Quantifying opportunities for greenhouse gas emissions mitigation using big data from smallholder crop and livestock farmers across Bangladesh

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HIGHLIGHTS

- We estimated GHG emissions and quantified mitigation potential from agricultural sector of Bangladesh
- Bangladesh's agriculture sector can mitigate 9.51 and 14.21 million tonne CO_2e year^{-1} by 2030 and 2050, respectively
- Adoption of profitable mitigation options can deliver three-fourth of this mitigation potential

GRAPHICAL ABSTRACT
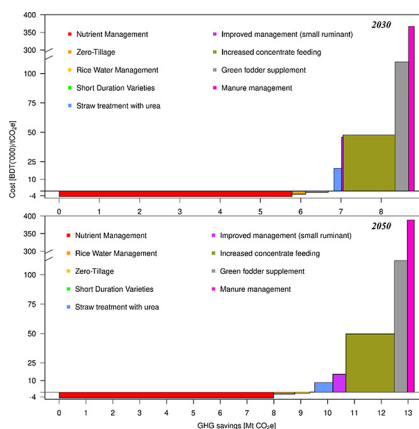
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ABSTRACT

Climate change is and will continue to have significant implications for agricultural systems. While adaptation to climate change should be the priority for smallholder production systems, adoption of cost-effective mitigation options in agriculture not only contributes to food security but also reduces the extent of climate change and future adaptation needs. Utilizing management data from 16,413 and 12,548 crop and livestock farmers and associated soil and climatic data, we estimated GHG emissions generated from crop and livestock production using crop and livestock models, respectively. Mitigation measures in crop and livestock production, their mitigation potential and cost/benefit of adoption were then obtained from literature review, stakeholder consultations and expert opinion. We applied the identified mitigation measures to a realistic scale of adoption scenario in the short- (2030) and long-term (2050). Our results were then validated through stakeholders consultations. Here, we present identified mitigation options, their mitigation potentials and cost or benefit of adoption in the form of Marginal Abatement Cost Curves (MACC). Based on our analysis, total GHG emissions from agricultural sector in Bangladesh for the year 2014–15 is 76.79 million tonne (Mt) carbon-dioxide equivalent (CO_2e). Business-as-usual GHG emissions from the agricultural sector in Bangladesh are approximately 86.87 and 100.44 Mt CO_2e year^{-1} by 2030 and 2050, respectively. Adoption of climate-smart crop and livestock

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management options to reduce emissions considering a realistic adoption scenario would offer GHG mitigation opportunities of 9.51 and 14.21 Mt CO_2e year^{-1} by 2030 and 2050, respectively. Of this mitigation potential, 70–75% can be achieved through cost-saving options that could benefit smallholder farmers. Realization of this potential mitigation benefit, however, largely depends on the degree to which supportive policies and measures can encourage farmers' adoption of the identified climate smart agricultural techniques. Therefore, government should focus on facilitating uptake of these options through appropriate policy interventions, incentive mechanisms and strengthening agricultural extension programs.

1. Introduction

Climate change affects food security directly by reducing agricultural productivity (Liu et al., 2014; Wang et al., 2014; Zhang et al., 2017), and also indirectly by affecting nutritional quality of food produced and disrupting food supply chains (Dunne et al., 2013; Mbow et al., 2019; Tigchelaar et al., 2018). At the same time, agricultural production is responsible for significant proportion of anthropogenic greenhouse gas (GHG) emission that contribute to climate change. For example, agriculture, forestry, and other land uses were responsible for around 13% of CO_2, 44% of methane (CH_4), and 81% of nitrous oxide (N_2O) emissions accounting for about 23% of total anthropogenic GHG emissions during 2007–2016 (Mbow et al., 2019; Rosenzweig et al., 2020). If emissions associated with pre- and post-production activities such as the manufacture of fertilizer, processing of food and subsequent transport, sales and food consumption are considered, the estimated range of emissions are from 21 to 37% of all net anthropogenic GHGs (Rosenzweig et al., 2020). Major sources of GHGs from agriculture include the emission of N_2O from the production and use of synthetic fertilizer, emissions from crop residue burning, CH_4 emission from rice cultivation under flooded conditions. Similarly, CH_4 emission from the anaerobic digestion of carbohydrates by ruminant animals, CH_4 and N_2O emissions from manure and CO_2 emissions associated with fossil fuel use for powering machinery and irrigation pumps are also major sources, in addition to the transport of agricultural goods (Searchinger et al., 2019).

GHG emissions from agriculture are expected to increase further in the future as a result of the need to produce more food to meet expanding and changing dietary demands — particularly for increased meat products. For example, to feed an anticipated global population of 9.1 billion with current dietary patterns, overall food production is projected to increase by 70% between 2005 and 2050. This will have significant consequences, including an additional 30% increase in global GHG emissions from agriculture (Tubiello et al., 2014). Where meat production and consumption expands with increasing incomes, particularly in eastern Asia, emissions are expected to further accelerate (Searchinger et al., 2019). In the face of these challenges, it is essential to reduce GHG emissions from all sectors of the economy. Therefore, meeting the goal of keeping emissions below 2 °C above pre-industrial levels as stipulated in the 2015 Paris Agreement of the United Nationals Framework convention on Climate Change (UNFCCC) would be impossible without reducing emissions from food systems (Clark et al., 2020). Furthermore, without ambitious action to limit GHGs, the future costs of adapting to climate change are likely to be considerably higher than they are today (Wollenberg et al., 2016).

Agricultural sector in Bangladesh has been estimated to emit about 50 $MtCO_2$ year^{-1} (GoB, 2012), mainly through rice cultivation, fertilizer-induced field emission, field residue burning and livestock production including manure management. In 2018, Bangladesh ranked seventh globally in terms of livestock density at 1.31 units per hectare and 15th in terms of cattle population (http://www.fao.org/faostat/en/#home). The GHG estimate of Bangladesh is largely based on national level data for crop/livestock type, crop area and livestock numbers, extrapolated using global emissions factors (EFs) developed by the IPCC (GoB, 2012). Information on soil type, nutrient or agricultural water management are either lacking or accounted for at a coarse level, without observations of farmers' management practices, and without consideration of interactions with soils or climate that can alter emissions. For example, variation in irrigation management in rice, which provides the bulk of calories consumed in Bangladesh (Shew et al., 2019), or poor management of livestock, or inefficient application of synthetic fertilizer – particularly nitrogen (N) and including livestock manure – will greatly influence emissions (Sapkota et al., 2019). As such, when aggregated, national levels of GHG emissions may be higher than those reported in the Government of Bangladesh (2012) national communication using IPCC methods.

This is not to discount the importance of earlier assessments that provided crucial initial evaluations of national GHG emissions of relevance for global policy dialogue. However, a more systematic and data-driven approach to estimating GHG emissions could be beneficial to identify specific and feasible mitigation options, while also quantifying trade-offs and benefits associated with their implementation. The identification of these options together with their potential at different administrative governance levels can not only help to contribute nuanced assessment of options for nationally determined contributions, but also to prioritize policy and investment consistent with national food security and environmental protection goals (Whittaker et al., 2013). Moreover, these approaches can help guide extension services to foster more climate smart agricultural practices that can enhance productivity and resilience while mitigating environmental externalities. For the first time in Bangladesh, we used a bottom-up approach to estimate administrative jurisdiction-level GHG emissions from agricultural activities, identified potential mitigation options, and determined the jurisdiction-level mitigation potential of those options based on their mitigation potential per unit of agricultural land or livestock species, potential levels of adoption of mitigation options within the jurisdiction, institutional capacity and market contexts.

2. Methodology

2.1. Study framework

Determination of spatially explicit mitigation potential from agricultural activities requires accurate estimation of baseline emission and projected future emissions under business-as-usual (BAU) and mitigation scenarios (Sapkota et al., 2020). The BAU scenario does not consider any mitigation measures whereas a mitigation scenario assumes that all technically feasible mitigation measures are adopted at a realistic scale. Mitigation potential is then determined as the difference in emissions under BAU and the mitigation scenario (Fig. 1). In the following sections, we present the details of data types and their sources, GHG estimation models, and emission scenarios to determine mitigation potential in the short-(2030) as well as long-term (2050).

2.2. Data sources

Assessment of total cultivated areas by major crops in Bangladesh (http://www.fao.org/faostat/en/#data) reveals that paddy [summer '*aman*', spring '*aus*', and winter '*boro*' rice (*Oryza sativa*)], potato (*Solanum tuberosum*), wheat (*Triticum aestivum*), jute (*Corchorus* spp.), maize (*Zea mays*) and lentil (*Lens culinaris*) cover over 90% of total
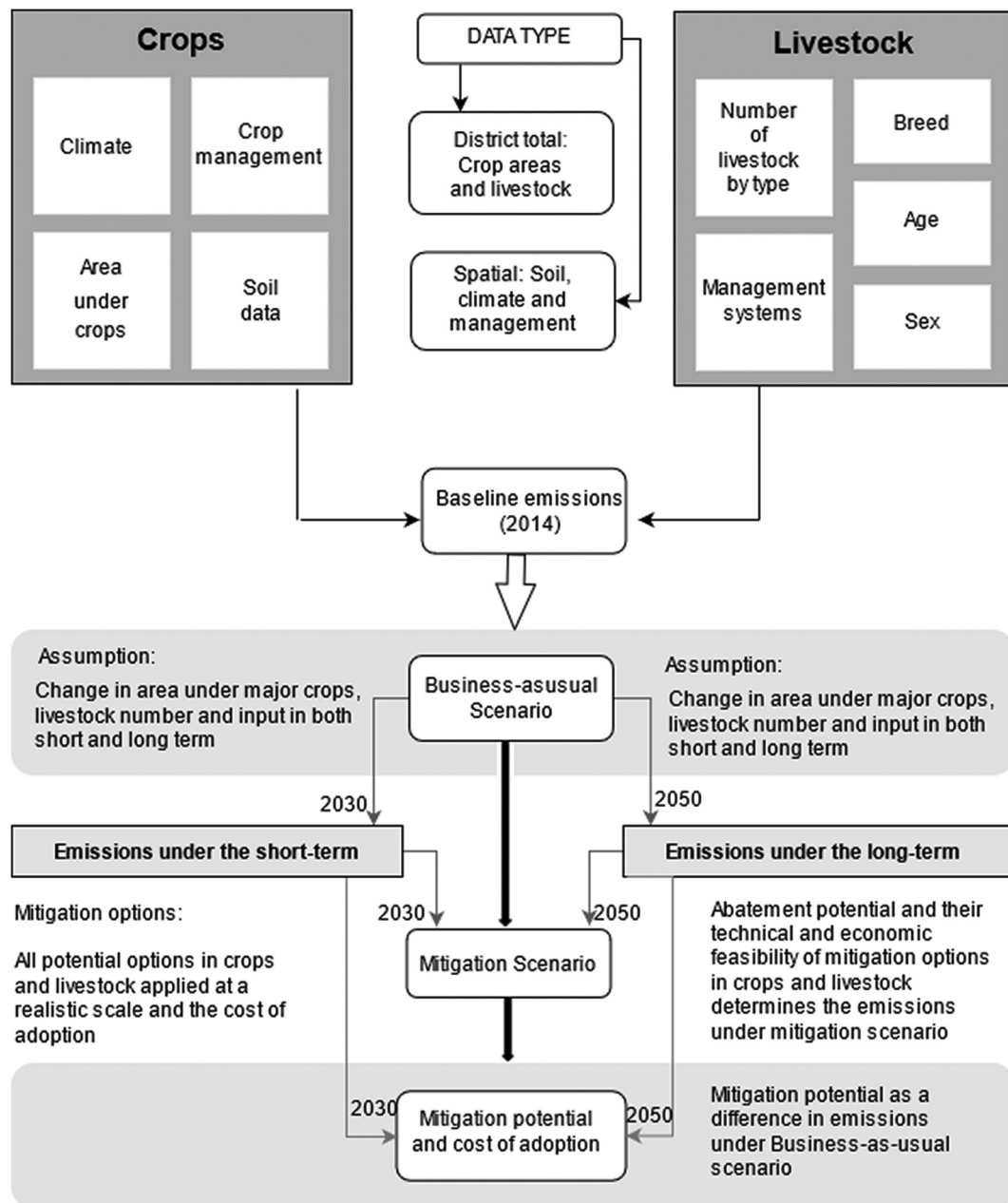
Fig. 1. The study framework employed to determine GHG mitigation potential from the agricultural sector in Bangladesh.

