Research Article

Spatio-temporal distribution of reactive nitrogen species in relation to wheat cultivation in Bangladesh

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Abstract

Farmers generally use more nitrogen fertilizer than others for crop production in Bangladesh because of its visible growth symptoms. Such practice is responsible for extra reactive N (Nr) load to the environment, but data are not available. Nitrous oxide (N_2O) data were collected from a field trial following static closed-chamber technique, which were used for calibration and validation of DeNitrification and DeComposition model along with soil clay fraction, pH, bulk density and organic carbon contents. The model was well fitted and estimated about 364 g N_2O–N ha^{-1} emission in Rajshahi region and only 15 g N_2O–N ha^{-1} in Barisal region. District-wise N_2O–N emissions varied from < 1–15.96 t $season^{-1}$. In 2011–2016, N_2O–N emissions from wheat fields were about 103–129 t yr^{-1} in Bangladesh. The model estimated nitric oxide (NO), ammonia (NH_3) and nitrate (NO_3) fluxes varied from 0.012 to 0.447, 7 to 12.5 and 0 to 4.7 kg N ha^{-1}, respectively, under ambient temperature condition. In about 79% yield variabilities were explainable by N_2O emission. In dominant wheat growing areas, if sowing is started from 15 to 30 November, N_2O emission could be reduced by 8–40% with 5–13% reduction in yields compared to 10 November sowing. In similar areas and same sowing date with 1.5 °C temperature rise, N_2O emission may increase by 8–45% and wheat yield might reduce by about 4–8%. Time of seeding and other cultural management in wheat cultivation would be the main avenue for reducing Nr loads to the environment.

Keywords Static close chamber · DNDC · Temperature rise · Sowing time · Yield

1 Introduction

Nitrous oxide is an important greenhouse gas (GHG) with a global warming potential of 265-fold greater than carbon dioxide (CO_2) within 100-year period [1]. It contributes about 6% to the global warming [2] because of anthropogenic interventions for crop production. Agricultural soils supply about 60% of the anthropogenic N_2O, which is mostly because of increased chemical fertilizer use [3]. With increasing food demands, N_2O emissions from agricultural soils are likely to be increased in future [4, 5] because of greater amounts of nitrogen (N) uses. Since factor productivities of N have decreased in many countries, farmers are adding more to maximize production resulting in greater N_2O emission from soils under different cropping systems [4, 6].

Cropping intensity has been augmented in many parts of the world to produce more food for the growing populations resulting in tremendous pressures on soil health and its fertility. In Bangladesh, soil health and its fertility status are decreasing [7, 8] because of intense utilization of soil and water resources, while on the other hand, land area is decreasing because of industrialization and urbanization but we have to produce from less area that must

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come from marginal and degraded soils. Increased salinity and soil mineralization are other type of challenges for producing more foods under changing climate, especially for major cereal production in Bangladesh including other tropical countries.

Rice, wheat and maize are the major cereals in Bangladesh in which rice and wheat crops are involved with many cropping patterns and wheat–fallow–rice pattern covers 1.061% of net cropped areas [9]. Although there are fertilizer recommendations from national agricultural research systems for growing different crops, farmers generally use more N rates than other fertilizers resulting in additional release of Nr to the environments [10, 11]. In general, the main sources of Nr are cultivation-induced biological N fixation, fossil fuel combustion (NOx) and use of ammonia producing fertilizers [12, 13]. Besides, animal waste management is also responsible for N_2O emissions. As global surface temperature is increasing, it is most likely that emissions of Nr will be greater in future because of enhanced microbial activities, but not much information is available in Bangladesh that needs to be investigated in relation to wheat cultivation.

Since rice and wheat crops grow in diverse agro-ecological regions of a country, there would be variations in Nr emission patterns under multidimensional agronomic management options. Either direct or indirect measurement technique can be adopted for measuring Nr emission, but it would be very costly to establish sophisticated laboratory for direct measurements from different parts of the country. Under such situations, crop model like DeNitrification and DeComposition (DNDC) would be very cost-effective. We hypothesize that there are spatio-temporal variations in Nr loads to the environment because of wheat cultivation in Bangladesh and it will vary depending on temperature regimes. Therefore, we have investigated the distribution patterns and quantity of Nr emissions from wheat fields in Bangladesh under ambient and 1.5 °C increased temperature conditions.

