Modelling greenhouse gas emissions and mitigation potentials in fertilized paddy rice fields in Bangladesh

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Abstract

Emissions of greenhouse gases (GHG) from paddy rice are significant, so reducing these emissions has significant potential for climate change mitigation. We investigated alternate wetting and drying (AWD) as part of an integrated management approach to enhance mitigation, together with combinations of mineral nitrogen (N), reduced tillage, a suitable combination of plant residues and well decomposed manure. To quantify GHG emissions, and the potential for mitigation without yield decline, a process-based model, DayCent, was used to simulate methane (CH_4) and nitrous oxide (N2O) emissions from paddy rice (*Oryza sativa* L.) in Bangladesh. The four test sites selected were amended with mineral N fertilizer or an organic amendment (rice straw). A good agreement ($p < 0.05$) was observed between model simulated and measured daily CH_4 flux at most of these test sites with no significant bias. The seasonal CH_4 emission from a site receiving mineral N fertilizer at a rate of 110 kg N ha^{-1} was predicted by the model to be 210 and 150 kg ha^{-1} for the water management scenarios of continuous flood (CF) and AWD, respectively. These values compare well with estimates of CH_4 emissions using Intergovernmental Panel on Climate Change tier 1 methods for the different water regimes. Our model results suggest emission factors for N_2O of 0.4% and 0.6% of applied fertilizer under CF and AWD water regimes, respectively. Based on modelling studies, AWD was found to be an important strategy not only with respect to reducing GHG emissions, but also in terms of cost effectiveness. We also found that integrated management is a promising option for farmers and policy makers interested in either yield increase, GHG mitigation or both. Yield scaled emissions intensity under AWD was found to be about 24% lower than under CF, followed by integrated management.

Keywords: Greenhouse gas; paddy soil; water management; mitigation potential; Bangladesh.

1. Introduction

The emission of greenhouse gases (GHG) from agriculture is of great environmental concern, with agriculture emitting around 4.6 Gt carbon dioxide equivalent (CO_2-eq.) yr^{-1} in 2010 (Tubiello et al, 2013). Of the non-CO_2 GHGs, methane (CH_4) and nitrous oxide (N_2O) are the most important gases emitted from agricultural activities, with 50% and 60%, respectively, of total anthropogenic emissions. In contrast to developed countries, the contribution of GHG emissions from developing countries account for three quarters of total global GHG emissions from agriculture (Smith, 2012). Among the agricultural sources, wetland rice (*Oryza sativa* L.) production is a major contributor to the global budget of GHG emissions from agriculture, which comprise 55% of global agricultural GHG emissions, of which 90% is emitted in Asia (Stocker, 2013). Methane and N_2O emissions are the potent GHGs that emitted from rice cultivation (Tian et al., 2018).

Annually, approximately 34 million tonnes (Mt) of rice (7% of world rice production) are produced in Bangladesh, covering over 70% of total land (BBS, 2016). Production is expected to increase by 50% to meet the demand of an increased population with changing dietary preferences by 2050 (BBS, 2016). Agriculture is estimated to be one of the largest sources of GHG emissions in Bangladesh, estimated at 78 Teragram (Tg) carbon di-oxide (CO_2)-eq. in 2016, to which rice cultivation contributes approximately 30% of total GHG (CO_2-eq.) emitted from agriculture (FAOSTAT, 2018). Although the contribution to global GHG emissions from agriculture is 8-9 times lower than the other major rice producing countries such as India and China, the per capita emissions in Bangladesh are essentially the same as for those two countries (FAOSTAT, 2018). Concurrently, Bangladesh is recognised as one of the world's most vulnerable countries to climate change, due to socio-economic conditions and its geographical location (Islam and Nursey-Bray, 2017). It is necessary to focus on the climate change vulnerability Bangladesh faced for the need of mitigation, and thus mitigation policy in agriculture should be developed. However, In Bangladesh, emphasis has been given to adaptation rather than mitigation, although there is potential to reduce GHG emissions from agriculture. Resources are being invested in sectors other than agriculture, due to lack of specific information to assess "business as usual" conditions (Jilani et al., 2015). For instance, in the Nationally Determined Contribution (NDC) 2015, Bangladesh pledged to reduce emissions from different non-agricultural sectors including power, transport and industry- unconditionally by 5% and conditionally by 15% of total emissions from business as usual level by 2030 (Begum et al., 2018a; Jilani et al., 2015). The detailed information on individual contributions of GHG emissions for CH_4 and N_2O, considering current agricultural practices are scarce. So current baseline emissions for CH_4 and N_2O, necessary to determine the mitigation potential, are not yet well characterised.

Irrigated land in Bangladesh occupies around 60% of the total agricultural land and more than half of that area is used for dry season rice, which is irrigated rice (locally known as *boro*) production (BBS, 2016). For high productivity, the irrigated area needs to be expanded to produce more rice for the increasing population; consequently, CH_4 and N_2O emissions are expected to increase above current levels (Ali et al., 2013). Sometimes, agronomic practices have opposite effects on CH_4 and N_2O emissions during the rice-growing season. For instance, changing water status from continuous flooding (CF) to alternate wetting and drying (AWD) conditions leads to a reduction in CH_4 emissions while increasing N_2O emissions and *vice versa* (Cheng et al., 2013). However, there is potential to reduce GHG emissions from paddy rice soils by management of water, nutrients and other traditional practices (Smith, 2012). Beach et al. (2015) found substantial GHG mitigation potential in Asia and the potential is higher for rice than upland crops. Therefore, it is important to address the effect of management on both CH_4 and N_2O emissions to propose effective mitigation management for paddy land in Bangladesh.

In Bangladesh, very few field experimental studies have been conducted on GHG emissions, and those that exist have investigated only one gas, either CH_4 or N_2O. A large number of factors influence regional and inter-annual variability in CH_4 flux (Babu et al., 2006) and empirical models are often regarded as too simple (Bell et al., 2012). Therefore, process-based models are a useful supplementary method for studying GHG emissions and mitigation potential under different agricultural management practices. Several modelling studies have simulated SOC change and mitigation potential with rice-based cropping systems in different regions of Asia (Xu et al., 2011; Bhattacharyya et al., 2007). For this study, we selected the DayCent model (Parton et al., 1998) which has recently had a methanogenesis sub-model added. Early studies with this version showed adequate model performance in simulating trends in SOC content and CH_4 fluxes in agricultural regions – in China (Cheng et al., 2013, 2014) and Brazil (Weiler et al., 2018). The DayCent was also applied in Bangladesh rice croplands to determine SOC sequestration potential at site level (Begum et al., 2018b) and the GHG mitigation potential in regional scale (Begum et al., 2018a). The present study aims to estimate CH_4 and N_2O emissions for paddy rice in Bangladesh for nitrogen (N) fertilized study sites, using the DayCent model to simulate emissions under different mitigation scenarios relative to current practices. Model based CH_4 and N_2O emissions in a single paddy rice system were determined and compared with estimated emissions using the Intergovernmental Panel on Climate Change (IPCC) tier 1 methods for CH_4 (Lasco et al., 2006) and N_2O emissions (De Klein et al., 2006).

