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Seasonal Variations in Grain Yield, Greenhouse Gas Emissions and Carbon Sequestration for Maize Cultivation in Bangladesh

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Abstract: Rationale: Greenhouse gas (GHG) emissions from crop agriculture are of great concern in the context of changing climatic conditions; however, in most cases, data based on lifecycle assessments are not available for grain yield variations or the carbon footprint of maize. The current study aimed to determine net carbon emissions and sequestration for maize grown in Bangladesh.

Methods: The static closed-chamber technique was used to determine total GHG emissions using data on GHG emissions from maize fields and secondary sources for inputs. A secondary source for regional yield data was used in the current study. GHG emission intensity is defined as the ratio of total emissions to grain yield. The net GHG emission/carbon sequestration was determined by subtracting total GHG emissions (CO₂ eq.) from net primary production (NPP). **Results:** Grain yields varied from 1590 to 9300 kg ha⁻¹ in the wet season and from 680 to 11,820 kg ha⁻¹ in the dry season. GHG emission intensities were 0.53–2.21 and 0.37–1.70 kg CO₂ eq. kg⁻¹ grain in the wet and dry seasons, respectively. In Bangladesh, the total estimated GHG emissions were 1.66–4.09 million tonnes (MT) CO₂ eq. from 2015 to 2020, whereas the net total CO₂ sequestration was 1.51–3.91 MT. The net CO₂ sequestration rates were 984.3–5757.4 kg ha⁻¹ in the wet season and 1188.62–5757.39 kg ha⁻¹ in the dry season. This study observed spatial variations in carbon emissions and sequestration depending on growing seasons. In the rice–maize pattern, maize sequestered about 1.23 MT CO₂ eq. per year⁻¹, but rice emitted about 0.16 MT CO₂ eq. per year⁻¹. This study showed potential spatiotemporal variations in carbon footprints. **Recommendation:** Special care is needed to improve maize grain yields in the wet season. Fertiliser and water use efficiencies need to be improved to minimise GHG emissions under changing climatic conditions. Efforts to increase the area under cultivation with rice–maize or other non-rice crop-based cropping systems are needed to augment CO₂ sequestration. The generation of a regional data bank on carbon footprints would be beneficial for combating the impact of climate change.

Keywords: wet and dry seasons; net carbon emissions and sequestration; spatial variability

1. Introduction

In many countries, the quantity of cereal grains produced governs food and nutritional security. A good harvest depends on climatic variability, management options and soil fertility [1–3]. The influence of production environment is particularly evident outside the core production zone. Varietal differences are also responsible for yield variability depending on the environment, especially temperature, which plays a critical role [3–6]. Among many management options, fertiliser rate and application patterns not only influence grain yield but also modulate GHG emissions [4,7] and, thus, control the carbon footprint.

Carbon is the backbone of life processes and significantly influences soil [8] and atmospheric properties depending on its form. It is established that emissions of carbon in the form of CO₂ and methane (CH₄) from agriculture are contributing to global warming [9,10]. However, carbon balance can also be a good indicator of soil fertility and environmental pollution [11]. In developing countries, most of us are somewhat familiar with carbon emissions from agriculture (mostly from organic amendments, livestock and rice cultivation, and also from tropical deforestation) because of numerous pronouncements from different quarters of the globe [12,13]. Unfortunately, there are no adequate data, in many developing countries, for delineating scenarios on the emission or sequestration of carbon during the cultivation of major crops. Depending on crop husbandry, carbon emissions vary greatly and, thus, either net emissions or carbon sequestration are possible. For instance, the quantities of GHGs emitted from flooded paddy fields and rainfed rice fields are not similar to those of maize or wheat crop fields grown under upland conditions [14–16].

Rice and wheat are the dominant cereals in Bangladesh; maize is third in terms of area coverage. The area under maize cultivation is increasing because of its diversified uses and economic profitability. It covers about 0.47 million ha, yielding about 4.02 MT [17]. Maize is grown in the wet and dry seasons in Bangladesh utilising considerable amounts of inputs, including pesticides, fertilisers and irrigation water. The use of inputs at variable rates during crop culture influences GHG emissions from the field not only directly but also indirectly because GHG emissions are also generated during the production of the inputs [11]. Lifting-up irrigation waters using fossil fuels or electricity also influences GHG emissions [18]. Moreover, agricultural operations are not fully mechanised in Bangladesh; rather, different sources of energy are used for growing maize and in its post-harvesting processes [19]. Labour forces are also responsible for GHG emissions [20], and that fact has not yet been considered in the determination of total emissions from crop cultivation. However, even if labour forces were not utilised in crop culture, they would still emit GHGs. As the use of production inputs (fertilisers, agrochemicals, etc.) and their manufacturing greatly influence carbon emission patterns across countries and even within a country [21,22], it is necessary to determine the carbon footprint of maize based on a life cycle analysis (LCA).

Agriculture is contributing to the rise in global surface temperatures because of GHG emissions [10,22] that have variable warming potential [23]. On the other hand, crop plants fix CO₂ during photosynthesis and store it in grains, straw, roots and in the soil as root exudates [24,25]. So, it needs to be determined whether there is net emission or carbon fixation by considering net primary production (NPP) and emissions under specific crop growing conditions [26–28]. Typically, all components of crop production practices are considered in calculating emissions, both direct and indirect, from agricultural crop fields. Currently, no such data are available in Bangladesh, where maize cultivation utilises energy from the human labour–animal–engine nexus. Moreover, GHG emission scenarios differ between tropical and temperate countries. Therefore, we measured GHG emissions from maize fields and estimated emissions and net carbon sequestration from 2015 to 2020 in Bangladesh, considering both direct and indirect emissions as well as NPP.

