https://doi.org/10.5194/bg-2023-165
Preprint. Discussion started: 26 September 2023

Biogeosciences
Discussions
Open Access

Carbon footprint and greenhouse gas emissions from rice based agricultural systems calculated with a co-designed carbon footprint calculation tool

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Abstract

There are many cropping systems followed in Floodplain soils for enhancing cropping intensity for increasing crop production, but greenhouse gas (GHG) emissions balances of agricultural systems are rarely reported. To estimate the carbon (C) footprints of agricultural products a co-designed C footprint calculation tool with a life cycle assessment approach was used in major cropping systems in Bangladesh: rice-rice-rice (R-R-R/boro-aus-aman), rice-fallow-rice (R-F-R/boro-fallow-aman), maize-fallow-rice (M-F-R), wheat-mungbean-rice (W-M-R), and potato-rice-fallow (P-R-F). GHG emissions were estimated using the tool along with the field measurements. It was found that rice-based cropping pattern with dryland crops had higher nitrous oxide (N_2O) emissions (3.98 in maize, 3.89 in potato and 0.72 kg N_2O-N ha^{-1} in mungbean) than sole rice-based (0.73 in boro, 0.57 in aus and 1.94 kg N_2O-N ha^{-1} in aman) cropping systems but methane (CH_4) emissions were higher in sole rice-based patterns than dryland crops. Methane contributed to about 50-80% of total GHG emissions from rice cultivation due to waterlogging conditions throughout the season. In R-R-R and R-F-R cropping patterns, the only ones including boro rice, had the highest total C footprint with 26.3 and 19.5 Mg CO_2e ha^{-1}, respectively while the P-F-R and M-F-R had the lowest C footprint with 13 Mg CO_2e ha^{-1}. Changes in soil organic C generally had a minor influence on C footprints in the studied systems, and only boro and aus from R-F-R and R-R-R patterns were relatively more suitable for reducing C footprint as they sequestered C in soil. Measured CH_4 and N_2O emissions agreed well with IPCC tier 1 estimates, but they were only available for boro, maize and wheat so further study is required for validation and suggesting suitable GHG mitigation strategies from agricultural fields.

Keywords: Carbon footprint, Co-designed Carbon footprint calculation tools, Greenhouse Gas (GHG) emissions, major cropping patterns

1. Introduction

Agriculture acts as the primary source of economic and food security for developing countries like Bangladesh. Increasing population and consumption are placing unprecedented demands on agriculture and natural resources in the region. We are confronted with one of the most difficult tasks of the twenty-first century: satisfying society's expanding food demands while decreasing agriculture's environmental impact (Foley et al., 2011). With the advancement of the 'Green Revolution', the intensive use of different inputs such as synthetic fertilizers, herbicides, and insecticides have been established as a key strategy aiming optimal productivity. The agricultural soils of Bangladesh have a deficit in all the nutrients since 1983-

84 (Moslehuddin et al., 1997; Sarker et al., 2018) and latest identified limiting nutrient is manganese (Mn) in 2010. As a result, synthetic fertilizers, commonly urea, are used as the mandatory source of N to maintain crop stable growth, development, and higher yield. Excessive N fertilizer application includes groundwater pollution, soil acidification and particularly the emissions of nitrous oxide (N_2O), a potent greenhouse gas (Lakshman et al., 2022) and ammonia (NH_3), a major air pollutant (Sanz-Cobena et al., 2014).

Rice, maize and wheat are the major crops of Bangladesh, where rice is in the top position. In 2020, Bangladesh ranked third in the world in rice cultivated area and production (FAO, 2023). Rice is a semi-aquatic plant, usually cultivated under complete flooded conditions, providing an anaerobic environment for methanogens and denitrifiers to degrade organic substances and reduce nitrate (NO_3^-), respectively (Jahangir et al., 2022), which enhances the greenhouse gas (GHG) emissions. Nitrogen loss with water is another key channel responsible for fertilizer N loss in paddy fields, including surface runoff, leaching, and lateral seepage, accounting for up to 50% of applied N fertilizer loss (Chen et al., 2014; Liang et al., 2007). The N use efficiency (NUE) of rice, maize and potato is approximately 30-50%, 33%, and 40–50% respectively (Sindelar et al., 2015) and the NUE in water spinach is 28% and 42% in white cabbage (Šturm et al., 2010). Organic inputs, such as crop residue, manures, and compost, improve soil fertility, agricultural productivity, and crop yield by enhancing C sequestration and nutrient mineralization in the soil (Lin et al., 2018; Sarkar et al., 2019; Abuarab et al., 2019; Gross et al., 2022). However, organic amendments can cause GHG emissions through different processes like the priming effect such as methanogenesis, nitrification, and denitrification (Thangarajan et al., 2013).

Rice-based production systems were reported to generate 523 million grams (Mg) of CO_2e per year, accounting for 8.8-10.2% of total agricultural emissions globally in 2012 (FAO, 2017). In Bangladesh, GHG emissions from the agriculture sector grew by 80% in the 1990-2017 period (Islam et al., 2020). Furthermore, the country is a net importer of cereals, which is associated with imports of virtual land, water, and GHG emissions (Udmale et al., 2021). Agricultural emissions contributed to about 40% of the total emissions of Bangladesh in 2017-2019, using data from PRIMAP-cfr (Jeffery et al., 2016) while just CH_4 from rice fields contributes about 7% of GHG emissions. According to FAOSTAT (FAO, 2023), total soil N_2O emissions between 1961 and 2020 grew from 1.5 to 4.2 kt N_2O for manure application, from 4.4 to 11.2 kt N_2O for crop residues and from 0.3 to 21.4 kt N_2O for synthetic fertilizers. The estimation of agricultural emissions in the national GHG inventory of Bangladesh highly relies on (Interdisciplinary Panel for Climate Change) IPCC tier 1 methods, which are mostly desk-based and cannot work as a standard for any specific region or crop, particularly when agriculture represents a significant share of total GHG emissions. Therefore, specific regional data on GHG emissions are necessary to understand and evaluate the contribution of agriculture to global warming.

The C footprint is a measure of the total amount of GHG emissions that is directly and indirectly caused by an activity or the life stages of a product, and it is generally calculated using Life Cycle Assessment (LCA), and typically measured in terms of carbon dioxide equivalents (CO_2e). A potential answer to slow the pace of climate change could be found in the quantification and assessment of the degree of C emissions and energy consumption in an agroecosystem (Yadav et al., 2018). The C footprint has achieved significant acceptance and application due to its importance in measuring environmental quality and management in agricultural sectors (Poore and Nemecek, 2018, Aguilera et al., 2021a) and specifically in rice production (Ahmad et al., 2023). Carbon sequestration or emissions depend on different factors, and they do not occur in a very specific or simultaneous manner. Due to seasonal variations in temperature and water regimes, varying lengths of crop growth, and variations in crop outputs (and yields), energy/feedstock use efficiencies, nutrient (fertilizer) inputs, residue/carbon returns, and other inputs influencing management activities and production, rice-based triple cropping systems have complex effects on GHG emissions (Jahangir et al., 2022). An accounting of net life cycle GHG emissions along with C sequestration in soil is needed to evaluate strategies of GHG mitigation for rice-dominant cropping, which is a major contributor to the C footprint of global agriculture.

In Bangladesh, the LCA for C footprint has only been done for a specific rice-based cropping pattern (Alam et al., 2019), however, there is a scarcity of measured and estimated data on GHG emissions from different cropping patterns, fertilization, and management practices. In this study, our main aim is to estimate the C footprint for diversified crops and cropping patterns in Bangladesh using a co-designed C footprint calculation tool. The specific objectives are to (i) compare GHG emissions and the corresponding C footprint for individual crop in a season as well as for the whole pattern in a year, and (ii) to evaluate the crops, in particular, or the cropping system, as a whole, for sequestering C and mitigating C loss.

2. Materials and Methods

The C footprint of the main products of major cropping systems in Bangladesh was assessed through an attributional LCA, using a co-designed calculation tool. The system boundaries were stablished "from cradle to farm gate". The components of the GHG balance include upstream, direct, and downstream GHG emissions and the soil organic carbon (SOC) balance, expressed as CO_2-equivalents (CO_2e) using 100-year Global Warming Potential (GWP) factors from the IPCC's 6th Assessment Report (Forster et al., 2021). Field GHG emissions were estimated through the IPCC tier 1 method, which was complemented with field measurements of emissions in some treatments to assess the reliability of the estimated data. All components of the net primary production (NPP) in terms of dry matter, C and N were estimated to assess soil C and N inputs. Emissions were allocated between the main product and the residues based on their corresponding economic value. The studied cropping systems were located in the field experiments on Soil Science Field Laboratory, Dept. of Soil Science, Bangladesh Agricultural University, and in farmers' fields in different regions representing the dominant flood plain soils of Bangladesh.

2.1 Co-designed carbon footprint calculation tool

The co-design of the C footprint calculation tool was performed through an iterative process based on repeated feedback between developers and the FAO-IAEA's Coordinated Research Project (CRP) participants. In each meeting, developers explained the novel features and the users calculated C footprints from selected regions in their countries and suggested modifications to account for the specific features of their systems. The participants comprised of 6 research teams (1-4 persons in each team) from 6 countries including Vietnam, Bangladesh, Pakistan, Argentina, Costa Rica, and Ethiopia. The case studies covered field experiments and commercial farms with a wide variety of crop types and management practices, with an emphasis on rice paddies.