2. Materials and methods

2.1. Site description

Four experimental sites were selected which are located in the same administrative unit (district) of Mymensingh. Three experiments were conducted at Bangladesh Agricultural

University (BAU) (site 1, site 2 and site 4), and another experimental site was located in the upazilla (sub district) of Bhaluka (site 3). The test sites are at 24.75^0 N latitude and 90.50^0 E longitude with an elevation of 18 m above sea level (Ali et al., 2014).

Generally, rice-rice or rice-wheat is the dominant cropping system in Bangladesh, the test sites however were fallow after the rice growing season. In all sites, irrigated rice was planted each year in winter (January) and harvested in summer (May). The experimental year for site 1, site 2 and site 3 is 2010. Analysis for site 4 was two years-2011 and 2012. The total duration of the crop was 120-140 days. Three week old seedlings of a high yielding variety were transplanted in the experimental sites. The weather data from the meteorological station of Mymensingh were used to drive the model for all sites (Fig. 1). The weather station was located 400 m away from the site (BMD, 2016). Average temperature during the experimental period (three years) recorded by Bangladesh Meteorological Department was 25.8 ^{0}C. Annual precipitation was 200 cm, with 80% of rainfall received between May and September. Temperature was below 20 ^{0}C during the months of December-January, while the maximum temperature was up to 30 ^{0}C at the beginning of April until the end of August (BMD, 2016). The ambient air temperature during the sampling period was 25-35 ^{0}C (Ali et al., 2014).

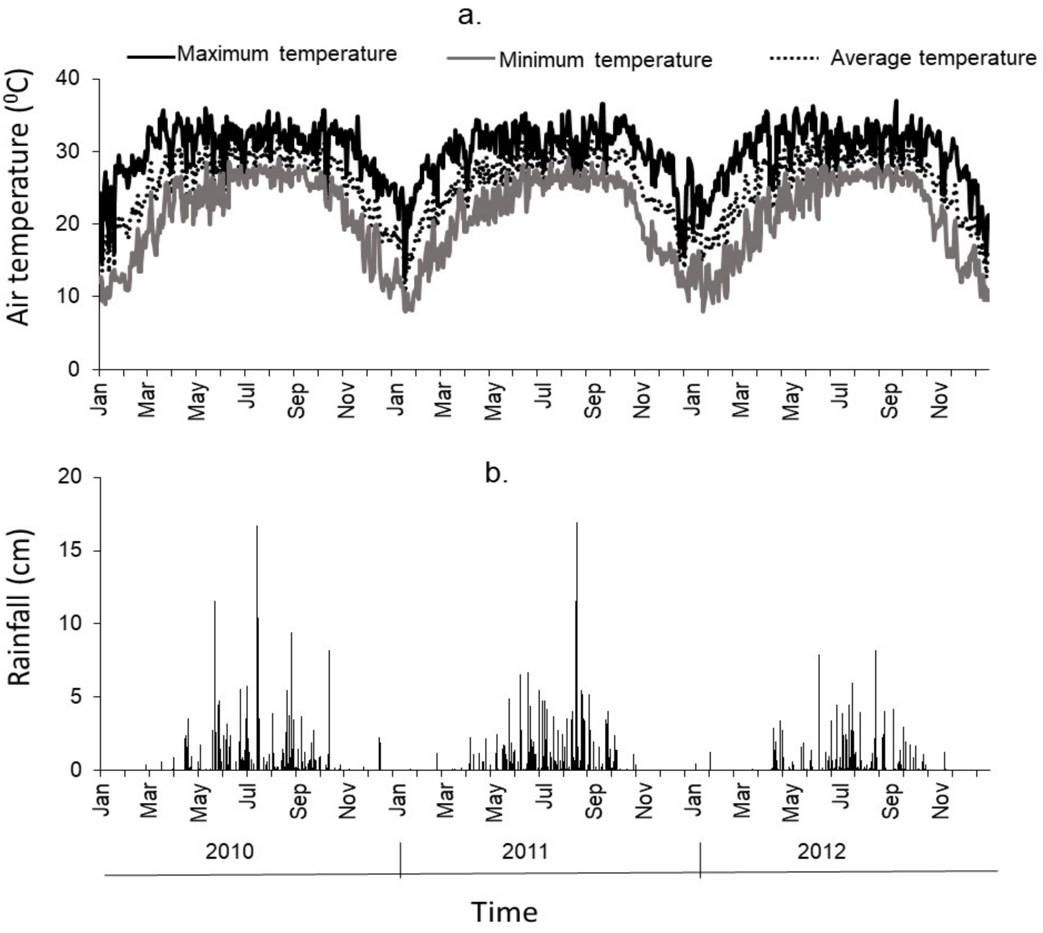

Fig. 1. Measured a) daily air temperature and b) rainfall during the experimental period (2010, 2011 and 2012) in the paddy rice test sites.

2.2. Treatments and CH_4 and N_2O emissions data

Treatments for three sites (site 1 to 3) involved the application of N fertilizer at a rate of 110-115 kg ha^{-1} and at site 4, a combination of N fertilizer and rice straw (N+RS) was applied (Table 1). The N was applied in three split applications, with around 40% of the N applied in one application before transplanting. The remaining portion was applied as two equal split applications at tiller initiation stage (about three weeks after transplantation) and panicle initiation stage (about six weeks after rice transplantation) (Ali et al., 2013). Rice straw alone was used as an organic amendment and was applied before rice cultivation at site 4. Each treatment had three replications. The soil details and properties are summarized in Table 1. Details of the measurements are described in Ali et al. (2012, 2013 and 2014).

Data for CH_4 and N_2O were available for CF and AWD water regimes for site 1 while for the other sites, only CH_4 emissions under CF conditions were measured. In the CF condition, the soil was fully saturated for the entire crop growing season, water level in the rice field was kept at 5cm depth while under AWD systems, the rice field was irrigated during the final land preparation to rice planting time, active tillering stage and flowering stages. The field was kept moist during the rest of the period (Ali et al., 2013). Static closed chambers were used for gas sampling during rice cultivation. The air gas samples from the transparent glass chamber (diameter 60 cm, and height 110 cm) were collected by using 60-ml gas-tight syringes at 0, 15 and 30-minute intervals after chamber placement over the rice-planted plots. The surface area of each chamber was 0.25 m^2 (0.5X0.5 m^2). While gas sampling, the chamber was placed over six hillsof rice vegetation. There were four holes at the bottom of each chamber through which water movement was controlled. Gas samples were simultaneously analysed with a modified gas chromatograph equipped with a flame ionization detector and an electron capture detector (Wang and Wang, 2003). The detailed description of sample analysis was found in Ali et al., (2012, 2013). Methane and N_2O emissions from paddy fields were calculated by using the equation (Rolston, 1986):

$$F = \rho * V/A * \Delta c/\Delta t * 273/T \qquad (1)$$

where, F = CH_4 flux (mg m^{-2} hr^{-1}) or N_2O flux, ρ = gas density (0.714 mg cm^{-3}), V = volume of chamber (m^3), A = surface area of chamber ($m^2 \Delta c/\Delta t$ = rate of changes in CH_4 or N_2O gas concentrations in the Chamber (mg m^{-3} hr^{-1}), and T (absolute temperature) = 273 + mean temperature in chamber (^{0}C) (Ali et al., 2013). Gas samples were collected 2 times per day, once a week during the cropping season. On average 7-8 observations were obtained for CH_4 emissions and 7 values for N_2O (Ali et al., 2012; Ali et al., 2013; Ali et al., 2014).