2. Materials and Methods

2.1. Experimental Procedures

The field experiment was conducted at the Bangladesh Agricultural Research Institute (BARI) farm in Gazipur, Bangladesh, during the dry seasons (*rabi* seasons) of 2018–2019 and 2019–2020. The soil belongs to the category of Grey Terrace soils of the Madhupur tract (AEZ-28). The recommended dose (RD) of nitrogen (225 kg ha⁻¹) in the form of prilled urea (PU) at 225 kg N ha⁻¹ was used. Phosphorus, K, S, Zn and B were applied at rates of 60, 110, 40, 4 and 1.4 kg ha⁻¹ from DAP, MoP, gypsum, zinc sulphate and boric acid, respectively. All of the PKSZnB was applied at the time of final land preparation. One-third of the PU was applied one day before sowing, and the remaining two-thirds were applied by broadcasting in equal parts at 40 days after sowing (DAS) and at 75 DAS. The unit plot size was 4 m × 2.5 m. The tested crop was BARI Hybrid Maize-9. Maize seed was sown at 60 cm × 20 cm spacing in the first week of December of 2018 and 2019. All intercultural operations, such as irrigation, weeding, insect control, etc., were done as and when necessary. The harvesting of the maize was done in mid-April of 2019 and 2020. Data concerning maize area and yields were collected from the Bangladesh Bureau of Statistics for all growing seasons from 2015–2016 to 2019–2020 [29]. Since only grain yields were available from the BBS data, stover yields were determined from the existing literature [30,31] according to the following formula:

$$\text{SYM} = \frac{\text{Grain yield}}{0.723118} \quad (1)$$

where SYM is the stover yield of maize in t ha⁻¹.

Net below-ground carbon (C) was estimated according to Amos and Walters, 2006, as follows:

$$\text{Net below-ground C (kg ha}^{-1}\text{)} = \text{Shoot biomass C (kg ha}^{-1}\text{)} * 0.29 \quad (2)$$

Litter C deposition was taken as about 7.5 kg ha⁻¹.

2.2. Greenhouse Gas Measurement

N₂O and CO₂ gas samples were collected from static closed chambers [28,32–34] placed between crop rows. The chamber size was 0.20 m × 0.20 m, and each chamber was equipped with a circulating fan and thermometer. Chambers were kept open at all times except during sample collection at 8:00 AM–12:00 noon in a single day at 7-day intervals. Gas samples were collected in 50 mL air-tight syringes at 0 and 30 min after closing the chamber and were then transferred into 20 mL air-evacuated glass vials sealed with a butyl rubber septum. Gas samples were analysed by gas chromatography (Shimadzu, GC-2014, Kyoto, Japan) equipped with a Porapak NQ column (Q 80–100 mesh). N₂O and CO₂ emissions were determined by ECD and TCD at 45 °C and 70 °C for CO₂ and N₂O, respectively. The injector and detector were adjusted at 75 °C and 270 °C, respectively, for CO₂ and 80 °C and 320 °C, respectively, for N₂O. Argon and helium were the carrier gases, and air and H₂ were used as burning gases.

Gas fluxes were estimated according to Lou et al. [35], as follows:

$$M = Q \times \frac{A}{B} \times \frac{\Delta d}{\Delta p} \times \frac{273}{T} \quad (3)$$

where M is the emission rate of CO₂ (mg m⁻² hr⁻¹) and N₂O (μg m⁻² hr⁻¹), Q is the gas density of CO₂ and N₂O in mg cm⁻³, W is chamber volume in m³, B is chamber surface in m², Δd/Δp is the rate of increase in GHG concentrations in mg m⁻³ hr⁻¹ and T is the chamber temperature (273 + mean temperature) in °C.

Seasonal fluxes of CO₂ and N₂O (SCCN) were estimated according to Singh et al. [36]:

$$\text{SCCN flux} = \sum_f^e (U_i \times V_i) \quad (4)$$

where U_i indicates the rate of CO₂ and N₂O flux (g m⁻² d⁻¹) at the ith sampling interval, V_i represents the day numbers for the fth sampling interval and e is the sampling number.

About 30–62% of people emit CH₄ [20]. We used a value of 45% of the labour force and calculated the CH₄ they produced in 8 working hours. Finally, the GHG emission factors (kg CO₂ eq. ha⁻¹) were calculated as shown in Table 1. However, the data sources were lacking in many instances; in such cases, data were estimated based on the existing literature and expert judgement.

Based on field emission data, the net ecosystem C balance (NECB) in kg CO₂ eq ha⁻¹ was calculated according to [27,28,37] and the net primary product (NPP, above- and below-ground biomass, litter and rhizodeposits in kg ha⁻¹) according to Smith et al. [26]:

$$\text{NECB} = \text{NPP} - \text{R}_{\text{ecosystem respiration}} - \text{Harvest} - \text{CH}_4 + \text{Manure/Fertiliser} \quad (5)$$

$$\text{NPP} = \text{NPP}_{\text{grain}} + \text{NPP}_{\text{straw}} + \text{NPP}_{\text{root}} + \text{NPP}_{\text{litter}} + \text{NPP}_{\text{rhizodeposit}} \quad (6)$$

Net CO₂ sequestration (NCS) in kg CO₂ ha⁻¹ was calculated as follows:

$$\text{NCS} = \text{NECB} - \text{N}_2\text{O emissions (kg CO}_2 \text{ eq ha}^{-1}) - \text{IDE (kg CO}_2 \text{ eq ha}^{-1}) \quad (7)$$

where the harvest includes grain and straw, CH₄ is the amount of methane as kg CO₂ ha⁻¹ and IDE is the indirect emissions (kg CO₂ eq ha⁻¹) in relation to crop production.

