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Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh

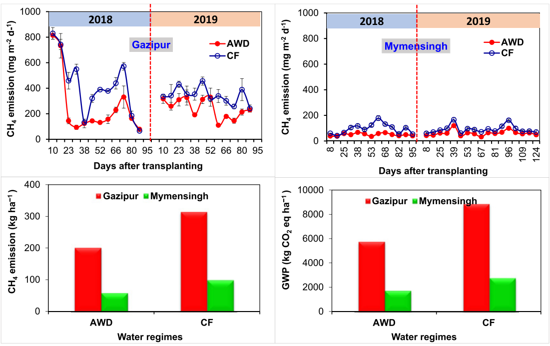
S.M. Mofijul Islam [a,*], Yam Kanta Gaihre [b], Md. Rafiqul Islam [a], Mahmuda Akter [a], Abdullah Al Mahmud [c], Upendra Singh [d], Bjoern Ole Sander [e]

[a] Soil Science Division, Bangladesh Rice Research Institute, Gazipur, Bangladesh
[b] International Fertilizer Development Center, Kathmandu, Nepal
[c] International Fertilizer Development Center, Dhaka, Bangladesh
[d] International Fertilizer Development Center, Muscle Shoals, AL, USA
[e] International Rice Research Institute, Los Baños, Philippines

HIGHLIGHTS

- Baseline emission factors for methane and nitrous oxide determined from rice fields in Bangladesh.
- Water regimes significantly reduced greenhouse gas (GHG) emissions from lowland rice cultivation.
- Alternate wetting and drying (AWD) scaling factor for methane ranged from 0.49 to 0.67.
- The AWD irrigation mitigated global warming potential (GWP) by 36% compared to farmers' practice of continuous flooding (CF).
- Increased nitrous oxide emissions due to AWD irrigation was off-set by reduced methane emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Alternate wetting and drying (AWD) irrigation in lowland rice cultivation increases water use efficiency and could reduce greenhouse gas (GHG) emissions compared to the farmers' practice of continuous flooding (CF). However, there is a dearth of studies on the impacts of water management on methane (CH_4) and nitrous oxide (N_2O) emissions in Bangladesh. Multi-location field experiments were conducted during the dry seasons of 2018 and 2019 to determine the baseline emissions of CH_4 and N_2O from rice fields and compare the emissions from AWD irrigation and CF. CH_4 and N_2O emissions were measured using the closed chamber technique and their concentrations were determined using a gas chromatograph. CH_4 and N_2O emissions varied across water management schemes and sites. AWD irrigation significantly ($p < 0.05$) reduced cumulative CH_4 emissions (37%, average across sites) without affecting grain yields compared to CF. The CH_4 emission factor for AWD was lower (1.39 kg ha^{-1} day^{-1}) compared to CF (2.21 kg ha^{-1} day^{-1}). Although AWD irrigation increased seasonal cumulative N_2O emissions by 46%, it did not offset reduced CH_4 emissions. AWD reduced the total global warming potential (GWP) by 36% compared to CF. Similarly, GHG intensity (GHGI) in AWD was 34% smaller compared to that in CF. Emissions varied across sites and the magnitudes of seasonal cumulative CH_4 and N_2O

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* Corresponding author.
E-mail addresses: mislambrri@gmail.com, mofijul.soil@brri.gov.bd (S.M.M. Islam), ygaihre@ifdc.org (Y.K. Gaihre), amahmud@ifdc.org (A. Al Mahmud), usingh@ifdc.org (U. Singh), b.sander@irri.org (B.O. Sander).

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emissions were higher at the Gazipur site compared to the Mymensingh site. AWD, which saves irrigation water without any yield penalty, could be considered a promising strategy to mitigate GHG emissions from rice fields in Bangladesh.

1. Introduction

The atmospheric concentration of greenhouse gases (GHGs) has been increasing substantially since the pre-industrial era. The concentration of carbon dioxide (CO_2) increased from a pre-industrial era of 280 ppm to 401 ppm, methane (CH_4) from 715 to 1800 ppb, and nitrous oxide (N_2O) from 270 to 328 ppb in 2015 (EPA, 2016). CH_4 and N_2O are two major GHGs with a global warming potential (GWP) of 28 and 265 times that of CO_2 in a 100-year time horizon, respectively (IPCC, 2014). On an average, atmospheric CH_4 concentration has been increasing at a rate of 0.5 to 1% per year and in 2010, it contributed 16% of the total global anthropogenic GHG emissions (IPCC, 2014). In the same year, N_2O contributed 6% to the total anthropogenic GHG emissions, playing a vital role in trapping heat in the atmosphere, and thus causing the destruction of the stratospheric ozone layer (IPCC, 2014).

Rice cultivation has been considered a significant anthropogenic source of CH_4 and N_2O emissions. Globally rice cultivation contributes 1.5% of total anthropogenic GHG emissions, while in Bangladesh it contributes 32% of agricultural GHG emissions (FAOSTAT, 2015). The irrigation scheme used, together with other crop management practices such as crop variety selection and fertilizer management, affects the magnitude of these emissions (Gaihre et al., 2011; Sun et al., 2013). Continuous flooding (CF) irrigation, which is a common practice in many rice-growing countries, produces a huge amount of CH_4. It makes the soil environment anaerobic, thereby decreasing the redox potential (<-150 mV). This results in the anaerobic degradation of complex organic substrates by methanogens and in the production of CH_4 (Wang et al., 1993; Minamikawa et al., 2006). CH_4 emissions from CF irrigation vary across soil types, locations (due to difference in organic carbon) (Gaihre et al., 2011; Sun et al., 2013), and rice-growing seasons (change of agro-climate) (Datta et al., 2013).