The tool is built in a Microsoft Excel environment to maximize the range of possible users and to allow for case-sensitive adjustments by the users. The tool has three main sheets: one for introducing crop data, one with emission factors and other coefficients (such as allometric and stoichiometric coefficients of the main crops) and one summarizing the results. Auxiliary sheets include soil data obtained from the Harmonized World Soil Database 2.0 (FAO and IIASA, 2023), climate data obtained from CRU TS 4 (Harris et al., 2020), and the electricity mix of each country, gathered from the World Development Indicators dabase (The World Bank, 2023).

The basic crop data to be introduced includes information on regarding location and main characteristics of the studied systems, intercropping period and management, crop and residue production, residue destiny shares (harvest, soil incorporation, burning, grazing), inputs of fertilizers, pesticides and electricity, number of passes of each machinery task, and prices of the products and residues. management, emissions, etc.). In the case of rice systems, water management information in the crop and intercrop period also has to be specified.

Crop coefficients include product and residue dry matter content, root:shoot ratio, product, residue and root C and N content over dry matter, and humification coefficients. Emission factors from the production of inputs (fertilizers, pesticides, machinery, fuel, electricity) are based on life cycle inventories (mainly Ecoinvent 3.0) and calculated with SimaPro software. Soil CH_4 and N_2O emissions are estimated using tier 1 or tier 2 (CH_4) methods from the revised 2006 Guidelines for National Inventories of the IPCC (IPCC, 2019).

In the results sheet, the soil C and N balances, GHG emissions and C footprints are calculated for each treatment with the data contained in the Crop Data, Factors, and Auxiliary data sheets. Potential vegetal biomass growth is estimated with the NCEAS model (Del Grosso et al., 2008), which is based on yearly water inputs (which in our case correspond to the sum of precipitation and irrigation). This potential biomass growth is scaled with qualitative information on weed management to estimate weed biomass production in the intercrop period and during the crop cycle. The calculation of the SOC balance is described in Section 2.2. The tool is designed to ensure maximum flexibility in the data availability while reporting the most reliable data. For example, climate and soil data can be inserted in the tool if they are available, or the tool retrieve them from global datasets if they are not. Crop residue, roots, and cover crop biomass are estimated with coefficients if no field measurements are available. In the same way, a prioritization procedure is implemented for the selection of GHG emission and C sequestration estimates, choosing measured data if they are available, then tier 2 estimated data, and then tier 1 estimated data.

2.2. Soil organic carbon balance

The SOC balance is calculated with the HSOC model (Aguilera et al., 2018), a dynamic model built as a simplification of the RothC model (Coleman and Jenkinson, 1996) with 2 active pools of SOC. This model has soil current SOC stocks, C inputs, input humification coefficients, and monthly temperature, soil water status, and soil cover as the main factors affecting the SOC balance. In this work, we modified the HSOC model in rice fields using the modifying factors for SOC mineralization rates from Jiang et al. (2013), to account for slower mineralization rates under flooded conditions. In order to facilitate the comparability of the data, we assumed that initial SOC content was equal to the SOC content in equilibrium in the most widespread of the studied rotations (Rice-Fallow-Rice), and all treatments were calculated as comparison to this value. In order to incorporate the SOC balance to the GHG balance and C footprint estimations, we ran the model for 100 years using the management and pedoclimatic data of each treatment and divided the result by 100 to get a yearly C sequestration rate. This rate was converted to CO_2e using the molecular weight ratio of CO_2 to C (3.67). This way, the reported SOC changes are in line with the other gases of the GHG emission balance, which are reported as 100-year GWP.

2.3 Field data: Cropping Patterns and Crop Management

The study was carried out on Soil Science Field Laboratory, (24.7471º N, 90.4203º E) Mymensingh, and farmers' fields at various sites of the country (North, Mid and Mid-west part of Bangladesh). The regions have a subtropical monsoon climate with a mean annual temperature of 26 °C, average annual rainfall of 1,800-2200 mm, and relative humidity of 85% (Local weather stations). The field sites have a noncalcareous dark grey floodplain soil (Aeric Haplaquept in the U.S. Soil Taxonomy), these soils are very deep and well drained occurs in Agroecological Zone 9 (AEZ-9; Old Brahmaputra Floodplain soil), AEZ-3, and AEZ-18 (FAO, 1988). The dominant regional soil type was Low Activity Clay (LAC) soil with 14-18% clay contents. The experiment was done with five different cropping patterns, followed by majority farmers of this country under conventional cultivation practice. Mid-winter to pre-monsoon season, monsoon and late monsoon to winter seasons were occupied by boro, T. aus (Transplanting aus), and T. aman rice growing seasons, respectively. There were also four dryland crops, wheat, maize, mungbean, and potato. The cropping patterns were rice-rice-rice (R-R-R/ boro-aus-aman), rice-fallow-rice (R-F-R/boro-fallow-aman), maize-fallow-rice (M-F-R), wheat-mungbean-rice (W-M-R), potato-rice-fallow (P-R-F). Rice-fallow-rice (R-F-R) is the most widely used pattern in Bangladesh. Therefore, it has been used as reference pattern in the estimation of SOC changes (see Section 2.2). In boro, aus and aman seasons the age of seedlings was 42, 33 and 35 days, respectively. Wheat, maize, mungbean and potato were direct seeded crops. The rice fields experienced non-flooded preseason for less than 50 days before transplanting of seedlings in most of the rice-based cropping patterns. The fallow period means there was no crop in the field but only spontaneous weed during ~12 weeks from May to August. Based on the Fertilizer Recommendation Guide (FRG, 2018), the rate of synthetic fertilizer application was determined for each of the crops. Urea, triple superphosphate (TSP), and Mourite of Potash (MoP), Gypsum was used as nutrient sources of N, P, K, S. No organic amendments were used besides crop residue and weed. In rice seasons the straw incorporation in soil ranged from 10-20 % where it was 100 % for potato. Regarding water management, aman was rainfed whereas flood irrigation was used for Boro and Aus. Furrow irrigation was used for maize, and potato. Wheat requires about 1-2 irrigation events, but the land used in that experiment always remained in wet condition due to topography. Irrigation water was supplied from ground water by using electric pumps. Machinery was used for land preparation and spraying of solutions in the field for all the crop seasons. Respective to crops and diseases herbicides and pesticides were sprayed once in a season.

2.4 Greenhouse Gas Sampling

In this study, GHG measurements were conducted in boro rice, wheat and maize fields using closed chamber method (Jahangir et al., 2022; Zaman et al., 2021). The observation period began with the first application of urea under continuous flooded conditions and continued until emissions reached background levels. Chambers made of soda glass and stainless-steel collars were placed on rice rows, covering four plants to a depth of 10 cm. Neoprene seals ensured an airtight connection between the chamber lid and the frame. Urea was applied inside the pre-installed collars using a broadcast method. Gas samples were collected at 0, 30, and 60 minutes after the camber set up during the day, between 10:00 a.m. and 4:00 p.m., on day 0, 1, 3, 5, 7, 10, 15, and 21 after each split urea application. A 60-ml Luer Lock syringe with a 25-gauge needle was used to collect 16-ml gas samples from the chamber headspace, which were then injected into pre-evacuated 12-ml vials. After storage for up to 7 days, the samples were analysed using a Varian 3,800 gas chromatograph equipped with specific detectors for N_2O, CO_2, and CH_4 (Jahangir et al., 2022).

2.5 Soil and biomass Sampling and Analysis

Composite soil samples were taken from each replicated plot at a depth of 0-15 cm, using an auger, four days after the second split application of urea, which coincided with the peak of N_2O emissions. The samples were collected from multiple locations near each GHG gas sampling chamber and stored in sealable plastic bags at 4 °C. In the field, soil pH was measured using a portable pH meter. A portion of the soil, after removing visible roots and litters through

https://doi.org/10.5194/bg-2023-165
Preprint. Discussion started: 26 September 2023

sieving with a 2-mm mesh, was analysed for ammonium (NH_4^+) and nitrate (NO_3^-) contents using the colorimetric method. Another portion of the soil was air-dried at room temperature (~25 °C) in the shade for two weeks and then processed (2 mm sieved) for analysis of SOC and total N (TN) using the wet oxidation method and Kjeldahl method, respectively (Jahangir et al., 2022). The values and corresponding sources used for the crops in this area are available in Begum et al. (2022), Jahangir et al., (2022) and Ferdous et al. (2023). To measure grain and residue biomass production, a 4 m^2 area was chosen at random in the plot area just before harvest. The plants were cut at ground level, put in mesh bags, and left to air dry. The weights of the grain and crop residue were calculated after the grain was threshed from the sample. To assess the water content, a portion of the crop residue was oven dried at 65 °C for 72 hours. Yields of crop residue were expressed on an oven-dry basis. Paddy grain yields were adjusted to 12% for rice and 14% moisture for wheat and maize.

3. Results

3.1 Net primary productivity

The R-F-R cropping pattern gave higher dry matter (DM) yield (6.05 Mg DM ha^{-1}) in the boro season than in the aman (4.63 Mg DM ha^{-1}) season, however the NPP was higher in aman season including fallow period (Fig. 1a). The NPP was the highest in M-F-R cropping pattern with 22.88 Mg DM ha^{-1} in maize and 17.75 Mg DM ha^{-1} in rice. Weeds were also considered in NPP of crops. Intercrop weed biomass production was present in the crops which had a fallow period before their season. Therefore, in potato-based pattern potato had higher NPP than rice because of having a fallow period before the season. The total NPP was highest in R-R-R (43.42 Mg DM ha^{-1}) followed by M-F-R (40.63 Mg DM ha^{-1}) and R-F-R (37.05 Mg DM ha^{-1} yr^{-1}) (Fig. 1b). The W-Mu-R has the lowest average productivity (8.38 Mg DM ha^{-1} yr^{-1}) with the least yield in mungbean (4.26 Mg DM ha^{-1}).