2 Materials and methods

Data were collected from field experiment and secondary sources. Primary data collection on N_2O emissions were done as stated below:

2.1 Experiment set up

The experiment was conducted at the Bangladesh Agricultural Research Institute, Gazipur (24°00′ N, 90°25′ E), Bangladesh. Soil belongs to Chhiata series of grey terrace soil, an Inceptisol. The treatments used were: native fertility (control) and recommended N dose from urea. The experiment was laid out in a randomized complete block design with four replications. Wheat (BARI Gom-30) seeds were sown in continuous line at 120 kg ha^{-1} on 28 November 2018 with row to row spacing of 20 cm. Fertilizers were used at $N_{150}P_{40}K_{120}S_{20}Zn_{1.5}B_1$ kg ha^{-1} as urea, triple superphosphate, muriate of potash, gypsum, zinc sulphate (hepta) and boric acid, respectively. The unit plot size was 4 m × 2.5 m. Two-third N and all quantities of P, K, S, Zn and B fertilizers were applied during final land preparation. Different intercultural operations such as irrigation, weeding and pest control were done as and when required. The rest amount of N was applied at crown root initiation stage of wheat.

2.2 Chemical analyses of soil samples

Initial soil samples were collected from the surface layer (0–15 cm), composited and air-dried. Sieved soils (< 2 mm) were analysed for pH (1:2.5water extraction), soil organic carbon (SOC) [14, 15], total N [16], available Olsen P [17], 0.16 M Ca $(H_2PO_4)_2$ extracted S [17] and DTPA extracted Zn [18].

2.3 Gas sampling and analysis

Static closed-chamber method [19] was used to estimate N_2O emission rate. Opaque acrylic column chambers (20 cm diameter and 50 cm height) were placed between wheat row [20]. The bottom 20 cm of the chamber was inserted into soil surface to prevent plant root intrusion. Weeds were removed continuously from the chambers during crop growing period. Chambers were kept open under the study period except during gas sampling. The chamber was equipped with a circulating fan for gas mixing and a thermometer to monitor temperature during sampling time.

Air gas samples were collected using 50-mL gas-tight syringe at 0 and 30 min after chamber closing. Gas samplings were carried out at 8:00, 12:00 and 16:00 h in a day. Three gas samples from each replication of a treatment were drawn off from the chamber headspace equipped with 3-way stop cock. Collected gas samples were immediately transferred into 20-ml air-evacuated glass vials sealed with a butyl rubber septum and then analysed by gas chromatography (Shimadzu, GC-2014, Japan) with Porapak NQ column (Q 80–100 mesh). A ^{63}Ni electron capture detector (ECD) was used for quantifying N_2O concentration. The temperatures of the column, injector and detector were adjusted at 70, 80 and 320 °C. Argon, helium and H_2 gases were used as the carrier and burning gases, respectively.

Nitrous oxide emission rates were calculated from the increase in its concentrations per unit surface area of the chamber for a specific time interval. A closed-chamber equation [21] was used to estimate seasonal fluxes as follows:

$$F = \rho \times (V/A) \times (\Delta c/\Delta t) \times (273/T)$$

where F is the N_2O flux (μg N_2O m^{-2} h^{-1}), ρ is the N_2O gas density under a standardized state (mg cm^{-3}), V is the volume of the chamber (m^3), A is the surface area of the chamber (m^2), $\Delta c/\Delta t$ is the rate of increase in N_2O gas concentration (mg m^{-3} h^{-1}) and T (absolute temperature) is 273 + mean temperature (°C) of the chamber.