GHG emission intensity (GHGI) was estimated as per the following formula:

$$\text{GHGI (kg CO}_2 \text{ eq kg}^{-1} \text{ grain)} = \frac{\text{Total emissions (kg ha}^{-1})}{\text{GY}_i} \quad (8)$$

where GY_i is the grain yield (kg ha⁻¹) of the ith district (i = 1, 2, 3 64)

Carbon dioxide sequestration intensity (kg CO₂ kg⁻¹ grain) was determined as follows:

$$\text{CO}_2 \text{ seq. intensity} = \frac{\text{Total net CO}_2 \text{ sequester (kg ha}^{-1})}{\text{GY}_i} \quad (9)$$

where GY_i is the grain yield (kg ha⁻¹) of the ith district (i = 1, 2, 3 64)

The net CO₂ sequestration rate was calculated as follows:

$$\text{CO}_2 \text{ seq. rate (kg ha}^{-1}) = \text{CO}_2 \text{ seq. intensity} * \text{Grain yield in each district} \quad (10)$$

Total GHG emissions were calculated as follows:

$$\text{Total GHG emissions} = \text{Measured emissions (kg ha}^{-1}) * \text{Area (ha)} \quad (11)$$

Total net CO₂ sequestration was determined by multiplying equation number 10 by area coverage.

2.3. Statistical Tools Used in the Current Study

Descriptive statistics were mostly used to show the variations in GHG emissions and net CO₂ fixation in relation to maize. Quantum Geographic Information System (QGIS) version 2.18 was used to show the spatial distribution of total GHG emissions and net CO₂ fixation in different districts of Bangladesh.

3. Results

3.1. Seasonal Grain Yield Variability

The grain yield of maize varied significantly with the growing seasons over the years (Figure 1). Ignoring the outlier values, the grain yield varied from 4810 to 5970 kg ha⁻¹ in the wet season, considering the 50th percentile, while it varied from 6144 to 6964 kg ha⁻¹ in the dry season (Figure 1a,b). Similarly, the range of the yield varied from 5652 to 7157 and from 7096 to 8386 kg ha⁻¹ in the wet and dry seasons, respectively, considering 75th percentile. However, there were wide variations in grain yields, which ranged from 1590 to 9300 kg ha⁻¹ in the wet season and from 680 to 11,820 kg ha⁻¹ in the dry season, excluding outliers.

Table 1. Greenhouse gas emissions during maize cultivation.

Items	Emissions (kg ha ⁻¹)	Comments
Land preparation	156.146	About 80% of the land was prepared by a power tiller and 20% by a tractor [19]. About 45% of labour force emits CH ₄ at 1.12 kg CO ₂ capita ⁻¹ man-day ⁻¹ (adapted from https://badgut.org). Diesel-burning emissions of 3.56 kg CO ₂ L ⁻¹ [38].
Seed (21 kg ha ⁻¹)	23.52	Seed rate 21–23 kg ha ⁻¹ [39] and CO ₂ eq. emissions of 1.12 kg ha ⁻¹ [40].
Seeding	10.08	About 20 man-days ha ⁻¹ for manual seeding. About 45% of labour force emits CH ₄ at 1.12 kg CO ₂ eq. man-day ⁻¹ .
Fertilisers	2152.702	Fertiliser at 484–214–166 kg ha ⁻¹ for urea, TSP and MoP, respectively [41]. One-fifth of urea is generally imported. For imported and manufactured urea, the GHGs were 0.93 and 4 kg CO ₂ kg ⁻¹ , respectively, and 1.29 kg CO ₂ eq kg ⁻¹ for TSP and 1.47 kg CO ₂ eq kg ⁻¹ for MoP [42,43].
Irrigation-3x	1594.13	The average water requirement for maize is 398.56 mm ha ⁻¹ [44]. GHG emissions were estimated based on [18].
Insecticide-2x	69.44	About 250 mL ha ⁻¹ was used for one spray. The emissions considered were 21.7 kg CO ₂ eq. ha ⁻¹ [45].
Weeding-2x	21.28	About 42 man-day ha ⁻¹ for hand weeding [17].
Harvesting	15.68	Harvesting is mostly done manually and requires about 31 man-day ha ⁻¹ .
Shelling/Threshing	115.3804	96% of maize is threshed by machine [46] and the rest is threshed manually. Diesel burning emits 3.56 kg CO ₂ eq. ha ⁻¹ [38].
Steel-embedded emissions for thresher	3.375	Emissions at 2.7 kg CO ₂ eq. kg ⁻¹ steel [42]. In 5 years, open-drum threshing for 300 ha and close-drum for 600 ha.
Total indirect	4161.733	
Field-measured N ₂ O (as CO ₂ eq.)	111.3	
Respiratory CO ₂	673.64	
Total direct	784.94	
Grand total	4946.673	

3.2. Seasonal GHG Emission Intensity

There were significant variations in GHG emission intensity in the growing seasons over the years. As a whole, GHG emission intensity varied from 0.53 to 2.21 kg CO₂ eq. kg⁻¹ grain yield in the wet season, excluding outlier values (Figure 2a), and it varied from 0.37

to 1.70 kg kg^{-1} in the dry season (Figure 2b). Considering the 50th percentile, the emission intensity was $0.83\text{--}1.03 \text{ kg kg}^{-1}$ in the wet season and $0.71\text{--}0.81 \text{ kg kg}^{-1}$ in the dry season. Similarly, it was $1.02\text{--}1.43 \text{ kg kg}^{-1}$ in the wet season and $0.91\text{--}1.15 \text{ kg kg}^{-1}$ in the dry season when considering the 75th percentile.

