figure represent the field management events: Ti (tillage), T (transplanting), F (fertilization) and H (harvesting).

rice-winter fallow) IWM system.

Carbon contents and C:N ratio of incorporated rice straw were significantly ($p < 0.05$) higher under IWM system than EWM system in spring season (Table 1). The lower carbon contents of spring incorporated residues in the EWM system was because of more decomposition of rice residues lying on onion/vegetable bridges than of the standing residues in fallow fields. The straw incorporated in the summer season showed no significant ($p < 0.05$) differences in C and N content between two systems.

Table 4
Rice grain yield, global warming potential (GWP) and greenhouse gas intensity (GHGI) in spring and summer rice seasons under efficient field water management [EWM] system and inefficient field water management [IWM] system with four water treatments; continuous flooding [C], midseason drainage [M], pre-planting plus midseason drainage [PM], and early-season plus midseason drainage [EM], and two residue amendments; full residue incorporation [F] and reduced residue incorporation [R]. Values represent the mean of three replicates/households (± standard error). The upper-case letters reflect a significant difference ($p < 0.05$) between residue amendments collectively in both systems within each water regimes; lower case letters indicate a significant difference ($p < 0.05$) between water regimes in each residue amendment separately.

		Spring season			Summer season		
		Rice yield (tonnes ha^{-1})	GWP (CH_4+N_2O) (kg CO_2-eq ha^{-1})	GHGI (kg CO_2-eq kg^{-1} yield)	Rice yield (tonnes ha^{-1})	GWP (CH_4+N_2O) (kg CO_2-eq ha^{-1})	GHGI (kg CO_2-eq kg^{-1} yield)
EWM-R	M	5.35 (±0.37)^{A}	2954 (±1010)$^{a\ A}$	0.53 (±0.12)^{a}	5.47 (±0.08)^{A}	5286 (±709)^{BC}	1.31 (±0.34)^{BC}
	PM	5.18 (±0.27)	2097 (±219)$^{ab\ C}$	0.41 (±0.04)$^{a\ C}$	4.23 (±0.55)^{B}	9354 (±1847)^{B}	2.20 (±0.31)
	EM	5.54 (±0.03)^{AB}	1499 (±45)$^{b\ B}$	0.27 (±0.01)$^{b\ B}$	4.93 (±0.40)^{A}	6733 (±1049)^{B}	1.36 (±0.19)^{B}
EWM-F	M	5.56 (±0.31)^{A}	2895 (±1458)$^{ab\ A}$	0.50 (±0.23)^{ab}	4.67 (±0.06)^{AB}	13648 (±3658)$^{ab\ AB}$	2.93 (±0.80)$^{b\ AB}$
	PM	5.48 (±0.78)	3487 (±796)$^{ab\ B}$	0.69 (±0.23)$^{ab\ B}$	5.14 (±0.31)^{A}	17761 (±2724)$^{ab\ A}$	3.45 (±0.47)^{ab}
	EM	5.94 (±0.18)^{A}	1532 (±450)$^{b\ B}$	0.26 (±0.08)$^{b\ B}$	4.82 (±0.46)^{AB}	6384 (±1747)$^{b\ B}$	1.33 (±0.36)$^{c\ B}$
	C	5.31 (±0.50)^{A}	4002 (±2071)$^{a\ B}$	0.78 (±0.33)$^{a\ B}$	4.99 (±0.31)^{A}	27317 (±7090)$^{a\ A}$	5.41 (±1.76)$^{a\ A}$
IWM-R	M	4.89 (±0.56)^{AB}	3146 (±270)^{A}	0.68 (±0.14)	3.82 (±0.24)^{C}	4365 (±445)$^{b\ C}$	1.15 (±0.14)^{C}
	PM	5.25 (±0.38)	3089 (±221)^{B}	0.59 (±0.04)^{B}	4.36 (±0.49)^{B}	10812 (±298)$^{a\ B}$	2.57 (±0.38)
	EM	4.20 (±0.04)^{C}	3761 (±748)^{A}	0.78 (±0.24)^{A}	4.18 (±0.01)^{BC}	10097 (±1704)$^{a\ A}$	2.42 (±0.41)^{A}
IWM-F	M	4.50 (±0.51)^{B}	2661 (±271)$^{b\ A}$	0.59 (±0.01)^{b}	3.98 (±0.12)^{BC}	12709 (±2459)$^{ab\ A}$	3.22 (±0.69)$^{ab\ A}$
	PM	5.32 (±0.19)	4694 (±1479)$^{ab\ A}$	0.87 (±0.25)$^{ab\ A}$	4.22 (±0.26)^{B}	13361 (±3434)$^{ab\ AB}$	3.41 (±1.09)^{ab}
	EM	4.47 (±0.34)^{BC}	3961 (±1446)$^{b\ A}$	0.85 (±0.25)$^{b\ A}$	3.98 (±0.25)^{C}	12738 (±976)$^{b\ A}$	3.24 (±0.36)$^{b\ A}$
	C	4.52 (±0.19)^{B}	7821 (±1701)$^{a\ A}$	1.70 (±0.32)$^{a\ A}$	3.61 (±0.12)^{B}	21077 (±2480)$^{a\ A}$	5.84 (±0.67)$^{a\ A}$