Contrastingly, as what previous studies have shown, alternate wetting and drying (AWD) irrigation could reduce GHG emissions by up to 40% (Hadi et al., 2010; Liu et al., 2010; Hou et al., 2012; Feng et al., 2013; Ku et al., 2017; Li et al., 2018). Intermittent irrigation greatly enhances the diffusion of atmospheric oxygen (O_2) into the soil, thus reducing the emission of CH_4 (Yang et al., 2012; Xu et al., 2015). Although AWD irrigation may slightly increase N_2O emission (Ku et al., 2017; Islam et al., 2018b) due to the increased nitrification of NH_4^+ during the dry episode and the subsequent denitrification of NO_3^- during re-wetting of dry soils, it still reduces total GHG emissions from rice fields mainly due to reduced CH_4 emissions. Decreasing the emission of CH_4 from the soil is the most effective way to mitigate the GWP in rice cultivation (Sander et al., 2014; Janz et al., 2019).

In Bangladesh, rice is cultivated in about 11.4 m ha of land in 2–3 seasons per year. Wet season (locally called Aman) rice is mainly cultivated as a rainfed crop from July/August to November/December. Boro (dry season, December/January–March/April) is the main rice crop (irrigated rice), which covers about 4.8 m ha of the total rice growing area (BBS, 2015). It is reported that Boro rice cultivation consumed huge amounts of irrigation water, particularly extracting groundwater. This has caused the groundwater table to have a declining trend due to excessive extraction (Lampayan et al., 2015) and has resulted in increased pumping costs to farmers. The importance of water saving irrigation techniques like AWD is increasingly being recognized across many rice-growing countries including in Bangladesh, as it has been known to reduce water use by up to 38% without any yield penalty (Lampayan et al., 2015).

Studies on the measurement of GHG emissions from rice fields in Bangladesh, particularly on the impacts of water management on CH_4 and N_2O emissions, are still limited though (Ali et al., 2013). Due to the lack of country-specific emission factors (or baseline emissions) from rice fields, a realistic mitigation target could not be set. Moreover, total emissions are being estimated using default emission factors set by the Intergovernmental Panel on Climate Change (IPCC), while preparing inventories of emissions. It is important to determine baseline data on GHG emissions from rice cultivation for the country across different agroecological zones and management practices. Field level measurements would also help to develop a baseline data for other countries with similar agroecology, soil type, and management practices to aid scientists and policy makers in developing mitigation strategies and planning for climate-smart agriculture. To gather the baseline data for Bangladesh, this study conducted field experiments in two locations—Gazipur and Mymensingh—during the dry season of 2018 and 2019 to determine CH_4 and N_2O emissions from rice fields, compare the emissions from AWD irrigation and the farmers' practice of CF irrigation, and quantify the potential trade-off relationship between CH_4 and N_2O emissions as affected by AWD irrigation.

2. Materials and methods

2.1. Experimental sites and weather conditions

The field experiments were conducted at the Bangladesh Rice Research Institute (BRRI) farm, Gazipur (latitude: 23°59′59″ N, longitude: 90°25′13″ E) and at Bhaluka, Mymensingh (latitude: 24°44′36″ N, longitude: 90°23′54″ E) during the 2018 and 2019 Boro (dry) season. In Gazipur, the soil of the experimental field was an Inceptisol (Vertic, Endoaquepts), while in Mymensingh it was also an Inceptisol (Aeric, Haplaquepts). Boro season rice cultivation starts from December/January to March/April and is completely dependent on irrigation. The mean air temperature during the Boro season is generally 15–30 °C and the total rainfall is ca. 227 mm. The daily mean air temperature and rainfall throughout the rice-growing season for both years are presented in Fig. 1. The physicochemical properties of the soil before the start of the experiments are shown in Table 1.

2.2. Experimental design and treatments

At each experimental site, plots for two irrigation regimes—AWD and CF—were arranged in a randomized complete block design with three replications. At the Mymensingh site, CF regime was followed as per farmers' practice. All other agronomic practices including nitrogen (N) fertilizer application were similar between the two treatments. N was applied at 78 and 90 kg ha^{-1} in Gazipur and Mymensingh, respectively. At the Gazipur site, each experimental plot was 4.8 m × 3.2 m while a larger plot (farmers' field, 8 m × 7 m) was used at the Mymensingh site.

2.3. Crop management

Two to three rice seedlings (40–45 days old) per hill were transplanted at 20 × 20 cm distance. Locally popular rice cultivars were selected for each site, i.e., BRRI dhan28 for Gazipur and BRRI