Seasonal N_2O flux for the crop growing period was computed according to Singh et al. [22]:

$$\text{Seasonal } N_2O \text{ flux } = \sum_{i}^{n} \left(R_i \times D_i\right)$$

where R_i is the rate of N_2O flux (g m^{-2} d^{-1}) in the ith sampling interval, D_i is the number of days in the ith sampling interval and n the number of sampling.

2.4 Secondary data collection and use of the model

Soil data from the existing literature and from our analyses were used for running DeNitrification and DeComposition (DNDC) model. Data on wheat areas and grain yields were collected from Bangladesh Bureau of statistics [23, 24] along with our field experiment. Soil parameters for different districts were adopted from soil resource development institute and our own data. The DNDC model was calibrated and validated using soil clay fraction, pH, bulk density and organic carbon contents. Performance of the model was evaluated as prediction error (P_e), coefficient of determination (R^2), normalized root mean square error (NRSME) and Willmott's index of agreement (d) as shown in equations of 1–4. The model was well fitted in terms of observed and estimated N_2O emissions (Fig. 1). Reactive nitrogen emission rates and its total emissions from different wheat growing regions of Bangladesh were estimated under ambient and 1.5 °C [25] rise in temperature conditions. Total N_2O emission in different wheat growing areas was calculated as follows:

$$\begin{aligned}\text{Total } N_2O \text{ emission } &\left(\text{kg N ha}^{-1}\right)\\ &= N_2O \text{ emission rate } \left(\text{g N ha}^{-1}\right)\\ &\ast \text{ Area coverage (ha)} \ast 1000.\end{aligned}$$

Relationships of grain yields with N_2O emissions were established through regression model. The effect of sowing time and increased temperature on grain yield was investigated for Thakurgaon (one of the important wheat growing areas) district by utilizing DNDC model. Seeding time considered was 10 November to 20 December at 5-day interval. Standard agronomic management options were considered and weather data were collected from Bangladesh Meteorological Department.

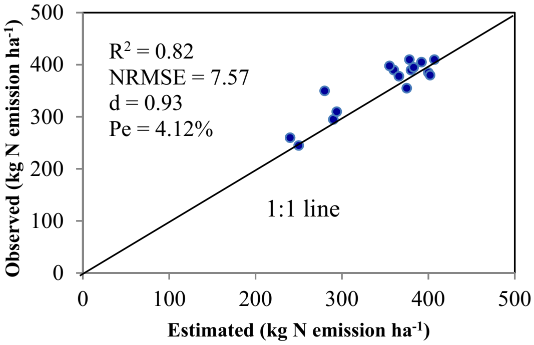

Fig. 1 Observed and estimated N_2O emissions from wheat field, BARI, Gazipur

2.5 Statistical tools used

Model calibration was done using following formulas:

$$P_e = \frac{\left(P_i - O_i\right)}{O_i} \times 100 \qquad (1)$$

$$R^2 = \left[\frac{\sum(Oi - \overline{O})\left(Pi - \overline{P}\right)}{\sqrt{\sum\left(Oi - \overline{O}\right)^2 \sum\left(Pi - \overline{P}\right)^2}}\right]^2 \qquad (2)$$

$$NRMSE = \frac{1}{\overline{O}}\sqrt{\frac{\sum(Pi - Oi)^2}{n}}100 \qquad (3)$$

$$d = 1 - \frac{\sum(Pi - Oi)^2}{\sum\left(/Pi - \overline{O}/ + /Oi - \overline{O}/\right)^2} \qquad (4)$$

where P_i and O_i is the predicted and observed data, $\overline{P}$ is the mean of predicted data and $\overline{O}$ is the mean of observed data.

Regression model to show relationship between grain yields and nitrous oxide emissions was established after stepwise evaluation. Student's t-test was employed to compares means.

3 Results

3.1 Nitrous oxide emission rate and total emission

Under present temperature condition, N_2O emission rates varied from 25 to > 350 g N ha^{-1} (Fig. 2a). In about 62.6% wheat growing areas, N_2O emission rate was 150–350 g N ha^{-1} and in 12.4% areas, it was > 350 g N ha^{-1}. Total N_2O emissions varied from < 50 to > 12,000 kg N $season^{-1}$ depending on area coverage and locations of the country (Fig. 2b). The highest total N_2O emissions were found in about 3% of wheat growing areas, and in about 10.7% areas it was 4000–12,000 kg N $season^{-1}$.