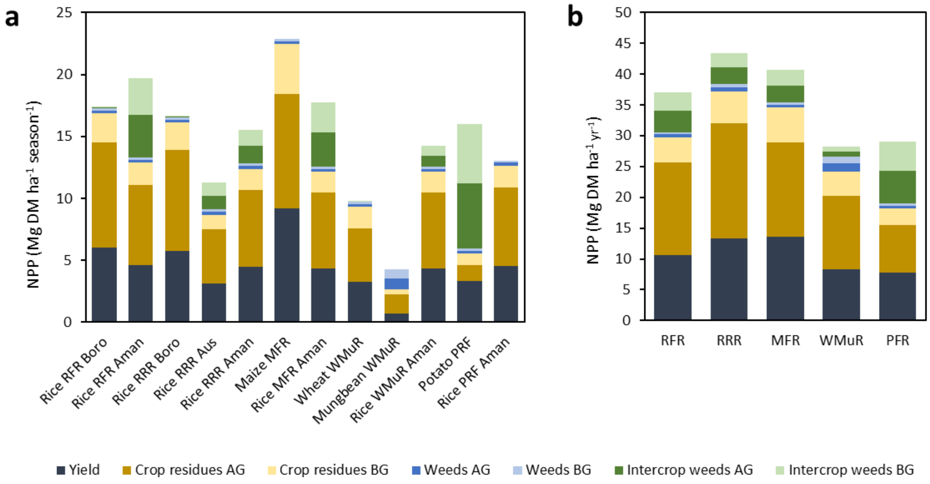

Fig. 1 Net primary productivity in the studied conventionally managed crops over their cropping season and intercrop period (a) and in their corresponding cropping systems over one year (b); DM = Dry Matter, AG = Above Ground, BG = Below Ground, RFR = Rice-Fallow-Rice, RRR = Rice-Rice-Rice, MFR = Maize-Fallow-Rice, WmuR = Wheat-Mungbean-Rice, PFR = Potato-Fallow-Rice

3.2 Nitrogen inputs for crops under different cropping patterns

Nitrogen inputs considered for the estimation of direct N_2O emissions according to IPCC guidelines are shown in Fig. 3. Synthetic fertilizer acted as the largest source of N supply for all the cropping patterns. The highest amount of N input was at maize, with about 17% of synthetic fertilizer used in all the crops (Fig. 3a). For both R-R-R and R-F-R cropping patterns the synthetic fertilizer use was higher in boro than other crops, but the total N input was higher in aman season for R-F-R pattern while boro had higher N input in R-R-R pattern. However, the R-R-R pattern had larger amount of N input than the R-F-R pattern. The P-R-F pattern had higher (4-21%) N input (549 kg N ha^{-1}yr^{-1}) than other patterns where M-F-R came as the second largest input of N (528 kg N ha^{-1}yr^{-1}) (Fig. 3b). In contrast, the least input of N occurred in the Wheat-Mungbean-Rice pattern (406 kg N ha^{-1}yr^{-1}). Both AG and BG crop residue contributed higher in R-R-R (71 kg N ha^{-1}yr^{-1}) than other patterns, P-R-F had the second highest (67 kg N ha^{-1}yr^{-1}) N input from that source. Synthetic fertilizer supplied around 23-78% of the N supply, while cover crop (AG + BG) contributed approximately 8-36% of the N supply. Highest

https://doi.org/10.5194/bg-2023-165
Preprint. Discussion started: 26 September 2023

contribution from weeds in the intercrop period was found from P-R-F (106.13 kg N ha^{-1} season^{-1}) and then in R-F-R (69.01 kg N ha^{-1} season^{-1}) pattern. In Bangladesh the common cropping pattern is R-F-R but the N input was higher in R-R-R pattern than in R-F-R pattern. The net SOM mineralization had a minor role in most cropping patterns where mungbean had the higher input both as absolute value (59 kg N ha^{-1}yr^{-1}) and as share of total N input (58%), followed by potato (29 kg N ha^{-1}yr^{-1}). Between R-R-R and R-F-R pattern the aman season had the SOM mineralized N input (9-10 kg N ha^{-1}yr^{-1}) which was about 3% and 2% of total input for the cropping patterns, respectively.

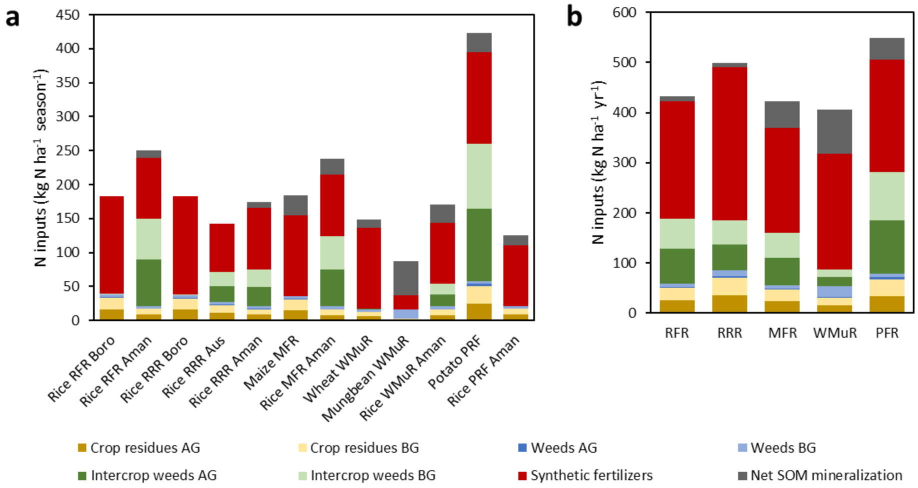

Fig. 2 Nitrogen (N) inputs in the studied conventionally managed crops over their cropping season and intercrop period (a) and in their corresponding cropping systems over one year (b); AG = Above ground, BG = Below ground, SOM = Soil organic matter, RFR = Rice-Fallow-Rice, RRR = Rice-Rice-Rice, MFR = Maize-Fallow-Rice, WmuR = Wheat-Mungbean-Rice, PFR = Potato-Fallow-Rice

3.3 Soil organic carbon balance

As the crops were conventionally managed, organic fertilization was not practiced. Weeds, crop residues and cover crops (AG and BG) contributed to the carbon (C) input in all the cropping patterns. The P-R-F had the highest C in put (7 kg C ha^{-1}yr^{-1}) while W-Mu-R pattern had the lowest (4 kg C ha^{-1}yr^{-1}). Between R-F-R (5.76 kg C ha^{-1}yr^{-1}) and R-R-R (6.13 kg C ha^{-1}yr^{-1}) pattern C input was about 7% higher in R-R-R. Carbon input in boro rice for both R-R-

R and R-F-R cropping patterns was about 91-92% through crop residues and rest amount came from weeds and cover crops. Weeds and cover crops grew during the fallow period (Fig. 4) where the crop residue was the largest source of C input for the cropping patterns. The P-R-F, M-F-R and R-R-R patterns had about 5-14% higher C input than R-F-R pattern. Humified C input was higher in P-R-F pattern (Fig. 4) than other patterns and it was about 14% higher than R-F-R pattern.

The C stock in equilibrium ranged from 13-90 Mg C ha^{-1} (Fig 4a, b). The boro from R-F-R season had the highest stock (90 Mg C ha^{-1}) (Fig. 4a). The highest C stocks among cropping patterns was achieved in the reference rotation, the R-F-R (76.1 Mg C ha^{-1}), similar to the R-R-R (74.3 Mg C ha^{-1}) (Fig 4b). The R-F-R pattern had 41%, 29% and 38% higher C stock than M-F-R, W-Mu-R and P-R-F patterns, respectively. Aman rice stock more C than potato and maize but less than wheat in R-F-R pattern.

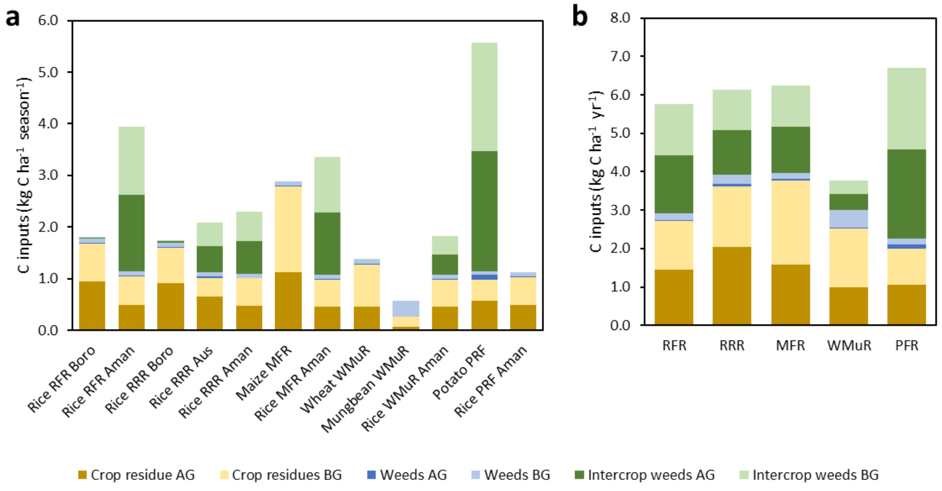

Fig. 3 Carbon inputs in the studied conventionally managed crops over their cropping season and intercrop period (a) and in their corresponding cropping systems over one year (b); AG = Above ground, BG = Below ground, SOM = Soil organic matter, RFR = Rice-Fallow-Rice, RRR = Rice-Rice-Rice, MFR = Maize-Fallow-Rice, WmuR = Wheat-Mungbean-Rice, PFR = Potato-Fallow-Rice

The values of C stock change rate in the studied crops ranged from -0.06 in the boro rice from the reference cropping pattern R-F-R to 0.51 Mg C ha^{-1} yr^{-1} in mungbean (Fig. 4c). The R-R-R cropping pattern had zero C stock rate change, reflecting our choice of this pattern as the reference one (Fig. 4d), while the R-R-R pattern also had a value close to zero (0.02 Mg C ha^{-1} yr^{-1}). The C stock change rates in the other rotations were very similar, ranging 0.22-0.3 Mg C ha^{-1} yr^{-1}.

