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Increases in soil sequestered carbon under conservation agriculture cropping decrease the estimated greenhouse gas emissions of wetland rice using life cycle assessment

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ABSTRACT

Wetland rainfed rice (*Oryza sativa* L.), which covers 60 million hectares in South Asia, contributes significantly to agricultural greenhouse gas (GHG) emissions. Mitigation strategies for GHG emissions by wetland rice production are of considerable importance. Life cycle assessment of GHG emissions can be used to assess the mitigation potential of new rice production practices such as seedling establishment on non-puddled soil. The aim of the study was firstly to determine the GHG mitigation potential of rain-fed rice production by changing to non-puddled transplanting and increased crop residue retention and secondly to determine the addition contribution of soil carbon sequestration to net GHG emissions with the altered crop establishment approach. A *cradle to farm-gate* Life Cycle Analysis was used to calculate GHG emissions associated with monsoon rice production in rice-based intensive cropping systems of Northwest Bangladesh. The non-puddled transplanting and low residue retention decreased the net life cycle assessment GHG emissions (CO_2eq) by 31% in comparison with the current puddled transplanting and increased crop residue retention. By contrast, non-puddling with increased residue retention reduced emission of the net GHG by 16% in comparison with current puddling and low residue retention. Regardless of rice establishment practices, CH_4 was the most prevalent GHG emission comprising 63–67% of the total GHGs, followed by 17–20% from CO_2 emissions from the field. The GHG emissions tonne^{-1} rice after accounting for soil carbon storage ranged from 1.04 to 1.18 tonne CO_2eq for non-puddling with low and increased crop residue retention, respectively. The inclusion of soil carbon in the footprint equation represents a 26% reduction of estimated GHG emissions under non-puddled soil with increased residue retention. Overall, non-puddled transplanting with increased crop residue retention was an effective GHG mitigation option in wetland monsoon rice production because the increased yield and extra soil organic carbon storage more than offset its higher CH_4 emissions than with low residue retention.

1. Introduction

Wetland rice (*Oryza sativa* L.) production contributes more than half of the world's agricultural greenhouse gas (GHG) emissions (The IPCC, 2007a), which correspond to around 15% of the total enhanced global warming (IPCC, 2013). Intensive rice production under both irrigated (*boro*) and rainfed (*aman* season) conditions will strongly influence aggregate on-farm GHG emissions (Tilman et al., 2002) across South Asia. However, irrigated and monsoon rice cultivation vary in consumption of energy and grain yields and hence are likely to vary in emissions of GHGs. The input use for monsoon rice cultivation is also lower than the irrigated rice (Lal et al., 2017). Alam et al. (2016) conducted life cycle analysis of GHG emissions for rice production in the EGP for the irrigated *boro* season. Irrigation application contributed 15–25% of the total on-farm GHGs of the *boro* rice crop while the rainfed monsoon rice crops in the EGP can save on energy and fuel consumption from irrigation (Lal, 2015). Although rice yield in the monsoon season is lower relative to yield in the irrigated *boro* season (Amin et al.,

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Abbreviations

ACIAR	Australian Centre for International Agricultural Research
ADB	Asian Development Bank
CA	Conservation agriculture
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CT	Conventional puddling
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DSR	Direct-seeding of rice
Eh	Redox potential
EGP	Eastern Gangetic plains
GHG	Greenhouse gas
GWP	Global Warming Potential
ha	Hectare
HR	High residue retention
IPCC	Inter–Governmental Panel on Climate Change
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LSD	Least significant difference
LR	Low residue retention
MOEF	Ministry of Environment and Forest, Peoples Republic of Bangladesh
MoP	Muriate of potash
N	Nitrogen
N_2O	Nitrous Oxide
NPP	Net primary production
SOC	Soil organic carbon
SPSS	Statistical Package for the Social Sciences
t	Tonne
TOC	Total organic carbon
UN-FCCC	United Nations Framework Convention on Climate Change
NP	Non-puddled transplanting of rice
NT	No-tillage
US$	United States Dollar
USA	United States of America

2015), the monsoon rice is a major contributor to food security in South Asia and accounts for more than half of annual production in Bangladesh. However, it remains unclear how GHGs of rice production differ in monsoon rice production relative to rice growing in other seasons and how it differs with novel crop establishment practices compared to the conventional approach. Conservation agriculture (CA) cropping is a potential strategy for mitigating climate change in rice-based systems of the EGP (Alam et al., 2016). However, the GWP of the rainfed monsoon rice crop in the EGP using a CA approach has not been quantified using a life cycle analysis methodology.

Any strategies which would reduce both CH_4 and N_2O emissions from wetland soils by keeping redox potential within an intermediate range (Hou et al., 2012) can contribute significantly to mitigation of GWP by rice (Alam et al., 2016). Avoiding puddling of soils for rice establishment is an emerging form of CA that has outperformed conventional transplanting into puddled soil in system productivity (Salahin, 2017), profitability (Haque et al., 2016), soil health improvement (Alam et al., 2018) and fuel consumption (Islam et al., 2013). Non-puddling of soil also reduces labour and water requirements for rice establishment (Islam, 2017). However, rice crop establishment practices and residue return at an increased rate have in some cases increased emissions of agricultural GHGs (Naser, 2005; CH_4 and N_2O), while in other cases they diminished emissions of the major GHGs (Zou et al., 2005; Yan et al., 2005), so further clarification is needed on the effect of CA practices on GHG emissions from rainfed rice in the EGP.

The measurement of GHG emissions of wetland rice production has been done by several researchers (Hayashi and Itsubo, 2005; Koga et al., 2006; Masuda, 2006). According to those studies, the driving factors for GHGs are provision of irrigation, production and delivery of inputs like N-containing fertilizers and chemicals related to crop protection and the usage and manufacture of machinery (Architectural Institute of Japan, 2003). According to Adhya et al. (2000), the net CH_4 emission from paddy fields was a major contributor to GHG emissions but that depends on the field water regime (Gathorne-Hardy, 2013) and the quantity of organic material in the soil (Yan et al., 2005). Kasmaprapruet et al. (2009) reported that during the life–cycle of rice, cultivation accounted for 95% of GWP, while harvesting and seeding and milling processes contributed 2% each of GWP. In a LCA study with the system boundary up to the farm-gate, Harada et al. (2007) reported that CH_4 emission decreased by 43% and total emission diminished by 1.78 tonne CO_2eq ha^{-1} with no-tillage rice relative to puddled rice. On the other hand, Eshun et al. (2013) and Woods et al. (2008) reported N_2O accounted for the major share of GHG emissions for upland rice (70%) and wheat production (80%), respectively. The N_2O emissions from flooded rice are significantly lower than from upland crops (Linquist et al., 2012). However, nitrification takes place in the oxidised rhizosphere of rice roots and when coupled with denitrification processes in the reduced layer below the surface of flooded paddy soils result in losses of N_2O (Patrick et al., 1985). The relative contributions of CH_4 and CO_2 between irrigated and rained rice may also be different.