With rise in temperature by 1.5 °C in future, the emission rates of N_2O are likely to vary from < 60 to > 400 g N ha^{-1} (Fig. 3a). It could be 200–400 g N ha^{-1} in about 62.5% wheat growing areas of the country. Like ambient temperature condition, total N_2O emission in future would be < 50 to > 13,000 kg N $season^{-1}$ (Fig. 3b), indicating that there might be some increase in total N_2O emissions.

Based on administration boundaries, total N_2O–N emissions were mostly observed in Khulna (14.54–15.49 t yr^{-1}), Dhaka (19.96–24.86 t yr^{-1}), Rangpur (27.01–35.77 t yr^{-1}) and Rajshahi (41.53–53.56 t yr^{-1}) divisions (Fig. 4). The

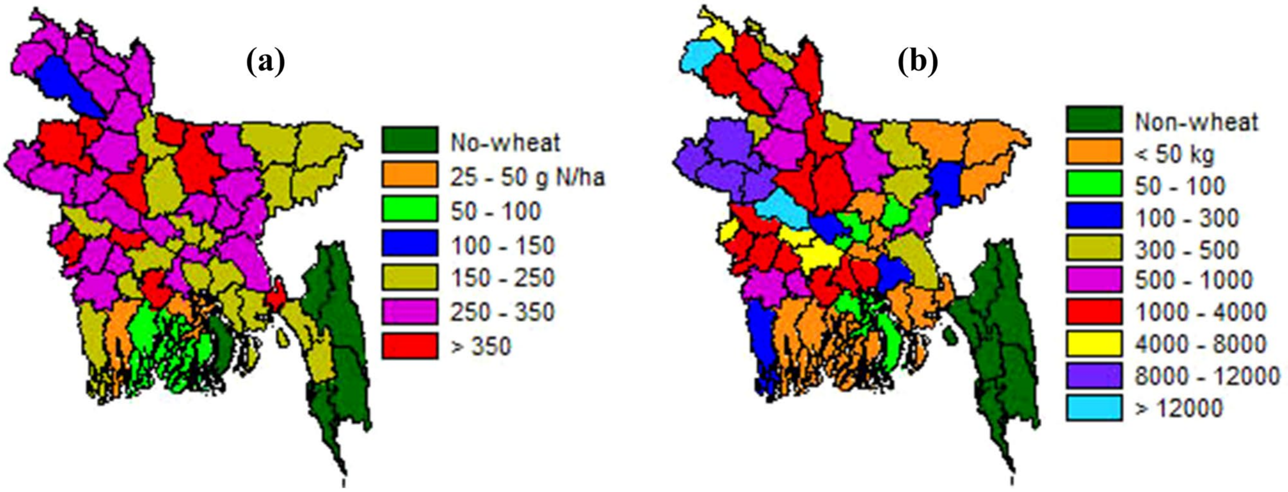

Fig. 2 Nitrous oxide (**a**) emission rate (g N ha^{-1}) and (**b**) total emission (kg N $season^{-1}$) from wheat field under ambient conditions