Table 1

Initial physico-chemical characteristics of four N fertilized test sites in Bangladesh.

Location (Experimental year)	Treatment	Texture	SOM (%)	Water regime	BD (g cm^{-3})	pH	Available measured data	Ref
BAU site 1 (2010)	110 kg N ha^{-1}	Silt loam	2	CF, AWD	1.18	6.2	CH_4 N_2O	Ali et al., 2013
BAU site 2 (2010)	115 kg N ha^{-1}	Silt loam	2.1	CF	1.25	6.1	CH_4	Ali et al., 2012
Bhaluka site 3 (2010)	115 Kg N ha^{-1}	Silty Clay loam	2.3	CF	1.29	5.8	CH_4	Ali et al., 2012
BAU site 4 (2011-2012)	110 kg N ha^{-1} + 2 t ha^{-1} rice straw (total C and N 39.50% and 0.95% respectively)	Clay loam	1.78	CF	1.34	5.9	CH_4	Ali et al., 2014

BAU: Bangladesh Agricultural University, SOM: Soil organic matter, CF: Continuous flood, AWD: Alternate wetting and drying, BD: Bulk density, Ref: References

2.3. Model description and simulations

We used the most recent version of the DayCent ecosystem model (Parton et al., 1998), developed for paddy rice (Cheng et al., 2013). It is the daily time-step version of the CENTURY model, and provides daily outputs of net primary production and heterotrophic respiration. The model simulates biogeochemical processes associated with carbon, N, phosphorus, and sulphur cycling, including SOM decomposition, nitrification and denitrification, plant production and soil water dynamics, and, in the version used in this study, methanogenesis (Cheng et al., 2013; Hartmann et al., 2016). The methanogenesis sub-module simulates CH_4 production based on C substrate supply derived from decomposition of SOM and root rhizodeposition. Soil texture, soil pH, redox potential (Eh), soil temperature, climate and agricultural management impact on methanogenesis, thereby CH_4 formation (Cheng et al., 2013). DayCent does not simulate diffusion of CH_4 through the surface water to the atmosphere because it is considered a minor pathway for CH_4 emissions (Cheng et al., 2013). Ebullition occurs when the soil CH_4 concentration exceeds a critical state that leads to formation of bubbles (Cheng et al., 2013; Hartmann et al., 2016). The trace gas sub-model of DayCent simulates soil N_2O and NOx gas emissions from nitrification and denitrification processes. Daily denitrification rates are estimated for each soil layer based on nitrate (NO_3^-) concentration, heterotrophic respiration (as a proxy for labile C availability), water content, texture, and temperature (Del Grosso et al., 2008). Detailed information about model concepts and mechanisms is described in greater detail elsewhere (Del Grosso et al., 2008; Cheng et al., 2013; Hartmann et al., 2016). The DayCent model has been applied for different land uses, including grasslands (Parton et al., 1998), agricultural lands (Begum et al., 2017, Senapati et al., 2016), forests (Cameron et al., 2013), and savannas (Parton et al., 1993).

DayCent requires precipitation, and maximum and minimum temperature at daily time steps, which is based on a meteorological station at Mymensingh for this study. Based on available SOM data measured to a 15 cm depth, the initial SOC stock (in t ha^{-1}) was estimated using an equation in Nayak et al. (2015), multiplying measured %SOM by 0.58, depth (in cm) and BD (in g cm^{-3}) which was used in a study of Chinese croplands including 50 studies of rice ecosystems. The simulated DayCent values, which are estimated for 20 cm, were adjusted to 15 cm depth by dividing DayCent outputs by 1.33. Field capacity (FC), wilting point (WP) and saturated hydraulic conductivity were estimated using a pedo-transfer function of Saxton and Rawls (2006). SOC pools in the model were initialized with a model spin-up for 1500 years using native vegetation and historical agricultural management as suggested by previous applications of the model (Begum et al., 2018b; Cheng et al., 2013; Del Grosso et al., 2006).

2.4. Statistical methods

Performance of the model was evaluated with statistical routines provided in MODEVAL (Smith et al., 1997; Smith and Smith, 2007). The sample correlation coefficient (*r*) was used (equation 2) to test for association between the modelled and measured values over time. Modelled and measured daily flux of CH_4 and N_2O emissions were compared by calculating the root mean square error (*RMSE*, equation 3), which indicates total difference between observed and predicted values (Smith et al., 1997). The mean difference between observation and simulation (*M*) was calculated to assess bias in the modelled results (equation 4).

$$r = \frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{[\sum_{i=1}^{n}(O_i-\bar{O})^2]}\sqrt{[(\sum_{i=1}^{n}(P_i-\bar{P})^2]}} \qquad (2)$$

$$RMSE = \frac{100}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{n}} \qquad (3)$$

$$M = \frac{\sum_{i=1}^{n}(O_i-P_i)}{n} \qquad (4)$$

Where $\bar{O}$ and $\bar{P}$ are the mean values of observed and predicted data, respectively, and Oi and Pi indicate the observed and predicted values at the ith iteration, respectively, and n is the number of samples. The significance of r and M were tested using an F-test (at probability levels of $p = 0.05$, 0.01 and 0.001), and a Student's two-tailed t-test (critical at 2.5%).

2.5. Mitigation scenarios and net GHG emissions

The model was used to simulate the impact of alternative management practices on mitigation of GHG emissions. Management associated with AWD, as practised in test site 1, was also included here as a mitigation option to estimate total GHG emissions, including predicting CO_2 emissions under this management. Along with this single-practice mitigation scenario, two integrated approaches were tested considering tillage, residue management, N fertilizer, and two different types of manure. The full list of practices considered was:

- RT: use of reduced tillage (RT, sowing with less disturbance to the top soil) instead of conventional tillage (CT).
- Rsd20: 20% of straw removal instead of the baseline of 5%.
- CD: well decomposed cowdung (CD) of approximately 8 t ha^{-1} (substitution of N in CD for baseline mineral fertilizer N) with 1.33% N and C:N ratio of 31.50 (Ali et al., 2014).
- GM: well decomposed green manure (GM) of approximately 4 t ha^{-1} (substitution of N in GM for baseline mineral fertilizer N). Sesbania (*Sesbania rostrata)* biomass with 2.80% N and C:N ratio of 23.50 was considered as green manure (Ali et al., 2014).
- AWD
- IM1: Integrated management of RT with residue return of 15% (Rsd15), CD with substitution of 60% baseline mineral N fertilizer, AWD and mineral N fertilizer at a current rate of 110 kg ha^{-1}.