cultivated land in Bangladesh. Between 64 and 84% of total fertilizer consumed in the Bangladesh is applied to these crops (Heffer et al., 2017). Similarly, cattle (*Bos taurus*), buffalo (*Bubalus bubalis*), sheep (*Ovis aries*) and goat (*Capra aegagrus hircus*) are the major livestock species raised in the country (BBS, 2016). We therefore limited our study to these eight crops and four livestock species assuming they are responsible for most of the agricultural emissions in Bangladesh.

We obtained crop production related data for the winter, spring, and summer seasons during 2014–15 from "Bangladesh Integrated Household Survey" (BIHS) conducted by Bangladesh Policy Research and Strategy Support Program (PRSSP) and the International Food Policy Research Institute (IFPRI).[1] The survey followed stratified random

sampling in two stages: selection of village as primary sampling units (PSU) and then selection of households within PSU to achieve a representative sample of all agricultural areas in Bangladesh (Ahmed, 2016). Prior to analysis, the BIHS data were processed to identify outliers – often with highly unrealistic reports of input use – using JMP software (https://www.jmp.com/en_sg/support/read-me/jmp13.html). For each of the variables extracted from the BIHS dataset, detected outliers were replaced by the mean of 95% of the non-outlying data.

Altogether, 16,413 farmer-observations for eight crops were retained for this analysis (Fig. 2). Plot-specific soil, climate and management information for all crops included in this study are given in Supplementary data S1 (Input_data_crop).

Plot-specific information on tillage type and events, crop establishment method, use of inputs including fertilizer type and quantity, and crop management information such as irrigation, organic matter application, and residue management were utilized for estimating GHG
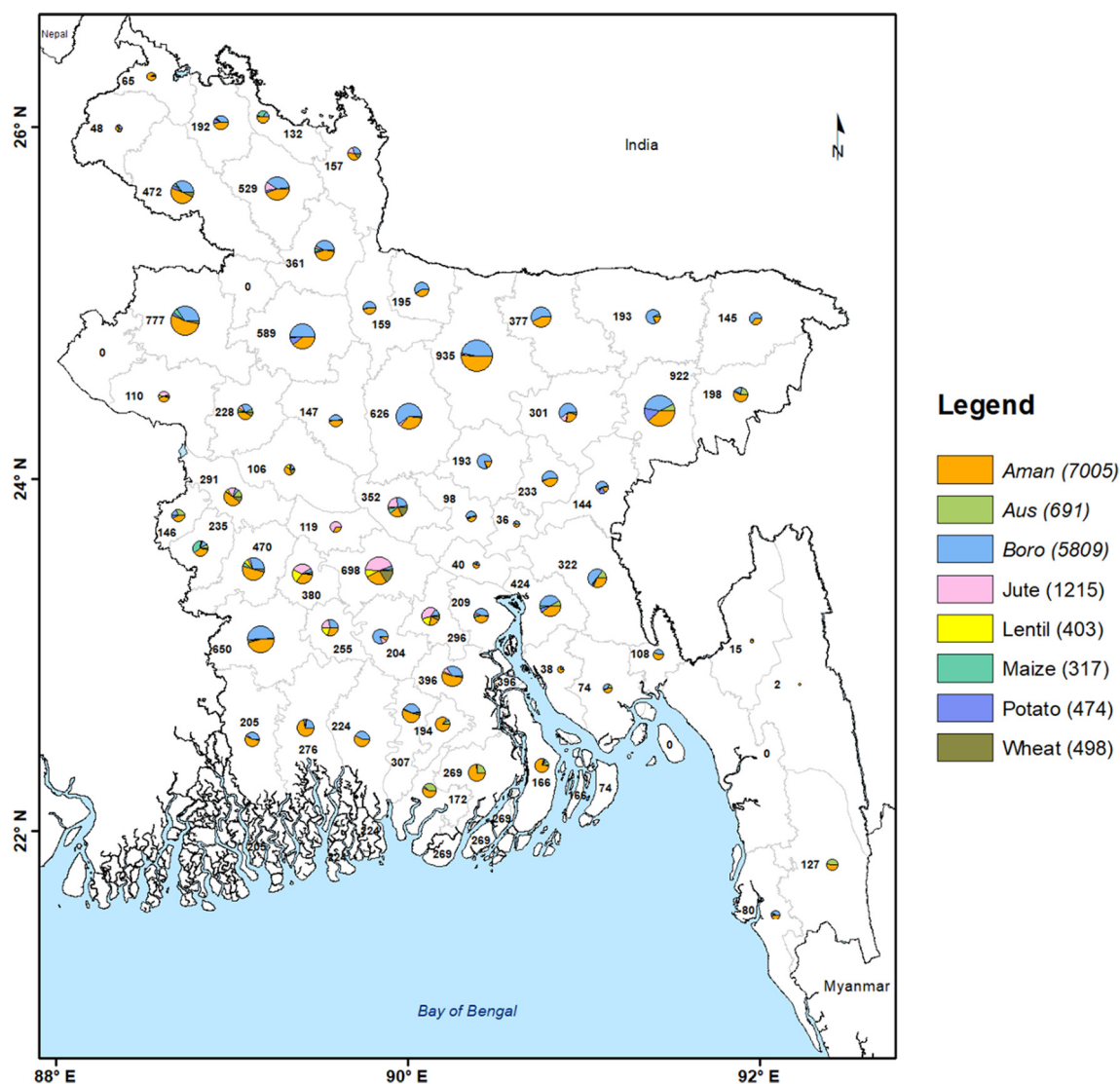
Fig. 2. Summary of the proportion of crop species considered in the study for all farmers retained from the Bangladesh Integrated Household Survey (BIHS) dataset in each district of Bangladesh. Size of pies are proportional to the number of data-points in each districts. In legend, the values in parenthesis, shows the total number of data-points for each crop.

emissions using the CCAFS Mitigation Options Tool (CCAFS-MOT) (Feliciano et al., 2017), explained in Section 2.3 below. Crop management information not available from the BIHS dataset but required by the model were collected from both primary and secondary data sources. For example, plot-specific soil information was obtained from a database compiled for pedo-transfer function validation of Bangladesh soil (Shiragi et al., 2017). In rice plots, the effect of puddling on soil pH buffering specific to soil types was accounted for following trends described by Greenland (1997). Visual analysis of 30 years of climatic data from Bangladesh Meteorological Department revealed that all Bangladesh have sub-tropical climate given that mean monthly temperature, corrected to sea level, is less than 18 °C for at least one or more months per year (Maclean et al., 2002). Specific climate categories for rice were determined by using the length of summer growing period reported by Maclean et al. (2002) and Yan et al. (2005). The water regime prior to the rice crop required by the model were determined following Yan et al. (2005). In-season water management was considered as continuously flooded for fully irrigated *boro* rice and as rainfed for spring *aus* rice. In-season water management for summer *aman* rice was based on a rice irrigation map developed by Gumma et al. (2014). As the BIHS data lacked information on crop residue management, we conducted a telephone survey in April–June of 2018 of 550 farmers randomly selected across Bangladesh. All farmers reported complete removal of residues

either by themselves and/or by gleaners following harvest. Based on this, we assumed all crop residues in our study to be removed as livestock feed, fuel or housing material. The BIHS data also lacked information on fuel consumed for farm operations such as tillage and irrigation. To determine average fuel consumption per tillage and/or irrigation event, we conducted another telephone survey in August of 2018 of 500 randomly selected irrigation pump and 500 two- and four-wheel tractor owners who reported average consumption rates. The district-wise area under each of the eight crop types by season in 2014–15 were obtained from Yearbook of Agricultural Statistics 2015 (BBS, 2016).

We obtained latest district-wise and national population of cattle, buffalo, sheep and goat from the Bangladesh Bureau of Statistics (BBS, 2010). The district-wise distribution of these animals were available only for 2008–09, but national totals were available for all years (http://www.bbs.gov.bd/). By using the national population from 2008 to 09 to 2014–15, we calculated the yearly growth rate for each livestock species (Supplementary data S1-livestock_pop&growth_rate), and applied these growth rates to estimate their district-wise population for 2014–15. We next conducted a structured survey in February-March of 2019 of 25 purposefully chosen livestock experts at the Department of Livestock services, ($n = 2$), Bangladesh Livestock Research Institute ($n = 7$), Bangladesh Agricultural University ($n = 12$), Krishi Gobeshona Foundation ($n = 2$) and the Center for

Environmental and Geographic Information Services ($n = 2$). From this survey, we obtained estimates of the proportion of these animals by breed, age, sex, body weight, feed consumption and livestock management system (i.e. stall feeding, grazing or mixed management systems) (Fig. 3). We applied these proportions to the district-wise population of animals derived as described above. This resulted in a total of 12,548 livestock data-points were used for the analysis (Supplementary data S1-livestock_pop_1014–15).