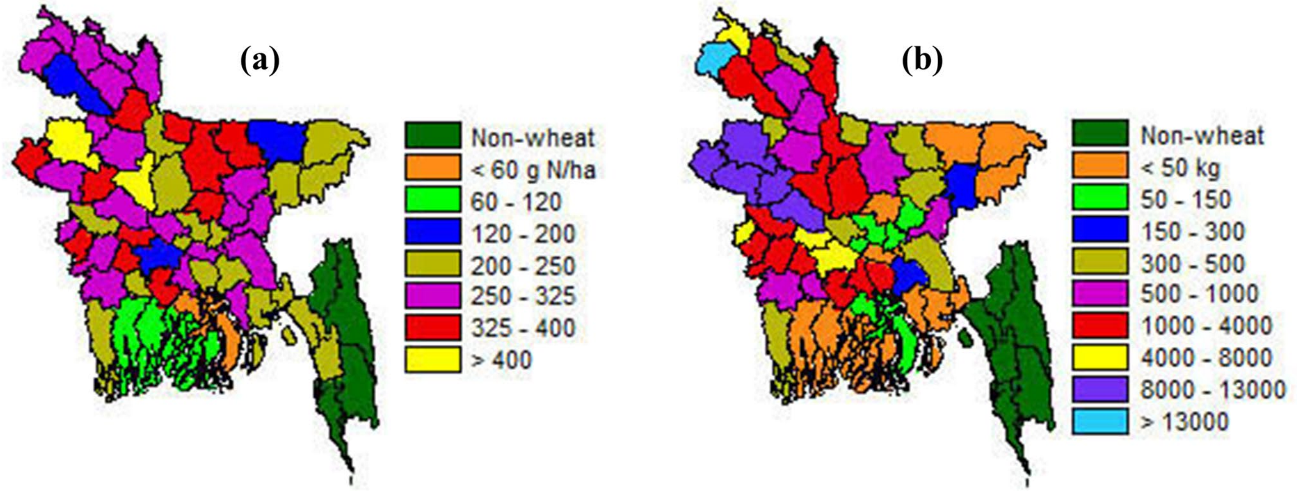

Fig. 3 Nitrous oxide emission (**a**) rate (g N ha^{-1}) and (**b**) total emission (kg N $season^{-1}$) from wheat fields under 1.5 °C rise in temperature

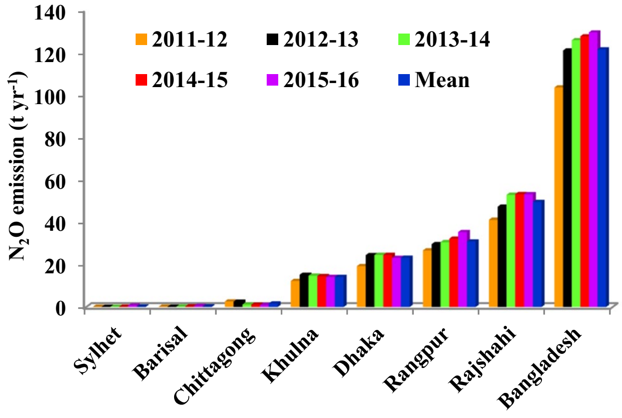

Fig. 4 Total nitrous oxide emission from wheat field in Bangladesh during 2011–2016

least N_2O–N emitting divisions were Sylhet, Barisal and Chittagong. During 2011–2016, total N_2O–N emissions in Bangladesh were about 103–129 t yr^{-1}.

3.2 Ammonia, nitrate and nitric oxide load to environment

DNDC-estimated loads of ammonia (NH_3) to the environment were 7.21–12.45 kg N ha^{-1} under ambient temperature, which were 0–12.82 kg N ha^{-1} with 1.5 °C rise in temperature (Table 1). Similarly, nitrate (NO_3) loads were 0–4.67 kg N ha^{-1} under ambient temperature that slightly reduced (0–3.81 kg N ha^{-1}) with 1.5 °C rise in temperature. Nitric oxide (NO) emissions varied from 12 to 447 g N ha^{-1} under ambient temperature, which showed a little reduction (0–433 g N ha^{-1}) under 1.5 °C rise in temperature.

3.3 Relationships of N_2O emission with grain yield

Grain yield of wheat showed a good relationship with N_2O emissions ($R^2 = 0.786$). Major share of grain yield variabilities (about 79%) was explainable with N_2O emission rates (Fig. 5).

3.4 Effects of sowing time and temperature rise

In general, grain yield of wheat was decreasing depending on delayed sowing dates compared to 10–15 November seeding under both ambient and 1.5 °C rise in temperature conditions (Fig. 6a). Similarly, growth durations were decreasing with delayed seeding (Fig. 6b). However, about 8–40% N_2O emission can be reduced by sowing wheat seeds in between 15 and 30 November with 2–13% grain yield reductions compared to 10–15 November sowing (Fig. 7).