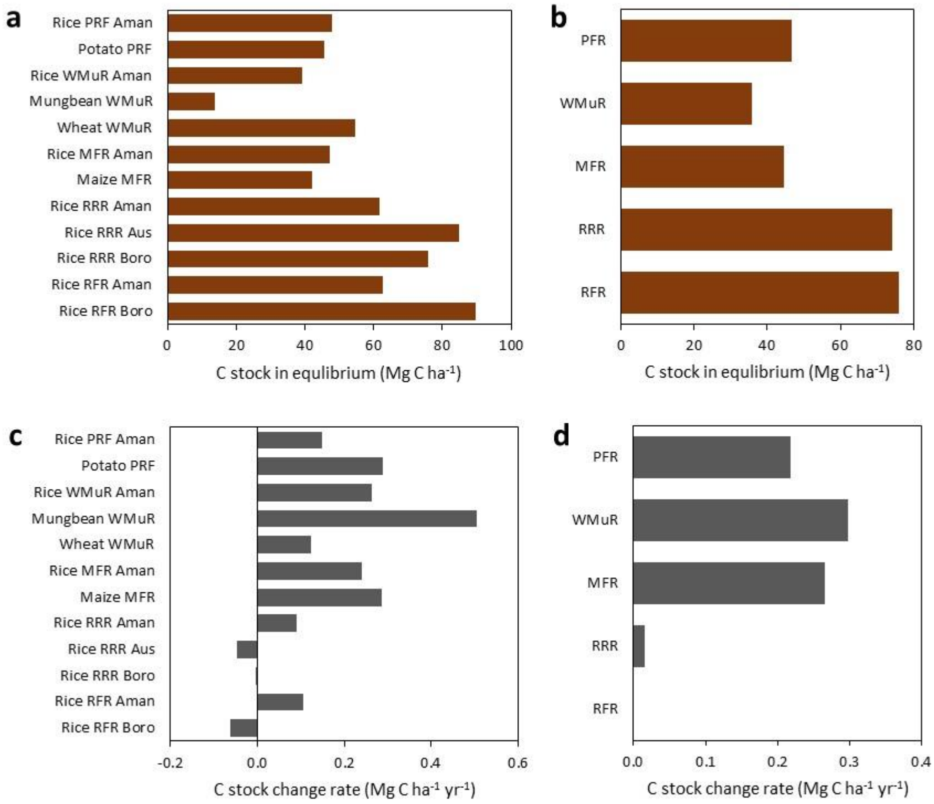

Fig. 4 Carbon (C) stock in equilibrium in the studied crops (a) and cropping systems (b), and C stock change rates in the studied crops (c) and cropping systems (d). RFR = Rice-Fallow-Rice, RRR = Rice-Rice-Rice, MFR = Maize-Fallow-Rice, WmuR = Wheat-Mungbean-Rice, PFR = Potato-Fallow-Rice

3.4 Soil fluxes of trace greenhouse gases

The IPCC default and Tier 1 CH_4 emission values are available only for rice cultivation, as it is assumed to be the only crop grown under waterlogging conditions. However, in field level we measured CH_4 emissions from boro rice and from wheat fields (Fig. 5). The comparison of the boro rice measured emissions with the IPCC-based estimates shows that the IPCC tier 1 approach resulted in a very similar value (376 kg CH_4 ha^{-1} yr^{-1}) to that obtained from measurements (385 kg CH_4 ha^{-1} yr^{-1}), while the IPCC default value was much lower (187 kg CH_4 ha^{-1} yr^{-1}). The wheat field caused 120 kg CH_4 ha^{-1} yr^{-1} emissions. The IPCC Tier 1 values estimated across all crops indicated that among the rice seasons boro caused the highest emissions (376 kg CH_4 ha^{-1} yr^{-1}) followed by aus (189 kg CH_4 ha^{-1} yr^{-1}) and then aman (108 kg CH_4 ha^{-1} yr^{-1}) in R-R-R pattern, however the emissions in R-F-R pattern would be 382 kg CH_4 ha^{-1} yr^{-1} in boro and 145 kg CH_4 ha^{-1} yr^{-1} in aman.

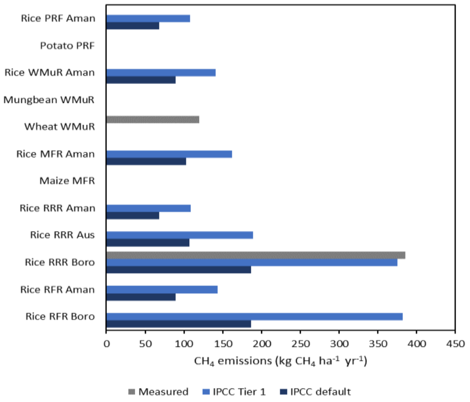

Fig. 5 Comparison of three different approaches to estimated methane (CH_4) emissions from the studied crop fields, including field measured emissions, IPCC Tier 1 approach, and IPCC default value. RFR = Rice-Fallow-Rice, RRR = Rice-Rice-Rice, MFR = Maize-Fallow-Rice, WmuR = Wheat-Mungbean-Rice, PFR = Potato-Fallow-Rice

The IPCC set a default value for N loss as N_2O from wet (rice) and dry crop (wheat, maize, potato, mungbean) fields but measured data for N_2O loss was only available for boro, maize and wheat field (Fig. 6a). In the Indo-Gangetic Plain N_2O loss was estimated by the IPCC Tier 1 method. The Tier 1 estimated value for boro rice is 0.73 kg N_2O-N ha^{-1} yr^{-1} while the estimated value was 1.08 kg N_2O-N ha^{-1} yr^{-1}. The Tier 1 value of N_2O emissions for maize was 2.3 kg N_2O-N ha^{-1} yr^{-1} but the estimated value was 2.62 kg N_2O-N ha^{-1} yr^{-1}. In wheat field 0.65 kg N_2O-N ha^{-1} yr^{-1} emitted as N_2O but the measured value was 0.31 kg N_2O-N ha^{-1} yr^{-1}. The tier 1 value was estimated without considering any crop management practices but from the experimental plots it was estimated 1.47 and1.13 times higher N_2O emissions than the tier 1 value in rice and maize field, respectively but in wheat field the measured data was 2.09 times lower than the Tier 1 value.

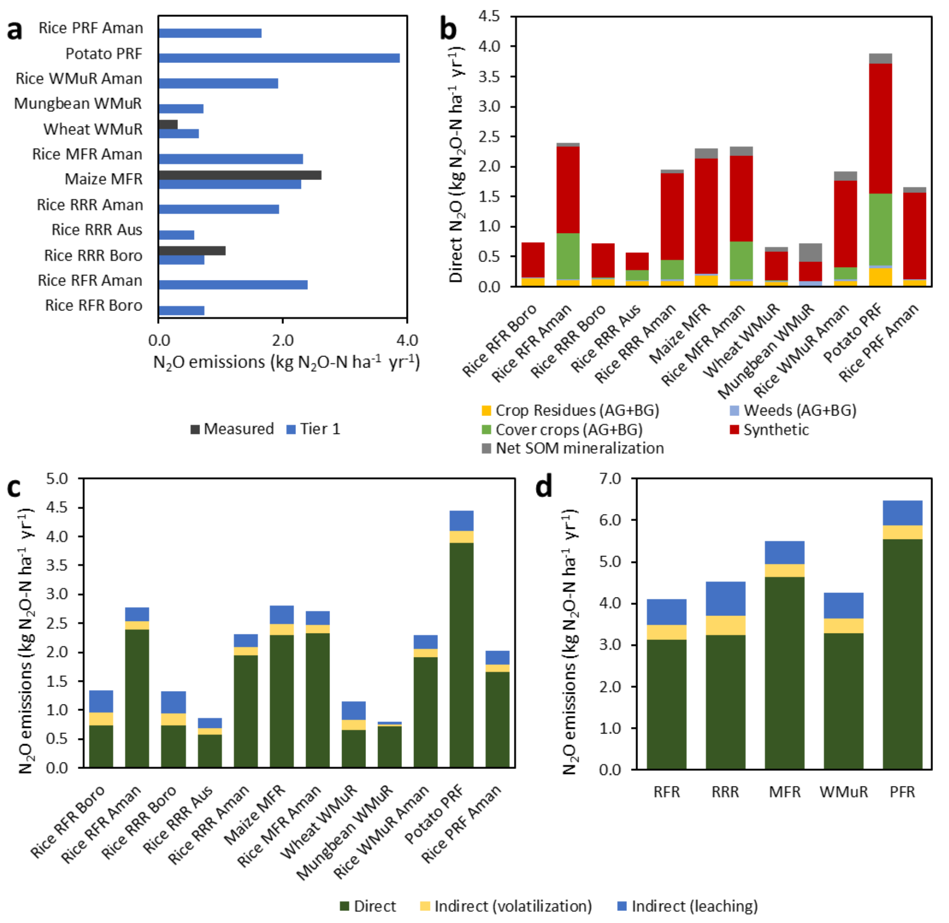

Fig. 6 Nitrous oxide (N_2O) emissions in the studied crops, including direct N_2O emissions comparing measured and IPCC tier 1 estimations (a), direct N_2O emission sources by crop (b), total N_2O emission by emission type and crop (c) and total N_2O emissions by emission type and cropping system (d). RFR = Rice-Fallow-Rice, RRR = Rice-Rice-Rice, MFR = Maize-Fallow-Rice, WmuR = Wheat-Mungbean-Rice, PFR = Potato-Fallow-Rice