2.3. Modeling GHG emissions

For both crop and livestock production, we confined our analysis only to the farm-gate, and did not consider emissions associated with processing, transport, consumption and waste management. GHG emissions and sequestrations as affected by tillage and crop establishment; crop management activities such as fertilizer application, water management and crop protection; organic inputs such as crop residues, cover crops, compost and manure under specific soil and climatic conditions were accounted for. While we considered the GHG emissions associated with fertilizer production and farm energy, we did not consider emissions associated with livestock feed production. This was based on experts' opinion that livestock feeding in Bangladesh largely depends on crop by-products (the emission footprint of which is included in crop production emission estimates) and to a lesser extent on concentrate feed, rather than dedicated forage or silage.

We employed the CCAFS' Mitigation Options Tool (CCAFS-MOT) (Feliciano et al., 2017) that uses a semi-life-cycle approach to estimate GHG emissions using field plot-level information from all farmer observations of production inputs and other management practices at the field level, supplemented with each plots' pedo-climatic characteristics. The CCAFS-MOT makes use of several empirical approaches (e.g. Bouwman et al., 2002; IPCC, 2006; Yan et al., 2005) to estimate GHG emissions from various crop management practices. A version of the CCAFS-MOT scripted in R software (R Core Team, 2020) was used to process our high-throughput sample.

For livestock, we employed the approach developed by Herrero et al. (2013) to estimate GHG emissions. This model estimates enteric fermentation and manure management related GHG emissions based on animal groupings by animal types (e.g. ruminants, small ruminants, etc.), age, breed, sex, body weight and other management practices (e.g. stall-fed, grazing or mixed management) under the particular agro-climatic conditions.

2.4. Data analysis and presentation

Both of the above-described crop and livestock models estimate the amount of CO_2, CH_4 and N_2O emissions per hectare for crops and per head for livestock, depending upon soil, climate and management factors. For the ease of comparison, we converted CH_4 and N_2O into CO_2 equivalent (CO_2e) using their global warming potential (GWP) of 28 and 265, respectively, based on a 100 year time horizon (IPCC, 2013). For each crop and livestock type included in the analysis, we derived the mean and standard deviation of emissions based on the spatial model run using all available crop and livestock data-points within each district studied. We then calculated a 95% confidence interval (CI) as shown in Eq. (1) to address uncertainty in our estimates

$$CI = \mu \pm t_{\alpha/2, n-1^*} \frac{s}{\sqrt{n}} \qquad (1)$$

where μ indicates mean emission and $t_{\alpha/2, n-1}$ is the inverse of Student's t statistic at the 0.05 probability, and s and n are the sample standard deviation and number of samples within the district, respectively. District level total emissions were then obtained by multiplying the district level average emission with the total cropped area or livestock number within district for each crops and livestock species studied. Summing all district level total crop and livestock emissions resulted our total national emission estimate.

2.5. GHG mitigation options

We obtained mitigation options in crop and livestock production through various sources including previous studies in the region, relevant options available in the CCAFS-MOT (Feliciano et al., 2017), as
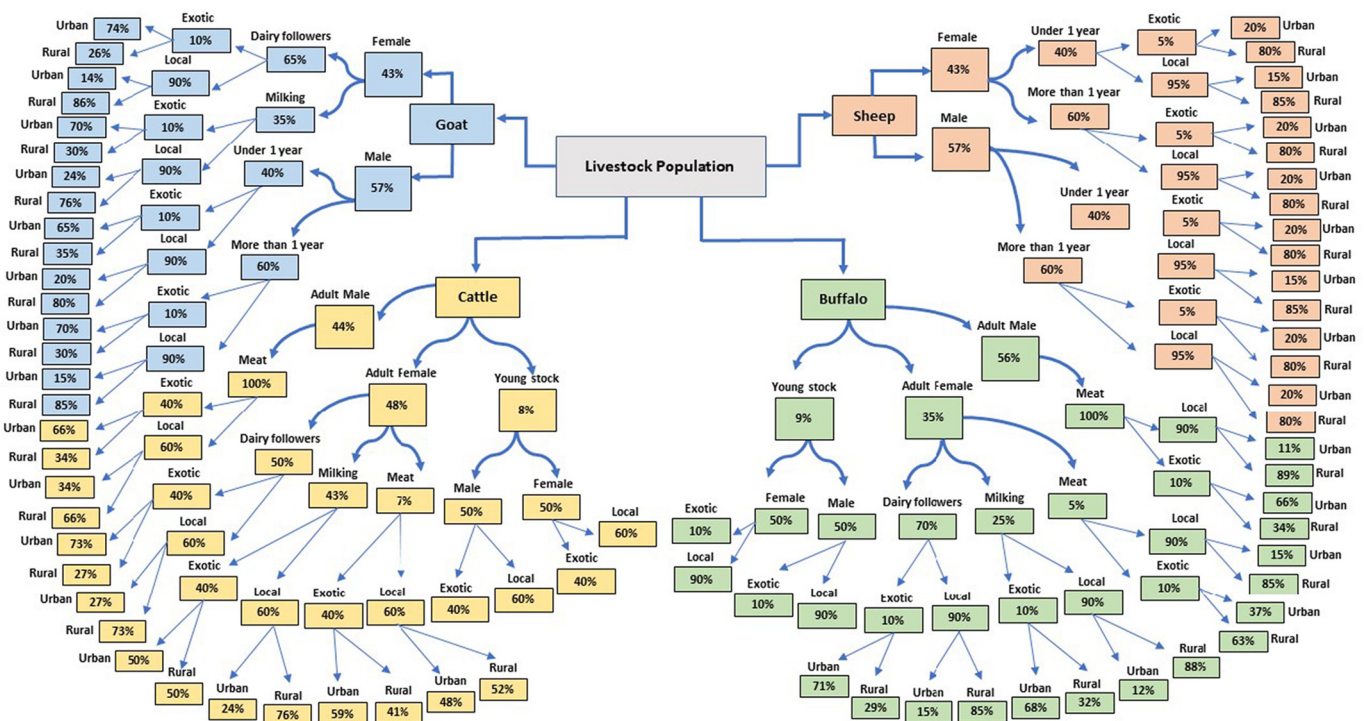

Fig. 3. Proportion of livestock population by sex, age and use types of animal in Bangladesh.

well as through expert opinion garnered through individual consultation as well as during an expert workshop held on October 24, 2019 in Dhaka, Bangladesh. Major mitigation options in crop and livestock production and their potential level of adoption under mitigation scenario in 2030 and 2050 are presented in supplementary material (S2). Examples of climate smart management practices and mitigation options included in our simulations for crops are alternate wetting and drying (AWD) in rice (Rahman and Bulbul, 2014), improved nutrient-use-efficiency particularly for N (Ladha et al., 2005; Sapkota et al., 2014), and adoption of strip-tillage (Gathala et al., 2016), as well as of short duration rice varieties (Rana et al., 2014). Similarly, mitigation options considered for livestock included green fodder supplement (Sarker et al., 2006; Sirohi et al., 2005), increased concentrate feeding (Sirohi et al., 2005) and feed improvement for large ruminants by urea/molasses treatment (Gerber et al., 2013; Khan et al., 1970; Sirohi et al., 2005; Sirohi and Michaelowa, 2008) and improved forage/diet management for small ruminants. Other mitigation options in livestock sector included improved manure management through better storage, separation and aeration (Gerber et al., 2013; Huque et al., 2017; Khanam et al., 2019; Sirohi et al., 2005; Sirohi and Michaelowa, 2008).

To calculate the GHG mitigation potential of improved N management, we used the nutrient-use-efficiency (NUE) method, which considers the optimum N application for specific crops. For the purpose of this analysis, NUE is the ratio of N removed in harvested product to the total N applied to the crop through organic as well as inorganic sources, expressed as a percentage (Eq. 2). We obtained the target level of NUE under mitigation scenario (explained later and presented in Supplementary materials S2) through literature (Ladha et al., 2005), as well as expert opinion from the stakeholder workshop. We then calculated the amount of N required to obtain target NUE without compromising yield using the same equation (Eq. 2) which is then used in spatial run.

$$NUE\ (\%) = \frac{N\ removed\ at\ harvest\ (kg)}{N\ input\ (kg)} \times 100 \qquad (2)$$

Water management strongly influences the emission of CH_4 and N_2O from rice by changing soils from aerobic to anaerobic conditions during flooding (Sapkota et al., 2017c). The only mitigation option for water management in Bangladesh's rice ecosystem was to covert a portion of rice field under continuously flooded conditions to intermittently irrigated with multiple drainage events, simulating AWD. We assumed that changing rice water management from continuously flooded to intermittently irrigated with multiple drainage events would change CH_4 and N_2O emissions by a factor of 0.405 and 5.81 based on the result of the meta-analysis carried out by Nayak et al. (2015). Current tillage and crop establishment practices in Bangladesh's crop production systems involve 3–4 full inversion tillage operations with crop residues taken off the field (Krupnik et al., 2014). Changing the current tillage practices to no-tillage/strip tillage can reduce GHG emissions not only through carbon sequestration but also by reducing fuel consumption associated with tillage operations. Strip tillage in developed countries with large equipment can result in significant soil disturbance. However, because strip tillage in Bangladesh involves excavating small 6–11 cm strips at depths <10 cm (Matin et al., 2021), we assumed it approximated no-tillage practices and utilized the carbon sequestration potential of adopting no-tillage reported by Powlson et al. (2014). Crop duration is one of the variables used to calculate CH_4 emissions from rice in the CCAFS-MOT; the model therefore takes into account the CH_4 emission reduction potential of short-duration rice varieties.

The cost of adopting mitigation options and additional benefits accrued through the application of these options were calculated considering all the costs associated with tillage and crop establishment, seed, fertilizer, biocides, irrigation, harvesting and residue management calculated from the BIHS data. Increases in green fodder and concentrate feeding, and cost associated with forage improvement and manure

management derived from surveys of livestock experts were also accounted for. The cost of inputs and outputs included in the study were based on average market prices in Bangladesh as of August 2018.

2.6. Scenario analysis

Mitigation potential can be estimated relative to base-year emissions or relative to business-as-usual (BAU) scenario emissions for the target year. Here, we determined the mitigation potential against BAU scenario for the short-(2030) and long-term (2050). Estimation of mitigation potential relative to BAU scenario demonstrates the potential of improved efficiency in agriculture for GHG abatement so that policy makers and agricultural development planners can prioritize activities commensurate to their GHG abatement goal. We determined the BAU emissions and mitigation potential for the short-and long-term for decision makers to focus on immediate action based on short-term goals as well as to prioritize action points for long-term solutions. Identification of cost/benefit of adoption of mitigation practices can help to determine whether the identified practices are cost-beneficial for farmers to take up technologies and management practices, or incur some additional costs that may require supportive policies or economic incentives. Providing cost of adoption of mitigation practices can also assist in comparing cost of mitigation from other sectors of economy and prioritize mitigation actions accordingly.