- IM2: All management was same as in IM1 except manure was replaced with a GM with 40% baseline N substitution.

Default model parameters were used to simulate plant production and different tillage intensities, as presented in Table 2 (Hartmann et al., 2016).

Table 2

The plant production and cultivation parameter file of DayCent model used for the current study to simulate CH_4 and N_2O emissions from rice cropland, Bangladesh

Name of the file	Parameter	Description	Unit	Value
Crop.100	PRDX	Coefficient for calculating potential aboveground monthly production as a function of solar radiation outside the atmosphere	Scaling factor, (g C production) m^{-2} $month^{-1}$ $Langley^{-1}$	3.00
	PPDF (1)	Optimum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	^{0}C	25
	PPDF (2)	Maximum temperature for production for parameterization of a Poisson Density Function curve to simulate temperature effect on growth	^{0}C	45
	HIMAX	Maximum harvest index		^{1}0.42-0.48
	TMXBIO	Maximum above ground biomass at the end of growing season	g biomass m^{-2}	^{1}1000-1100
Cult.100	CULTRA (5)	Fraction of standing dead transferred to top soil layer		CT: 0.6 RT: 0
	CLTEFF	Cultivation factor for soil organic matter decomposition; functions as a multiplier for increased decomposition in the month of the cultivation		CT: 3.85 RT: 3.41

[1] The ranges varies among test sites; CT: conventional tillage, RT: reduced tillage.

GHG emissions (kg CO_2-eq. ha^{-1} yr^{-1}) were estimated using global warming potential (GWP) (CO_2-eq.) over a 100 year time span (Forster et al., 2007) (equation 5).

$$GHG = (25 \text{ X } [CH_4]) + (298 \text{ X } [N_2O]) \qquad (5)$$

where GHG is the total CH_4 and N_2O emissions in kg CO_2-eq. ha^{-1} yr^{-1}. The GWP for CH_4 and N_2O are 25 and 298 over a 100-year time span (Forster et al., 2007). To get relative changes of GHG emissions, baseline emissions were deducted from emissions under mitigation management, and then the difference divided by baseline emissions (equation 6), all expressed in kg CO_2-eq. ha^{-1} yr^{-1}.

$$\text{Relative } \Delta GHG = (GHG_{Miti} - GHG_{BL})/GHG_{BL} \qquad (6)$$

Where relative ΔGHG is the relative change of emissions associated with different management options. GHG_{Miti} is emissions under the mitigation scenario, and GHG_{BL} is baseline emissions. Negative values suggest an alternative scenario could mitigate GHG emissions; positive values indicate an increase in GHG emissions relative to the baseline. The relative changes in paddy rice yield were also calculated so that the combined impact of management change on both yield and GHG emissions could be tracked (equation 7).

$$\text{Relative } \Delta yield = (yield_{Miti} - yield_{BL})/yield_{BL} \qquad (7)$$

Where relative Δyield is the relative changes of yield associated with different mitigation options. $yield_{Miti}$ is crop yield under the mitigation scenario, and GHG_{BL} is baseline crop yield, all expressed in kg ha^{-1} yr^{-1}. Additionally, to determine the emissions intensity of production, GHG emissions per unit of crop yield were calculated (equation 8).

$$GHGI = GHG/yield \qquad (8)$$

where GHGI is the GHG emission intensity (kg CO_2-eq. kg^{-1} yield), GHG is the total emissions (CH_4 and N_2O) (kg CO_2-eq. ha^{-1} yr^{-1}) and yield denotes crop production (kg^{-1} yr^{-1}). The relative changes of GHGI under different mitigation option to that of baseline were calculated to determine net mitigation potential of the selected management (equation 9).

$$\text{Relative } \Delta\text{GHGI} = (\text{GHGI}_{\text{Miti}} - \text{GHGI}_{\text{BL}})/\text{GHGI}_{\text{BL}} \quad (9)$$

where $\text{GHGI}_{\text{Miti}}$ and $\text{GHGI}_{\text{BL denotes}}$ GHG emission intensities under mitigation and baseline management respectively.

3. Results

3.1. Simulated CH_4 and N_2O emissions

The observed and simulated daily CH_4 fluxes for four experimental sites are presented in Fig. 2a-f. Daily CH_4 flux for all experimental sites increased from the tillering stage, with the highest peak observed at the flowering to maturity stage (77-100 day after transplantation), during the month of March-April, and gradually declined towards the harvesting stage. DayCent simulates the dynamics of the observations quite well except for one instance at BAU site 4 for the year 2012 ($p < 0.05$) (Table 3). Overall, the daily CH_4 flux was lower in AWD and higher under combined application treatments (N+RS) than the emissions under CF with mineral N application, observed both in simulations and observations. Although the statistical error between modelled and measured was from 0.01-0.08 g m^2 d^{-1} (*RMSE* 25-53%), no bias was observed at either of the test sites (Table 3). In contrast to the daily fluxes, the cumulative seasonal CH_4 emissions are over estimated compared to the reported values for CH_4 emissions (Table 4). However, the modelled seasonal CH_4 emissions under different management and treatment follows a similar trend as seen in the observations, with the following order from lowest to highest emissions: N treatment with AWD > N treatment with CF > N+RS treatment with CF. Compared to CF, AWD reduced CH_4 emissions by nearly 30%, according to both observations and simulations. On average, seasonal CH_4 emissions increased by around 6%

with combined treatment of N+RS application under CF (Site 4) compared to mineral N-only application (site 1), while the model simulated an increase of nearly 17%. The IPCC estimated values with N fertilized paddy field under CF and AWD, and with rice straw application suggest average seasonal CH_4 emissions of 200, 114 and 224 kg ha^{-1} which is close to the values predicted by DayCent under similar management (Table 4).

The model simulated a relatively larger peak in daily N_2O flux under CF conditions after the third fertilizer application. The emissions tend to be lower after fertilization, until the land is drained (before harvesting) (Fig. 2g). However, the trend of N_2O emissions was underestimated by the model (0.15 g m^{-2} d^{-1}) during the entire cropping seasons without bias (Fig. 2g, Table 3). The maximum peak of daily N_2O flux was also found under AWD treatment, both in observations and simulations, showing peaks three times higher that under the CF treatment. A few large peaks observed in the field before harvesting were not captured by the model. Although there was not close agreement between modelled and measured flux ($p < 0.05$, $RMSE = 67\%$), no systematic bias was found for either of the management types (Table 3). Overall seasonal N_2O emissions were simulated as 0.61 kg ha^{-1} by model, but were observed to be 0.98 kg ha^{-1} in the measurements (Table 4). N_2O emissions measured in the test site under AWD were 78% higher than measured under CF, while the model predicts 36% higher N_2O emissions under AWD conditions to that of simulated under CF. Based on mineral fertilizer applied, IPCC estimated values in a lowland paddy soil irrespective of water management was 0.52 kg ha^{-1}. Our DayCent values were 13% lower under CF management and 17% higher under AWD than those IPCC estimated values.