4. Discussion

4.1. Efficiency of drainage patterns to reduce methane emissions

The conventional practice based on continuous flooding of paddy fields is a significant source of CH_4 emissions. Modification of conventional water practices is essential in order to reduce the CH_4 emissions when rice residues are incorporated into the soil, otherwise there will be a risk of higher CH_4 emissions from rice fields. This two-seasons participatory study in farmers' fields in north of Vietnam provides evidence that drainage practices can have a significant effect on CH_4 mitigation from intensive rice production systems.

It is likely that the higher CH_4 emissions in the summer compared to the spring season were due to the higher summer temperature. The mean seasonal temperature was 24 °C and 30 °C in the spring and summer seasons respectively (Fig. S2). High temperatures in the summer season accelerate residue decompositions (Tang et al., 2014) and alter microbial activities (Dalal et al., 2008), which may be the driver for high CH_4 emissions. Furthermore, high air temperatures during the summer season increase the aerenchyma conductance (Kludze et al., 1993), resulting in high CH_4 transport from soil to atmosphere.

The early season peaks in CH_4 emissions during the summer season were due to the availability of readily available carbon from fresh straw. However, these peaks were absent in the spring season (Fig. 2). Winter degradation of rice straw and low temperatures are likely to have been responsible for the lack of early spring season CH_4 peaks. Yang and Chang (2001) reported a similar pattern of CH_4 emissions in two rice cropping seasons in Taiwan. Ly et al. (2013) also found similar peaks following the incorporation of residues from previous rice crops. In the present study, F residue treatment resulted in an increase CH_4 emissions of 45–52% and 24–47% under the M and PM treatments respectively, compared to R treatment. Romasanta et al. (2017) found 40–54% higher CH_4 emissions with complete residue incorporation than with partial incorporation (35 cm remaining stubbles, ca. 50% residue incorporation). Bossio et al. (1999) also reported significantly high CH_4 emissions with full residue incorporation compared to partial residue incorporation.

It was hypothesized that drainage early in the season has long-lasting seasonal CH_4 mitigation effects (Tariq et al., 2017). Soil aeration in the early stage of straw incorporation resulted in rapid oxidation of straw carbon, which results in less CH_4 emissions in the later growth stage (Tariq, forthcoming). Soil aeration leads to increased soil Eh (Zou et al., 2005), which suppressed the methanogenic activity and facilitate CH_4 oxidation by methanotrophs (Woese et al., 1978). In the present study of farmers' fields, EM treatment effectively lowered the CH_4 emissions than C, M and PM treatments under EWM system in both seasons (Table 3). However, the PM treatment showed no significant reduction in CH_4 emission than C and M treatments under both systems. The lower effectiveness of PM than EM in CH_4 emission reduction was primarily due to less effective soil drainage during the pre-planting compared to the early-season. Further, the differences in CH_4 emission reduction in the EM treatments between the EWM and IWM systems were mainly due to the good aeration of the soil in the EWM system compared to the IWM system, where soil was kept saturated during the drainage periods. In an earlier growth chamber pot experiment, EM drainage was found to have the potential to mitigate 75–90% of CH_4 emissions compared to M drainage (Tariq et al., 2017). Ly et al. (2015)

reported a 45–71% reduction in CH_4 emissions from rice straw amended paddy soils following early-season drainage in a similar pot experiment. Lu et al. (2000) reported 61% CH_4 reduction by AWD practices compared to continuous flooding in southeast China. It is important to note that the CH_4 mitigation potential of drainage practices is higher in the system where there is an adequate control of water compared to inefficient water control system in farmers' fields.