For the EGP where rainfed monsoon rice covers over 60 million hectares, GHGs including pre-farm input related emissions, on-farm emissions and sequestered SOC have not been estimated for the rice crop. Khoshnevisan et al. (2014), Yusoff and Panchakaran (2015) and Jimmy et al. (2017) conducted LCA on rice production but they used secondary data from different sources which might not reflect the scenarios prevailing in the EGP. While Jimmy et al. (2017) conducted a study in a typical rice scenario of Bangladesh, the rice growing season was not specified. As summarised in Table 1, most of the LCA studies were conducted in rainfed conditions in other rice growing areas. By contrast, Bautista and Saito (2015) in Philippines and Thanawong et al. (2014) in North East Thailand conducted studies in both rainfed and irrigated conditions and showed that GHGs up to farmgate stage were lower under rainfed conditions. The LCA studies have examined the effects of rice crop establishment and production systems like direct water seeding, organic rice, environment-friendly, dry and wet direct seeding, while Harada et al. (2007) contrasted no-tilling and non-puddling practices for irrigated rice production with puddling practices (Table 1). In the study, the net GHG up to milling (brown rice) for puddling, no-tilling and non-puddling were 0.94, 0.44 and 0.76 t CO_2eq t^{-1} brown rice. The non-puddling practice adopted in the study of Harada et al. (2007) was conventional tillage and planting without puddling. The elimination of puddling, therefore, saved 0.18 t CO_2eq t^{-1} brown rice. The emerging non-puddled transplanting of rice following minimal disturbance of soil (strip

Table 1
Summary of life cycle greenhouse gas emission data of studies on rice production in the rice growing areas around the world.

Study (ref.)	Cultivation practices	Emission (t CO_2eq t^{-1} rice)	Yield (t ha^{-1})	Growing environment
Alam et al. (2016), Bangladesh	Conventional puddling, Non-puddling	Total net life cycle GHG emissions to farm gate (1.11-non-puddling; 1.57-puddling)	6.36 (puddling) 6.68 (non-puddling)	Irrigated (dry season)
Brodt et al. (2014), USA (California)	Direct water-seeding practices	100-year GWP: 1.47 kg CO_2eq t^{-1} of milled rice (to farmgate 1.01); IPCC Tier 1 estimates: 3.60 (to farmgate 1.09).	9.3 (dried paddy rice)	Continuously flooded (rain-fed)
Hokazono and Hayashi (2012), Japan	Conventional, environment-friendly and organic rice farming	Total net life cycle GHG of milled rice Conventional-1.46 Environmentally friendly-1.58 Organic-2.0	Organic (3.38), environmentally friendly (4.44), and conventional rice (4.36), respectively	Rain-fed
Ecoinvent Centre (2008)	Existing/traditional	Total net life cycle GHG to farm gate (0.47)	7.5	Rain-fed
Blengini and Busto (2009), Italy	Traditional rice establishment	Total net life cycle GHG to milling 2.52–2.66	6.1	Rice cultivated without flooding and grown under a reduced water regime.
Thanawong et al. (2014), NE Thailand	Sowing by dry seeded and wet seeded/transplanting (nursery)	Total net life cycle GHG to farmgate 2.97–5.55	2.36–3.02	Both rain-fed and irrigated systems
Wang et al. (2010), China	Traditional rice establishment	Total net life cycle GHG to farmgate (1.50)	8.8	Rice–wheat system where rice grown in monsoon season
Bautista and Saito (2015), Philippines	Traditional rice establishment	Total net life cycle GHG to farm gate (0.93) Total net life cycle GHG to farm gate (0.47)	4.21 (Irrigated) 2.93 (rain-fed)	Irrigated and rain-fed
Harada et al. (2007)	Puddling, No-tilling, Non-puddling	Net life cycle GHG to milling (Brown rice) Puddling-0.94 No-tilling-0.44 Non-puddling-0.76	Puddling-4.43 No-tilling-5.49 Non-puddling-5.63	Irrigated

Φ Life cycle GHG-Life cycle greenhouse gas emission.

tillage) in a rice-based triple cropping system (where other upland crops are established by strip planting) has performed well in both biogenic GHGs and yield scale GHG reduction under flooded, irrigated conditions (Alam et al., 2016). However, there is a need for accurate GHG emission estimates under rainfed conditions in the monsoon season when the rice field experiences variations in standing water depth (see Appendix 1).

Soil C sequestration counterbalances fossil fuel emission of GHGs (Lal, 2004). The practices of CA (minimum disturbance of soil, residue return of previous crops and growing diverse crops in rotation) may also sequester SOC over time. Soil carbon sequestration accounting is necessary for estimating the net contribution of the crop grown under novel crop or soil management practices that alter SOC over time otherwise there will be an overestimation of GHG emissions (Marble et al., 2011). The GHG estimation can additionally be made from a C budget after summing C inputs and outputs. To estimate exactly the impact of agricultural practices on the net GWP, soil C stock change should be quantified together with biogenic GHG (CH_4 & N_2O) fluxes. Therefore, the effects of the novel non-puddled rice establishment and related management practices on net GHG emissions from rice fields needed to be estimated, after accounting for both GHG emissions and the changes in SOC.

Objectives of the study were to determine:

1. Greenhouse gas emissions (CO_2eq) for 1 tonne of paddy rice production for CA practices compared to conventional practices.
2. The hotspots and processes from cradle to farm-gate boundary of rainfed wetland rice production that were most responsible for the GHG emissions.

2. Materials and methods

2.1. Study site and experimental design

A summary of the study site and other details are given in Table 2. Further details of the study site and experimental design can be found in Alam et al. (2016).

The field study covered the period from the July 19, 2016 to October 15, 2016 and tested conventionally puddled (CT) and non-puddling rice establishment practices, both with high crop residue retention (HR) and low residue retention (LR). The non-puddling

Table 2
Summary of the characteristics of the study site used to assess GHG emissions.