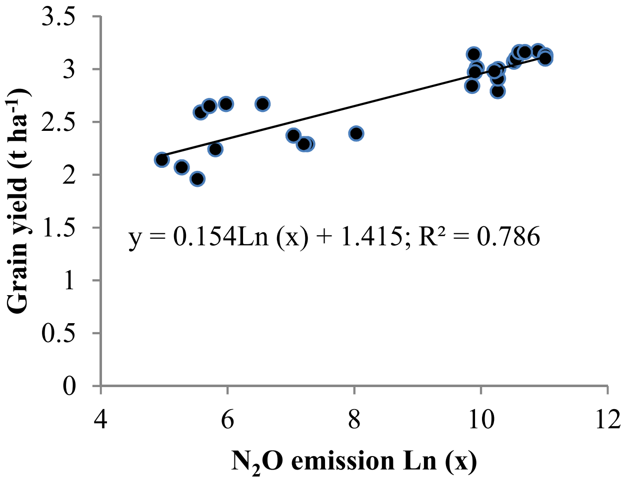

Fig. 5 Relationships of wheat grain yield with N_2O emissions

4 Discussion

The DNDC model estimated N_2O emission with < 5% prediction error. Other parameters like R^2 (0.82) was close to 1 indicating good agreement [26], NRMSE was 7.57 which is less than 10% indicating excellent simulation [27], and *d* value was close to unity (0.93). Depending on model calibration parameters, we believe that our findings are reproducible under similar conditions.

The calibrated and validated DNDC model estimated N_2O emissions varied greatly both under ambient and 1.5 °C rise in temperature conditions in different locations of the country (Figs. 2 and 3) might be because of soil types, nature of soil fertility and its moisture contents. Besides, there were variations in soil pH (4.38–8.12) that have influenced N_2O emission rates. Similar results were reported by Wang et al. [28]. They found that N_2O emission factor increases significantly with decrease in soil pH

Table 1 Ammonia, nitrate and nitric oxide loss during wheat cultivation in Bangladesh under ambient and 1.5 °C increased temperatures

	Ammonia (kg N ha^{-1})			Nitrate (kg N ha^{-1})			Nitric oxide (g N ha^{-1})		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean
Ambient	12.45	7.21	9.38	4.67	0	1.13	447	12	361.28
1.5 °C increased	12.82	0	9.09	3.81	0	0.99	433	0	343.69

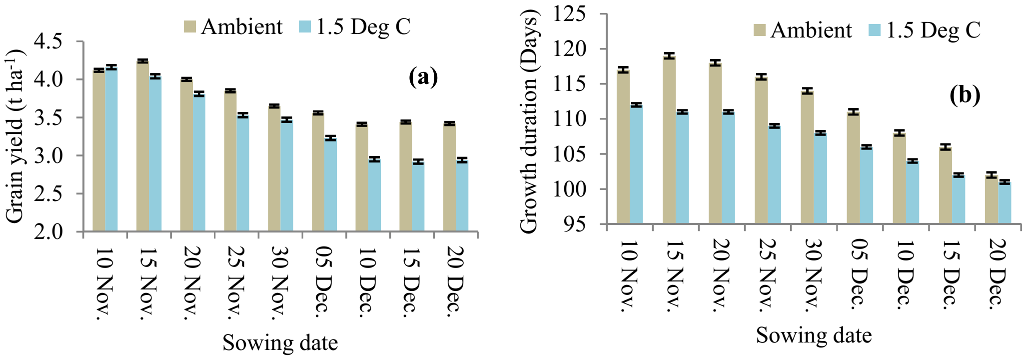

Fig. 6 Influence of sowing time and temperature rise on (**a**) grain yield and (**b**) growth duration of wheat in Thakurgaon, Bangladesh