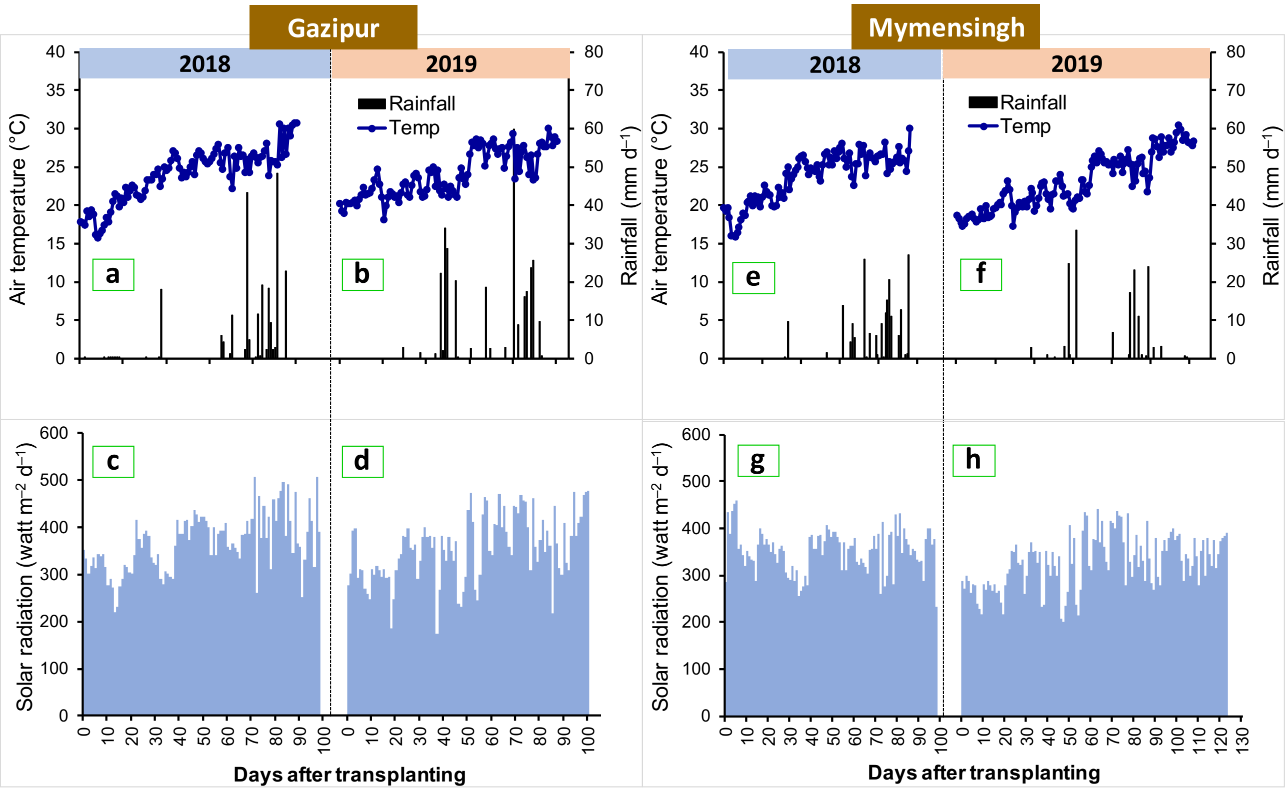

Fig. 1. Daily average rainfall, air temperature, and solar radiation during the experimental period in Boro season 2018 and 2019.

dhan29 for Mymensingh. The dominant cropping pattern in both sites is Boro rice-fallow-Aman rice. However, at the Gazipur site, mustard crop was grown before the Boro season rice in 2018 (after harvest of Aman season rice) and all residues were incorporated during land preparation. Major crop management practices including fertilizer management were adopted as per government recommendation. Details of crop management activities are provided in Table 2. Basal fertilizers, i.e., phosphorus (triple super phosphate) and potassium (muriate of potash) were applied during final land preparation in all plots at 25 and 20 kg P and 85 and 70 kg K ha^{-1} at the Gazipur and Mymensingh sites, respectively. Sulfur (S) and zinc (Zn) were applied to all plots as basal at the rate of 15 and 10 kg S as gypsum and 3 and 2 kg Zn ha^{-1} as zinc sulphate at the Gazipur and Mymensingh sites, respectively. For N, prilled urea was applied as broadcast in three equal splits at 7–10 days after transplanting (DAT) at maximum tillering and panicle initiation stages.

Grain and straw yield were recorded at final harvest from a 5 m^2 in each plot. The grain yield was calculated at 14% moisture content, while straw yield was estimated based on oven dry basis.

2.4. Irrigation management

All plots under the CF irrigation regime were continuously flooded until two weeks before harvesting (Fig. 2e–h), while plots under AWD were irrigated following the principle of 'safe AWD' (Lampayan et al., 2015). AWD plots were irrigated when water level drops 12-15 cm below soil surface, while CF plots were irrigated regularly as and when needed (12–15 times). To monitor floodwater depth in the AWD plots, two perforated PVC pipes were inserted (15 cm depth) in each plot at 10 DAT. Floodwater depth inside the PVC pipes was monitored every day and plots were irrigated

Table 1
Physicochemical properties of the soil before the start of the experiments.

Soil properties	Gazipur	Mymensingh	Method of extraction
pH-H_2O	6.13	6.03	–
Organic carbon (%)	1.31	1.24	Wet oxidation
Total N (%)	0.16	0.13	Kjeldahl
Available P (mg kg^{-1})	12.65	10.87	0.5 M $NaHCO_3$ extracted
Available K (cmol$_c$ kg^{-1})	0.12	0.15	Neutral 1.0 N NH_4OAc extraction
Available S (mg kg^{-1})	9.31	7.65	$Ca(H_2PO_4)_2$ extraction
Available Fe (mg kg^{-1})	565.5	542.0	DTPA extraction
Available Mn (mg kg^{-1})	69.4	123.0	DTPA extraction
Available Zn (mg kg^{-1})	14.3	3.95	DTPA extraction
Particle size (%)			–
Sand	29.96	28.64	
Silt	40.10	51.07	
Clay	29.94	20.30	

Table 2
Dates of crop management practices in Gazipur and Mymensingh site.