Characteristics of study site	Details
Location	Northwest Bangladesh at Alipur village, Durgapur upazilla, Rajshahi division
Texture class	Silt loam
Soil type	Calcareous Brown Flood Plain
Subgroup (USDA)	*Aeric Eutrochrept*
Parent material types	Ganges river alluvium
Location (Latitude and longitude)	24° North latitude, 88° East longitude.
Landform	Narrow terraced strips on the gently undulating hill slopes.
Altitude	8 m above sea level
Rainfall	1047–1693 mm; lower than other parts of the country; concentrated in monsoon season (June to September)
Dominant minerals	Mica–vermiculite–smectite (interstratified) and kaolinite–smectite (interstratified), Mica, Kaolinite (Moslehuddin et al., 2009)
Drainage	Moderate

mm = millimetre; m = metre; USDA= United States Department of Agriculture.

practice of rice crop establishment was done following strip tillage and then flooding of soils for ~24 h (Haque et al., 2016). The experiment was commenced in 2010 with four replicates of each practice in a split plot design (Islam, 2017). The low crop residue retention practices were based on farmers' practice in the region where rice residue was retained at a low rate (20% by height) while high residue retention involved retention of 50% by height of standing rice residue. Residues of all the previous crops (lentil (*Lens culinaris* L.), mungbean (*Vigna mungo* L.) and mustard (*Brassica juncea* L.)) in the rotation were removed based on the current farmers' practice for LR. On the other hand, HR involved return of all residues of these crops to the respective sub plots. Lentil, mungbean and monsoon rice were grown on the field in a sequence for the first three years. Mustard, irrigated rice and monsoon rice were grown in a sequence in the following three years on the same field. Chemicals for crop nutrition and protection were characteristic of the practice followed in the locality and were recorded.

Greenhouse gas emissions (CO_2, CH_4 and N_2O) from soil were measured using chambers similar to the study of Alam et al. (2016). The gas samplings from each subplot are repeated every 7 days throughout the study period using a closed chamber system. The measurement frequency for GHGs was increased to 2 or 3 days after application of split doses of N.

2.2. Soil sampling method and soil C sequestration estimation

The carbon sequestered in soils due to the continual application of the treatments above was also included in the carbon accounting. Soils at 0–30 cm depth from each treatment were collected in cores to determine bulk density and analysed for SOC content. In this study, C sequestration estimation only uses data from crop 15 to crop 18 to represent recent trends because the rate of SOC accumulation during the initial years of CA establishment and after three years may not be the same. Soil C accumulation was calculated from the increase in SOC between crops 15 and 18. The total organic carbon (TOC) content in soil was calculated from the organic carbon content (wet oxidation method) (Alam et al., 2016), while the TOC stock was calculated according to Ellert and Bettany (1995). The details of C stock calculation can be found at Alam et al. (2018). The TOC was then divided by the number of crops to approximate the C accumulated over a single crop growing season. A comparative C balance was estimated by using C inputs and outputs. The C balance was calculated by subtracting C loss through C gaseous emission (CO_2 and CH_4) and crop C harvest (grain consumption and residue removal) from net primary production (NPP) (Naser, 2005).

C sequestration = NPP − (CO_2 emission + CH_4 emission + Grain C harvest + Straw C harvest + C in residue lost by decomposition)

Where, NPP (Net Primary Production) includes C in residue retained from the previous irrigated rice crop and total biomass C of monsoon rice including roots.

The field study to determine the amount of irrigated rice residue remaining after the monsoon season was conducted using the mesh litterbag technique (Bocock and Gilbert, 1957). Known quantities of rice residues (30 g) and rice roots (30 g) were put in sealed non-degradable mesh (1 mm) bags that were placed on the soil surface. Bags were recovered after 88 days to determine the loss of mass assuming that all the mass lost from litterbags was mineralized (Curtin et al., 2008). Four randomly pre-selected hills of rice were sampled for root distribution at maximum vegetative stage. The roots were collected up to 50 cm depth. The samples for residue retention and removal were collected from three 1.5 m^2 quadrats which were marked immediately after sowing. The collected samples were then oven dried at 65–70 °C and weighed for biomass calculation per hectare.

2.3. GHGs measurement and gas flux calculations

A detailed description of gas sample collection for measuring GHG emissions is reported in Alam et al. (2016). The following variations were used for the present study. For measuring CH_4 and N_2O, triplicate transparent chambers made with 5 mm thick acrylic sheets with the dimensions of 60 cm × 30 cm × 100 cm (length × width × height) were installed in each plot. The measurements of soil CO_2 efflux representing the product of heterotrophic respiration were done with chambers of dimensions 30 cm × 30 cm × 60 cm (length × width × height) made with 3 mm thick acrylic sheets (Hutchinson and Livingston, 1993).

The calculation of gas flux over the season was done in line with Yagi et al. (1991). It was assumed that GHG emissions fluctuated linearly during the period between gas sampling times. Then, the total GHG fluxes over the rice growing season were summed up from the average gas emissions as done by Alam et al. (2016) who interpolated average gas emissions between the sampling days.

2.4. Life cycle GHG emissions during monsoon rice production

The LCA conducted was a single impact, focused LCA used only for investigating the emissions that are responsible for global warming impact (Finkbeiner et al., 2011). The streamlined LCA was applied to account for GHGs resulting from the stages of '*cradle–to–farm gate*' of monsoon rice production (Todd and Curran, 1999). According to ISO 14040–44 (2006), the four steps of the LCA approach that were considered for estimation of the GHG emissions are: setting of goal and definition of scope; preparation of life cycle inventory (LCI); life cycle impact assessment and; interpreting the results. The breakdown of GHG emissions in terms of inputs and outputs of the stages (i.e. cradle–farm gate) was analysed to identify hotspot(s), i.e. the inputs and outputs causing the most GHG emissions, and then to propose strategies to mitigate greenhouse gas emissions from monsoon rice production.

2.4.1. Goal setting and scope definition

The emission of GHGs associated with the production of monsoon rice was calculated for four cropping practices: i) Transplanting of rice following puddling of soil with low residue retention (CTLR), or ii) with high residue retention (CTHR); iii) non-puddled transplanting with low residue retention (NPLR) or iv) with high residue retention (NPHR). The system boundary of the study was determined up to farm-gate (pre-farm and on-farm stages) of the production of monsoon rice (Fig. 1). The functional unit of the LCA is one tonne of monsoon rice grain (paddy rice). A mass balance has been conducted to estimate the inputs and outputs per tonne production of monsoon rice grain during pre-farm and on-farm stages, which is also known as a life cycle inventory. The GHGs associated with the pre-farm activities were estimated by multiplying the emission factors (EF) with the amount of inputs required for their production and transportation to the field of the current study, while GHGs emanated by on-farm activities are outputs associated with operating farm machineries and applying chemicals. The total GHG emission from the production of one tonne of monsoon was calculated by adding emissions from both the stages (pre- and on-farm).