Synthetic fertilizers acted as the largest source of N_2O emission, about 44-90% of total emissions in the studied patterns (Fig. 6b). The highest emissions were in M-F-R pattern (6.31 kg N_2O-N ha^{-1} yr^{-1}) and P-R-F pattern had the second highest (5.54 kg N_2O-N ha^{-1} yr^{-1}). In R-F-R pattern, synthetic fertilizers had the least (3.13 kg N_2O-N ha^{-1} yr^{-1}) amount of N_2O emission occur where aman caused about 76% emissions. In boro and aman seasons crop residue caused about 18% and 4% of emissions, respectively. It could be due to 1-2% of emissions from weeds and crop residues in this pattern. The second lowest emissions were from R-R-R pattern where

However, M-F-R pattern emitted 1.15–2.6 times higher N_2O emissions than other crops. The potato-based pattern has contributed to the second highest amount of total direct N_2O emission (5.54 kg N_2O-N ha^{-1} yr^{-1}) where 23% of emissions occur from synthetic sources. (Fig. 4a). The W-Mu-R pattern was the third largest source of total direct N_2O emission with 3.31 kg N_2O-N ha^{-1} yr^{-1}. The dry land crops maize, potato had higher emissions than wet land crops.

Among three different types of emission, direct N_2O emission was the dominant pathway across cropping patterns, with emissions being 3-19 times and 2-10 times higher than volatilization and leaching, respectively (Fig. 6c and d). Between volatilization and leaching loss, higher N_2O emissions through volatilization were estimated for all the crops. In case of mungbean (1.25 kg N_2O-N ha^{-1}yr^{-1}) (Fig. 6c) there was a few leaching causing the lowest total emission in W-Mu-R (6.18 kg N_2O-N ha^{-1}yr^{-1}) whereas in R-R-R had the largest value of total emission, approximately 14 kg N_2O-N ha^{-1}yr^{-1} (Fig. 6d). The M-F-R pattern holds the second position in terms of overall emission value, with higher emissions in maize (5.83 kg N_2O-N ha^{-1}yr^{-1}).

3.5 Global warming potential and C footprint

Major portion of the area-based GWP was due to soil CH_4 emission from rice and wheat based cropping patterns, which was about 50-80% of total GWP (Fig. 7a). The C footprint varied with the studied crops for different cropping patterns. All the predictors impacted on C footprint. The R-F-R pattern decreased about 34% C footprint over the R-R-R pattern. Among the crops boro in R-F-R (12.98 Mg ha^{-1}) and R-R-R (12.94 Mg ha^{-1}) had higher C footprint than other crops (Fig.7a). The boro < aman < aus < wheat < maize < potato < mungbean trend was followed in C footprint. Maize, potato and mungbean had no soil CH_4 emissions. Boro rice in both R-F-R and R-R-R pattern generated the most CH_4 emissions, around 10.1 – 10.3 Mg CO_2e ha^{-1}, accounting for 40-53% of total emissions, and resulting in the highest GWP among the studied crops. Therefore, the R-R-R and R-F-R cropping patterns, the only ones including boro rice, had the highest total GWP, with 26.3 and 19.5 Mg CO_2e ha^{-1}, respectively (Fig. 7b). The total C footprint varied from 12.34 Mg ha^{-1} in P-R-F to 26.29 Mg ha^{-1} in R-R-R (Fig. 7b). The P-F-R and M-F-R had the lowest GWP (13 Mg CO_2e ha^{-1}). Fertilizer production was the second-largest source of total emissions with 8-30%. Pesticide production contributed largely in aman season from R-R-R pattern had higher C footprint. During rice season the irrigation energy contributed to C footprint. Considering all cropping patterns, the role of SOC was relatively minor in the GWP, which demonstrated a balance between emission and sequestration as compared to the reference cropping pattern R-F-R. The highest share was observed for mungbean, in which SOC-related CO_2 emissions represented 53% of the GWP due to the combination of high C mineralization, low C input, and low levels of the other emissions. Net C sequestration was found in boro (R-F-R) and aus (R-R-R) crop only, although it only compensated for 1% of the GWP.

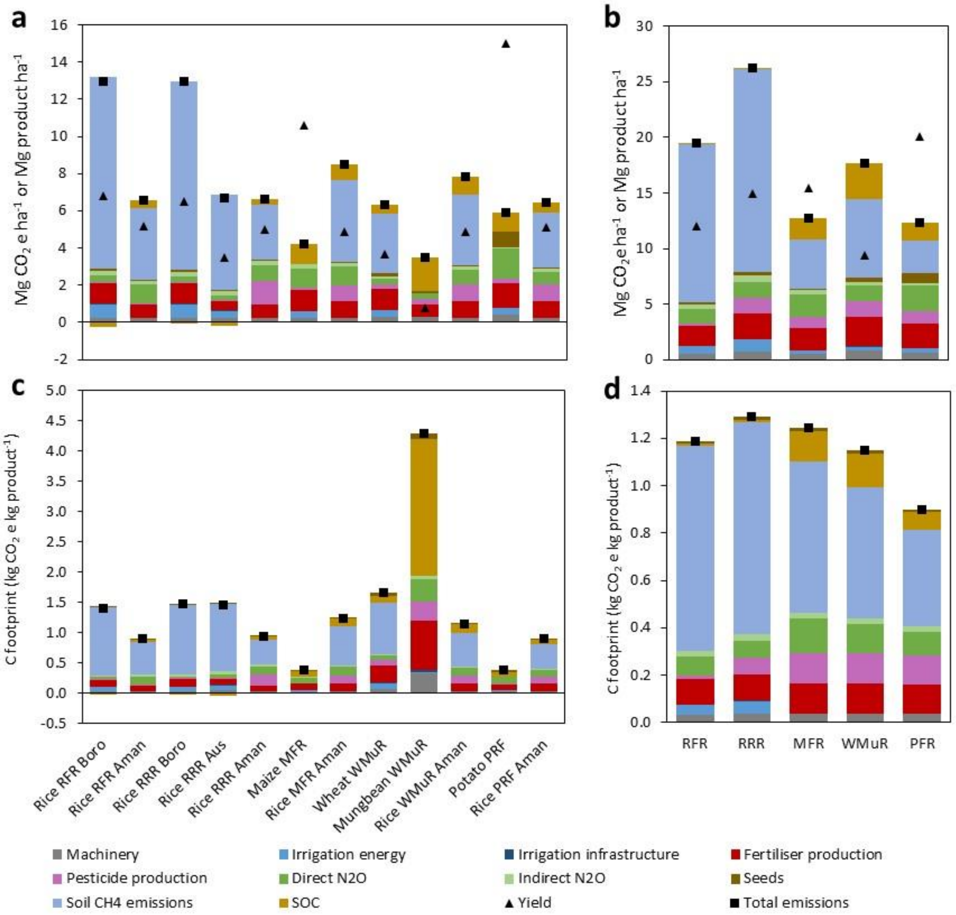

Fig. 7 Area-based greenhouse gas (GHG) emissions (kg CO_2e kg ha^{-1}) and yield (Mg ha^{-1}) of studied products in all crop seasons (a) and over the full year in each cropping pattern (b), Carbon (C) footprint (kg CO_2e kg product^{-1}) of studied products in all crop seasons (c) and weighted average C footprint of rice in each crop pattern (d). RFR = Rice-Fallow-Rice, RRR = Rice-Rice-Rice, MFR = Maize-Fallow-Rice, WmuR = Wheat-Mungbean-Rice, PFR = Potato-Fallow-Rice

Though wheat is a dry land crop the cropping pattern containing W-Mu-R had higher CO_2-e emissions than other two dry land crops, such as potato and maize, due to CH_4 emissions resulting from water-logging conditions. Cropping patterns containing dryland crops obtained higher yields than other rice-based patterns. Potato and maize-based patterns had the largest production, roughly 20.1 Mg CO_2e ha^{-1} and 15.48 Mg CO_2e ha^{-1}, respectively. The lowest yield was observed in Mungbean (0.8 Mg CO_2e ha^{-1}) and Mungbean-based pattern (9.4 Mg CO_2e ha^{-1}). Direct and indirect N_2O also contributed to C footprint. The major portion of C footprint in P-R-F pattern was from N_2O (2.6 Mg CO_2e ha^{-1}) and then in M-F-R (2.4 Mg CO_2e ha^{-1}) pattern and the lowest was in W-Mu-R pattern. Machinery and seed impeded effect on C footprint mostly in P-R-F pattern (Fig. 7b) while it was same for all the rice seasons (Fig. 7a) in every pattern. The contribution of pesticide production was higher R-R-R and W-Mn-R (1.42 Mg CO_2e ha^{-1}) and lower in R-F-R (0.18 Mg CO_2e ha^{-1}).