Management practices	Gazipur		Mymensingh	
	Boro 2018	Boro 2019	Boro 2018	Boro 2019
Basal fertilization	24-01-2018	10-01-2019	22-01-2018	31-12-2018
Variety	BRRI dhan28	BRRI dhan28	BRRI dhan28	BRRI dhan29
Growth duration (day)	135–140	135–140	135–140	160–165
Seedling age (day)	40	41	40	45
Transplanting	25-01-2018	11-01-2019	23-01-2018	01-01-2019
First topdressing	01-02-2018	19-01-2019	30-01-2018	08-01-2019
Second topdressing	01-03-2018	13-02-2019	22-02-2018	08-02-2019
Third topdressing	20-03-2018	06-03-2019	16-03-2018	10-03-2019
Harvest	30-04-2018	15-04-2019	28-04-2018	01-05-2029

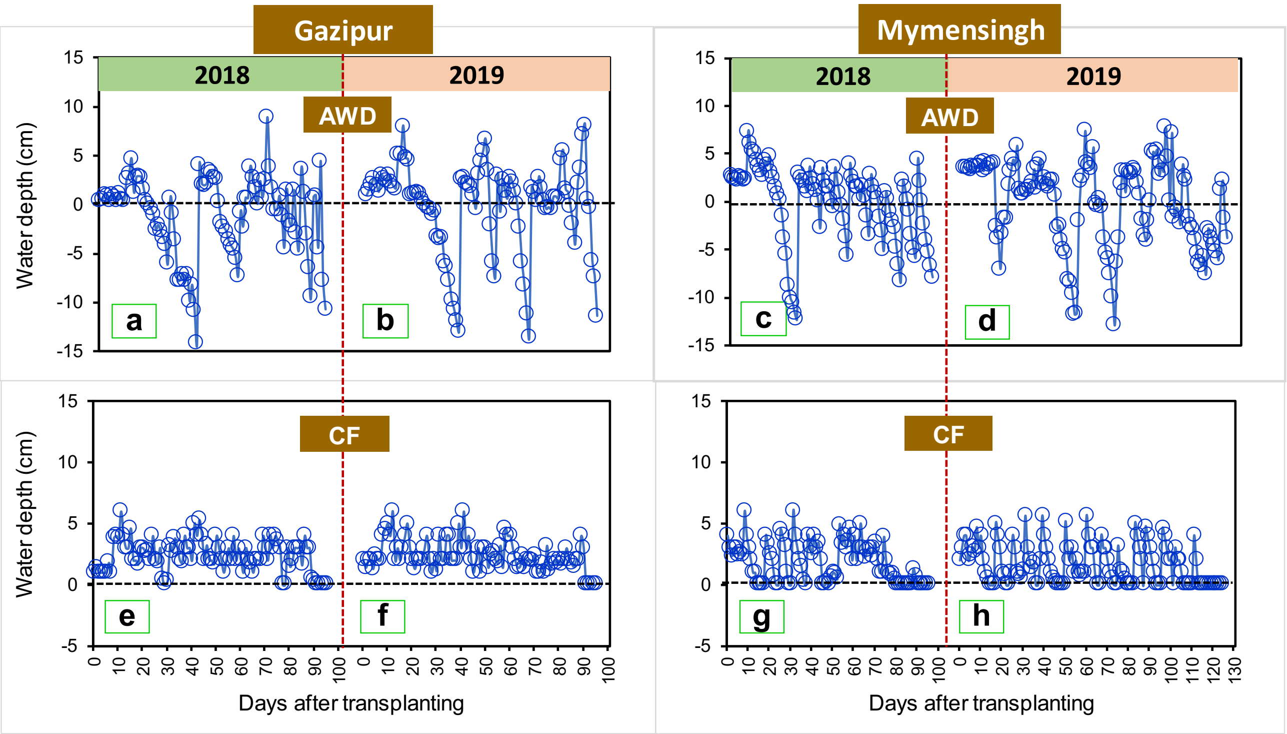

Fig. 2. Daily field water depth from transplanting to harvesting of rice plant in the Boro season under AWD and CF condition. AWD and CF denote alternate wetting and drying and continuous flooding irrigation, respectively.

when water depth dropped to 12–15 cm below the soil surface (Fig. 2a–d).

2.5. Gas sampling and analysis

Gas samples for CH_4 and N_2O emission measurements were collected using the 'closed chamber technique'. Each closed chamber had a base (60 cm length and 40 cm breadth, volume 70 L) and a top (216 L) which were both made of a transparent acrylic sheet with metal frame. Each chamber base, covering six rice hills, was installed in the rice field by inserting it at 8–10 cm soil depth and was kept in the field throughout the experiment period. During each gas sampling time, the chamber top was placed over the base to make the chamber air tight using water as a sealing material. Each gas chamber was equipped with a battery-powered fan to ensure uniform mixing of the air inside. A thermometer was used to measure the temperature inside the chamber to calculate the emission rates of CH_4 and N_2O. A pipette tip with three-way stop cock was fixed in the chamber wall to collect gas samples. Using a 50-mL airtight syringe, gas samples were collected once a week at 9:00 AM for 12 weeks in Gazipur and 13 (2018) to 17 (2019) weeks in Mymensingh sites, respectively. During each sampling time, three gas samples were taken at 15-min intervals (0, 15, and 30 min) for 30 min. Samples were collected throughout the rice-growing season and were immediately transferred into 30-mL evacuated glass vials sealed with a butyl rubber septum for laboratory analysis.