2.4.2. Life cycle inventory

The factors related to the production of each tonne of rice (e.g., chemicals for crop nutrition and crop protection, machinery) were used to develop a complete LCI, which is a pre-requisite to estimate

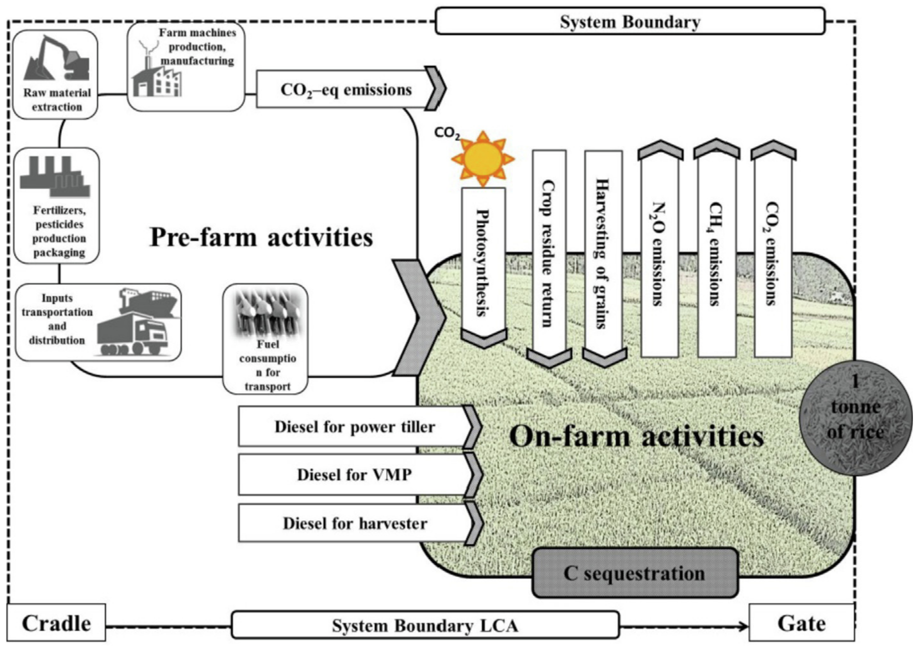


Fig. 1. System boundaries and input–output relationships for monsoon rice production.

Table 3
Life Cycle Inventory of farm activities, inputs and outputs for the production of one tonne of rice on the Eastern Gangetic Plain in the monsoon season.

Inputs (units)	Rice establishment treatments			
	CTLR[b]	CTHR[c]	NPLR[d]	NPHR[e]
Pre–farm				
a) Seeds and chemicals (kg tonne^{-1} of rice production)				
1. Seeds	9.88	9.45	9.3	8.53
2. Nitrogen	42.86	40.88	40.29	36.93
3. Phosphorus	24.18	23.06	22.73	20.83
4. Potassium	29.67	28.3	27.89	25.57
5. Sulfur	13.19	12.58	12.4	11.36
6. Zinc	1.76	1.68	1.65	1.52
7. Boron	0.55	0.52	0.52	0.47
8. Fungicides	0.35	0.34	0.33	0.3
9. Herbicides	0.4	0.38	0.37	0.34
10. Insecticides	0.55	0.52	0.52	0.47
b) Transport (km for road + t–nm for sea)[a]				
1. Urea	86.8	82.8	81.6	74.9
2. Triple superphosphate	114.8 + 752	109.6 + 717	108.0 + 707	99.1 + 648
3. Muriate of potash	114.8 + 525	109.6 + 500	108.0 + 494	99.1 + 453
4. Gypsum	114.8 + 525	109.6 + 500	108.0 + 494	99.1 + 453
5. Zinc	114.8 + 525	109.6 + 500	108.0 + 494	99.1 + 453
6. Boric acid	114.8 + 366	109.6 + 350	108.0 + 345	99.1 + 316
7. Insecticides	91.65429	87.42704	86.18802	78.94545
8. Fungicides	27.28344	28.2171	33.95192	37.72218
9. Herbicides	114.8 + 239	109.6 + 227	108.0 + 225	99.1 + 206
c) Farm machinery (US$ tonne^{-1} of rice production)				
1. Power Tiller/Versatile Multi–crop Planter	0.14	0.14	0.06	0.06
2. Harvester	0.02	0.02	0.02	0.02
d) Farm machinery transport (km for road + t–nm for sea)				
1. Harvester	114.8 + 366	109.6 + 350	108.0 + 345	99.1 + 316
2. Power tiller	114.8 + 366	109.6 + 350	–	–
3. VMP	–	–	108.0 + 345	99.1 + 316
On–farm (litre tonne^{-1} of rice production)				
1. Power tiller/Versatile Multi–crop Planter	3.3	3.2	1.3	1.2
2. Harvester	21.8	24.2	25.4	30.2
Rice yield (tonne ha^{-1})	4.55	4.77	4.84	5.28

[a] t–nm = tonne–nautical mile.
[b] Puddled transplanting with low residue retention (CTLR).
[c] puddled transplanting with high residue retention (CTHR).
[d] Non-puddled transplanting with low residue retention (NPLR) and.
[e] Non-puddled transplanting with high residue retention (NPHR).

the emitted GHGs for the manufacturing, transport and use of inputs and outputs. Soil emissions (CO_2, CH_4 and N_2O) are positive outputs and soil C-sequestration is a negative output of pre– and on–farm stages (Table 3) of monsoon rice production.

2.4.2.1. Inputs and outputs. For the rainfed rice cultivation under both the novel non-puddled and conventional puddled transplanting system, the insecticides, fungicides and herbicides used were tabulated (Table 3). The fertilizers applied for crop production are also listed in Table 3. Regarding the fertilizers, urea, triple superphosphate (TSP), murate of potash (MoP), gypsum, zinc sulphate monohydrate and boric acid were applied as sources of N, P, K, S, Zn and B nutrients. They were considered as inputs. Light-duty diesel trucks capable of carrying ca. 5 t were used for carrying inputs in Bangladesh. Trans-oceanic freighters were used for inputs imported from other countries (Table 3). All distances of the system inputs are specifically shown in Table 3. Additionally, the details of inputs can be found in Tables 3 and 4. The three major greenhouse gases (CO_2, CH_4 and N_2O), the savings of C in soil and the harvested products (grain and residues) were considered as the outputs of the production systems and of the study.