4.2. Nitrous oxide emission with different drainage patterns in farmers' fields

Increased N_2O emissions following N-fertilizer application is commonly reported due to easily available mineral N for microbial turnover (Das and Adhya, 2014). In the present study, high N_2O fluxes occurred following the fertilization (Fig. 3). This was probably due to the high availability of mineral N for nitrifying bacteria (Linquist et al., 2015). Cui et al. (2012) reported that N-fertilizer application in flooded rice fields results in increased N_2O fluxes, amounting to 73% of yearly emissions. The lack of N_2O fluxes after the first fertilization events in both seasons were probably associated with rapid plant uptake, as well as immobilization by microorganisms due to the high C:N ratio of rice straw (Das and Adhya, 2014). Comparatively low N_2O fluxes were observed in continuously flooded fields. Cai et al. (1997) reported very low N_2O fluxes during continuous waterlogged conditions and high fluxes just after the water table is lowered. The initial N_2O peaks in the EM showed a connection with early-season drainage in both seasons. The aeration of continuously flooded rice fields release the trapped N_2O in the soil solution and provide favorable conditions for N_2O production (Cai et al., 1997).

The total seasonal N_2O emissions was lower during the summer season (< 1 kg N_2O ha^{-1}) than spring season (between 1 and 2 kg N_2O ha^{-1}), which could be related to lower field water levels during the spring season. However, the sampling frequency was lower in the spring season as compared to summer season (Fig. 1b). At the same time spring season was longer than summer season. These both factors (sampling frequency and duration of season) likely contribute to the differences found in cumulative N_2O emissions of the two seasons. The significantly ($p < 0.05$) lower N_2O emissions in the IWM system than EWM system in the spring season could be due to the higher C:N ratio of added residue in the IWM (63) system than in the EWM (37) system (Table 1). Xia et al. (2014) reported that crop residues with a C:N ratio greater than 40 stimulate microbial N-immobilization. Furthermore, total N_2O emissions in this study were lowered as compared the other field studies (Xu et al., 2004; Zou et al., 2005). The sampling frequency in this study was probably not high enough to capture all N_2O peaks which often last for few hours or days only (de Klein and Harvey, 2015). Therefore, some N_2O peaks might have been missed while others might not last for as long as it is shown in Fig. 3. However, in this study, sampling frequency ($\sim$7–10 days) is in general agreement with common GHG sampling practices (Sander and Wassmann, 2014) and thus we consider our cumulative N_2O emission results as valid findings to report. The estimated N_2O emission factors were lower in the IWM system (< 1% of N applied) than in the EWM system (> 2% of N applied). This could be related to the high nitrogen losses through water run-off in the IWM system. Furthermore, a significantly lower yield in the IWM system than in the EWM system explained the excessive nutrient loss in the IWM system (Table 4). Nutrient loss through water run-off and evaporation was not measured during the study period.

4.3. Global warming potential (GWP)

GWP (kg CO_2 equivalent ha^{-1}) of CH_4 and N_2O emissions over the 100-year time scale were estimated in order to assess the integrated effect of water and residue treatments under different water management systems. The net CO_2 emissions and soil organic carbon changes were not considered in the present study since significant changes occur over a longer period than that of the field study. CH_4 contributions to GWP were significantly ($p < 0.05$) high compared to N_2O, with the share of CH_4 being more than 95% of total GWP. Linquist et al. (2015) and Peyron et al. (2016) also reported a significant reduction in GWP associated with a reduction in CH_4 emissions, with the contribution of N_2O being minimal in the flooded paddy field experiments.

The EM treatment resulted in a reduction of GWP by 52%, 62% and 66% compared to M, PM and C respectively in the EWM system. In the IWM system, EM resulted in a significant reduction (42%) in GWP compared to the C only. In an earlier pot study, there was a 72% reduction in GWP with EM compared to the M from residue amended soils (Tariq et al., 2017). In the present study, the EM significantly ($p < 0.05$) lowered the GWP compared to C, M and PM only under EWM system. The differences between the farmers' efficient and inefficient field water management systems, and the fully controlled pot-trial system underlined the importance of the actual, in-field water control system in reducing the overall GWP.