The concentrations of CH_4 and N_2O were measured using a gas chromatograph (Shimadzu GC-2014, Japan) equipped with a flame ionization detector (FID) and electron capture detector (ECD). The column was packed with Propak Q (80–100 mesh) and column temperature was maintained at 50 °C. The detector temperature was operated at 150 °C and 300 °C for FID and ECD, respectively. Nitrogen (N_2) and argon were used as the carrier gases for CH_4 and N_2O analysis, respectively. Hydrogen and air were used as the burning gas and supporting gas, respectively, for CH_4 analysis. Gas samples were analyzed within a week of collection.

2.6. Estimation of CH_4 and N_2O emissions

Emission rates were determined from the slope of the linear regression curve of CH_4 or N_2O concentration against the chamber closing time. The slope was then converted to mass per unit area per unit time (mg m^{-2} d^{-1}) using the following equation (Gaihre et al., 2013):

$$\mathrm{CH_4 and\ N_2O\ emission\ rate}\left(\mathrm{mg\ m^{-2}d^{-1}}\right) = \frac{\mathrm{Slope}\left(\mathrm{ppm\ \ min^{-1}}\right) \times Vc \times MW \times 60 \times 24}{22.4 \times (273 + T/273) \times Ac \times 1000}$$

where Vc is the volume of the gas chamber in liters (L), MW is the molecular weight of the respective gas, 60 is min h^{-1}, 24 is h d^{-1}, 22.4 is the volume of 1 mol of gas in L at standard temperature and pressure, 273 is the standard temperature in °K, T is the temperature inside the chamber in °C, Ac is the area of the chamber in m^2, and 1000 is μg mg^{-1}.

The GWP of CH_4 and N_2O was calculated using the following equation:

$$\mathrm{GWP}\left(\mathrm{kg\ CO_2\ equivalent\ ha^{-1}}\right) = (\mathrm{TCH_4} \times 28 + \mathrm{TN_2O} \times 265)$$

where, TCH_4 is the total amount of CH_4 emission (kg ha^{-1}), TN_2O is the total amount of N_2O emission (kg ha^{-1}), 28 and 265 are the GWP values for CH_4 and N_2O, respectively, to CO_2 over a 100-year time horizon (IPCC, 2014).

Greenhouse gas emission intensity (GHGI) was calculated using following equation:

$$\mathrm{GHGI} = \frac{\mathrm{TGHG}}{\mathrm{Yield}}$$

where, GHGI is the total GHG emission per unit of rice yield (kg CO_2 eq kg^{-1} grain yield).

Scaling factor (used to adjust the baseline emissions) for AWD was estimated dividing a cumulative emission from AWD by a cumulative emission from CF.

2.7. Data analysis

Analysis of variance of the seasonal cumulative emission of CH_4 and N_2O gases, GWP, GHGI, and grain yield was done with the Statistical Tool for Agricultural Research (STAR 2.0.1, International Rice Research Institute, Philippines) software. A pair-wise mean comparison of treatments was done with Tukey's honest significant difference test at a 5% level of probability.

3. Results

3.1. Dynamics of CH_4 emissions

The dynamics of CH_4 emissions measured from the two locations are presented in Fig. 3a–d. Magnitudes and patterns of CH_4 emissions varied with irrigation regimes, locations, and year. At the Gazipur site (2018), CH_4 emission rates were initially high and larger peak emissions were observed just after transplanting under both AWD and CF irrigation regimes. However, early season peak was not observed in 2019. CH_4 emission rates declined rapidly after final drainage at crop maturity. Over the rice-growing season, daily CH_4 emission rates ranged from 79 to 815 mg m^{-2} d^{-1} under AWD irrigation and 66 to 830 mg m^{-2} d^{-1} under CF condition during Boro 2018, while these ranged from 110 to 330 mg m^{-2} d^{-1} under AWD irrigation and 242 to 457 mg m^{-2} d^{-1} under CF condition during Boro 2019.

In contrast, CH_4 emission rates were lower and increased with crop growth at the Mymensingh site. The magnitude of CH_4 emissions was also lower and the differences on emissions between the two irrigation regimes were not prominent. Over the rice-growing season, daily CH_4 emission rates ranged from 36 to 67 mg m^{-2} d^{-1} under AWD irrigation and from 42 to 178 mg m^{-2} d^{-1} under CF condition in Boro 2018. In Boro 2019, daily CH_4 emission rates ranged from 32 to 120 mg m^{-2} d^{-1} under AWD irrigation and from 60 to 166 mg m^{-2} d^{-1} under CF condition. After the final drainage, CH_4 emission rates dropped to background level in both CF and AWD irrigation schemes.

3.2. Dynamics of N_2O emissions

The dynamics of N_2O emissions measured from the two locations, i.e., Gazipur and Mymensingh during the Boro season 2018 and 2019 are presented in Fig. 3e–h. N_2O emission peaks were sporadic and event-specific; they were observed after each topdressing of urea or during dry periods. Except during the peak emission events, N_2O emission rates were within a range of ±1 mg N m^{-2} d^{-1} irrespective of water regimes, sites, and seasons.

At the Gazipur site, the highest N_2O emission peak (2.99 mg m^{-2} d^{-1}) was found after the first topdressing of urea. Some N_2O emission peaks were observed during dry episodes in the AWD treatment plots. At the Mymensingh site, fertilizer-induced N_2O emission peaks were not as prominent as in the Gazipur site. N_2O emission peaks that were observed during the dry episodes (AWD treatment) ranged from 0.64 to 1.36 mg N m^{-2} d^{-1}.