2.4.2.2. Pre–farm emissions. Greenhouse gas emissions of activities related to input production (chemicals, energy and machinery) and their delivery to the field were estimated. Based on the LCA study conducted for *boro* rice production, indirect emissions from manufacturing of farm machinery were calculated by following the database of inputs and outputs (Suh, 2004) as described by Alam et al. (2016). The EF of farm machinery production (0.15 kg CO_2eq US$$^{-1}$) was multiplied by the cost of machinery manufacture for each functional unit determined according to 1998 US$ value (WB, 2014).

The chemicals used for rice production following the establishment practices under study were recorded per tonne of rice production. These EFs were sourced from Alam et al. (2016) as they represent the general condition in Northwest Bangladesh. The EFs of crop nutrients used from Alam et al. (2016) were for fertilizers (urea, TSP), crop protection insecticides (Malathion™, Sumithion™), fungicides (Amistar™ and Tilt™) and herbicides (Refit™ and glyphosate). For the insecticide, Wonder 5WG (Emamectin Benzoate), and fungicide, Rovral 50WP (Ipridione), the local EF was determined from the embodied electrical energy consumption (DEFRA, 2008) of these chemicals, multiplied by the local EFs for electrical energy production (Brander et al., 2011). The GHG EFs of urea, TSP and pesticide production were sourced from the work of Alam et al. (2016) who considered the EF for electricity generation was 0.64 kg CO_2eq kWh^{-1} following UN–FCCC (2017). The source countries of imported inputs were collected from Bangladesh Business News (2013), while the EFs of the inputs imported to Bangladesh (urea, TSP, MoP, gypsum, zinc sulphate monohydrate and boric acid) were obtained from Alam et al. (2016) as the EF values represent the overall situation of the study area.

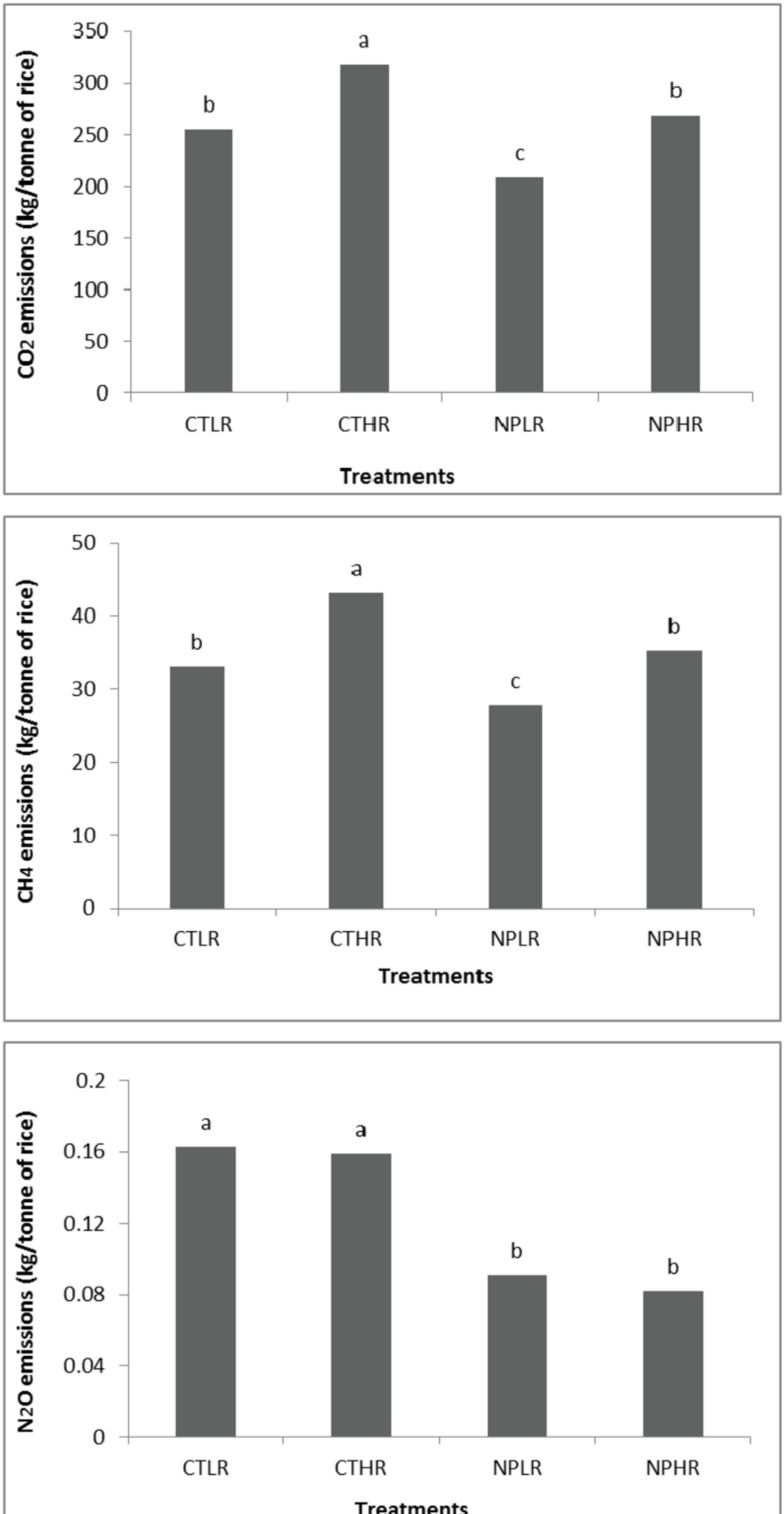
The GHG emissions of each mode of transport associated with this rice production were obtained from the database of HBEFA (2014). The modes of transportation include the transportation by sea (trans-oceanic bulk cargo carrier) and trucks (3–7 tonnes) for road transport. The emission of GHGs for input deliveries from factory to crop field are expressed in terms of tonne kilometres (tkm) travelled by road and tonne-nautical miles (t-nm) travelled by sea. The distance between the paddy field and its source was multiplied by the weight of input to determine 'tkm' (Alam et al., 2016).

2.4.2.3. On–farm emissions. Greenhouse gas emitting activities in the monsoon rice season start with the preparation of land by a wet tillage (crop establishment) operation, include soil emissions after application of chemicals for crop nutrition and protection and intercultural operations and finally fuel use for harvesting. For the rain-fed monsoon season, the rice crop required no irrigation so required no use of diesel for operating a pump.