2.6.1. Baseline emission scenario

We determined the GHG emissions from agricultural sector in Bangladesh using crops and livestock activity data available for crop-year 2014–15. We summed the emissions from major crops and livestock at the administrative district level. District level emission estimation was more relevant because some activity data such as total cropped area or livestock numbers were available only at this level. In addition, agricultural extension services that would be required to implement mitigation options are administered at the district level.

2.6.2. Business-as-usual (BAU) scenario

We developed our BAU scenario assuming that the government will not implement any new policies targeted explicitly for reducing GHG emissions from the agricultural sector. In this scenario, we projected emissions for the year 2030 and 2050 from crop and livestock sector based on a set of growth assumptions such as change in area under major crops, change in input rates (e.g. fertilizer, water) and change and livestock numbers. We considered climate-induced changes in production landscapes, population growth, farmers' incentives to switch over particular crops, government priorities and trends of change in fertilizer rate and livestock numbers to estimate these changes under BAU scenario (Supplementary Materials S3). We validated these expected changes in crop area, production inputs and livestock numbers through a stakeholders' workshop held in Dhaka on 24 October of 2019 with 12 high-level governmental experts from the Ministry of Agriculture and Department of Livestock Services, universities, donor organizations, and other think tanks from the agriculture and livestock sectors. We applied proposed changes (Supplementary Materials S3) to baseline data and performed spatial model run to determine district-wise BAU emissions for short-(2030) and long-term (2050).

2.6.3. Mitigation scenario

In this scenario, we took the respective 'BAU' scenarios for 2030 and 2050 and projected the impacts of respective changes in the area under major crops, changes in input rates used by farmers, changes in livestock densities (Supplementary materials S3), and considered all possible mitigation options available presently or that could be available by the target years. We applied these mitigation options at a feasible scale of adoption based on the level of awareness, socio-economic trends, government schemes, policies and priorities (Supplementary

materials S2). Identified mitigation options and their scale of adoption under the mitigation scenarios for 2030 and 2050 were also discussed, evaluated and validated through the October 2019 stakeholders' workshop.

2.7. Mitigation potential and cost of adoption

We ran crop (Feliciano et al., 2017) and livestock (Herrero et al., 2013) models using spatial datasets developed for BAU and mitigation scenarios to estimate emissions from all crops and livestock under respective scenarios for 2030 and 2050. We then calculated district level average emissions for all crops and livestock and quantified their uncertainties. We next multiplied average district-level emissions with the projected crop area and livestock numbers under each scenario within the same district for 2030 and 2050, and then summed the total emissions from all crops and livestock to obtain total emissions from BAU and mitigation scenarios for 2030 and 2050. For each crop and livestock species, we subtracted total emissions under mitigation scenario for 2030 and 2050 from the total BAU emissions for the respective year to estimate district-wise mitigation potential, respectively. We then summed total mitigation potential from all crops and livestock to obtain total district-level mitigation potential from agriculture. To estimate the cost of adopting mitigation options, we multiplied the unit cost of adopting a particular mitigation option with total area or number of livestock to which the that mitigation option can be applied. Within each district, we divided total cost of adoption by total mitigation potential to estimate cost per unit of CO_2e abated.

3. Results

3.1. Total GHG emissions

On an average, estimated GHG emissions per ha was the highest in *aman* rice (mean $\pm$ SD = 4702 $\pm$ 1385 kg CO_2e ha^{-1}) followed by *boro* rice (4041 $\pm$ 539 kg CO_2e ha^{-1}). Average emission from other crops including *aus* rice ranged from 512 to 1660 CO_2e ha^{-1}. In case of

livestock, average GHG emissions was the highest for buffalo (1179 $\pm$ 257 kg CO_2e head^{-1} yr^{-1}) followed by cattle (864 $\pm$ 231 kg head^{-1} CO_2e yr^{-1}). Average emissions from goat and sheep ranged from 178 to 225 CO_2e head^{-1} yr^{-1}.

Based on our estimate, total GHG emissions from the agricultural sector (crop and livestock combined) in Bangladesh for the year 2014–15 was ca. 76.79 megatonne (Mt) with a 95% CI of 71.05–81.76 Mt CO_2e (Fig. 4). Crop and livestock production contributed 65% and 35% of total agricultural emissions, respectively. In Bangladesh, rice production was the most important source of emissions, which contributed about 62% of total agricultural emissions followed by cattle, goats, and non-rice crops. Rice and cattle production together therefore appear to be responsible for about 91% of all agricultural emissions in Bangladesh. Production of *aman* and *boro* rice was responsible for about 93% of total crop related emissions, while cattle production accounted for about 83% of total livestock related emissions.

Administrative district-wise annual agricultural emissions (crop and livestock combined) were the highest in Dinajpur followed by Mymensingh, Naogaon, Bogura and Rangpur districts. Jashore, Thakurgaon, Tangail and Gaibandha are other districts that appear to have relatively higher agricultural emissions. Total crop related and livestock related emissions was also higher in these compared to other districts. Total agricultural emissions were >2 Mt CO_2e in eight districts, between 1 and 2 Mt CO_2e in 26 districts, and <1 Mt CO_2e in the remaining districts. Out of 64 districts in Bangladesh, total crop related emissions were >1 Mt CO_2e in 17 districts, whereas total livestock related emissions were >1 Mt CO_2e in just three districts (Fig. 5).

GHG emissions associated with paddy rice production in the *aus*, *aman* and *boro* rice seasons combined were highest in Dinajpur followed by Mymensingh, Naogaon, Bogura and Rangpur, whereas those from wheat production were highest in Thakurgaon followed by Pabna and Rajshahi (Fig. 6). Similarly, emissions from lentil production was highest in Rajshahi, Faridpur, Natore, Jashore, as well as Magura. Emissions from maize were highest in Chuadanga followed by Dinajpur, Thakuregaon and Lalmonirhat. Jute production related emissions were the highest in Faridpur, Kushtia, and Jamalpur. Those arising from
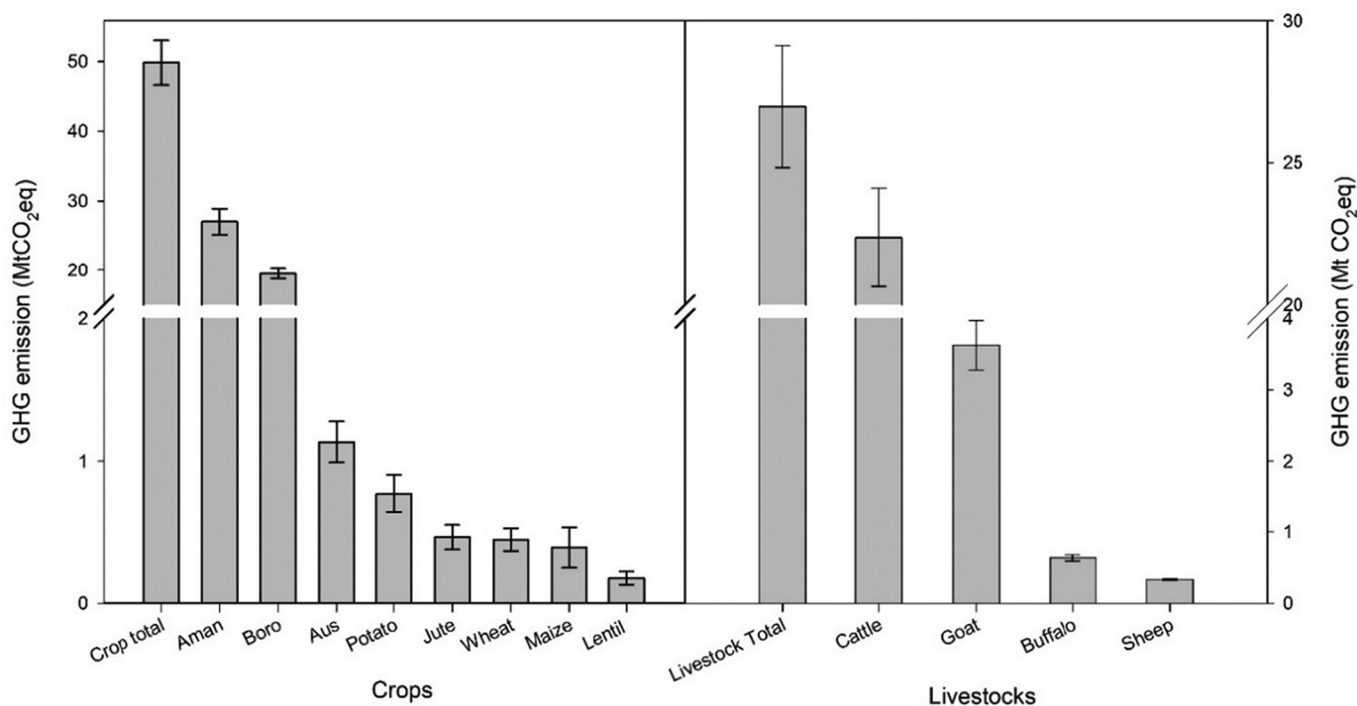

Fig. 4. Total annual greenhouse gas emissions from crops (left panel) and livestock (right panel) in Bangladesh. Error bars show the 95% confidence interval.
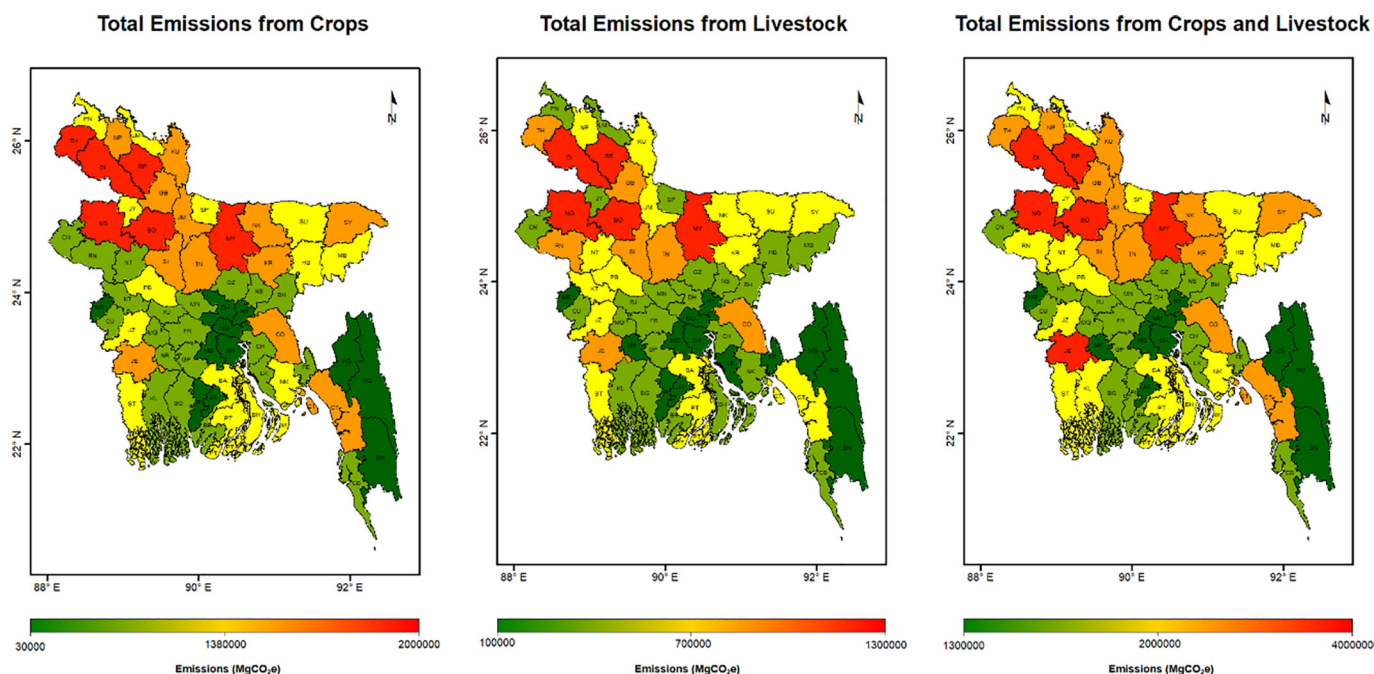
Total Emissions from Crops