4. Discussion

4.1 N_2O emission from soil

Direct N_2O emissions were about half in rice and wheat (1.44 kg N_2O-N ha^{-1} yr^{-1} on average), which were cultivated under water-logging conditions, then in dry land crops also intensively fertilized such as maize and potato (3.09 kg N_2O-N ha^{-1} yr^{-1} on average). Maize emits 1.66 to 4.09 MT CO_2eq GHGs in growing seasons (Biswas et al., 2022). During rice production, puddling is operated which normally shuts the water transmission pores resulting in very low water percolation and gaseous exchange between water and air surface. Emissions of N_2O are the result of microbial nitrification and denitrification in soils, controlled principally by soil water and mineral N contents, labile organic carbon, and temperature (Ferdous et al., 2022). Transformational modifications (anaerobic rice systems into aerobic) in rice cultivation practices sustain yield but at the cost of higher N loss (Farooq et al., 2022) with high N_2O emissions. The highest emissions were in M-F-R pattern, P-R-F pattern had the second highest. Among the N sources synthetic fertilizer was the highest emitter because of high application rate, particularly in maize and potato, which had the highest N input requirement (482 and 293 kg ha^{-1} urea, respectively). In dry land the aerobic condition facilities the nitrification process (ammonium-nitrite-nitrate), after irrigation (anaerobic condition) which provides the substrates of denitrification (nitrate-nitrogen dioxide-nitrous oxide) in crops with transitional (aerobic-anaerobic) water state condition (Ferdous et al., 2022). For a rice-based cropping system, Islam et al., 2022 reported the effect of fertilizer, 50% from urea (synthetic) and 50% from poultry litter, on GHG emissions from rice fields during the aus and aman seasons in Bangladesh. According

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to Jahangir et al. (2022), cumulative N_2O emissions during the growing season increased significantly with increasing N application rates. Mazz et al. (2022) reported from their meta-analysis is that intensive rice system and SOC increase N_2O emissions consistently, however, rice system has 57% lower emissions than other cereals whilst, maize has 71% higher N_2O emissions than rice in Asia-Africa and the emissions increase by 5% with each percent increase in SOC. Chemical source of N also increases N_2O emissions and about 0.4% increase of N_2O is associated with addition of 1 kg N ha^{-1} (Mazz et al., 2022).

Results from an increasing number of experiments using different N fertilizer rates showed that emissions of N_2O respond exponentially to increasing N inputs in a variety of soil types, climates, and fertilizer formulas (Hoben et al., 2011; Signor et al., 2013). However, the IPCC tier 1 method that we have applied in this work is based on fixed emission factors of the applied N (depending on climate, flooding conditions and input type), which implies a linear relationship between N inputs and emissions. Therefore, more field studies are needed in Bangladesh and similar areas to improve N_2O estimations in inventories and in LCA studies. Compared to all the four patterns R-F-R pattern had the lowest N_2O emissions (3.13 kg N_2O-N ha^{-1} yr^{-1}) may be due to the anaerobic condition, lower crop residues-weeds and lack of substrate for denitrification. According to a global meta-analysis by Chen et al. (2013), crop residues generated equivalent to or more N_2O emissions than synthetic fertilizers, but another meta-analysis showed much lower emissions from crop residues (Charles et al., 2017).

However, according to Shan and Yan (2013), the addition of crop residue with synthetic fertilizer reduced N_2O emissions by 11.7% when compared to synthetic fertilizers alone. The R-F-R had lower emissions than R-R-R may be attributed to the fallow period where the fallow period had only spontaneous weed growth with lower emissions but cropping pattern with three crops had emissions from each crop. However, contradictory statement from numerous studies stated that the N_2O emissions from fertilized paddy fields during the fallow season is significantly larger than the N_2O emissions during the cropping season (Abao et al., 2000).

There is a lack of data on indirect N_2O emissions from different crop fields. Loss of N through volatilization and leaching are not included in many studies but they can represent an important contribution to fertilizer-related global warming through indirect N_2O emissions (Aguilera et al., 2021b).

4.2 Methane emission and soil organic carbon balance

Carbon input was the highest for the R-F-R and R-R-R patterns where the inputs were mostly done through crop residues, and weeds and according to this, the R-R-R and R-F-R patterns showed the highest soil CH_4 emission. These emissions were also present in all rice treatments and in wheat. Our finding of significant soil CH_4 emissions in wheat cultivation (representing 51% of the GWP of this crop) is, to our knowledge, unprecedented in the literature, and indicates the need to study the extent of rice cultivation under these soil conditions in Bangladesh and in other parts of the world, in order to know the magnitude of these soil CH_4 emissions. The emissions were absent in maize, potato and mungbean crop. In conventional practice rice is grown under continuous flooding (anaerobic) conditions which is the prerequisite for CH_4 emissions. Methane is the final product of anaerobic breakdown of SOM by the action of methanogens in wetland paddy field, absence of oxygen is required for the function of methanogens. On flooding, short-term evolution of hydrogen immediately follows the disappearance of oxygen, CO_2 increases, and, with decreasing carbon dioxide, methane formation increases (Neue and Scharpenseel 1984). Methane is largely produced by transmethylation of acetic acid and, to some extent, by the reduction of CO_2 (Takai 1970). In R-R-R and R-F-R cropping pattern the cover crops, crop residues and weeds were present where they act as carbon source to form volatile acids i.e., acetic acid. Large portions of methane formed in an anaerobic soil may remain trapped in the flooded soil. Entrapped methane may be oxidized to carbon dioxide when the floodwater is drained during the rice growing season or when the soil dries at the end of or after the rice growing season. But large amounts of entrapped methane may escape to the atmosphere immediately after the floodwater recede. The low solubility of methane in water limits its diffusive transport in the flooded soil, and most methane is oxidized to carbon dioxide via methanol, formaldehyde, and format as it passes the aerobic soil-water interface. The release of methane by diffusion through the wet soil column is negligible in clayey soil, but it may become significant in sandy soils in which bigger pores between soil particles prevail. The rate and pattern of organic matter addition and decomposition determine the rate and pattern of methane formation. Wheat also needs less irrigation, but the studied field had moist condition throughout the season due to near water table, which caused CH_4 emissions from wheat field. Large portions of CH_4 formed in an anaerobic soil may remain trapped in the flooded soil. Therefore, crop residues through soil CH_4 emission have contributed to the highest CO_2e emission. Similar results were found by Vu et al., (2015) in their study, the lowest CH_4 emission was found in mineral fertilizer compared to the highest value for farmyard manure and compost manure. This is due to the inclusion of materials that are rich in quickly biodegradable organic matter and offered readily biodegradable C sources for CH_4 synthesis (Vu et al., 2015). Yagi and Minami (1990) found that the average value for CH_4 flux in rice straw was higher in comparison to the compost and mineral-treated plots. Zhang et al. (2017) found that residue retention increased CH_4 emission by two times compared to the paddy fields where residue retention did not take place. Sanchis et al. (2012) reported that continuously flooded rice fields without any added straw produced average CH_4 emissions that were 93% higher compared to rainfed, intermittently flooded, or non-flooded irrigated water management. That means, independent of the addition of organic matter to the soil, continual flooding can foster the conditions for CH_4 production. However, organic fertilizers and flood irrigation also promote C sequestration, which can result in reduced net GHG emissions despite higher CH_4 emissions (Shang et al., 2021). In the R-F-R pattern, there was a fallow period, and also the SOC sequestration for boro rice was approximately 0.23 Mg CO_2 ha^{-1} and aus sequestrated 0.17 Mg CO_2 ha^{-1} in R-R-R though the emissions were the highest for rice crop. As a result, R-F-R and R-R-R had higher CH_4 emissions but they were also the only crops which were able to sequestrate C in soil. In our study, the estimated magnitude of this sequestration was very low in terms of GWP compared to CH_4 emissions, but long-term field studies are needed to verify these results and to assess SOC changes in the R-F-R rotation, which we assumed to be at equilibrium.

4.3 Greenhouse gas emissions and carbon footprint

Methane was the main component of the GHG balance and C footprints of the studied crops cultivated under flooded or waterlogging conditions, including rice but also wheat. The dominance of soil CH_4 emissions in the C footprint of rice is well established in the literature. For example, Poore and Nemecek (2018) found that soil CH_4 emissions represented 28-82% of life cycle rice GHG emissions in a comprehensive global meta-analysis. This result is also in line with previous LCA studies in our study region. For example, Alam et al., 2019 found that on-farm CH_4 emissions were the largest contributor to overall emissions in the monsoon paddy in Bangladesh. They also verified that, regardless of retained residue levels, CH_4 is produced during the organic matter decomposition process in anaerobic soil conditions in the profile of both puddled and non-puddled submerged fields. In non-flooded crops the GHG was mostly attributed to CF application. In wheat field the irrigation requirement was lower than rice but the studied field was always with high moisture level which might be a reason of CH4 emissions. The C footprint values of paddy rice production found in our study, ranging 0.9-1.46 kg CO_2e kg^{-1}, are lower than the global median values (2.4 and 1.68 kg CO_2e kg^{-1}, after converting the value from milled rice) reported by Poore and Nemecek (2018) and Clune (2017) respectively. Our results are also lower to those of another study in Bangladesh (3.15 kg CO_2e kg^{-1}, Jimmy et al., 2017) but similar to other studies in this country, e.g., 1.11-1.57 kg CO_2e kg^{-1} by Alam et al. (2016), and 1.35 kg CO_2e kg^{-1} (after converting from milled rice) reported by Shew et al. (2019). In Bangladesh about 293 kg CO_2e ha^{-1} d^{-1} GWP was found in boro rice growing season (Jahangir et al., 2022) and in this study it was about 13 Mg CO_2e ha^{-1} emissions. We found 4.20 Mg CO_2e ha^{-1} emissions in maize where few references are provided here where the found about 4.9 Mg CO_2e ha^{-1} emissions (Biswas et al., 2022) in Bangladesh, 3.4 Mg CO_2e ha^{-1} emissions in India (Jain et al., 2016) and 14.8 Mg CO_2e ha^{-1} emissions (Zhang et al, 2017) in China. These values were used as total emissions for a crop since there was no regional data available in Bangladesh, there were huge variations in GHG emissions because of field management, seasonal variation, residue management and mostly fertilization rates.