Farm machinery—In the case of the conventional system, a rotary tiller was used for land preparation and for the puddling of soil, and a strip planter was used to prepare strips for transplanting rice crop into non-puddled soil (Haque et al., 2016). A harvester of 9 kW was used for harvesting rice. Fuel consumption in terms of litres per hectare by the farm machinery was measured during farming operations and was dependent on area of land, operating width of the machinery (tiller and harvester) and the number of machinery passes across the land (Alam et al., 2016). The EFs of fuel combustion for the usage of light machinery (≤500 kW) were collected from Suh (2004) and these values were used to calculate GHG emissions. The light machinery considered for this experiment is commonly used in the EGP region. The fuel use (litres ha^{-1}) was based on machinery usage in the region (for Versatile Multi-crop

Table 4
Different inputs use for rainfed rice cultivation, their emission factors and sources of data.

Input		Emission factor	Comment/References
Fertilizer			
	Urea-N	5.5 kg CO_2/kg N	Alam et al. (2016)
	TSP-P	0.34 kg CO_2/kg P	Alam et al. (2016)
	MoP–K	0.58 kg CO_2/kg K	Alam et al. (2016)
	Gypsum-S	0.3 kg CO_2/kg S	Wells (2001); Saunders et al. (2006)
Herbicides			
	Glyphosate	33.4 kg CO_2/kg a.i.	Bosch and Kuenen (2009); Brander et al. (2011)
	Refit 50 EC	16.1 kg CO_2/kg a.i.	Bosch and Kuenen (2009); Brander et al. (2011)
Fungicides			
	Amistar 250 EC (Propiconazole)	17.5 kg CO_2/kg a.i.	Lal (2004)
	Tilt 250 EC (Propiconazole)	17.3 kg CO_2/kg a.i.	Lal (2004)
	Rovral 50WP (Ipridione)	16.9 kg CO_2/kg a.i.	DEFRA (2008)
Insecticides			
	Malathion (Organophosphorus)	17.7 kg CO_2/kg a.i.	Alam et al. (2016)
	Sumithion (Organophosphorus)	17.7 kg CO_2/kg a.i.	Alam et al. (2016)
	Wonder 5WG (Emamectin Benzoate)	17.7 kg CO_2/kg a.i.	Alam et al. (2016)
Vehicle	Light-duty diesel truck	2.85 kg CO_2/L	HBEFA (2014)
	Trans-oceanic freighter	14.5 g CO_2/t-nm	Spielman et al. (2007)
Electricity	Electricity Generation	0.64 kg CO_2eq kWh^{-1}	UN–FCCC (2017)
Machinery	Farm machinery production	0.15 kg CO_2eq US$$^{-1}$	Suh (2004)
Fuel	Fuel use (Diesel)	3.1 kg CO_2/L	Lal (2004)


CO2 emissions (kg/tonne of rice)
350
300
250
200
150
100
50
0
b
a
c
b
CTLR
CTHR
NPLR
NPHR
Treatments
CH4 emissions (kg/tonne of rice)
50
40
30
20
10
0
b
a
c
b
CTLR
CTHR
NPLR
NPHR
Treatments
N2O emissions (kg/tonne of rice)
0.2
0.16
0.12
0.08
0.04
0
a
a
b
b
CTLR
CTHR
NPLR
NPHR
Treatments

Planter 1.25, for rotary tiller 3.22 to 3.32 and for harvester 1.82–2.11 $L\,t^{-1}$).

Soil – The major GHGs (CO_2, CH_4 and N_2O) emitted directly from soil of the experimental site were measured as detailed in the GHGs measurement and gas flux calculations section above. The emissions of N_2O that occur indirectly via volatilization of ammonia and leaching of nitrate were excluded from the study owing to lack of data. In addition for this soil, occurrence of a hard pan beneath the plough layer (Islam, 2017) restricts leaching loss of N from the root zone (Patil and Das, 2013) while continuous standing water in the field (Appendix 1) lowers the risk of synthesis of N_2O via denitrification (Dobbie and Smith, 2006).

2.4.3. Impact assessment

A global warming impact value for the 100-year time horizon was used to estimate the CO_2 equivalent GHG emissions for the production of each functional unit (1 tonne) of monsoon rice. The conversion factors used for converting CH_4 and N_2O to the baseline unit, CO_2, were 25 and 298 (IPCC, 2007b). To calculate the total CO_2eq emitted per hectare (kg CO_2eq ha^{-1}), the CO_2eq emissions were summed for the studied rice season covering the period from late June to October. Finally, the net GHGs were calculated by subtracting sequestered C in the monsoon rice season from the total GHGs in order to obtain a net GHG value for production of each unit (one tonne) of monsoon rice. Excel spreadsheet was used to multiply LCI inputs with the corresponding EFs to determine the overall global warming intensity (Engelbrecht et al., 2015).

2.5. Statistical analysis

The effects of soil disturbance for crop establishment and residue return on the CO_2eq emission from pre-farm, on-farm, total and net GHG emissions and on soil sequestered carbon were statistically analysed with a two–factor split plot analysis of variance by using SPSS software v21 (SPSS Inc., Chicago, IL, USA). Least significant difference (LSD) values were calculated to test differences among means at 5% significance level.

3. Results

The study estimated life cycle assessed GHG emissions for rainfed rice crops with and without accounting for soil C sequestration recorded under four practices over five years. The results covered single GHG emissions, overall GHG emissions, the implications of the practices employed on GHGs and their hotspots and processes responsible for major GHG contributions.

3.1. Greenhouse gas emissions under on-farm stage

Non-puddled rice crop establishment regardless of crop residue retention practices reduced on-farm emissions of CO_2, CH_4 and N_2O ($P < 0.05$) under rainfed conditions. The non-puddling practice with low crop residue retention had the lowest emissions of all three important GHGs (CO_2, CH_4 and N_2O). The conventional puddling with increased residue retention practice had 24, 52 and 18% higher CO_2 emission than CTLR, NPLR and NPHR, respectively. The CH_4 emission from soil under CTHR was 31, 56 and 22% higher than emissions from soils under CTLR, NPLR and NPHR, respectively. On the other hand, the CT with LR and HR had similar N_2O emissions ($P > 0.05$), while NP with LR and HR also had similar emission ($P > 0.05$). The CT practice irrespective of the residue retention levels emitted higher amounts of N_2O than in soils under NP with LR and HR ($P < 0.05$) (Fig. 2).