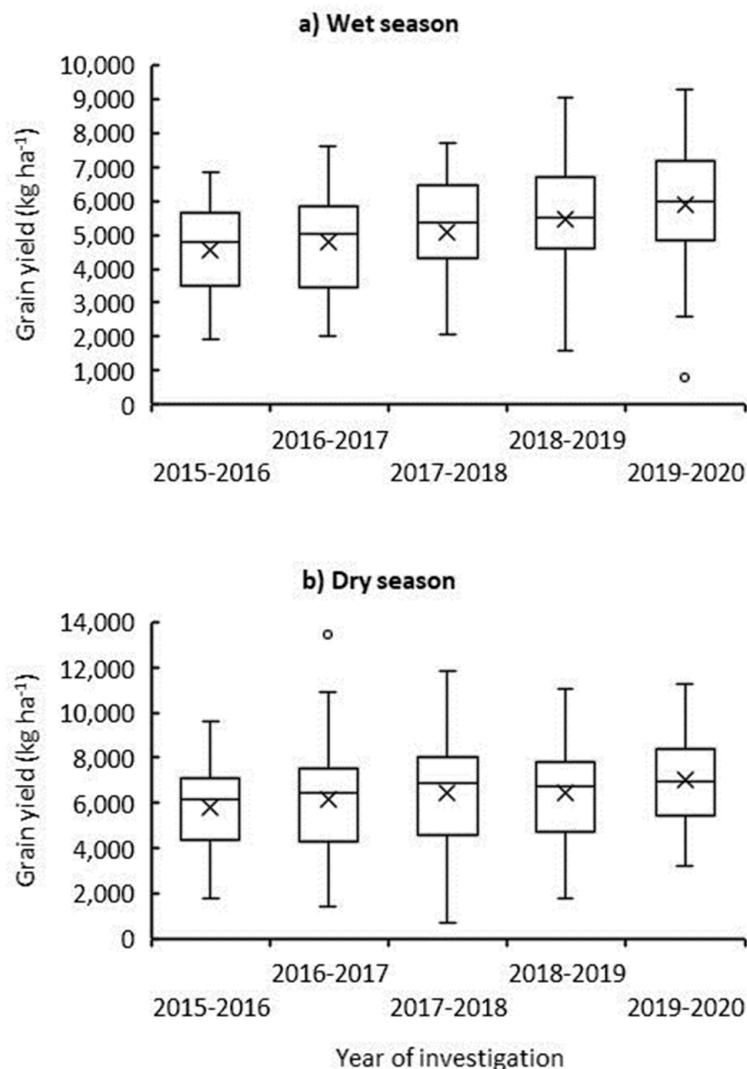


Figure 1. Variability in maize grain yields, 2015–2020, Bangladesh.

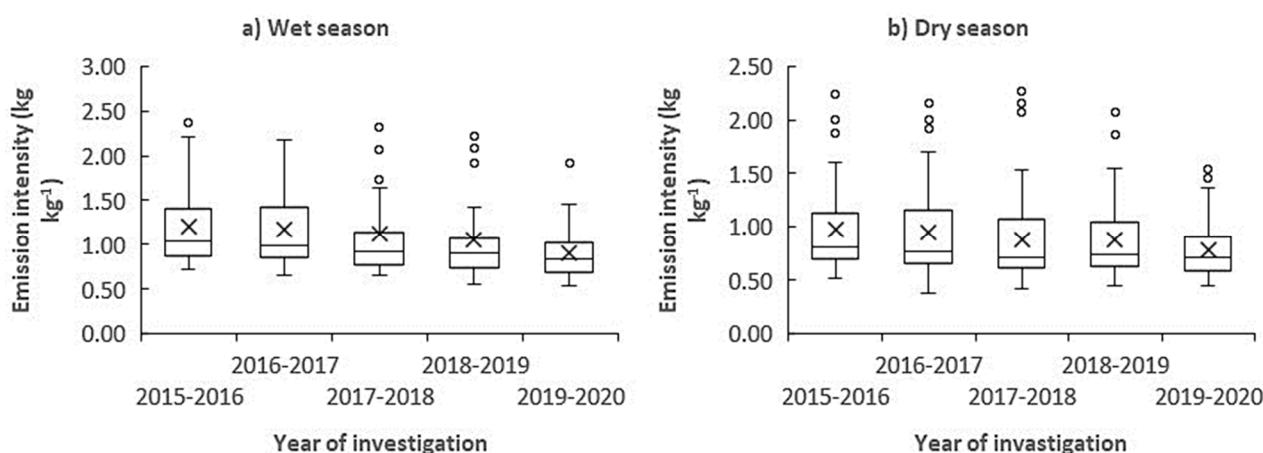


Figure 2. GHG emission (CO₂ eq) intensity in the wet and dry seasons over the years studied in Bangladesh.