4.4 Co-designed carbon footprint calculation tool

The participative approach to develop the carbon footprint calculation tool allows for the incorporation of a wide range of perspectives and expertise, resulting in a comprehensive and accurate assessment of GHG emissions. It is also highly versatile, with the possibility to incorporate changes in the assumptions, parameters, and data that are used in the calculations. This tool can be useful for identifying opportunities for reducing GHG emissions. By providing a detailed understanding of the sources of emissions, as well as C and N flows, co-designed calculation tool can help identify specific areas where changes in practices or technologies could lead to significant reductions in emissions. This can be especially valuable for policymakers and industry representatives, as it can inform the development of more effective and targeted policies and strategies for reducing emissions. However, this tool is not a one-time solution but a continuous process, it needs to be regularly updated to reflect the latest research and data, and new technologies and practices that may emerge.

5. Conclusion

There are many cropping systems followed in Bangladesh for enhancing cropping intensity and increasing crop production, but GHG emissions from agricultural fields are rarely reported. We used a co-designed C footprint calculation tool to estimate the emitted GHG and the C footprint from typical cropping systems in Bangladesh. It was found that rice-based cropping pattern with dryland crops had higher N_2O than sole rice-based cropping systems but CH_4 emissions were higher in sole rice-based patterns, resulting in higher GHG emissions and C footprint overall. Methane contributed about 50-80% of total GHG emissions from upstream-downstream and crop production. Among the rice-based cropping systems, boro and aus from

https://doi.org/10.5194/bg-2023-165
Preprint. Discussion started: 26 September 2023

R-F-R and R-R-R patterns sequestrated C in soil, although this had a negligible effect on the C footprint. A novel finding of this study is the presence of CH_4 emissions from wheat field, as the field was under moist condition throughout the season. The IPCC Tier 1 value was only available for rice seasons (aus, aman and boro) and measured data only available for boro and wheat so further study is required for validation and developing suitable GHG mitigation strategies in agricultural fields in Bangladesh.

Disclosure statement

There is no conflict of interests.

Acknowledgement

This research was financially supported by the Soil and Water Management & Crop Nutrition, Joint FAO/IAEA Division of Nuclear Techniques in Food & Agriculture, Vienna, Austria under the CRP D1.50.20 project.

6. Supplementary information

6.1 Allocation of the Product Value

Based on product value, products shared 79–100% of the greenhouse gas emissions in different crops, while residues shared the rest of the percentage (Suppl. 1). As residue of maize, mungbean, and potato have no price/market value, it has no contribution in the systems, whereas the products contribute 100% due to its product value. Among rice, rainfed T. aman rice residue has the highest contribution as it's large proportion (90%) is used as co-product and high price of residue in Bangladesh. Supplementary data associated with this article is presented in Suppl. 1.

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- J. Ferdous (Lecturer, Dept. of Soil Science, Bangladesh Agricultural University), F. Mahjabin, A.A. Asif (post-graduate students at Bangladesh Agricultural University) worked on data processing, analysis, data interpretation and writing.
- E. Aguilera (Post-doc, CEIGRAM, Universidad Politécnica de Madrid, Madrid, España), Maximilian Bauer (), Alberto Sanz Cobeña (Professor, CEIGRAM, Universidad Politécnica de Madrid, Madrid, España) worked for the development of co-designed carbon footprint calculation tool.

References

Abao, E. B., Bronson, K. F., Wassmann, R., and Singh, U.: Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rainfed conditions. Methane Emissions from Major Rice Ecosystems in Asia. Dev. Plant Soil Sci., Springer, 131-139, https://doi.org/10.1007/978-94-010-0898-3_12, 2000.

Abuarab, M. E., El-Mogy, M. M., Hasan, A. M., Abdeldaym, E. A., Abdelkader, N. H., and El-Sawy, M. B. I.: The effects of root aeration and different soil conditioners on the nutritional values, yield, and water productivity of potato in clay loam soil, Agron., 9, 418, https://doi.org/10.3390/agronomy9080418, 2019.

Aguilera, E., Guzmán, G. I., Alvaro-Fuentes, J., Infante-Amate, J., García-Ruiz, R., Carranza-Gallego, G., Soto, D., and González De Molina, M.: A historical perspective on soil organic carbon in Mediterranean cropland (Spain, 1900-2008), Sci. Total Environ., 621, 634-648, https://doi.org/10.1016/j.scitotenv.2017.11.243, 2018.

Aguilera, E., Reyes-Palomo, C., Díaz-Gaona, C., Sanz-Cobena, A., Smith, P., García-Laureano, R., and Rodríguez-Estévez, V.: Greenhouse gas emissions from Mediterranean agriculture: Evidence of unbalanced research efforts and knowledge gaps, Glob. Environ. Change., 69, 102319, doi.org/10.1016/j.gloenvcha.2021.102319, 2021a.

Aguilera, E., Sanz-Cobena, A., Infante-Amate, J., García-Ruiz, R., Vila-Traver, J., Guzmán, G. I., González de Molina, M., Rodriguez, A., Piñero, P., and Lassaletta, L.: Long-term trajectories of the C footprint of N fertilization in Mediterranean agriculture (Spain, 1860–2018). Environ. Res. Lett., 16, 085010, https://doi.org/ 10.1088/1748-9326/ac17b7, 2021b.

Ahmad, A., Zoli, M., Latella, C., Bacenetti, J.: Rice cultivation and processing: Highlights from a life cycle thinking perspective. Sci. Total Environ., 871, 162079, https://doi.org/10.1088/1748-9326/ac17b7, 2023.

Alam, M.K., Bell, R.W., and Biswas, W.K.: Decreasing the carbon footprint of an intensive rice-based cropping system using conservation agriculture on the Eastern Gangetic Plains. J. Clean. Prod., 218, 259-272, doi.org/10.1016/j.jclepro.2019.01.328, 2019.

Begum, R., Jahangir, M. M. R., Jahiruddin, M., Islam, M. R., Bokhtiar, S. M., and Islam, K. R.: Reduced tillage with residue retention improves labile carbon pools and management indices of soils in a seven-year trial with wheat-mung bean-rice rotation, Pedosphere, 89, 2117-2126, https://doi.org/10.1016/S1002-0160(xx)60xxx-x, 2022.

Biswas, J. C., Mamiruzzaman, M., Haque, M. M., Hossain, M. B., Naher, U. A., Akhtar, S., and Biswas, J. K.: Greenhouse gas emissions from paddy fields in Bangladesh compared to top twenty rice producing countries and emission reduction strategies, Paddy Water Environ., 20(3), 381-393, https://doi.org/10.1007/s10333-022-00899-2, 2022.

Charles, A., Rochette, P., Whalen, J. K., Angers, D. A., Chantigny, M. H., and Bertrand, N.: Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis, Agri. Ecosyst. Environ., 236, 88-98, https://doi.org/10.1016/j.agee.2016.11.021, 2017.

Chen, H., Li, X., Hu, F., and Shi, W.: Soil nitrous oxide emissions following crop residue addition: a meta-analysis, Glob. Change Biol., 19(10), 2956-2964, https://doi.org/10.1111/gcb.12274, 2013.

Chen, X. P., Cui, Z. L., Fan, M. S., Peter, V., Zhao, M., Ma, W. Q., Wang, Z. L., Zhang, W. J., Yan, X. Y., Yang, J. C., Deng, X. P., Gao, Q., Zhang, Q., Guo, S. W., Ren, J., Li, S. Q., Ye, Y. L., Wang, Z. H., Huang, J. L., and Zhang, F. S.: Producing more grain with lower environmental costs, Nature, 514, 486–489, https://doi.org/10.1016/j.resconrec.2021.105661, 2014.

Clune, S., Crossin, E., and Verghese, K.: Systematic review of greenhouse gas emissions for different fresh food categories, J. Clean. Prod., 140, 766-783, https://doi.org/10.1016/j.jclepro.2016.04.082, 2017.

Coleman, K., and Jenkinson, D.S.: RothC-26.3 - A Model for the turnover of carbon in soil. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models, Springer Berlin Heidelberg, Berlin, Heidelberg, 237-246, https://doi.org/10.1007/978-3-642-61094-3_17, 1996.

FAO: The Future of Food and Agriculture–Trends and Challenges, Food and Agriculture Organization of the United Nations., Rome, Italy, 163, 2017.

FAO: FAOSTAT—FAO database for food and agriculture, Rome: Food and agriculture Organisation of United Nations (FAO), 2023.

FAO: IIASA, Harmonized World Soil Database version 2.0, Rome and Luxenburg, 2023.

Farooq, M. S., Uzair, M., Maqbool, Z., Fiaz, S., Yousuf, M., Yang, S. H. and Khan, M. R.: Improving nitrogen use efficiency in aerobic rice based on insights into the ecophysiology of archaeal and bacterial ammonia oxidizers, Front. Plant Sci. 13, 913204, https://doi.org/10.3389/fpls.2022.913204, 2022.

Ferdous, J., Mumu, N. J., Hossain, M. B., Hoque, M. A., Zaman, M., Müller, C., and Jahangir, M. M. R.: Co-application of biochar and compost with decreased N fertilizer reduced annual ammonia emissions in wetland rice, Front. Sustain. Food Syst., 6, 1067112. http://doi.org/10.3389/fsufs.2022.1067112, 2023.