Total Emissions from Livestock

Total Emissions from Crops and Livestock

Fig. 5. District-wise annual greenhouse gas emissions from crops, livestock and crops-livestock combined. The full form of the district names is given in supplementary data S1 (District_abbreviation).

potato production were the highest in Bogura followed by Rangpur, Dinajpur, Joypurhat and Munshiganj.

Emissions from cattle production were highest in Dinajpur followed by Mymensingh, Naogaon and Bogura whereas emissions from buffalo production was highest in Patuakhali district followed by Bhola, Sylhet and Noakhali (Fig. 7). Goat production related emissions were here in Dinajpur, Jashore, Naogaon, Rajshahi and Mymensingh. Emissions from sheep production was the highest in Gaibandha followed by and Naogaon, Bogura, Dinajpur and Sirajganj.

3.2. GHG mitigation potential

We calculated the spatially-explicit mitigation potential from crop and livestock production as the difference in GHG emissions under the BAU and mitigation scenarios in the short-(2030) as well as in long-term (2050). District-wise distribution of GHG emissions in the base year (2014–15) as well as the BAU & mitigation scenarios, together with yearly mitigation potential segregated by crop/livestock types and mitigation measures in 2030 and 2050, are provided in Supplementary materials S4. Under BAU scenario, where we assumed no specific policies and actions for reducing GHG emissions, projected emissions from the agricultural sector would be 86.87 and 100.44 Mt CO_2e year^{-1} by 2030 and 2050, respectively. Conversely, emissions under the mitigation scenario, under which we considered the application of all possible mitigation options, would be 77.36 and 86.23 Mt CO_2e year^{-1} in 2030 and 2050, respectively (Fig. 8). This suggests that the adoption of identified mitigation practices to the scale identified under the mitigation scenarios would offer a technical mitigation potential of 9.51 and 14.21 Mt CO_2e year^{-1} by 2030 and 2050, respectively. In other words, adoption these technically feasible mitigation measures in agriculture could abate 11 and 14% of respective BAU emissions by 2030 and 2050, respectively.

Similar to the baseline scenario, rice is the most important source of projected emissions under the BAU scenarios followed by cattle, goats and other upland crops in 2030 as well as 2050. Among the major crops and livestock in Bangladesh, the highest mitigation potential is likely to be realized through change in the management of *boro* rice (2.80 and 3.85 Mt CO_2e year^{-1} in 2030 and 2050, respectively), *aman*

rice (2.60 and 3.41 Mt CO_2e year^{-1} in 2030 and 2050, respectively) and cattle (1.88 and 3.12 Mt CO_2e year^{-1} in 2030 and 2050, respectively). Potato, maize, jute, wheat and *aus* rice appear to have mitigation potentials of ca. 0.25 Mt CO_2e each per year in 2030. In 2050, each of these crops, as well as improvement in husbandry of goats, would have a mitigation potential of ca. 0.5 Mt CO_2e each per year.

3.3. Mitigation options and their potential in crop production

Mitigation options in crop production offered about 78 and 72% of the total mitigation potential in the agricultural sector in 2030 and 2050, respectively. Of this, nutrient management in crops offered the highest technical mitigation potential. In short-term, adoption of improved and more efficient nutrient management practices in major crops in Bangladesh would offer a technical mitigation potential of 5.78 Mt CO_2e year^{-1} without compromising crop yield. This would result into the cost savings of ca. 5000 Bangladeshi Taka (BDT) or USD 58.9 t CO_2e^{-1} abated (Fig. 9, upper panel). Similarly, in the long-term, improved nutrient management practices in Bangladesh would offer a technical mitigation potential of 7.98 Mt CO_2e year^{-1} without compromising crop production while resulting in similar cost savings as in the short-term (Fig. 9, lower panel). Improved rice water management would have a technical mitigation potential of ca. 0.60, and 0.80 Mt CO_2e year^{-1} with a cost saving of about 1068 and 1486 BDT (12.6 and 17.5 USD) t CO_2e^{-1} abated in 2030 and 2050, respectively. Similarly, adoption of zero- or strip-tillage would have a technical mitigation potential of 0.34 and 0.55 Mt CO_2e year^{-1} with the cost saving of 1760 and 1093 BDT (20.8 and 12.9 USD) t CO_2e^{-1} abated by 2030 and 2050, respectively. Adoption of short duration rice varieties would conversely reduce GHG emissions by 0.14 and 0.19 Mt CO_2e year^{-1}, with the marginal abatement cost of 96 and 154 BDT (1.1 and 1.8 USD) t CO_2e^{-1} abated by 2030 and 2050, respectively (Fig. 9).

3.4. Mitigation options and their potential in livestock production

Mitigation options identified in livestock production had a relatively smaller share of the total estimated mitigation potential of the agricultural sector in Bangladesh. By 2030 and 2050, all mitigation options in
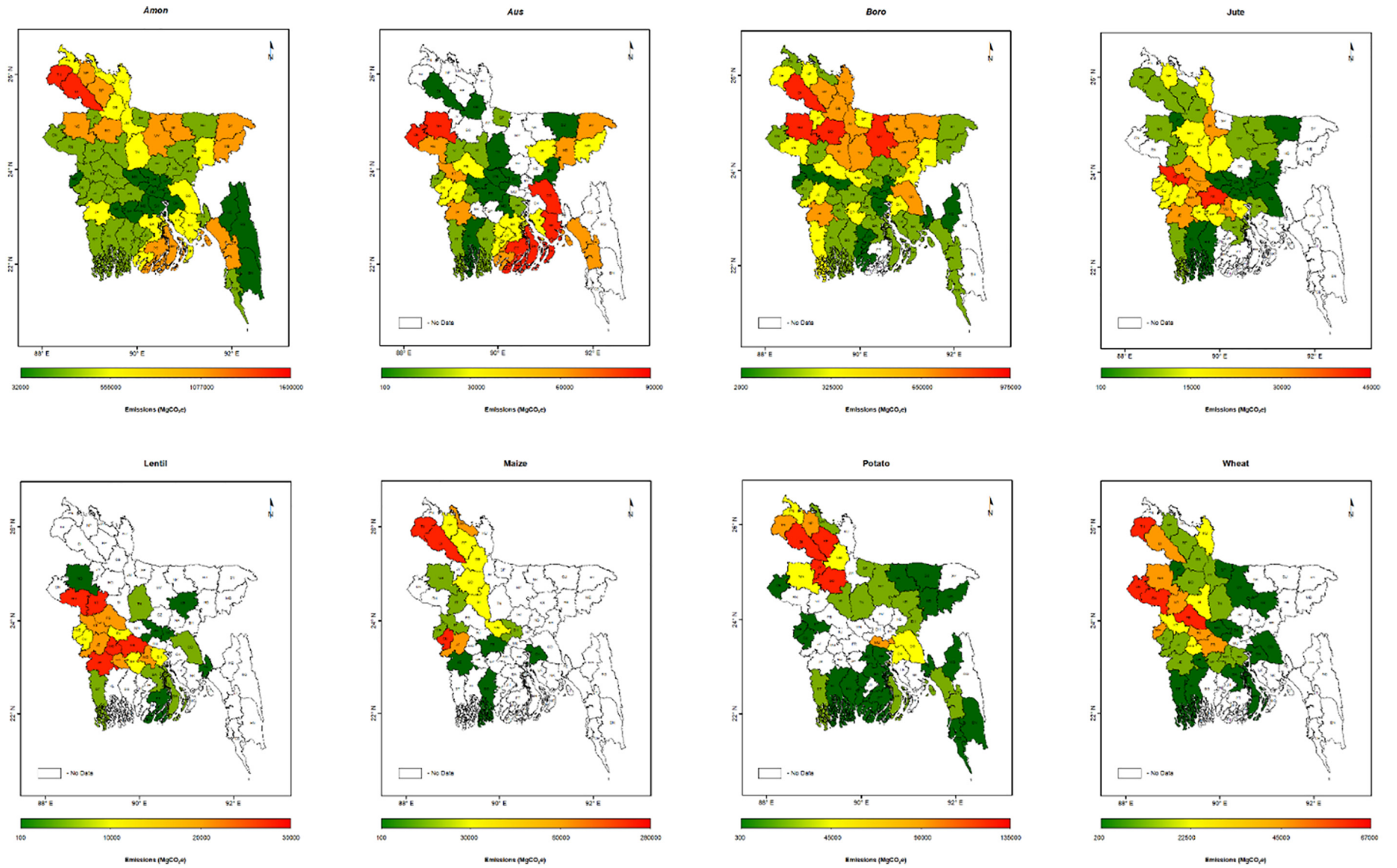
Fig. 6. District-wise total annual greenhouse gas emissions from eight major crops in Bangladesh. The full form of the district names is given in supplementary data S1 (District_abbreviation).
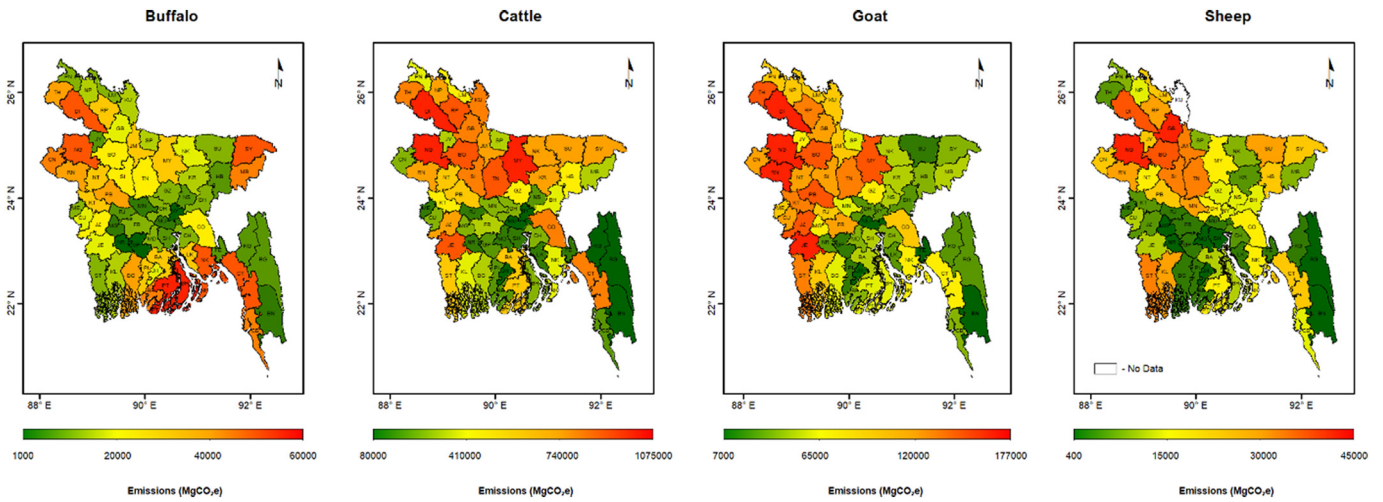
Buffalo **Cattle** **Goat** **Sheep**