The average crop yield under different management types varied from 4240 to 5070 kg ha^{-1} and as with the observations, a higher yield (14%) was attained by the model with combined application of N+RS (Site 4, Table 4).

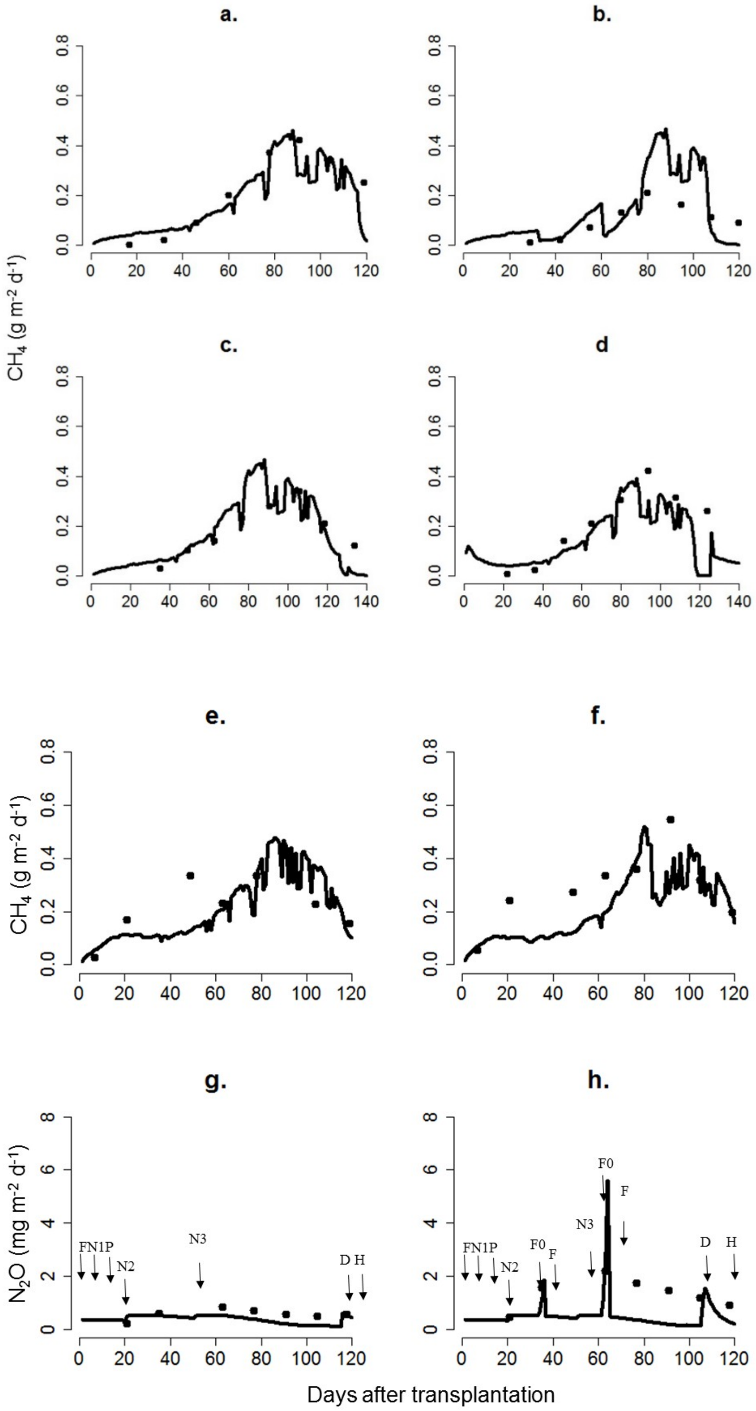

Fig. 2. Daily observed (dots) and simulated (lines) CH$_4$ and N$_2$O flux in paddy rice test sites under different water and nutrient management regimes. Fig. 2a-f daily CH$_4$ flux on four test sites under a) CF with mineral N for BAU site 1, b) AWD with mineral N for BAU site 1, c) CF with mineral N for BAU site 2, d) CF with mineral N for Bhaluka site 3, e) CF with mineral N and rice straw for BAU site 4 for the year 2011 and f) CF with mineral N and rice straw for BAU site 4 for the year 2012 respectively. Fig. 2g-h daily N$_2$O flux on the first test site under g) CF and h) AWD with mineral N. The experimental year for site 1, site 2 and site 3 is 2010. A detailed description

of test sites is available in Table 1. CF: Continuous flood, AWD: Alternate wetting and drying. The letter with the arrow inside the Fig. 2g and 2h denotes: F: flooding, N1, N2 and N3: first, second and third split of mineral N fertilizer, P: planting, D: drainage, F0: No flooding, H: harvesting.

Table 3

The calculation of *r*, *RMSE* and *M* showing *F* (P=0.05, 0.01, 0.001) and critical *t* (2.5% Two-tailed) between simulated and observed daily CH_4 and N_2O emissions under CF and AWD water management at the two paddy rice test sites (description of individual site tests is available in Table 1).

Location (Experimental year)	**Treatment**	**Water regime**	**^{1}Available measured data**	***r***	***RMSE* (%)**	***M* g m^{-2} d^{-1}/ mg m^{-2} d^{-1}**
BAU site 1 (2010)	110 kg N ha^{-1}	CF	CH_4 (8)	0.82**	44.86	0.04^{ns}
		AWD	CH_4 (8)	0.80*	52.78	0.01^{ns}
		CF	N_2O (7)	0.10^{ns}	49.90	0.15^{ns}
		AWD	N_2O (7)	0.65^{ns}	67.35	0.55^{ns}
BAU site 2 (2010)	115 Kg N ha^{-1}	CF	CH_4 (8)	0.96***	25.35	0.01^{ns}
Bhaluka site 3 (2010)	115 Kg N ha^{-1}	CF	CH_4 (7)	0.73*	42.98	0.05^{ns}
BAU site 4 (2011)	110 kg N ha^{-1} + 2t ha^{-1} rice straw (N+RS)	CF	CH_4 (8)	0.75*	39.22	0.02^{ns}
BAU site 4 (2012)	110 kg N ha^{-1} + 2t ha^{-1} rice straw (N+RS)	CF	CH_4 (8)	0.71^{ns}	42.65	0.08^{ns}

[1] Figure in parenthesis in column 4 denotes sample number. CF: Continuous flood, AWD: Alternate wetting and drying.