Foley, J., Ramankutty, N., and Brauman, K.: Solutions for a cultivated planet, Nature, 478, 337–342, https://doi.org/10.1038/nature10452, 2011.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J. L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., and Zhang, H.: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 923–1054, 2021.

FRG: Fertilizer Recommendation Guide-2018, Farmgate: Bangladesh Agricultural research Council (BARC), 2018.

Gross, C. D., Bork, E., Carlyle, C. N., and Chang, S. X.: Biochar and its manure-based feedstock have divergent effects on soil organic carbon and greenhouse gas emissions in croplands, Sci. Total Environ., 806, 151337, https://doi.org/10.1016/j.scitotenv.2021.151337, 2021.

Harris, I., Osborn, T. J., Jones, P., and Lister, D.: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset, Scientific Data. 7, 109, https://doi.org/10.1038/s41597-020-0453-3, 2020.

Hoben, J. P., Gehl, R. J., Millar, N., Grace, P. R., and Robertson, G. P.: Nonlinear nitrous oxide (N_2O) response to N fertilizer in on-farm corn crops of the US Midwest, Glob. Chang. Biol., 17 (2), 1140–1152, https://doi.org/10.1111/j.1365-2486.2010.02349.x, 2011.

IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 151, 2014.

Islam, S. M., Gaihre, Y. K., Islam, M. R., Ahmed, M. N., Akter, M., Singh, U., and Sander, B. O.: Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. J. Environ. Manag., 307, 114520. https://doi.org/10.1016/j.jenvman.2022.114520, 2022.

Islam, S. M., Gaihre, Y. K., Islam, M. R., Akter, M., Al Mahmud, A., Singh, U., and Sander, B.O.: Effects of water management on greenhouse gas emissions from farmers' rice fields in Bangladesh, Sci. Total Environ., 734, 139382, https://doi.org/10.1016/j.scitotenv.2020.39382, 2020.

Jahangir, M. M. R., Bell, R. W., Uddin, S., Ferdous, J., Nasreen, S. S., Haque, M. E., and Müller, C.: Conservation Agriculture with Optimum Fertilizer N Rate Reduces GWP for Rice Cultivation in Floodplain Soils, Front. Environ. Sci., 291, https://doi.org/10.3389/fenvs.2022.853655.2022, 2022.

Jeffery, S., Verheijen, F. G., Kammann, C. and Abalos, D.: Biochar effects on methane emissions from soils: a meta-analysis. Soil Biol, Biochem., 101, 251-258, https://doi.org/10.1016/j.soilbio.2016.07.021, 2016.

Lakshman, K., Chandrakala, M., Prasad, P. S., Babu, G. P., Srinivas, T., Naik, N. R. and Korah, A.: Liquid Nano-Urea: An Emerging Nano Fertilizer Substitute for Conventional Urea. Chronic. Biores. Manag., 6, 054-059, 2022.

Liang, X. Q., Chen, Y. X., Li, H., Tian, G. M., Ni, W. Z., He, M. M., and Zhang, Z. J.: Modeling transport and fate of N from urea applied to a near-trench paddy field, Environ. Pollu., 150, 313–320, https://doi.org/10.1016/j.envpol.2007.02.003, 2007.

Lin, Y., Watts, D. B., van Santen, E., and Cao, G.: Influence of poultry litter on crop productivity under different field conditions: A meta-analysis, Agron., 110, 807, https://doi.org/10.2134/agronj2017.09.0513, 2018.

Maaz, T. M., Sapkota, T. B., Eagle, A. J., Kantar, M. B., Bruulsema, T. W. and Majumdar, K.: Meta-analysis of yield and nitrous oxide outcomes for nitrogen management in agriculture, Glob. Chang. Biol., 27(11), 2343-2360, https://doi.org/10.1111/gcb.15588, 2021.

Moslehuddin, A. Z. M, Laizoo S., and Kazuhiko E.: Fertility status of Bangladesh soils-A review, J. Facul. Agri., Kyushu University, 257-267, 1997.

Neue, H. U., and Scharpenseel, H. W.: Gaseous products of the decomposition of organic matter in submerged soils, Organic matter and rice, 311, 328, 1984.

Poore, J., and Nemecek, T.: Reducing food's environmental impacts through producers and consumers, Sci., 360, 987-992, https://doi.org/10.1126/science.aaq0216, 2018.

Sanchis, E., Ferrer, M., Torres, A. G., Cambra-López, M., and Calvet, S.: Effect of water and straw management practices on methane emissions from rice fields: a review through a meta-analysis, Environ. Eng. Sci., 29 (12), 1053-1062, https://doi.org/10.1089/ees.2012.0006, 2012.

Sanz-Cobena, A., Lassaletta, L., Estellés, F., Del Prado, A., Guardia, G., Abalos, D., and Billen, G.: Yield-scaled mitigation of ammonia emission from N fertilization: the Spanish case, Environ. Res. Lett., 9 (12), 125005, https://doi.org/10.1088/1748-9326/9/12/125005, 2014.

Sarkar, M. I. U., Jahan, A., Haque, M. M., Islam, S. M. M., Ahmed, M. N., and Islam, M. R.: Long term effects of integrated plant nutrition system on rice yield, N dynamics and biochemical properties in soil of rice–rice cropping system, A. J. Soil Sci. Plant Nutri., 4, 1–14, https://doi.org/10.9734/AJSSPN/2019/v4i430050, 2019.

Sarker, M. M. H., Moslehuddin, A. Z. M., Jahiruddin, M., and Islam, M. R.: Available status and changing trend of micronutrients in floodplain soils of Bangladesh, SAARC J. Agri., 16 (1), 35-48, http://dx.doi.org/10.3329/sja.v16i1.37421, 2018.

Shan, J. and Yan, X.: Effects of crop residue returning on nitrous oxide emissions in agricultural soils, Atmos. Environ., 71, 70-175, https://doi.org/10.1016/j.atmosenv.2013.02.009, 2013.

Shang, Z., Abdalla, M., Xia, L., Zhou, F., Sun, W. and Smith, P.: Can cropland management practices lower net greenhouse emissions without compromising yield? Glob. Chang. Biol., 27(19), 4657-4670, https://doi.org/10.1111/gcb.15796, 2021.

Signor, D., Cerri, C. E. P., and Conant, R.: N_2O emissions due to N fertilizer applications in two regions of sugarcane cultivation in Brazil, Environ. Res., 8 (1), 01, https://doi.org/10.1088/1748-9326/8/1/015013, 2013.

Sindelar, A. J., Coulter, J. A., Lamb, J. A., and Vetsch, J. A.: N, stover, and tillage management affect N use efficiency in continuous corn. Agron, Soil Environ. Quality, 107, 843–850, https://doi.org/10.2134/agronj14.0535, 2015.

Šturm, M., Kacjan-Maršić, N., Zupanc, V., Bračič-Železnik, B., Lojen, S., and Pintar, M.: Effect of different fertilisation and irrigation practices on yield, nitrogen uptake and fertiliser use efficiency of white cabbage (*Brassica oleracea* var. capitata L.), Sci. Hortic., 125(2), 103-109, https://doi.org/10.1016/j.scienta.2010.03.017, 2010.

Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R., and Kunhikrishnan, A.: Role of organic amendment application on greenhouse gas emission from soil, Sci. Total Environ., 465, 72-96, https://doi.org/10.1016/j.scitotenv.2013.01.031, 2013.

The World Bank: World Development Indicators. The World Bank IBRD-IDA, https://databank.worldbank.org/reports.aspx?source=World-Development-ndicators#, 2023.

Udmale, P., Ishidaira, H., Thapa, B. R. and Shakya, N. M.: The status of domestic water demand: supply deficit in the Kathmandu Valley, Nepal, Water, 8(5), 196, https://doi.org/10.3390/w8050196, 2016.

Vu, Q. D., de Neergaard, A., Tran, T. D., Hoang, Q. Q., Ly, P., Tran, T. M., and Jensen, L. S.: Manure, biogas digestate and crop residue management affects methane gas emissions from rice paddy fields on Vietnamese smallholder livestock farms, Nutr. Cycl. Agroecosystems, 103, 329-346, https://doi.org/10.1007/s10705-015-9746-x, 2015.

Yadav, G.S., Das, A., Lal, R., Babu, S., Meena, R. S., Saha, P., Singh, R., and Datta, M.: Energy budget and carbon footprint in a no-till and mulch-based rice–mustard cropping system, J. Clean. Prod., 191, 144–157, https://doi.org/10.1016/j.jclepro.2018.04.173, 2018.

Yagi, K., and Minami, K.: Effect of organic matter application on methane emission from some Japanese paddy fields, Soil Sci. Plant Nutr., 36, 599-610, https://doi.org/10.1080/00380768.1990.10416797, 1990.

Zaman, M., Kleineidam, K., Bakken, L., Berendt, J., Bracken, C., Butterbach-Bahl, K., and Müller, C.: Methodology for measuring greenhouse gas emissions from agricultural soils using non-isotopic techniques. Measuring Emission of Agricultural Greenhouse Gases and Developing Mitigation Options using Nuclear and Related Techniques: Applications of Nuclear Techniques for GHGs, https://doi.org/10.1007/978-3-030-55396-8, 2021.

Zhang, D., Shen, J., Zhang, F., Li, Y., and Zhang, W.: Carbon footprint of grain production in China. Science., 7, 4126, https://doi.org/10.1038/s41598-017-04182-x, 2017.