3.3. Cumulative CH_4 and N_2O emissions

Irrigation regimes had significant ($p < 0.05$) interaction effects with the experiment sites for cumulative CH_4 emissions (Table 3). At each site, CH_4 emissions were significantly higher under CF irrigation compared to AWD irrigation. AWD irrigation reduced CH_4 emissions by 36% and 41% at the Gazipur and Mymensingh sites, respectively. Across the year, cumulative CH_4 emissions were higher at the Gazipur site under CF irrigation compared to those recorded at the Mymensingh

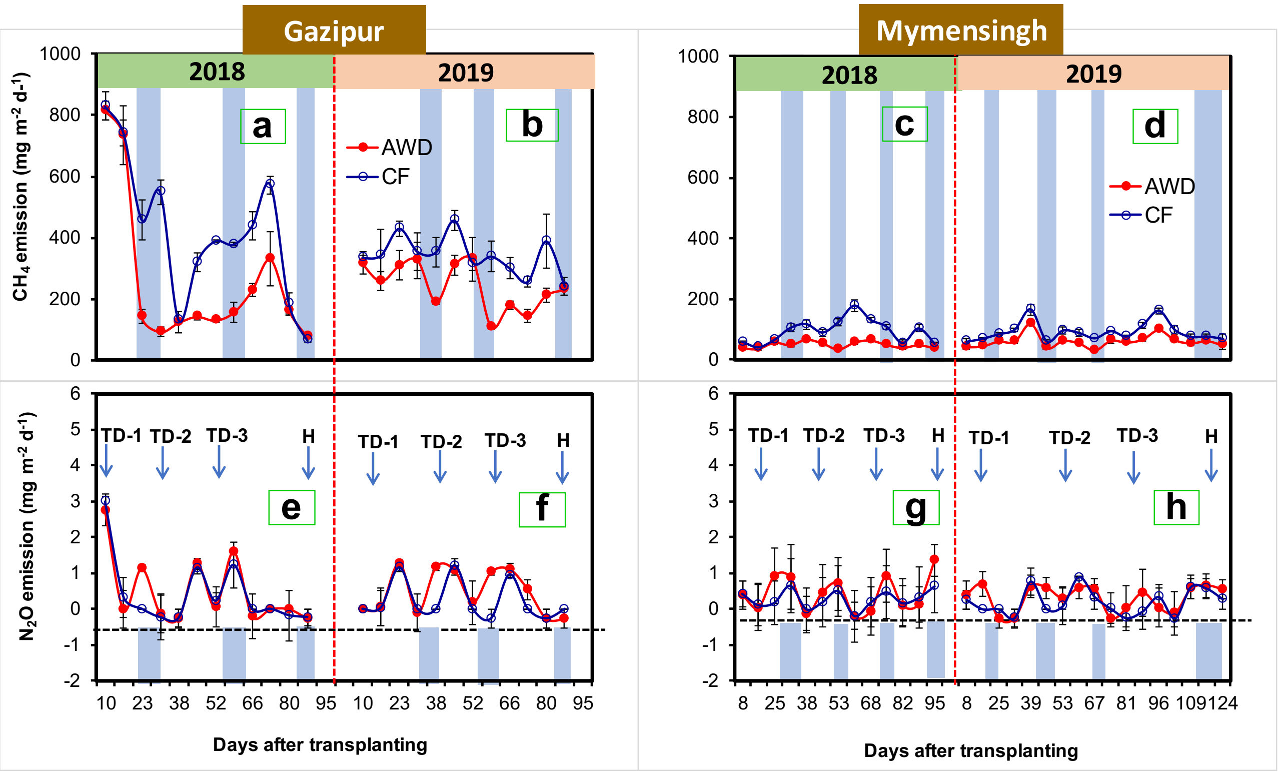

Fig. 3. Temporal dynamics of CH_4 and N_2O emission rates under AWD and CF irrigation regimes during the Boro season at BRRI farms in Gazipur and Mymensingh. T, TD-1, TD-2, TD-3, and H represent transplanting, first topdressing, second topdressing, third topdressing, and harvesting, respectively. Shaded area indicates the drying period under AWD irrigation. Vertical bars indicate standard error of mean ($n = 3$).

Table 3
Effects of irrigation regimes and experiment sites on rice yield, seasonal CH_4 and N_2O emissions, and emission factor of CH_4 and N_2O, GWP, and GHGI in the Boro season.