3.3. Seasonal Total GHG Emissions

Total GHG emissions during maize cultivation varied greatly. In the wet season, total GHG emissions varied from 0.26 to 0.39 MT over the years studied, although such variations ranged from 1.40 to 3.73 MT in the dry season (Figure 3). Considering both growing seasons, the total GHG emissions ranged from 1.66 to 4.09 MT.

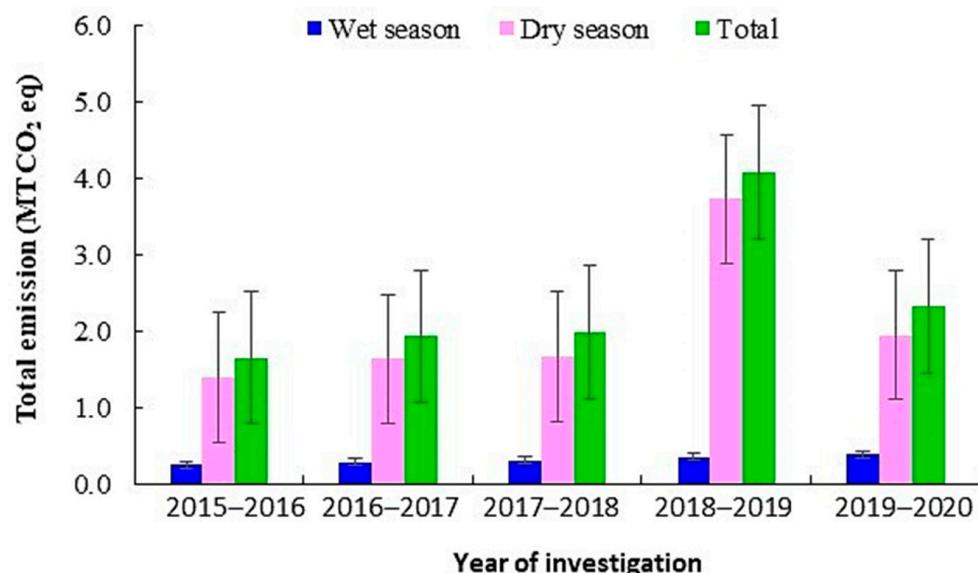


Figure 3. Total estimated GHG emissions during maize cultivation in Bangladesh. Error bars indicate standard deviations.

3.4. Net Carbon Sequestration Rate

The net carbon sequestration rate, as with CO₂, varied significantly over the growing seasons during the 2015–2020 period (Figure 4). In the wet season, the net CO₂ sequestration rate ranged from 2977.75 to 3695.87 kg ha⁻¹ considering the 50th percentile and from 3499.32 to 4431.02 kg ha⁻¹ based on the 75th percentile. However, in the same season, the minimum net CO₂ sequestration rate was 984.33 kg ha⁻¹ and the maximum rate was 5757.38 kg ha⁻¹, excluding the outlier values. The net CO₂ sequestration rate in the dry season ranged from 2977.75 to 3726.83 kg ha⁻¹ considering the 50th percentile and from 3499.32 to 4475.33 kg ha⁻¹ based on the 75th percentile, although the minimum sequestration rate was 1188.62 kg ha⁻¹ and the highest rate was 5757.39 kg ha⁻¹.

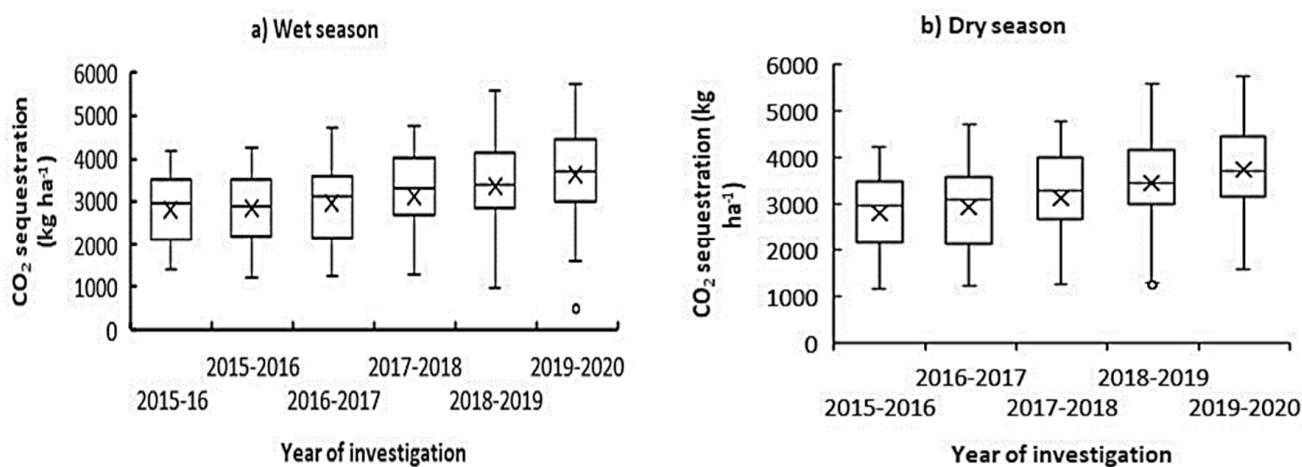


Figure 4. Net carbon dioxide sequestration rates during maize cultivation in Bangladesh.