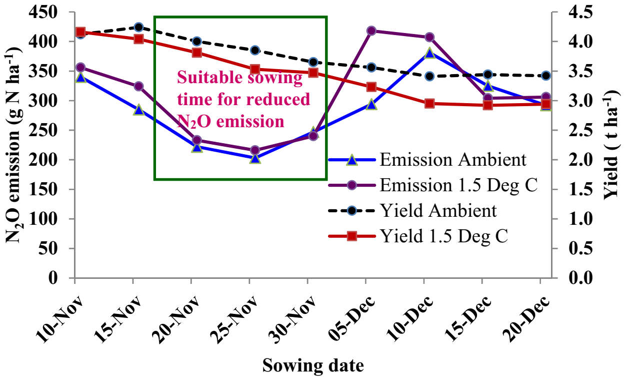

Fig. 7 Grain yield of wheat and estimated N_2O emission as influenced by time of sowing, Thakurgaon, Bangladesh. Small bar indicates standard of error of means

and its emission in acidic soils were more sensitive to N management than in alkaline soils. Samad et al. [29] also reported that pH was strongly and inversely associated with N_2O emissions. There were variations in total N_2O emissions during 2011–2016 in all major wheat growing areas of Bangladesh but were mostly concentrated in Rajshahi and Rangpur divisions (Fig. 4), the major wheat growing areas of the country. Such variations were related to wheat area coverages over the years and N_2O emission rates. Rice, wheat, maize, potato, mustard, pulses, onion, garlic, etc. are grown during winter season in Bangladesh, indicating that farmers have many choices to grow a particular crop that generally depends on seed availability, profitability and own consumption requirements. So, wheat areas varied in every year and thus total N_2O emissions. Although we have used recommended fertilizer dose and standard crop management practices, farmers in many cases do not follow standard production practices and thus there would be less or higher Nr emissions from wheat fields that need to be confirmed through field observations. Since no data on Nr emission from wheat fields are available in Bangladesh, our findings can be utilized as benchmark data for Nr loads to the environment.

Agricultural practices, especially increased N fertilizer rates, greatly influence N_2O emissions [3, 30]. So, it is most likely that there are spatial variations in N_2O emission at farm levels because of variable fertilizer doses used by the farmers. Panek et al. [31] reported that both nitrification and denitrification also contribute to N_2O emissions. Although uncertainty range for N_2O emission could be 0.3–3.0 kg N_2O per 100 kg N applied, generally 1.0 kg N_2O emission is likely for every 100 kg N application [32]. But in major wheat growing areas (more than 60% areas), we have found 0.2–0.5 kg N_2O emission per 100 kg added N, indicating that N_2O emission is less than IPCC guideline for Bangladesh. Wallace et al. [33] found 75–270 g N_2O-N ha^{-1} in whole growing season, which is similar with our findings. They also reported that 14–22% of applied N is lost as N_2O emission. On the contrary, UNEP [34] reported that 80% of applied N is lost to the environment as NH_3, nitrogen oxides and NO_3. These variations might be because of uncertainty of N_2O emission as associated with its negative fluxes of ± 0.5 to ± 378.6 $\mu g\ m^{-2}\ h^{-1}$ during wheat growing season [35] along with production practices such as sowing time, fertilizer dose and irrigation water management. Moreover, indigenous N fertility varies among soils in different locations of a country and thus played an important role in varied N_2O emission patterns.

The loads of NH_3 in relation to wheat crop cultivation were the highest compared to NO_3 and NO under ambient temperature, which were almost similar with 1.5 °C rise in temperature. Since NH_3 volatilization is dependent on temperature and soil pH, its loss to the environment could be higher in future because of global surface temperature rise. As Nr emissions are likely to increase in future, environmental loads of all Nr except N_2O could be responsible for smog, air pollution and freshwater eutrophication [36], while on the other hand, N_2O play an important role in global warming indicating that its emission rates need to be reduced through efficient utilization of added N fertilizers. Although adequate data are available on N_2O emissions, modest quantitative information is available on NO fluxes, especially with wheat crop production [37, 38] indicating that some more works are yet needed. The estimated NO emission from Asian cultivated soils was 0.8–1.2 Tg NO–N yr^{-1} in 1980s and 1990s [37]. Our findings on NO emissions could be utilized to update such data. As emissions of NO are sporadic depending on N fertilizer application time, drying and wetting of soils, continuous measurements at least on daily basis are needed, but it is costly and sometimes opportunities are not available in developing countries. So, our estimated technique can be utilized for assessing NO emissions from wheat fields.