Site	Water regimes	Year	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	CH_4 emission (kg ha^{-1})	EF of CH_4 (kg ha^{-1} d^{-1})	N_2O emission (g ha^{-1})	EF of N_2O (g ha^{-1} d^{-1})	GWP[a]	GHGI[b]
Site and water regimes interaction										
Gazipur	AWD	Mean	5.47	5.3a	201.3b	2.24b	379.2a	4.21a	5743.1b	1.05b
	CF		5.72	5.6a	313.8a	3.49a	264.5bc	2.94bc	8856.1a	1.56a
Mymensingh	AWD	Mean	5.87	5.3a	58.5d	0.54d	345.8ab	3.24ab	1729.8d	0.29d
	CF		5.96	5.4a	99.3c	0.93c	232.0c	2.20c	2782.8c	0.47c
Water regimes and year interaction										
Mean	AWD	2018	5.19a	4.9b	117.2c	1.28b	334.9ab	3.60ab	3370.7c	0.64b
	CF		5.33a	5.1b	207.4a	2.26a	246.0b	2.67bc	5813.8a	1.07a
Mean	AWD	2019	6.14b	5.8a	142.6b	1.50b	390.1a	3.86a	4102.3b	0.71b
	CF		6.34b	5.9a	205.8a	2.16a	250.0b	2.47c	5825.1a	0.96a
Effects of water regimes										
Mean	AWD	Mean	5.67a	5.3a	129.9b	1.39b	362.5a	3.73a	3736.5b	0.67b
	CF		5.84a	5.5a	206.6a	2.21a	248.3b	2.72b	5819.4a	1.01a
ANOVA (p values)										
Site (S)			0.0241	0.5933	0.0000	0.0000	0.1552	0.0029	0.0000	0.0000
Water regimes (W)			0.2017	0.1956	0.0000	0.0000	0.0002	0.0003	0.0000	0.0000
Year (Y)			0.0000	0.0000	0.0544	0.3824	0.1960	0.9080	0.0394	0.5517
W × S			0.5537	0.5658	0.0000	0.0000	0.9805	0.6295	0.0000	0.0003
S × Y			0.0001	0.0008	0.0454	0.9887	0.7170	0.0631	0.0386	0.3097
W × Y			0.8191	0.6948	0.0319	0.0209	0.2693	0.3587	0.0448	0.0162
S × W × Y			0.7891	0.9029	0.1326	0.2497	0.5313	0.3530	0.0968	0.1266

Within a column, means followed by common letters are not significantly different at 5% level of probability. CF and AWD represent continuous flooding and alternate wetting and drying, respectively.

[a] GWP (global warming potential; kg CO_2 equivalent ha^{-1}) of CH_4 and N_2O were calculated using GWP of 28 and 265 for CH_4 and N_2O, respectively (IPCC, 2014).

[b] GHGI (greenhouse gas intensity; kg CO_2 equivalent kg^{-1} grain yield) were calculated by dividing grain yield (kg ha^{-1}) on total GWP.

site (Table 3). Across sites and years, AWD reduced emissions by 37% over the farmers' practice of CF irrigation. N_2O emissions were affected only by the type of water regime implemented. Across sites and years, AWD irrigation significantly ($p < 0.05$) increased cumulative N_2O emissions (46%) compared to CF irrigation.

3.4. Rice yield, GWP, and GHGI

Irrigation regimes had significant ($p < 0.05$) interaction effects with the experiment sites on GWP and GHGI, but not on grain yields (Table 3). GWP ranged from 5743.1 to 8856.1 kg CO_2 equivalent ha^{-1} in Gazipur and from 1729.8 to 2782.8 kg CO_2 equivalent ha^{-1} in Mymensingh. AWD reduced GWP in both sites. However, the magnitude of reduction was higher (40%) in Mymensingh than in Gazipur (35%). Across sites and years, AWD irrigation reduced total GWP by 36% compared to CF irrigation. Similarly, AWD reduced GHGI by about 34% compared to CF irrigation. GHGI ranged from 1.0 to 1.56 kg CO_2 equivalent kg^{-1} grain yield in Gazipur and from 0.29 to 0.47 kg CO_2 equivalent kg^{-1} grain yield in Mymensingh. Regardless of water regimes, total GWP and GHGI were much lower at the Mymensingh site compared to the Gazipur site (Table 3).

4. Discussion

4.1. Dynamics of CH_4 and N_2O emissions

CH_4 emissions increase with increasing rice growth until the flowering stage and then decline sharply thereafter (Gaihre et al., 2014) as what previous studies have shown. However, in this study, higher emission rates were observed during the early rice-growing period at the Gazipur site in Boro 2018 (Fig. 3a-b) probably due to the incorporation of mustard biomass before transplanting. The added crop residue could provide additional substrate for CH_4 production (Wassmann et al., 2000; Janz et al., 2019). The lower emission rates at the Mymensingh site could be associated with the difference in crop management including water management, and soil type (Table 1). The experimental rice fields at the Mymensingh site were frequently dried which was evident from higher frequency of irrigation compared to Gazipur site (Fig. 2a–h). This was due to the landscape position which was at a relatively higher elevation compared to the surrounding fields. This might have affected oxidation state of the soils leading to the inhibition of methanogenic activity, which finally suppresses the emission rates of CH_4 (Sun et al., 2016). Higher CH_4 emissions at Gazipur site could also be associated with higher organic C and clay content in the soils compared to Mymensingh site.

N_2O emission peaks were observed during both drying and fertilizer application periods (Fig. 3e-h), with higher magnitudes noted during the drying period compared to the period of N fertilization topdressing, which are in close agreement with results of previous studies (Gaihre et al., 2015, 2018; Islam et al., 2018b). Higher N_2O emissions in the AWD plots could be explained by increased microbial nitrification and denitrification. In contrast, the reduced N_2O emission peaks under CF condition are likely related to its further reduction to N_2 through denitrification under strong anaerobic condition (Firestone and Davidson, 1989; Zou et al., 2005).

4.2. Effects of water regimes on GHG emissions, emission factors, GWP, and GHGI

Water management affects CH_4 emissions from rice cultivation. In this study, AWD irrigation significantly ($p < 0.05$) reduced CH_4 emissions by 37% compared to the farmers' practice (Table 3). These results are in line with previous findings (Ali et al., 2013; Ku et al., 2017; Li et al., 2018). The substantial reduction of CH_4 emission is expected when AWD irrigation is maintained properly. The effectiveness of AWD in reducing CH_4 emission depends on the efficiency of water control, soil type, and other cultivation practices (Xu et al., 2015). Intermittent aeration makes the soil environment oxic, which results in the oxidation of CH_4 by the methanotrophs, causing a drop in CH_4 emission. It is reported that up to 80% of the CH_4 produced during the rice-growing season is oxidized by the methanotrophs (Singh et al., 2010). In contrast, CF rice cultivation makes the soil environment anaerobic, resulting in decreasing redox potential (−150 mV), which leads to the anaerobic decomposition of complex organic substrates by methanogens that finally drive CH_4 production (Wang et al., 1993; Minamikawa et al., 2006).