3.2. GHG emission for monsoon rice production under crop establishment and residue return practices

Non-puddling with low and increased residue return (NPLR and NPHR) had a lower carbon footprint than conventional puddling with low and increased residue retention ($p < 0.05$) (Figs. 3, 4 and 5A). Among the studied practices, CTHR led the total GHG emissions for the production of a single tonne of monsoon rice. Non-puddling of rice with low residue retention saved 47 and 20% GHG emissions relative to CTHR and CTLR, respectively, while with NPHR savings were 26% relative to CTHR. Non-puddling with HR and CTLR had similar total GHGs ($p > 0.05$) (Figs. 4 and 5A). However, NPLR reduced CH_4 emissions associated with the aerobic digestion of residues and thereby on–farm emissions. While NPHR outperformed NPLR with regard to yield, total GHG emitted for the production of each tonne of rice in NPHR exceeded that with NPLR. The CTLR and NPHR had statistically similar on–farm emissions of GHGs ($p > 0.05$; Fig. 3). The pre–farm emission in NPHR, CTHR and CTLR was similar ($p > 0.05$) but NPHR had significantly lower emissions than CTLR (17%) ($p < 0.05$) (Fig. 6).

On the whole, the emissions during pre–farm stages represented only 14–22% of the on-farm emissions.

3.3. GHG emissions from pre–farm and on–farm stages

Pre–farm stage: The NPHR had 17%, 11%, 9% lower pre-farm emissions than CTLR, CTHR and NPHR, respectively, due to increased yield compared to the input requirement ($p < 0.05$; Fig. 6). The production of inputs contributed 13%, 11%, 15% and 12% to the net GHG emissions during the pre-farm stage for CTLR, CTHR, NPLR, and NPHR, respectively (Fig. 6). Of all these chemical inputs, pesticides and fertilizer inputs were the main contributors (i.e. > 90%) of pre-farm GHG emissions. Among different activities, the manufacture and transport of inputs (chemicals) to the field claimed the maximum share, respectively. And among the different inputs, fertilizer provision up to field made up the highest portion of the emissions at the pre-farm stage.

On–farm stage: The GHGs emitted from monsoon rice cultivation at the on-farm stage under different practices contributed the major part of total GHG emissions. The NPLR had the lowest proportion of on-farm emissions, followed by CTLR and NPHR, respectively. Due to increased methane emissions, the CTHR had the highest emissions from soils under monsoon rice cultivation. The on-farm stage accounted for 81 and 78%, for CT and NP with LR, while the contributions by CTHR and NPHR amounted to 86 and 84% of the total GHG emitted during monsoon rice production, respectively (Fig. 4). The GHGs emitted by CTLR practice at on-farm stage were not significantly different from NPHR ($p > 0.05$), in spite of keeping decreased residue in the field (Fig. 3). The NPLR had greatest saving for total GHG emissions compared to other tillage and crop residue retention combinations.

3.4. Hotspots of the LCA of monsoon rice

Methane emission from wetland rice fields was the most prevalent GHG measured in the study and accounted for the foremost

Fig. 2. Effect of rice establishment techniques and crop residue retention on the on-farm emission of greenhouse gases ($p < 0.05$). Bars with the same letter above them are not significantly different at $p < 0.05$. SE (±) for CO_2, CH_4 and N_2O emissions are 35.9, 6.60 and 0.041. [Legend: CT - Conventional puddled transplanting of rice; NP – non-puddled transplanting of rice; LR - Low residue retention level; HR - Increased residue retention level].

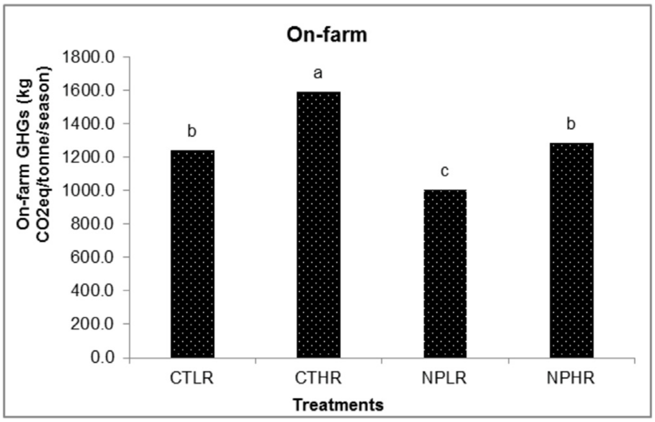


Fig. 3. On-farm life cycle greenhouse gas (GHG) emissions produced per season for one tonne of rice production as influenced by crop establishment techniques and residue retention ($p < 0.05$). Bars with the same letter above them are not significantly different at $p < 0.05$. Comparisons are made among emissions converted to CO_2eq according to global warming potentials of CO_2, CH_4 and N_2O over 100-year time horizons. [Legend: CT–Conventional puddled transplanting of rice; NP–Non-puddled transplanting of rice; LR–Low residue retention level; HR–Increased residue retention level].

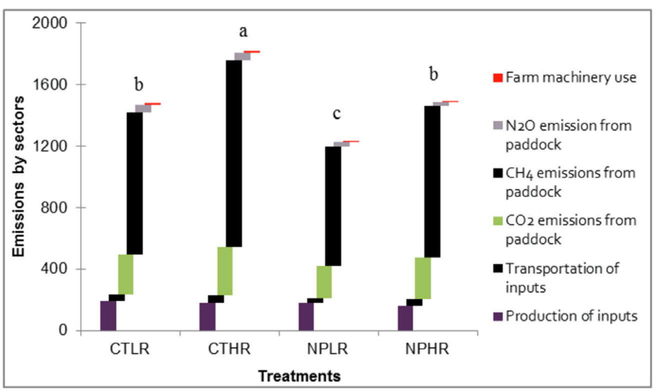


Fig. 4. Greenhouse gas emissions produced by sectors per season for one tonne of rice production as influenced by crop establishment techniques and residue retention ($p < 0.05$). Comparisons are made among emissions converted to CO_2eq according to global warming potentials of CO_2, CH_4 and N_2O over 100-year time horizons. [Legend: CT–Conventional puddled transplanting of rice; NP–Non-puddled transplanting of rice; LR–Low residue retention level; HR–Increased residue retention level]. Columns with the same letter are not different from each other at $P < 0.05$ level of significance.

portion of the total GHG emission (Figs. 3–6). The share of CH_4 was 62–63% for LR, and 66–67% for HR practices. Carbon dioxide emissions from paddy fields (17–18%) followed on-farm CH_4 emission, and were followed by production of inputs (10–15%). Of the total on-farm emissions, CO_2 emissions comprised about 17–21%. The N_2O emissions made up only 2–3% of the total GHGs (Figs. 3–6). The farm machinery used for land preparation and harvesting accounted for the lowest part (0.5–1%) of the GHGs (Fig. 4). Among the total pre-farm emissions, manufacturing inputs and their delivery to rice fields made up about 80 and 20%, respectively.