*Significant correlation (*r*) between modelled and measured values at $p < 0.05$, or significance mean error (M) at $p = 0.025$.

** Significant correlation (*r*) between modelled and measured values at $p < 0.01$.

*** Significant correlation (*r*) between modelled and measured values at $p < 0.001$.

ns = non-significant between modelled and measured values at $p < 0.05$, or no significance mean error (*M*) at $p = 0.025$.

Table 4

Yearly observed and simulated CH_4 (four sites), N_2O emissions (first site) along with IPCC default values and crop yield under contrasting water and nutrient management on selected sites (description of individual site tests are available in Table 1).

Test site	**Water regime**	**CH_4 (kg ha^{-1} yr^{-1})**			**N_2O (kg ha^{-1} yr^{-1})**			**Crop yield (kg ha^{-1} yr^{-1})**	
		Measured	Modelled	IPCC	Measured	Modelled	IPCC	Measured	Modelled
BAU site 1 (2010)	CF	124	210	190	0.55	0.45	0.52	4290	4241
BAU site 1 (2010)	AWD	90	150	114	0.98	0.61	0.52	4350	4118
BAU site 2 (2010)	CF	106	226	206	NA	NA		4189	4593
Bhaluka site 3 (2010)	CF	129	200	200	NA	NA		4450	4980
BAU site 4 (2011)	CF	125	246	224	NA	NA		4900	5070
BAU site 4 (2012)	CF	140	251	224	NA	NA		5020	5050

NA: Measured data not available, CF: Continuous flood, AWD: Alternate wetting and drying.

3.2. Modelling GHG mitigation

Changes in management for GHG mitigation in most cases lead to opposite impacts on CH_4 and N_2O emissions (Fig. 3a). The two exceptions are residue management and RT, which show hardly any change (up to 2%). Application of manure in place of mineral N fertilizer reduces N_2O emissions up to nearly 50% (with CD application) while it increases CH_4 emissions by nearly same amount (with GM application) compared to the baseline. The opposite trend was seen for other management options, including an increase in N_2O emissions by up to 70% under integrated management along with GM (IM2), and up to a 30% decrease in CH_4 emissions under AWD management (site 1 test simulations).

Comparing the relative changes between net GHG emissions (CO_2-eq. ha^{-1} yr^{-1}) using GWP for a 100 year time horizon and yield, GHG emissions were lower with AWD water regimes by 26%, with a negligible yield decline (2%) (Fig. 3b). GHG emissions increased by up to 50% under single manure application, which also reduced yield by around 34-55%. Based on the model results, three options can be selected for reducing emissions without having a negative impact on yield, including from highest to lowest as: AWD > IM1 > IM2 > RT while the best outcomes are achieved under integrated management (IM1 and IM2) which reduced GHG emissions by up to 6% (with IM1), and also increased yield by up to 6% (with IM2).

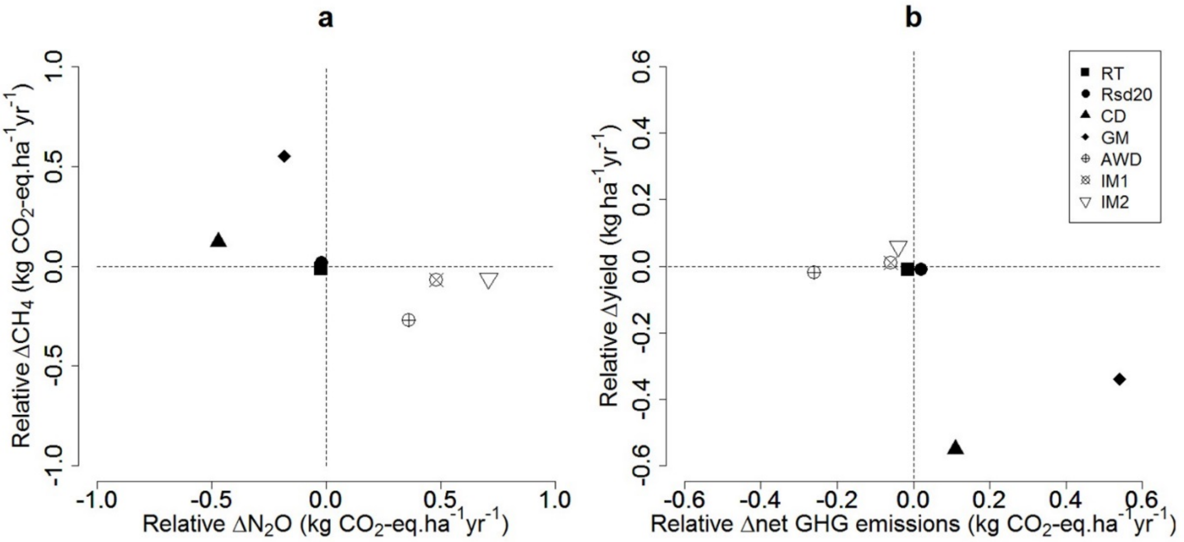

Fig. 3. The relationship between CH_4 and N_2O emissions (a), and total GHG emissions and yield (b) under selected mitigation management options compared to baseline conditions at site 1. RT: reduced tillage; Rsd20: residue return by 20%; CD: cowdung; GM: Green manure; AWD: Alternate wet and drying, IM1: Integrated management of RT with residue return of 15% (Rsd15), CD with 60% of baseline N substitution, AWD and mineral N fertilizer at a current rate of 110 kg ha^{-1}, IM2: Integrated management of RT with residue return of 15% (Rsd15), GM with 40% of baseline N substitution, AWD and mineral N fertilizer at a current rate of 110 kg ha^{-1}.

Maximum GHG reductions were seen for AWD, with a yield scaled emissions intensity about 24% lower than under CF, followed by IM1 and IM2, respectively (Fig. 4). The change in emissions intensity was negligible under adoption of tillage and residue management (<3%), while it was predicted to be 1.3-1.5 times higher under manure application scenarios.