Fig. 7. District-wise total annual GHG emissions from four major livestock species in Bangladesh. The full form of the district names is given in supplementary data S1 (District_abbreviation).

the livestock sector would offer 22 and 28% of the total potential in agricultural sector as a whole, respectively. Yet of all the mitigation options in livestock sector, increased concentrate feeding to large ruminants would offer the highest mitigation potential i.e. 1.29 and 1.81 Mt CO_2e year^{-1} by 2030 and 2050, respectively, with the abatement cost of about 50,000 BDT (589 USD) t CO_2e^{-1} (Fig. 9). Similarly, providing green fodder supplement to large ruminants would have a technical mitigation potential of 0.33 Mt CO_2e year^{-1} by 2030 and 0.48 Mt CO_2e year^{-1} by 2050 with an estimated abatement cost of about 100,000 BDT (1179.4 USD) t CO_2e^{-1}. Feeding animals with urea treated straw would have a mitigation potential of 0.19 Mt year^{-1} with the abatement cost of ca. 19,000 (224.0 USD) t CO_2e^{-1} abated in 2030 and 0.68 Mt CO_2e year^{-1}, with the abatement cost of ca. 8000 (94.3) t CO_2e^{-1} in 2050. Similarly, improved manure management through better storage, separation and aeration would offer a technical mitigation potential of 0.14 and 0.26 Mt CO_2e year^{-1} by 2030 and 2050, respectively, though with

the highest abatement cost of about BDT 365,000 (4304.9 USD) t CO_2e^{-1}. In addition, improvements in diet, grazing and feeding systems for sheep and goat would reduce GHG emissions by 0.04 Mt CO_2e year^{-1} with the additional cost of ca. 45,000 BDT (530.7 USD) t CO_2e^{-1} abated in 2030 and 0.49 Mt CO_2e year^{-1} with an abatement cost of ca. 1500 BDT (17.7 USD) t CO_2e^{-1}.

3.5. Mitigation hotspots

We also analyzed the spatial distribution of mitigation potential of all the mitigation options in crop as well as livestock production to identify the hotspots of mitigation for possible policy action. District-wise mitigation potential by each crop and livestock species and those achievable through different mitigation options for 2030 and 2050 are summarized in Supplementary Figs. S1–S6. In 2030 as well as in 2050, the mitigation potential of all mitigation options in crop production
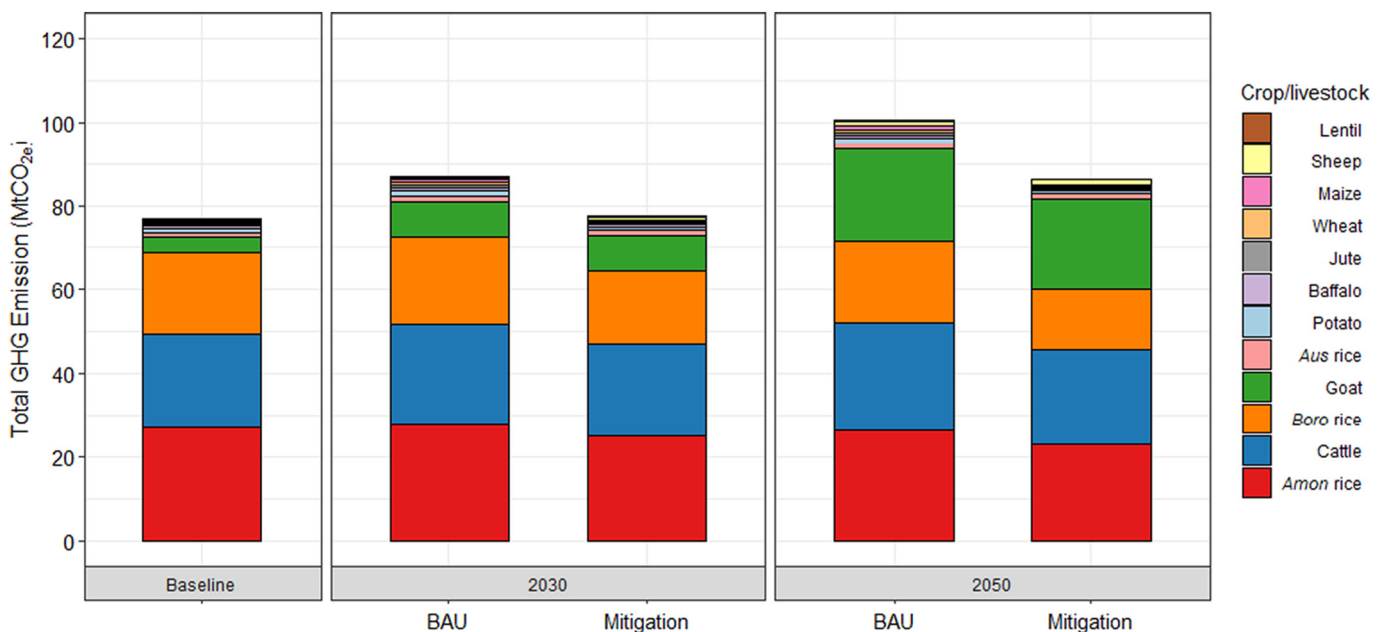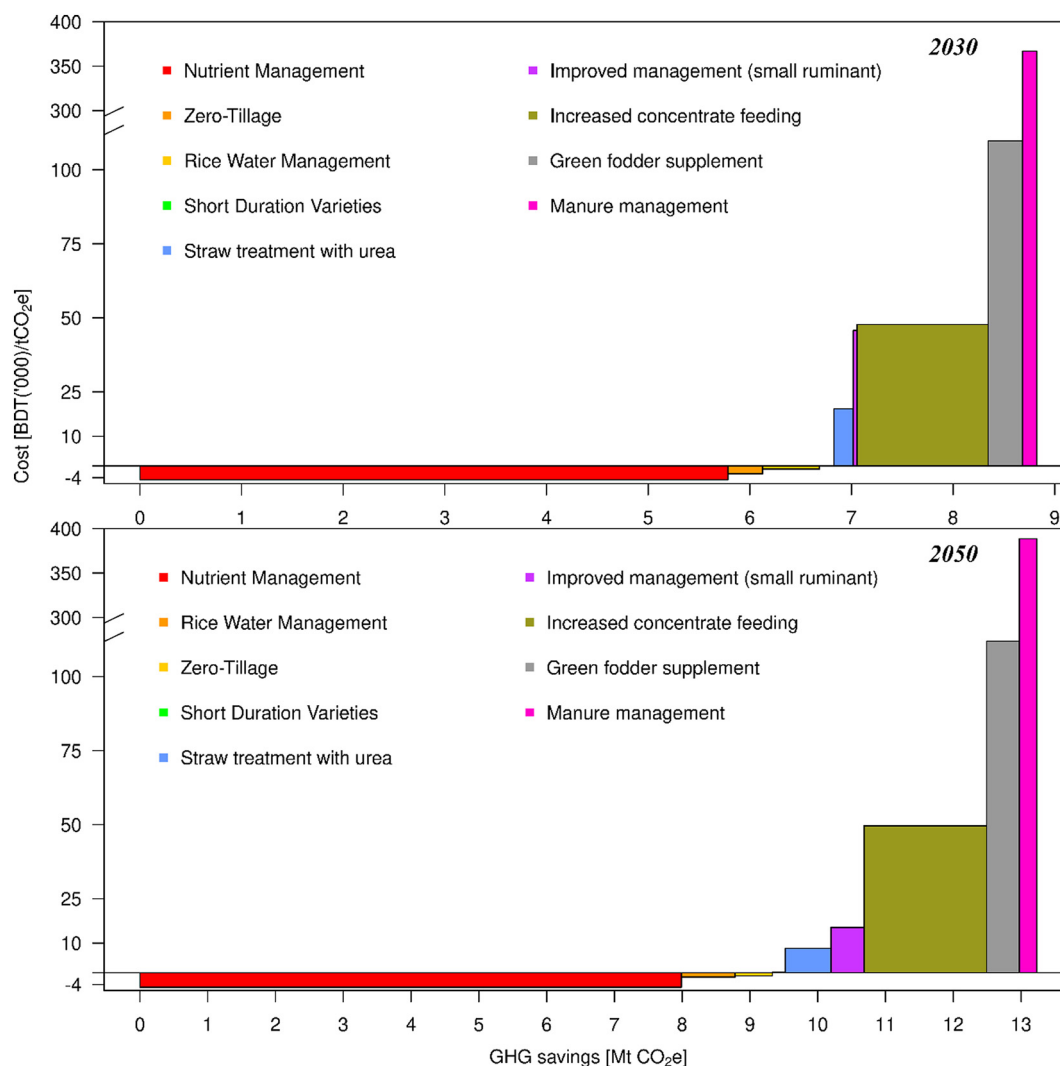

Fig. 8. Contribution of various crops and livestock species to total annual agricultural greenhouse gas emissions for baseline (2014–2015) as well as business-as-usual (BAU) and Mitigation scenario in 2030 and 2050. In 2030 and 2050, the difference in emissions between BAU and mitigation scenario is the total mitigation potential for the respective years.