4.4. Rice grain yield and greenhouse gas intensity

The rice grain yield was not greatly affected by the treatments within the systems, but lower rice grain yields were observed in the IWM system than in the EWM system (Table 4). Wang et al. (2011) also found no significant differences in rice yield following different residue and nutrient amendments. The lower GHGI in the spring than summer season was related to very low CH_4 emissions in the spring season. The GHGI was significantly higher in the IWM system compared to the EWM system, which was attributed to the significantly higher CH_4 emissions and low rice yield in the IWM system in both seasons (Tables 3 and 4). Zhang et al. (2016) found that significant changes in GHGI between management practices were related to differences in rice yield. The higher rice yield in EWM than IWM system is more likely related to effective water management., which improve the nutrient and water use efficiency that consequently increase the yield. EM was the only water treatment that significantly lowered GHGI compared to C in the spring (50–64%) and summer (45–48%) seasons, with similar rice yields. This is attributed to reduction in CH_4 emissions and GWP under EM than C treatment. Linquist et al. (2015) reported a 45% reduction in GHGI following AWD practices early in the season, which is attributed to significantly lower CH_4 emissions and GWP. Feng et al. (2013) also found CH_4 emission to be a significant factor for GHGI, since all the organic amendments have similar impacts on N_2O emissions and rice yield. Li et al. (2006) and Liang et al. (2016) found that improved water management practices significantly lower the GHG emissions without compromise on farmers' rice yield.

This study clearly showed that significant differences in GHGI between the water management systems and in water treatments are mainly related to differences in CH_4 emissions and GWP reduction, while rice yield was same.

5. Conclusions

These two-season trials in farmers' fields with variability in farmers' practices, residue amendments and field water management systems is a good way of testing and comparing the efficiency of drainage practices on GWP of rice production. The potential of improved drainage practices to mitigate the total GHGs effect of CH_4 and N_2O emissions were tested with residue integration in water management systems with an efficient and inefficient field water management. The results identified that the fields' water management system and drainage patterns were major factors in reducing CH_4 emissions. The EWM system reduced CH_4 by 15–20% and GWP by 12–15% than the IWM system. The EM treatment showed the potential to mitigate CH_4 emissions compared to other water treatments. The efficiency of water management system to control the field water influenced the GHG mitigating potential of drainage practices. The CH_4 emission was reduced by 14–55% and 43–67% with EM compared to M and C. The PM showed no significant reduction in CH_4 emissions compared to C and M, since pre-planting drainage was not as efficient as early-season drainage due to the constraints with farmers' field operations under both water management systems. This study suggests that EWM system and EM is an effective for mitigating the overall GWP without yield loss.

For further studies, a long-term continuous farmer field experiment is proposed to identify the long-lasting mitigation potential of drainage practices and the net carbon balance of added rice residues and gaseous carbon emissions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2017.08.011.