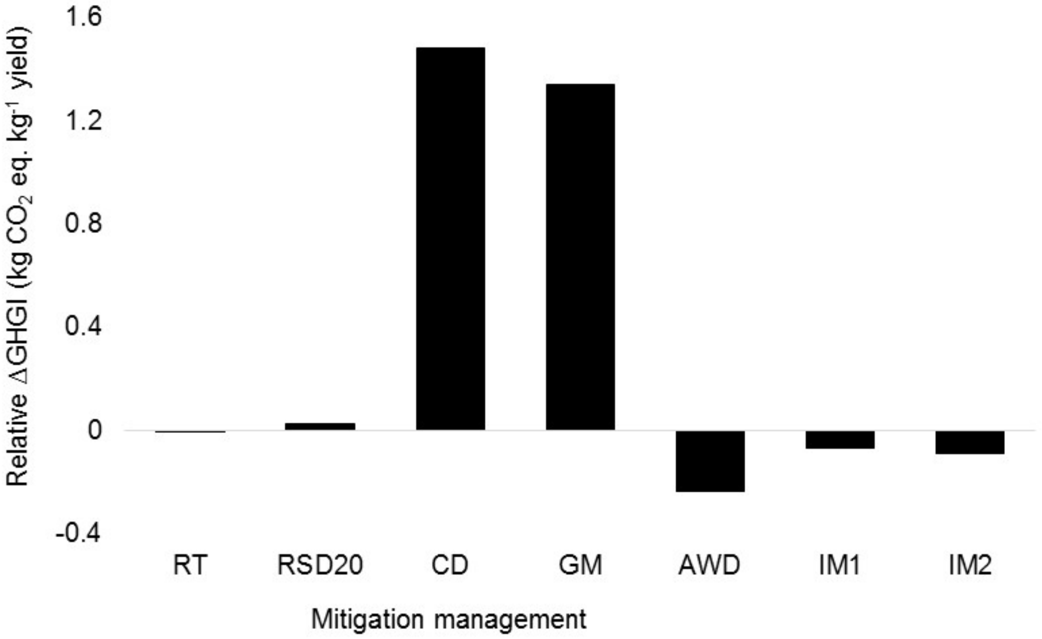

Fig. 4. Relative changes of GHG emissions intensity under selected mitigation management practices in irrigated paddy fields in Bangladesh. RT: reduced tillage; Rsd20: residue return by 20%; CD: cowdung; GM: Green manure; AWD: Alternate wet and drying, IM1: Integrated management of RT with residue return of 15% (Rsd15), CD with 60% of baseline N substitution, AWD and mineral N fertilizer at a current rate of 110 kg ha^{-1}, IM2: Integrated management of RT with residue return of 15% (Rsd15), GM with 40% of baseline N substitution, AWD and mineral N fertilizer at a current rate of 110 kg ha^{-1}.

4. Discussion

4.1. Modelled CH_4 and N_2O emissions and yield

Simulation of substrate C available for methanogenesis by DayCent under different water and nutrient management is crucial for predicting CH_4 emissions accurately (Cheng et al., 2013). A large CH_4 flux was simulated at plant maturity stage in the month of April-May, when carbohydrates derived from plant was greater. Higher temperature is another controlling factor that favours methanogenic bacteria, hence CH_4 emissions (Zhang et al., 2013; Neue and Scharpenseel, 1984). In the test sites, higher temperatures were observed at the plant maturity stage, which favours methanogenic activity (Ali et al., 2012). In response to measured soil temperature of 26-32 ^{0}C, the simulated soil temperature was predicted to be 20-30 ^{0}C. DayCent-simulated soil Eh under CF water regime was relatively high, predicted to be -188 mV compared to that of -81 mV under AWD conditions. The measured Eh in the real field under CF and AWD water regime were reported as -95 mV and -71 mV, respectively (Ali et al., 2013).

A difference between seasonal modelled and measured CH_4 emissions was observed, but this might be expected since cumulative emissions were calculated using relatively few data points (Ali et al., 2013; Ali et al., 2014). The impact of different nutrient management and water regimes on CH_4 emission was satisfactorily replicated by the model. Compared to CF, DayCent simulated lower water filled pore space, enhanced aerobic microbial activity and thereby Eh, and overall reduced CH_4 emissions under AWD conditions. In contrast, increasing labile C with organic matter application (rice straw for site 4) in a continuously flooded soil tended to increase CH_4 emissions compared to a mineral N fertilized sites (site 1). The cumulative seasonal CH_4 emissions for irrigated rice from Bangladesh field experimental studies, found to vary from 98 to 800 kg ha^{-1} depends on water management, nutrient management and farming practices (Ali et al., 2013; Ali et al., 2014, Frei et al., 2007). Using an empirical model CH_4MOD2.5, the average annual CH_4 emission from irrigated rice with mineral N and farmyard manure application was estimated by Khan and Saleh (2015) to be 237 kg ha^{-1}. Modelled seasonal CH_4 emissions compared well with estimates using the IPCC Tier 1 methodology and previous studies.

Our model results showed that N_2O emissions peaks were driven by water management and fertilization. Both the observations and DayCent simulations suggest lower N_2O emissions for flooded paddy soil compared to AWD management. A slight underestimation of N_2O emissions by the model in CF conditions could be attributed to a limited source of N, or lack of nitrification under flooded conditions. The default values of N_2/N_2O ratio in DayCent were set in a way to simulate less N_2O emissions from saturated soils, while in real fields there might be external sources of N, including from aquatic weeds and algae (Roger and Ladha, 1992; Ladha et al., 2016); these are not considered in the N and C balance of the model. Further, O_2 released from the rhizosphere zone of paddy fields might enhance nitrification and denitrification processes and increase N_2O emissions (Babu et al., 2006). Although there are no zero input treatments among the selected tested sites, Gaihre et al., (2015) found around 0.07 kg ha^{-1} N_2O emissions from unfertilized plots at two irrigated rice test sites associated with CF conditions in Bangladesh. This is one potential reason for the slight underestimation of modelled N_2O emissions compared to the measurements. Relatively higher N_2O emissions were simulated under AWD management compared to CF, which could be attributed to anaerobic-aerobic conditions that influence microbial nitrification, thereby the denitrification process. In AWD systems, the model simulates enhanced nitrification in presence of O_2, and denitrification when the soil is saturated. In reality, it is not always possible to control the water level in paddy fields. The measured peak at the pre-harvesting stage missed by the model. The soil NO_3^--N concentration in the tested site was found to be three times higher in AWD systems compared to CF measured at pre-harvesting stage, (not shown), while similar N_2O emissions were predicted by the model for the same period. The emission factor (EF) for N_2O emissions under flooded paddy rice was simulated by the model to be 0.4% of applied fertilizer, which is slightly lower than the observations (0.5% of applied fertilizer), but slightly higher than the IPCC default EF (0.3% of applied fertilizer). A relatively higher EF for AWD systems (0.6% of applied fertilizer) suggests that a separate EF for paddy rice under alternative water management should be considered, as was suggested by Shepherd et al. (2015). Their study found EF values (relative to N applied) for paddy rice under urea application in neutral soil of

0.03% under CF, and 0.31-0.72% under reduced water use management, and in high acidity soil they found an EF of 0.16% under CF and 0.22% under intermittent saturation conditions.