Fig. 9. Annual mitigation potential and cost of various greenhouse gas mitigation options in the agricultural sector in Bangladesh in the short- (2030) and long-term (2050). In each panel, the width of each bar represents estimated mitigation potential and its height represents the average cost/benefit per unit of CO_2e abated. The area of each bar (height x width) shows the total cost or benefit of action at the national level, i.e. how much it would cost or benefit altogether to deliver all CO_2e savings possible from a particular mitigation option.

was highest in Dinajpur followed by Bogura, Naogaon, Mymensingh, and Rangpur (Fig. 10). Similarly, mitigation potential in the livestock sector was highest in Dinajpur followed by Mymensingh, Naogaon, Bogura and Rangpur. As crop mitigation options contributed to the substantial portion of total mitigation potential, the order of districts with the highest total mitigation potential was same as for total crop mitigation potential.

Our analysis showed that improved nutrient use efficiency through better N management could contribute to about 60–65% of the total mitigation potential from the agricultural sector in Bangladesh. Dinajpur appears to offer the highest mitigation potential from improved N management in both 2030 as well as 2050, followed by Bogura, Naogaon, Rangpur and Mymensingh in 2030 and followed by Bogura, Naogaon, Thakurgaon and Mymensingh in 2050 (Fig. 11).

4. Discussion

4.1. Baseline emissions

This bottom-up analysis made use of spatially explicit management data and district-wise crop area and livestock population to estimate administrative district level GHG emissions for 2014–15. Our estimate of total GHG emissions from the agricultural sector in Bangladesh for the

year 2014–2015 (76.79 Mt CO_2e, Fig. 4) is very similar to FAO's estimate for Bangladesh for the same year (76.94 MtCO_2e; http://www.fao.org/faostat/en/#data). Both our estimate and FAO's estimate were, however, much higher than the values reported in the Second National Communication of Bangladesh to the United Nations Framework Convention on Climate Change, i.e. 65.56 Mt CO_2e for the year 2004–2005 (MOEF, 2012).

This difference may be due to a number of reasons. Firstly, the emission values reported by the government of Bangladesh in its Second National Communication is for the year 2004–2005, whereas our estimate is for the year 2014–2015. While we expect some increase in emissions from 2005 to 2015, major differences are probably due to the estimation approach adopted. The estimates included in the Second National Communication were derived following a simple inventory approach using crop land coverage data and emission factors (MOEF, 2012, section 3.7), whereas our analysis involved a detailed bottom-up analysis using spatially explicit crop and livestock management data from all 64 districts supplemented with soil and climatic information.

As CH_4 emissions from rice is very sensitive to soil pH, with higher emissions resulting in soil with a pH range 4.5–5.5 (Yan et al., 2005), and given that many of Bangladesh's soils are acidic, the inventory type of assessment in Bangladesh's national communication – which did not consider soil types – was probably not able to capture such
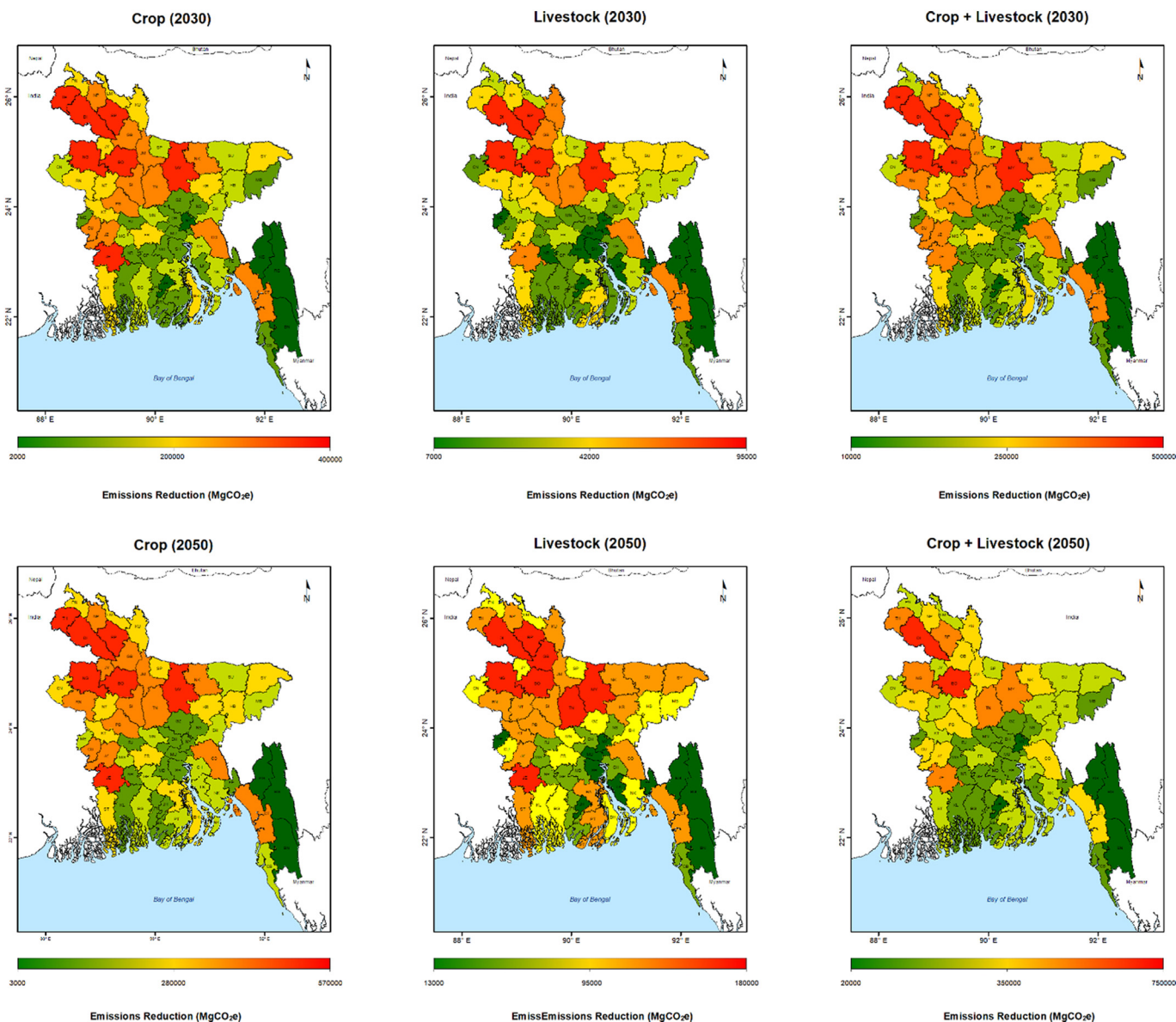
Fig. 10. District-wise distribution of greenhouse gas mitigation potential from all mitigation options in crop, livestock and crop-livestock combined in 2030 (upper panels) and 2050 (lower panels). The full form of the district names is given in supplementary data S1 (District_abbreviation).

sensitivity. Our semi-life cycle approach of GHG estimation in the crop sector considered emissions associated with not only production activities, but also that associated with the production and transportation of fertilizers and energy consumed in farm operations. In contrast, emissions associated with fertilizer and fuel are not included in agricultural emissions estimates in national inventories. Furthermore, the Second National Communication of Bangladesh used a global warming potential of CH_4 and N_2O as 25 and 310, respectively, based on IPCC (2006) guidelines, whereas we used 28 and 265 as global warming potential of CH_4 and N_2O, respectively, based on the 2013 IPCC report (IPCC, 2013).

In our analysis, crop production contributed a higher share (65%) of total agricultural emissions than did livestock (35%). This is in agreement with the estimate of the FAO (crop and livestock production contributed to 66% and 34%, respectively). The share of crop production to total agricultural emissions in our analysis was higher than Bangladesh's Second National Communication (53%), mainly because later did not consider emissions associated with the production and transportation of fertilizer, nor did it account for farm energy use. Lastly, our bottom-up analysis was more responsive to production

management, soil and climatic conditions. Higher total agricultural emissions in districts such as Dinajpur, Mymensingh, Naogaon, Bogura and Rangpur were mainly due to the larger area under rice cropping and larger population of indigenous cattle with poor dietary systems in these districts.

4.2. GHG abatement potential and associated cost

Through this bottom-up analysis, we demonstrate that 70–75% of total technical mitigation potential in the agricultural sector of Bangladesh can be achieved by adopting profitable mitigation options that have no cost of adoption (Fig. 9). The crop sector offers a higher mitigation potential than the livestock sector. Crop and soil management practices such as improved nutrient management, improved water management in rice, and zero- or strip-tillage, as well as the adoption of short duration rice varieties provided the bulk of the mitigation potential at national level. Of the total technical mitigation potential in the agricultural sector of Bangladesh, improvements in nutrient management would offer the greatest technical mitigation potential (5.78 and 7.98 Mt CO_2e year^{-1} in 2030 and 2050, respectively; Fig. 9).
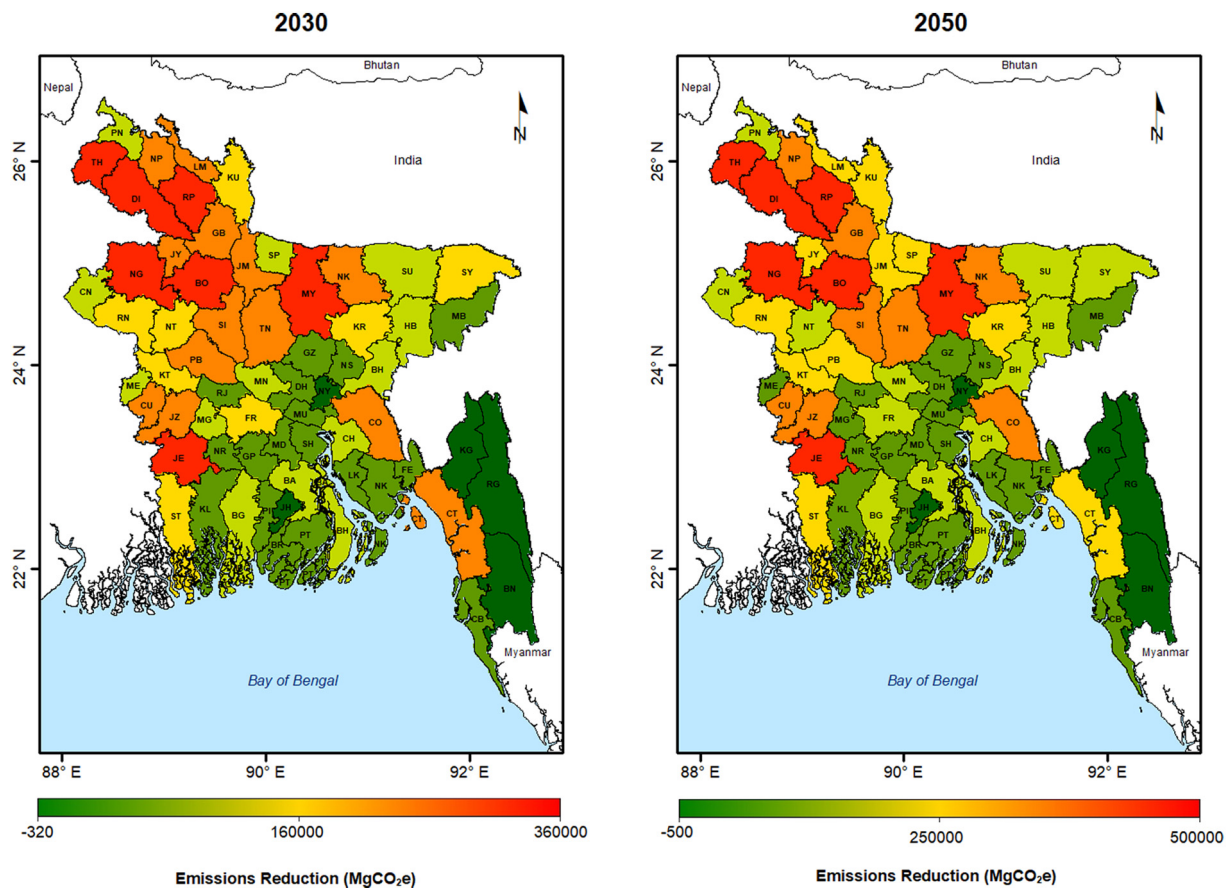
2030