3.5. Total Net CO₂ Sequestration

Total net CO₂ sequestration varied significantly between growing seasons over the years studied (Figure 5). In the wet season, net total CO₂ sequestration varied from about 0.18 to 0.30 MT, and it was 1.33–3.63 MT in the dry season. Considering both growing seasons, the net total CO₂ sequestration for 2015–2020 was 1.51–3.91 MT in Bangladesh.

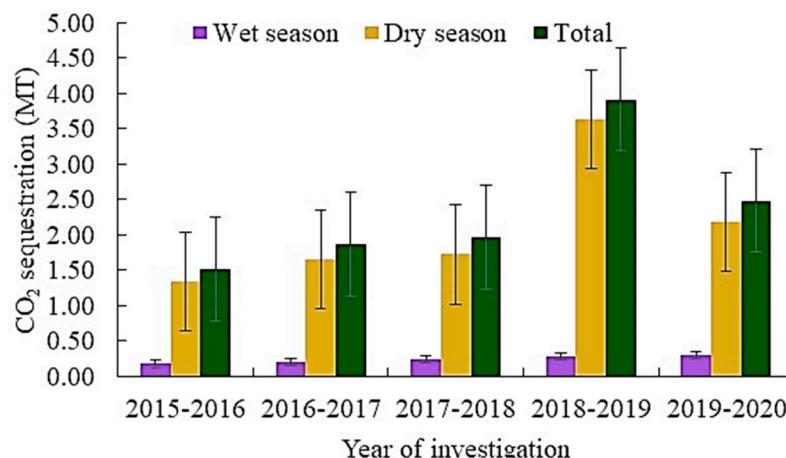


Figure 5. Total net CO₂ sequestration during maize cultivation in Bangladesh. Error bars indicate standard deviations.

3.6. Spatio-Temporal Distribution of Carbon Emissions and Sequestration

The distribution of average total emissions in each district (i.e., administrative unit) varied greatly depending on the growing seasons. Most emissions were from the northern and north-west parts of the country, as well as the central region, with minor amounts from the hilly regions of the country (Figure 6).

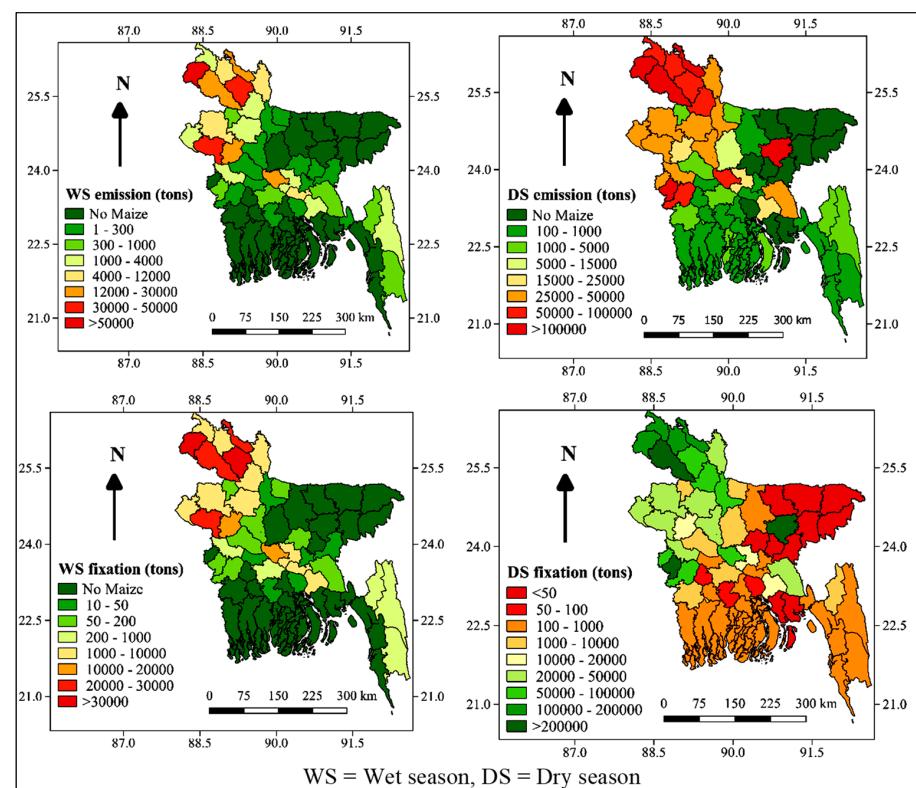


Figure 6. Average GHG emissions and net CO₂ sequestration in the wet and dry seasons of 2015–2020 during maize cultivation in Bangladesh.

Depending on the location of maize cultivation, the average emissions for 2015–2020 ranged from 1 tonne to >50,000 tonnes in the wet season and from 100 tonnes to >100,000 tonnes in the dry season. In a similar fashion, the total net CO₂ sequestration was distributed in the same production zones and varied from 10 to >30,000 tonnes in the wet season and from <50 to >200,000 tonnes in the dry season.