In Asia, Nr transfers to the atmosphere as NH_3 volatilization could be 19 Tg N yr^{-1} in coming three decades in which contribution of India would be 29% [39]. However, all emitted NH_3 returned to the surface because of deposition [39, 40]. There are also variations in N_2O emission in Asian countries. For example, India and China contribute about 74% of total N_2O emissions from agriculture [41] and thus create transboundary environmental hazards [42]. These indicate that Nr loads to the environment should be minimized without sacrificing grain production in south Asia and other countries.

The relationship of wheat grain yields with N_2O emissions was well explained by the function, $y = 0.154\text{Ln}(x) + 1.415$. This function suggests that seasonal N_2O emission from wheat fields could be effectively predicted by crop yield. Similar finding was reported by Chen et al. [43]. They also found good fit between grain yield of wheat and N_2O emission than biological yields.

Grain yield and growth duration of wheat reduce depending on sowing times [44], which was also reflected with 1.5 °C rise in temperature indicating that we have to find out a suitable sowing window for satisfactory wheat yield but N_2O emissions can also be minimized. We have found that sowing time of wheat can be delayed up to a certain period without significant yield reduction (Fig. 7). For example, seeding can be done in 15 November instead of 10 November for reducing N_2O emissions from wheat fields under Bangladesh conditions. Sowing of wheat seeds during 15 to 30 November in a rice–wheat system in Indian subcontinent could be achieved if short duration wet season rice varieties are grown at the right time. Short duration wet season rice varieties having high yield potentials are available. It requires massive demonstrations to convince the farmers for adoption of such rice varieties in wet season. Moreover, development of wheat varieties having high yielding potentials, short growth duration and tolerant to heat is the requirement of the time. As climate change impacts are visible in terms of temperature rise and increase in episodic events such as extreme temperature, dry spell and rainfall, it is the duty of the agricultural scientists to find out ways and means to cope up such natural calamities and to enhance food production for the world communities in future.

5 Conclusion

The findings are based on calibration and validation of DNDC model, which was done by using soil clay fraction, pH, bulk density and organic carbon contents under observed weather data. There were spatio-temporal variations in Nr loads to the environment in relation to wheat cultivation in Bangladesh because of variations in prevailing temperatures during crop growing period and soil texture and pH. The highest N_2O emission rate (364 g N ha^{-1}) was observed in the main wheat growing areas and the least (15 g N ha^{-1}) in minor wheat growing areas. In 2011–2016, about 103–129 t N_2O–N yr^{-1} were emitted because of wheat cultivation. Model estimated NO, NH_3 and NO_3 fluxes varied from 0.012 to 0.447, 7 to 12.5 and 0 to 4.7 kg N ha^{-1}, respectively, under ambient temperature condition. As temperature is rising because of climate change impact, optimum temperature window for growing wheat crop will be narrowed down in future that warrant development of cool wheat varieties for sustaining food production around the globe. Besides, variations in crop management like changes in planting time would be another avenue to minimize yield reduction. For example, N_2O emission could be reduced by 8–40% depending on 15–30 seeding without significant yield reduction compared to early or late sowing dates as we have found in the present investigation. Temperature rise by 1.5 °C might reduce 4–8% of wheat grain yields in future and could lead to 8–45% higher N_2O emissions than present conditions. Time of sowing and other cultural management options, such as cultivation of heat tolerant varieties, improvement in water and fertilizer management would be the main avenue for reducing Nr loads to the environment in future.

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Compliance with ethical standards

Conflict of interest There are no conflicts of interests among the authors.

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