Spatial variation in emissions between two sites (smaller seasonal total CH_4 emissions at the Mymensingh site compared to the Gazipur site) could be associated with the frequent drying of plots and difference in soil properties as explained earlier. Magnitude of CH_4 emissions across both sites were within the range of reported studies in China (Sun et al., 2016, 2020), Philippines (Sander et al., 2014; Sibayan et al., 2018), Vietnam (Tariq et al., 2017) and India (Oo et al., 2018). In China (Sun et al., 2020), the reported emissions ranged from 21 kg ha^{-1} to 335 kg ha^{-1}. Similarly, emissions (monsoon rice) ranged from 113 kg ha^{-1} to 165 kg ha^{-1} in India (Oo et al., 2018), which is comparable to our results at Mymensingh site. Compared to previous studies, emissions at Mymensingh site were at lower range, while they were at higher range in Gazipur site. These wide spatial variabilities suggest that more measurements are needed covering different agro-ecological zones to derive the representative baseline emissions for the country. Nevertheless, our results could be used as the baseline emissions in the areas with similar soil type, crop management and agro-ecological zone.

Across locations and years, CH_4 emission factors (EF) were 1.39 kg ha^{-1} day^{-1} under AWD irrigation, while it was 2.21 kg ha^{-1} day^{-1} under CF condition (Table 3). These EFs are higher than the IPCC default EF of 1.19 and 0.85 kg ha^{-1} day^{-1} of world and south Asia (without residue incorporation), respectively (IPCC, 2019). Similarly, the AWD scaling factor for CH_4 ranged from 0.49 to 0.70. Higher reduction (scaling factor 0.58) was observed at the Mymensingh site compared to that at the Gazipur site of 0.64; these scaling factors are in line with the IPPC default factor of 0.6 (IPCC, 2019).

Water management significantly affected cumulative N_2O emissions (Table 3). Although N_2O emissions from paddy fields cultivated under CF condition are negligible, significantly higher emissions occur in fields cultivated under AWD irrigation. Shifting water regimes from CF to AWD influences nitrification and denitrification intensities, depending on oxygen availability. During a drying cycle, the upper soil layer becomes aerobic initially but the lower layer remains anaerobic even if the water level reaches 15 cm below the soil surface. Thus, a significant amount of N_2O is produced via nitrification of NH_4^+ and denitrification of NO_3^-.

Water regimes showed a tradeoff relationship between CH_4 and N_2O emissions. Although AWD irrigation significantly increased (46%) the cumulative N_2O emissions compared to CF irrigation, it offset the total GWP by only 1–3%. Overall, AWD reduced GWP by 36% over CF irrigation. These results confirm that the total GWP in rice fields is solely determined by CH_4 emission. Although the radiative forcing of N_2O is much higher than CH_4, the magnitude of N_2O emissions is very small. Thus, CH_4 is the major contributor of GWP in rice cultivation, representing over 90% of the total GWP (Sander et al., 2014; Janz et al., 2019). In this study, the total GWP attributed to CH_4 emissions was 97.4% in AWD and 98.9% in CF. These results are consistent with previous studies (Ku et al., 2017; Sander et al., 2017; Islam et al., 2018a; Oo et al., 2018). As with GWP, AWD irrigation showed a potential to reduce GHGI by 34% compared to CF irrigation, as was also found in previous studies (Ku et al., 2017; Islam et al., 2018a; Li et al., 2018). Therefore, the most effective measures to reduce GWP and GHGI in rice cultivation should be focused on the reduction of CH_4 emission.

5. Conclusions

In this study, AWD irrigation reduced CH_4 emissions by 37% (ranging from 30% to 51%) compared to CF irrigation. The AWD scaling factor for CH_4 ranged from 0.49 to 0.67 (average, 0.58) and from 0.58 to 0.70 (average, 0.64) at the Mymensingh and Gazipur sites, respectively. Although shifting water regimes from CF to AWD increased N_2O emissions by 46% (range of 28% to 59%), it offset only 1–3% of the GWP reduced by CH_4. On the average, AWD reduced GWP by 36% and yield-scaled emissions by 34% without any yield penalty compared to CF irrigation. To our knowledge, this is the first study which reports emissions from farmers' fields in Bangladesh. Thus, these results could be used as a baseline emission data for rice-growing countries with similar soil types and management practices. These results further confirm that AWD irrigation could be one of the effective strategies for mitigating GHG emissions, while saving irrigation water in Bangladesh. However, a large spatial variability in CH_4 and N_2O emissions was observed throughout the rice-growing season, indicating the need for further measurements across different soil types, agroecological zones, and farmers' management conditions to develop representative baseline emissions and the GHG emission mitigation potential of AWD in different environments.

CRediT authorship contribution statement

S.M. Mofijul Islam: Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing.**Yam Kanta Gaihre:** Methodology, Investigation, Writing - original draft, Writing - review & editing.**Md. Rafiqul Islam:**Investigation.**Mahmuda Akter:**Investigation.**Abdullah Al Mahmud:**Investigation.**Upendra Singh:**Methodology.**Bjoern Ole Sander:**Methodology, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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