4. Discussion

4.1. Grain Yield Variability

The grain yield of any crop varies depending on multiple factors, such as input management, sowing time and crop suitability. In our study, we found a large variability in grain yield, mostly because of differences in production zones and growing seasons. Growing maize in unfavourable regions, such as the southern part of the country, gives a comparatively lower yield than in major production zones in the northern, north-west and central parts of the country. Favourable production zones are located in the northern, north-western and central regions of the country, where grain yields varied from about 6.22 to 9.30 t ha⁻¹ in the wet season and from 7.12 to 11.26 t ha⁻¹ in the dry season. In contrast, unfavourable maize growing regions (mostly low-lying and heavily textured soil areas) provided grain yields of maize ranging from 1.92 to <6.00 t ha⁻¹ in the wet season and from 3.12 to <7.00 t ha⁻¹ in the dry season. Weather variability, soil moisture status and fertiliser management greatly contribute to maize yield variability. Similar findings were reported by Ahmed et al. [2] and Stuch et al. [47]. Ray et al. [1] reported that about 32–39% and even >60% of yield variations are explainable by climate variability. In future, crop yields will be mostly reduced because of temperature and precipitation variations over the locations in the globe [48] (Konduri et al., 2020) in which efficient irrigation water management will be a crucial factor for sustainable agriculture [49] (Shirmohammadi Chelan et al., 2020). In the wet season, maize is generally exposed to higher temperatures than in the dry season, and conditions are thus unfavourable for higher grain yields in the wet season. A maximum temperature above 29 °C for long periods sharply decreases maize yields [6,50]. Generally, the cooler temperatures in the dry season (about 12–27 °C for night–day temperatures from November to March) compared to the wet season (about 25–32 °C for night–day temperatures from June to September) and the clear sunshine conditions favour the physiological processes of maize; thus, high grain yields are attained in the dry season. A mean optimum temperature of 20–22 °C during the whole growing season is synergistic for getting a high yield of maize [51], and that temperature range generally prevails in Bangladesh during the dry season. However, a rise in mean temperature of 1 °C can reduce maize yields by 3–13% [52], which justifies the yield reductions observed during the wet season in Bangladesh.

4.2. GHG Emission Intensity

During the study period, the GHG intensity was 1.09 ± 0.46 kg CO₂ eq kg⁻¹ grain in the wet season and 0.89 ± 0.40 kg CO₂ eq kg⁻¹ grain in the dry season. This seasonal variation in GHG intensities was related to the grain yields of maize. We found a lower GHG intensity than what was recorded in China (1.76 kg CO₂ eq kg⁻¹ grain) as per the report of Zhang et al. [11], but a higher intensity than the report in [21]. The latter authors only reported a range from –0.027 to 0.436 kg CO₂ eq kg⁻¹ grain in the United States of America. In India, the GHG intensity for maize cultivation was 0.71 kg CO₂ eq kg⁻¹ grain [53], which was very similar to our findings for dry-season maize. In general, grain yields were higher in the dry season than in the wet season and, thus, a lower GHG intensity was observed in the dry season. As stated earlier, grain yields were higher in the north, north-west and central parts of Bangladesh, and these higher grain yields were responsible for the lower GHG intensity in those areas compared to other maize-growing regions in the country.

4.3. Total GHG Emissions

We found $4946.7 \text{ kg ha}^{-1} \text{ CO}_2 \text{ eq}$ emissions (Table 1) in relation to maize cultivation; this figure was used for total emissions because there were no regional data available in Bangladesh.

Moreover, the fertilisers used by the farmers and other cultural practices may be different for growing maize in different regions of the country; that variable has been ignored in the present investigation. A few references are provided here in support of our data on per-unit GHG emissions. For example, Zhang et al. [11] reported significantly higher emissions ($14,857.33 \text{ kg CO}_2 \text{ eq ha}^{-1}$) for maize cultivation in China, mainly because of mechanised cultivation and the excessive use of fertilisers. Based on field-measured data, Jain et al. [53] reported emissions of $3428.33 \text{ kg CO}_2 \text{ eq ha}^{-1}$ for maize cultivation in India. Jayasundara et al. [54] found emissions of $1862\text{--}3742 \text{ kg CO}_2 \text{ ha}^{-1}$ in Canada based on a lifecycle-based assessment. However, Camargo et al. [55] reported a general range of $2440\text{--}4200 \text{ kg CO}_2 \text{ eq ha}^{-1}$ emissions during maize cultivation. Thus, the above-mentioned literature shows that our finding falls within the established range of GHG emissions globally. Since total GHG emissions in this study were determined based on a lifecycle (field-measured + input-related) assessment and area coverage, there were huge variations in total emissions in both the wet and dry seasons as a whole. Our estimation provides an incentive to policy planners for future action on grain yield improvement and GHG-reduction strategies.

4.4. Net Carbon Sequestration Rate

We found a rate of $4964.43 \text{ kg CO}_2 \text{ ha}^{-1}$ sequestration based on a lifecycle assessment, and the estimated CO_2 sequestration ranged from 237.72 to $6761.46 \text{ kg ha}^{-1}$ depending on the maize growing season. Our findings are comparable with the existing literature, such as Holka and Beńkowski [56], who reported a rate of $1000\text{--}1700 \text{ kg CO}_2 \text{ ha}^{-1}$ sequestration for a tonne of grain production. Khorramdel et al. [57] found a rate of about $30\text{--}15,033 \text{ kg CO}_2 \text{ ha}^{-1}$ depending on the level of inputs used, whereas [42] reported comparatively higher amounts of carbon absorption ($23,466\text{--}34,503 \text{ kg CO}_2 \text{ ha}^{-1}$) with summer maize production depending on the tillage system and stover management. Such wide variations in CO_2 sequestration are related to soil fertility, weather patterns, the use of inputs and crop management practices in different corners of the globe. Terrestrial plants sequester about 123 gigatonnes of CO_2 during photosynthesis [24], and maize contributes to this noble function under changing climatic conditions.