4.2. Mitigation scenarios and net GHG balance

As with previous studies (Ali et al., 2013; Ma et al., 2013; Wang et al., 2013), our modelled results found a trade-off among the major GHGs with different management options. Based on modelled results, it is recommended that both CH_4 and N_2O need to be considered together along with the yield impact before implementation of alternative management practices. Methane emissions from flooded paddy rice appear to be dominant followed by N_2O emissions, irrespective of management, as observed in previous studies (Zhang et al., 2013). Applying the same amount of N in the form of manure does not give as high a yield, and increases total GHG emissions. Our model results suggest that N mineralization through application of manure might not be large enough to ensure the potential yield. More residue incorporation, or use of manure, might not be possible if yields are reduced, and may be limited by socioeconomic consequences in Bangladesh. Increasing levels of crop residue incorporation in Bangladesh is quite challenging because of the use of residues for other household purposes, e.g., as a fuel or fodder for animals (Hossain, 2001; Haider, 2013; Huq and Shoaib, 2013). Similarly, there is a restriction to applying all the manure produced in Bangladesh as an organic amendment, because CD has alternative uses, e.g., as fuel and biogas (BLRI, 2017; Huq and Shoaib, 2013). Among the selected single scenarios, AWD management is considered to be an effective option which has only a slight impact on current yield, but reduces total GHG emissions by 26% relative to the baseline. This outcome agreed well with the findings Ali et al. (2013) which were 24-26% reductions in total GHG emissions from AWD practices on this site. The model also matches well with decrease of emission intensity of 24% reported by Ali et al. (2013). Although additional costs are likely to be higher initially due to the need for weeding, overall labour costs are found to decrease compared to traditional systems (Rejesus et al., 2011), and water is saved (Price et al., 2013). Our model results also suggest that integrated management associated with RT coupled with 15% crop residue return, application of GM along with current mineral N fertilizer and AWD management appears to be the best option for reducing GHG emissions and increasing crop yield. Emission intensity also found to be reduce under this approach. The impact on GHG mitigation under this integrated management, however, is lower than for AWD only, but positively impacts on yield. Applying DNDC model in China paddy filed, Tian et al., (2018) found that combined midseason drainage and balanced fertilization leads to reduced CH_4 and N_2O emissions without yield penalty.

DayCent cannot simulate water level of the rice field but there is scope to improve the water sub-model in DayCent to better reflect the real field conditions. The current version of DayCent manipulated the water table by FLOD events set by the model. The Eh in soil changes based on the flooded or drainage conditions. Continuous flooding, whether by rainfall, irrigation or both, would be a FLOD 2 period in the model schedule, with maximum Eh of -250 mV (Cheng et al., 2013, Weiler et al., 2018). The water conditions under rainfall do not saturate in the model, therefore fixed values (-20 mV) were indicated as FLOD 1. Eh approximations are specific to the methane model. Further development of the Eh algorithm was suggested by Weiler et al., (2018), where they found contrasting results between simulated and observed CH_4 emissions in flood-irrigated rice paddy fields under no tillage in southern Brazil. Soil water and gas filled pore space in the current version are normal inputs to the N_2O emissions, but are not currently considered in the methane Eh equations.

The model was tested with only 7-8 observations. The data were not recorded routinely in an hourly or daily basis due to lack of funding and manpower. There are no field experiments that test the efficacy of mitigation practices in Bangladesh, which is why we are attempting to model them here. In this paper, we have tested the model against the best (though imperfect) datasets available in Bangladesh to show that the model can adequately capture the impacts of soil types, climate, management and water status on CH_4 and N_2O emissions. We aimed to show through this step that the model is able to capture the influence of these factors on emissions. Having demonstrated that the model performs adequately, and that we have some confidence in model predictions from this validation, we have then applied the model to explore potential mitigation options. Given that there are no field data on mitigation options, we cannot perform a further validation of the model; instead we aimed to show direction and magnitude of impacts, which we hope will be tested through future field experiments. The testing of the model against the only available field data is our only option for validation, and from our results, we suggest that model performance is adequate for testing the mitigation options. We have focussed on relative changes in GHG emissions from different management practices rather than absolute values, due to the acknowledged limitations in the validation data. We hope this study can be used to guide further research on CH_4 and N_2O emissions from Bangladesh paddy soils.

Due to lack of measured data, GHG mitigation is estimated here without considering CO_2 emissions. The contribution of CO_2 emissions from agriculture is lower to that of other anthropogenic sources (Smith et al., 2007, Cheng et al., 2014). Additionally, for paddy fields, CH_4 and N_2O emissions dominate the overall GHG balance (Wang et al., 2017). For this study, the relative GHGI under the selected integrated approach was predicted to be the same without considering CO_2 (not presented). Total GHGI under AWD was found to be 5% lower when considering all three GHGs compared to when only CH_4 and N_2O were considered. Although CO_2 emissions from agriculture are small, it is crucial to estimate SOC sequestration potential from paddy fields in order to improve soil quality. Around 90% of total GHG mitigation from agriculture globally is estimated to be from SOC sequestration (Smith et al., 2007). Applying

DayCent model in a long term double rice system in Bangladesh, located at BAU, Begum et al., (2018b) predicted SOC changes of -0.05 to 0.36 t C ha^{-1} yr^{-1} under different management scenarios. Therefore, further refinement is possible to measure SOC, CH_4 and N_2O for the same sites to evaluate total GHG mitigation potentials and yield impacts of GHGs in Bangladesh.

If these results could be scaled to the country level, if 50% of the harvested area under irrigated rice were under integrated management, a reduction of approximately 1.40 Tg CO_2-eq. yr^{-1} could be realised. This rough estimate could vary depending on availability and applicability of manure, and taking into account the amount already being applied. Crop yield is considered as the main priority in developing countries, so there is no opportunity to reduce mineral fertilizer use, but farmers have been encouraged to increase N use efficiency. Deep placement of fertilizers, rather than applying urea in a traditional broadcast method, increases N use efficiency and yield while reducing N_2O emissions (Gaihre et al., 2015). Changing the composition in mineral fertilizer is another mitigation approach that may increase yields while reducing N_2O emissions. An alternative model experiment (data not presented), using 50% ammonium N (NH_4^+-N) and 50% NO_3^--N, compared to 100% of NH_4^+-N as in urea, or using nitrification inhibitor under integrated approach, reduced net GHG emissions by 4%, while increasing yield by 6%. Recent field experimental studies Bangladesh paddy rice field, found an increase of both CH_4 but mitigate N_2O emissions with the use of biochar amendment while increasing yields (Ali et al., 2013). The development of biochar amendment simulations in DayCent is ongoing.

4. Conclusion

The results presented here suggest that there is scope to reduce GHG emissions from rice production in Bangladesh by modifying current agricultural management practices. By modifying traditional flooding practice, it is possible to reduce net GHG emissions (CO_2-eq.

ha^{-1} yr^{-1}) from paddy soil by ~26%. Although such management leads to a slight yield decline, farmers can also save water from irrigated rice by adoption of AWD systems. Integrated management that consider RT, more residue return, AWD and GM application along with mineral N fertilizer, is predicted to increase yield while reducing emissions. As farmers become more interested in yield, an integrated approach is likely to be the most effective approach to maintain or increase yields while also reducing GHG emissions in rice production systems of Bangladesh. Further measurements of emissions for tillage and manure (CD and GM) practices are necessary before implementing the model outcomes.

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