References

Bossio, D.A., Horwath, W.R., Mutters, R.G., van Kessel, C., 1999. Methane pool and flux dynamics in a rice field following straw incorporation. Soil Biol. Biochem. 31, 1313–1322.
Cai, Z., Xing, G., Yan, X., Xu, H., Tsuruta, H., Yagi, K., Minami, K., 1997. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. Plant Soil 196, 7–14.
Cui, F., Yan, G., Zhou, Z., Zheng, X., Deng, J., 2012. Annual emissions of nitrous oxide and nitric oxide from a wheat–maize cropping system on a silt loam calcareous soil in the North China Plain. Soil Biol. Biochem. 48, 10–19.
Dalal, R.C., Allen, D.E., Livesley, S.J., Richards, G., 2008. Magnitude and biophysical regulators of methane emission and consumption in the Australian agricultural, forest, and submerged landscapes: a review. Plant Soil 309, 43–76.
Das, S., Adhya, T.K., 2014. Effect of combine application of organic manure and inorganic fertilizer on methane and nitrous oxide emissions from a tropical flooded soil planted to rice. Geoderma 213, 185–192.
de Klein, C.A.M., Harvey, M.J., 2015. Nitrous Oxide Chamber Methodology Guidelines-Version 1.1. Ministry for Primary Industries, Wellington, New Zealand, pp. 34–91.
Feng, J., Chen, C., Zhang, Y., Song, Z., Deng, A., Zheng, C., Zhang, W., 2013. Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: a meta-analysis. Agric. Ecosyst. Environ. 164, 220–228.
Granli, T., Bøckman, O.C., 1994. Nitrous oxide (N_2O) from agriculture. In: Borin, M., Sattin, M. (Eds.), Third Congress of the European Society for Agronomy, Proceedings. European Society Agronomy, Colmar, pp. 800–801.
Hai, H.T., Tuyet, N.T.A., 2010. Benefits of the 3R Approach for Agricultural Waste Management (AWM) in Vietnam. Institute for Global Environmental Strategies, Hayama, Japan.
Haider, M.Z., 2013. Determinants of rice residue burning in the field. J. Environ. Manage. 128, 15–21.
Kludze, H.K., DeLaune, R.D., Patrick, W.H., 1993. Aerenchyma formation and methane and oxygen exchange in rice. Soil Sci. Soc. Am. J. 57, 386–391.
Le Bellec, F., Rajaud, A., Ozier-Lafontaine, H., Bockstaller, C., Malezieux, E., 2012. Evidence for farmers' active involvement in co-designing citrus cropping systems using an improved participatory method. Agron. Sustain. Dev. 32, 703–714.
Li, C.S., Salas, W., DeAngelo, B., Rose, S., 2006. Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in china over the next twenty years. J. Environ. Qual. 35, 1554–1565.
Liang, K., Zhong, X., Huang, N., Lampayan, R.M., Pan, J., Tian, K., Liu, Y., 2016. Grain yield, water productivity and CH 4 emission of irrigated rice in response to water management in south China. Agric. Water Manage. 163, 319–331.
Lindau, C.W., Bollich, P.K., Delaune, R.D., Patrick, W.H., Law, V.J., 1991. Effect of urea fertilizer and environmental factors on CH4 emissions from a Louisiana, USA rice field. Plant Soil 136, 195–203.
Linquist, B.A., Anders, M.M., Adviento-Borbe, M.A.A., Chaney, R.L., Nalley, L.L., Da Rosa, E.F.F., Kessel, C., 2015. Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems. Glob. Change Biol. 21, 407–417.
Lu, W.F., Chen, W., Duan, B.W., Guo, W.M., Lu, Y., Lantin, R.S., Wassmann, R., Neue, H.U., 2000. Methane emissions and mitigation options in irrigated rice fields in southeast China. Nutr. Cycl. Agroecosyst. 58, 65–73.
Ly, P., Jensen, L.S., Bruun, T.B., de Neergaard, A., 2013. Methane (CH_4) and nitrous oxide (N_2O) emissions from the system of rice intensification (SRI) under a rain-fed lowland rice ecosystem in Cambodia. Nutr. Cycl. Agroecosyst. 97, 13–27.
Ly, P., Vu, Q.D., Jensen, L.S., Pandey, A., de Neergaard, A., 2015. Effects of rice straw: biochar and mineral fertiliser on methane (CH_4) and nitrous oxide (N_2O) emissions from rice (*Oryza sativa* L.) grown in a rain-fed lowland rice soil of Cambodia: a pot experiment. Paddy Water Environ. 13, 465–475.
Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G.T.T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York, USA, pp. 33–116.
Pandey, A., Vu, D.Q., Bui, T.P.L., Mai, T.L.A., Jensen, L.S., de Neergaard, A., 2014. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. Agric. Ecosyst. Environ. 196, 137–146.
Pathak, H., Wassmann, R., 2007. Introducing greenhouse gas mitigation as a development objective in rice-based agriculture: I. Generation of technical coefficients. Agric. Syst. 94, 807–825.
Peyron, M., Bertora, C., Pelissetti, S., Said-Pullicino, D., Celi, L., Miniotti, E., Romani, M., Sacco, D., 2016. Greenhouse gas emissions as affected by different water management practices in temperate rice paddies. Agric. Ecosyst. Environ. 232, 17–28.