4.5. Total Net CO_2 Sequestration

Net CO_2 sequestration is the balance between inputs and outputs, and such an assessment was conducted in the present investigation. Total net CO_2 sequestration was $1.51\text{--}3.91 \text{ MT}$ for 2015–2020 in relation to maize cultivation, indicating that maize production contributes in minimising CO_2 emissions from crop agriculture in Bangladesh. It is also implied that net CO_2 sequestration takes place in other maize-growing countries around the world. Since total net CO_2 absorption depends on total biomass production and root deposition, amounts vary in different parts of the world. As maize is grown in rotation with rice (either before or after rice) in about $247,505 \text{ ha year}^{-1}$ in Bangladesh [58], it can sequester about $1.23 \text{ MT CO}_2 \text{ eq year}^{-1}$ ($4964.43 \times 247,505$), indicating that emissions from rice fields are minimised under a rice–maize cropping system (Table 2) compared to a rice–rice cropping system.

Table 2. Area coverage and estimated GHG emissions (CO_2 eq) and carbon sequestration in rice–maize cropping patterns in Bangladesh.

Patterns	Area (ha)	Paddy Field Emissions (Tonnes)	CO_2 Sequestration by Maize (Tonnes)
Maize–Fallow–T. Aman	101,460	66,963.60	503,691.18
Potato–Maize–T. Aman	47,690	31,475.40	236,753.72
Maize–Jute–T. Aman	21,325	14,074.50	105,866.49
Maize–Vegetable–T. Aman	1810	1194.60	8985.62
Wheat–Maize–T. Aman	16,320	10,771.20	81,019.52
Maize–Aus–Fallow	13,615	8985.90	67,590.73
Potato–Maize–Aus	4300	2838.00	21,347.05
Tobacco–Maize–T. Aman	7470	4930.20	37,084.30
Vegetable–Maize–T. Aman	4500	2970.00	22,339.94
Maize–B. Aman	5030	3319.80	24,971.09
Maize–Mung bean–T. Aman	4900	3234.00	24,325.71
Maize–Maize–T. Aman	3070	2026.20	15,240.80
Maize–Aus–Vegetable	3000	1980.00	14,893.29
Maize–Aus–T. Aman	2970	1960.20	14,744.36
Lentil–Maize–T. Aman	2920	1927.20	14,496.14
Maize–Sesame–T. Aman	1835	1211.10	9109.73
Onion–Maize–T. Aman	1490	983.40	7397.00
Maize–Boro–T. Aman	1400	924.00	6950.20
Maize–Aus–Black gram	1370	904.20	6801.27
Boro–Maize–Fallow	410	270.60	2035.42
Potato+Maize–B. Aman	410	270.60	2035.42
Potato+Maize–Vegetable–T. Aman	210	138.60	1042.53
Total	247,505	163,353.30	122,8721.53

Source: [59,60].

In another study, about $660 \text{ kg CO}_2 \text{ ha}^{-1}$ net emissions were recorded from irrigated rice fields [61], indicating that net emissions from rice fields under rice–maize patterns are only about $0.16 \text{ MT CO}_2 \text{ eq year}^{-1}$, which is far below the CO_2 sequestration by maize in the same system. Our findings indicate that total carbon emissions and sequestration should be determined in order to obtain a clear picture of GHG emissions from crop agriculture. Unless we consider the balance between the total input and output of carbon, data does not reflect the total scenario of GHG emissions from crop agriculture in a particular country.

4.6. Spatio-Temporal Distribution of Carbon Emissions and Sequestration

Just as maize areas in Bangladesh change depending on growing seasons over the years, carbon emissions and sequestration patterns also vary greatly. Based on the average values for 2015–2020, it was found that GHG emissions and carbon sequestration were mostly concentrated in the north, north-west, central and hilly regions of the country (Figure 6). In general, higher levels of emissions and sequestration were observed in the dry season than in the wet season. Multiple factors were responsible for such variations. For example, soil organic matter content [28,60], tillage systems and soil moisture [16,34] influence GHG emissions and crop yields and, thus, carbon sequestration. Tiefenbacher et al. [25] also reported that carbon sequestration is significantly influenced by soil properties and the crop management practices adopted by growers. Moreover, total biomass production and grain yields are significantly influenced by weather, edaphic factors and crop husbandry. The compound effects of those variables resulted in large variations in maize grain yield, ranging from $<2.0 \text{ t ha}^{-1}$ to $>11.0 \text{ t ha}^{-1}$ (Figure 1); this, in turn, led to large variations in total carbon sequestration in different regions of the country.

5. Conclusions

Region-specific data on GHG emissions from maize fields and carbon sequestration are not available in Bangladesh. We generated GHG emission data from field research at BARI,

Gazipur, and we utilised those data for the whole country, considering the grain yields of maize as well as area coverage. There were variations in grain yields, GHG emission intensities and net CO₂ sequestration depending on growing seasons and locations in the country. In general, GHG emission intensity was lower in favourable maize production zones than in other areas, indicating that yield gaps existed that need to be minimised. However, the estimated net CO₂ sequestration outweighed the net total emissions for all maize-growing regions of the country, indicating that maize and other upland crops in rice-based cropping systems are beneficial not only for minimising GHG emissions but also for nutrition security in Bangladesh, along with many other developing countries around the globe. As the data is limiting for such types of studies in various countries, emphasis should be placed by the global community on generating data on GHG emissions for the major food crops of the world. Such initiative may provide opportunities for adopting strategies to reduce GHG emissions from agriculture under changing climatic conditions.

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Informed Consent Statement: We do not have any person's data in any form. We do not have any individual person's data in any form.

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