2050

Fig. 11. District-wise distribution of annual greenhouse gas mitigation potential through improved and more efficient fertilizer management in the crop sector of Bangladesh in 2030 (left panel) and 2050 (right panel). The full form of the district names is given in supplementary data S1 (District_abbreviation).

Indeed, improvements in nutrient management in Bangladesh's crop sector has the potential to not only reduce GHG emissions, but also to mitigate other environmental externalities while increasing production and farmers' income, thereby offering net benefits per unit of GHG abated (Fig. 9). Many studies have demonstrated the potential to improve crop nutrient-use-efficiency by adopting various precision nutrient management approaches such as adjusting fertilizer rates based on crop demand (Krupnik et al., 2015; Sapkota et al., 2017a, 2014; Singh et al., 2014), using the right form of fertilizer including enhanced efficiency fertilizer (Halvorson and Del Grosso, 2012), applying fertilizer at the right time during plant uptake (Bijay-Singh et al., 2015), and by adopting appropriate fertilizer application methods (Hobbs and Gupta, 2004; Yadvinder-Singh et al., 2015). Similarly, adoption of zero-tillage and strip tillage practices for crop establishment offers GHG mitigation advantages by both enhancing carbon sequestration and reducing fuel consumption (Sapkota et al., 2017b). Although the effect of no-tillage or strip tillage on soil C sequestration can be small (Powlson et al., 2016), variable (Baker et al., 2007) and may continue only for a finite time (West and Marland, 2002), the reduction in emissions resulting from reduced fuel consumption are potentially long lasting in that they continue as long as fuel-efficient tillage practices are implemented (Govaerts et al., 2009).

Improved water management in rice contributes to GHG mitigation by reduced water consumption and associated energy use for irrigation, as well as by reducing CH_4 emissions from flooded rice fields (Wassmann et al., 2004). Converting continuously flooded rice fields into AWD results in more aerobic soil conditions, leading to CH_4 oxidization that is subsequently dissolved in the soil solution (Wassmann et al., 2000). Aerobic soil conditions also favor the growth of methanotrophic populations (Sapkota et al., 2015) which oxidize a considerable portion of total CH_4 produced in soil (Ma et al., 2010). It

has been reported that even a single drainage event during rice growing season reduced seasonal CH_4 emissions by 40%, and multiple drainage events by almost half, relative to continuous flooding (Yan et al., 2005). However, the adoption of AWD in Bangladesh to date has been limited due to the mismatch between water supply and the lack of volumetric water pricing used by pump owners that would incentivize reduced water use among farmers (Pearson et al., 2018). An integrated strategy and supportive policies to overcome the multiple constraints to AWD adoption are therefore urgently required. While daily CH_4 emission is determined by the combination of all controlling variables such as soil, climate, added organic matter and water management regimes (Yan et al., 2005), adoption of short duration varieties could also reduce CH_4 emissions by reducing the number of days the field remains under anaerobic conditions.

In livestock production, enteric fermentation constitutes about 40% of total livestock related emissions and its reduction through improved diet management appears to play a vital role in reducing livestock related emissions (Havlik et al., 2014). Various studies have demonstrated the positive effect of improved feed digestibility through inclusion of green fodder, concentrate, and treated straw in reducing CH_4 emissions per unit product (de Vries et al., 2015; Herrero et al., 2016; Sapkota et al., 2019; Thornton and Herrero, 2010). Improved diet management offers considerable mitigation potential, especially in developing countries like Bangladesh with poor livestock management systems. In the livestock systems of Bangladesh, increased green fodder and energy-dense feed (i.e. concentrate) in ruminants offer the greatest potential to both increase productivity and reduce emissions, although increased inclusion of concentrate in the form of grain feeding depends on economic feasibility relative to market prices for human food. Crop residues, which are low in nutritive value, are the main source of livestock feed globally, including in Bangladesh where rice straw is the

predominant feed (Valbuena et al., 2012). Improving their nutritive values could therefore considerably increase livestock productivity while keeping enteric CH_4 emissions constant (Thornton and Herrero, 2010). Better diets including green fodder, concentrate, and treated or fortified straw can improve the efficiency of feed conversion by animals. This can in turn lead to increased productivity and reduced mortality (Sirohi et al., 2005). By increasing livestock productivity, Bangladesh can probably meet its future demand for livestock products without substantially increasing the animal population as in the BAU scenario. This is important because in the smallholder production systems that dominate Bangladesh, a reduction in herd size by increasing productivity is likely to further increase feed availability, as there will be a lower livestock population to satisfy with finite feed resources. In case of animals slaughtered, increased live weight gain rates through improved dietary management can result in reduced age at culling, thereby reducing the duration of rumination and significantly decreasing GHG emissions per unit of livestock product (Herrero et al., 2016).

Emission of N_2O and CH_4 takes place during different stages of manure management from excretion of manure by livestock to storage, treatment, and finally to land spreading (Chadwick et al., 2011). Livestock production systems in rural Bangladesh are generally extensive, and manure excretion takes place in grazed fields after crop harvest. Such open grazing is supplemented with confined feeding, particularly at night. In either case, collection of manure for cooking fuel or fertilizer is done after animal wastes dry, leading to large N volatilization losses. Simple measures such as preparing proper collection pits for farmyard manure, or compacting and covering manure following collection can be taken to avoid nutrient losses to the environment through volatilization and leaching (Herrero et al., 2016). Moreover, proper incorporation of manure into the soil immediately after its application in the field not only reduces loss of nutrients, but also improves crop productivity and contributes to soil health (Hou et al., 2017). Bangladesh can also reduce manure-related GHG emissions by increasing the use of small-scale biogas plants and through vermicomposting, although these options may require initial capital investment resulting in a higher abatement costs, and are knowledge-intensive (Fig. 9). Appropriate incentive and financing mechanisms through access to finance for such investments, coupled with extension and training efforts may be necessary to increase adoption of these options.

In this study, we limited our analysis only to supply-side mitigation options and their potential for emissions reduction through changes in crop and livestock production practices. Estimates of emissions from aquaculture are already available (Henriksson et al., 2018) and should also be considered in future studies. In addition, we acknowledge that changes in other components of food systems such as food transport and processing, management of food loss and waste, as well as dietary changes – particularly away from red meat – also have implications for the mitigation of GHG emissions. Estimates of these sources of GHG emissions from demand-side actions are however beyond the scope of this study and warrant a holistic subsequent analysis from food system perspective.

5. Conclusions

Efforts to achieve sustainable intensification in agriculture aim not only to increase food production, but also to reduce contributions to GHG emissions. Climate smart agricultural practices, which achieve increased productivity and resilience, and mitigate emissions, are core to this objective, and provide an umbrella for many of the technical mitigation options discussed in this study. We estimated current emission levels from Bangladesh's crop and livestock sectors using spatially explicit crop and livestock management data (16,413 and 12,548 datapoints for crops and livestock, respectively) together with associated soil and climatic data. We further quantified spatially explicit mitigation potential considering a range of climate smart mitigation options.

Our data-driven and bottom-up approach estimated GHG emissions from agriculture in Bangladesh for the year 2014–15 to be 76.79 Mt CO_2e. Bangladesh's agricultural sector has the potential to mitigate 9.51 and 14.21 Mt CO_2e year^{-1} by 2030 and 2050, respectively, 70–75% of which can be achieved through easy-to-implement, cost-effective options that do not require long-term commitment by farmers. The remaining mitigation potential can be realized through introduction of appropriate incentives and financing mechanisms as well as through improved agricultural extension programs. However, realization of these mitigation benefits depends on farmers' adoption of those options. We therefore recommend that well-constructed policies should focus on understanding and responding to the barriers of adoption for appropriate technologies through awareness raising, risk-mitigating, training, and incentive mechanisms.

Spatially explicit (district-wise) data on GHG emissions segregated by each crops and livestock types together with their mitigation potential will be helpful for the government of Bangladesh to better prioritize mitigation options in ways that are consistent with overall food production, food security and environmental goals. Our data-driven and evidence-based results can also help Bangladesh to better negotiate for recognition of its national level contribution to environmental services, including applications for mitigation funds such as Green Climate Fund.

CRedit authorship contribution statement

Tek B. Sapkota: Conceptualization, Methodology, Supervision, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Fahmida Khanam:** Investigation, Data curation, Writing – review & editing. **Gokul Prasad Mathivanan:** Investigation, Formal analysis, Writing – review & editing. **Sylvia Vetter:** Investigation, Formal analysis, Writing – review & editing. **Sk. Ghulam Hussain:** Investigation, Data curation, Writing – review & editing. **Anne-Laure Pilat:** Writing – review & editing, Investigation, Data curation. **Sumona Shahrin:** Writing – review & editing, Investigation, Data curation. **Md. Khaled Hossain:** Investigation, Data curation, Writing – review & editing. **Nathu Ram Sarker:** Writing – review & editing. **Timothy J. Krupnik:** Conceptualization, Methodology, Supervision, Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgment

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.147344.

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