Rochette, P., Eriksen-Hamel, N.S., 2008. Chamber measurements of soil nitrous oxide flux: are absolute values reliable? Soil Sci. Soc. Am. J. 72, 331–342.
Romasanta, R.R., Sander, B.O., Gaihre, Y.K., Alberto, M.C., Gummert, M., Quilty, J., Nguyen, V.H., Castalone, A.G., Balingbing, C., Sandro, J., Correa, T., Wassmann, R., 2017. How does burning of rice straw affect CH_4 and N_2O emissions? A comparative experiment of different on-field straw management practices. Agric. Ecosyst. Environ. 239, 143–153.
Sander, B.O., Wassmann, R., 2014. Common practices for manual greenhouse gas sampling in rice production: a literature study on sampling modalities of the closed chamber method. Greenh. Gas Meas. Manage. 4, 1–13.
Sass, R.L., Fisher, F.M., Harcombe, P.A., Turner, F.T., 1991. Mitigation of methane emission from rice fields: possible adverse effects of incorporated rice straw. Glob. Biogeochem. Cycles 5, 275–287.
Searchinger, T., Adhya, T.K., Linquist, B., Wassmann, R., Yan, X., 2014. In: Waite, R. (Ed.), Wetting and Drying: Reducing Greenhouse Gas Emissions and Saving Water from Rice Production. Working Paper. World Resources Institute, Washington DC, USA, pp. 1–28.
Skinner, C., Gattinger, A., Muller, A., Mäder, P., Flieβbach, A., Stolze, M., Ruser, R., Niggli, U., 2014. Greenhouse gas fluxes from agricultural soils under organic and non-organic management—a global meta-analysis. Sci. Total Environ. 468, 553–563.
Smith, K.A., Conen, F., 2004. Measurement of trace gases: I. Gas analysis, chamber methods, and related procedures. In: Smith, K.A., Cresser, M.S. (Eds.), Soil and Environmental Analysis: Modern Instrumental Techniques, third edition. Marcel Dekker, New York, pp. 450–456.
Tang, H.-M., Xiao, X.-P., Tang, W.-G., Wang, K., Sun, J.-M., Li, W.-Y., Yang, G.-L., 2014. Effects of winter cover crops straws incorporation on CH4 and N2O emission from double-cropping paddy fields in Southern China. PLoS One 9, 1–8.
Tariq, A., Jensen, L.S., de Tourdonnet, S., Sander, B.O., de Neergaard, A., 2017. Early drainage mitigates methane and nitrous oxide emissions from organically amended paddy soils. Geoderma 304, 49–58.
Triol-Padre, A., Dang, H.T., Nghia, H.T., 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 of different landscapes and water management practices. In: Nauditt, A., Ribbe, L. (Eds.), Land Use and Climate Change Interaction in Central Vietnam, Water Resources Development and Management. Springer Science + Business Media, Singapore, pp. 103–121.
Truc, N.T.T., Sumalde, Z.M., Espaldon, M.V.O., Pacardo, E.P., Rapera, C.L., Palis, F.G., 2012. Farmers' awareness and factors affecting adoption of rapid composting in Mekong Delta, Vietnam and Central Luzon, Philippines. J. Environ. Sci. Manage. 15, 59–73.
Vereijken, P., 1997. A methodical way of prototyping integrated and ecological arable farming systems (I/EAFS) in interaction with pilot farms. Dev. Crop Sci. 25, 293–308.
Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.
Wang, J., Jia, J., Xiong, Z., Khalil, M., Xing, G., 2011. Water regime–nitrogen fertilizer–straw incorporation interaction: field study on nitrous oxide emissions from a rice agroecosystem in Nanjing, China. Agric. Ecosyst. Environ. 141, 437–446.
Wang, J., Zhang, X., Xiong, Z., Khalil, M., Zhao, X., Xie, Y., Xing, G., 2012. Methane emissions from a rice agroecosystem in South China: effects of water regime, straw incorporation and nitrogen fertilizer. Nutr. Cycl. Agroecosyst. 93, 103–112.
Watanabe, A., Takeda, T., Kimura, M., 1999. Evaluation of origins of CH4 carbon emitted from rice paddies. J. Geophys. Res. 104, 23623–23629.

Woese, C.R., Magrum, L.J., Fox, G.E., 1978. Archaebacteria. J. Mol. Evol. 11, 245–252.
Xia, L., Wang, S., Yan, X., 2014. Effects of long-term straw incorporation on the net global warming potential and the net economic benefit in a rice–wheat cropping system in China. Agric. Ecosyst. Environ. 197, 118–127.
Xu, Y.C., Shen, Q.R., Li, M.L., Dittert, K., Sattelmacher, B., 2004. Effect of soil water status and mulching on N2O and CH4 emission from lowland rice field in China. Biol. Fert. Soils 39, 215–217.
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. Glob. Biogeochem. Cycles 23, 1–15.
Yang, S.S., Chang, H.L., 2001. Effect of green manure amendment and flooding on methane emission from paddy fields. Chemosphere-Glob. Change Sci. 3, 41–49.
Zhang, X., Xu, X., Liu, Y., Wang, J., Xiong, Z., 2016. Global warming potential and greenhouse gas intensity in rice agriculture driven by high yields and nitrogen use efficiency. Biogeosciences 13, 2701–2714.
Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. Glob. Biogeochem. Cycles 19, 1–9.