3.5. Overall GHG emissions

Total GHGs emitted per t of monsoon rice production differed among NPLR, NPHR, CTLR and CTHR practices (Figs. 5 and 6). The total GHG emissions for the system boundary (from both the stages) were 1.48, 1.82, 1.23 and 1.49 tonne CO_2eq t^{-1} monsoon ice production under CTLR, CTHR, NPLR and NPHR, respectively. When increased C storage in soil was included in the accounting, the net GHGs t^{-1} of monsoon rice production were reduced to 1.36, 1.58, 1.04 and 1.18 tonne, respectively. Similarly, when C sequestration was estimated by subtracting all C losses from NPP, the net GHGs t^{-1} of monsoon rice production were 1.69, 1.75, 1.22 and 1.24 tonne CO_2eq.

4. Discussion

The present study examined the performance of the novel non-puddled rice transplanting practice, developed to fit CA in rice-based triple cropping systems in the EGP, in terms of reducing GHG emissions from rainfed wetland rice field while accounting for effect of increased C storage in soil on reducing GHGs. In addition, the hotspots (stages or steps) identified from the rainfed rice LCA were compared with the results from similar studies. A key finding was that inclusion of soil C sequestered by the CA practice was essential to make an accurate estimate of the net GHG emissions.

4.1. GHG emissions from monsoon rice production

Non–puddled soil for monsoon rice establishment with LR and HR had the lowest GHGs over the 100-year time horizon (both total and net) per tonne of monsoon rice produced (Figs. 4 and 5). The decrease relative to current practice (CTLR) can be ascribed to minimal disturbance of soil, relatively higher soil redox potential (Eh), lower standing water depth (Appendix 1), less CO_2 and CH_4 produced (Fig. 2 and Shao et al., 2017) and greater accumulation of SOC (Alam et al., 2018). The total GHG in NPHR exceeded that with NPLR, probably because the effects of extra CH_4 emissions in NPHR exceeded the effects of yield benefits of the practice with the increased residue retention. The NP in the present study deployed minimum soil disturbance, maintained higher Eh values and accordingly, restricted CH_4 synthesis and emissions as also found with irrigated rice (Alam et al., 2016). Crop establishment practices and residue return had varied Eh values which ranged from −200 mV in CTLR to −300 mV in CTHR and −150 mV in NPLR to −250 mV in NPHR (data not presented here). The higher Eh values in non-puddled soils may oxidise CH_4 at an increased rate and reduce its emission by promoting the activities of methane-oxidising bacteria (le Mer and Roger, 2001). The higher total and net GHGs under CTHR and CTLR practices can be attributed to heavy disturbance of soils by tillage followed by puddling of soil which exacerbates the anaerobic conditions and resulted in a lower redox potential of soil (Alam et al., 2016). The anaerobic, saturated rice soil conditions that develop within a few hours after flooding (Bodelier, 2003) favour the increase of methanogenic bacteria numbers and activities and production of by–product CH_4 through the microbial anaerobic respiration. The increased residue incorporation under conventional puddling of soils facilitates the supply of C substrate to methanogens and also stimulates the organisms to grow luxuriantly. Yao et al. (1999) also found that the application of C-rich straw helps methanogens to survive and lowers redox potential in soils. These are the ideal conditions for the organisms to increase CH_4 emission.

Strip planting and non-puddling of soils together with increased crop residue retention over 5 years sequestered more C in soil (Alam et al., 2018). The increase in SOC can be attributed to: surface retention of crop residues of three crops per year as cover and the increase in C addition due to increased biomass production; decreased disturbance of SOM and plant root residue; lower CO_2 emissions and; crop sequences with diverse species producing different residue qualities (Wang et al., 2012). Hence, the lower methane emissions coupled with increased C sequestered in soils are the principle causes for lower GHGs (both total and net) for 1 tonne of rice production under NPLR and NPHR practices (Figs. 4 and 5).

The emissions of monsoon rice during the pre-farm stage were significantly lower than many other studies conducted in rice growing regions of the world. The reasons behind the low emissions in our study were the absence of irrigation due to regular rain throughout the season (Zou et al., 2012), the requirement for lower inputs of chemical inputs (fertilisers, fungicides, insecticides), use of natural gas as the raw material for urea fertilizer production and electricity generation within Bangladesh and light vehicle use for transportation of the inputs to the paddock (Alam et al., 2016). The lowest pre-farm emission per tonne of grain found in NPHR can be attributed to higher grain yield of NPHR. Though CTHR outperforms NPLR in case of rice crop production, the pre-farm emission under the latter practice was lower than the former (Fig. 6). This can be attributed to lower fuel input requirements for NPLR and NPHR practices (Hossen et al., 2018) resulting in lower pre-farm stage emissions of GHG. The emissions of GHG at pre-farm stages of the current study were comparable to those reported by Xu et al. (2013) and Blengini and Busto (2009), but higher than those obtained by Alam et al. (2016) and Thanawong et al. (2014) and Wang et al. (2010). In the case of irrigated *boro* rice (Alam et al., 2016), higher yield of irrigated rice (6.2–6.7 t ha^{-1} versus 4.6 to 5.3 t ha^{-1} in the present study) decreased pre-farm emission per tonne of rice. The yield of rice during the monsoon season in South Asia is low despite the use of carbon-intensive inputs due to low solar radiation. The pre-farm emissions in the present study in the monsoon season were 40–70% higher than the similar study conducted in irrigated season (Alam et al., 2016). Brodt et al. (2014) reported higher rice grain yield (9.3 Mt ha^{-1}) was associated with lower pre-farm emission than the case reported by Wang et al. (2010) which despite a yield of 8.8 Mt ha^{-1} used more than double the inputs. Fusi et al. (2014) in a LCA study found that production of pre-farm inputs mainly fertilisers, deliveries of the inputs to the field and input use per tonne of harvest accounted for 30–40% of the total GHGs. The result of the current study also contrasted with the GHG results of Blengini and Busto (2009) where the pre-farm stage was energy intensive due to the use of heavy duty vehicles for transporting inputs, the use of high levels of fertilisers and pesticides and electricity generation from diesel fuel as the feed–stock which consequently contributed to high emissions.

As the present study was conducted in the monsoon season, the fuel consumption during on-farm activities was limited to land preparation and harvesting. The factors influencing the on-farm GHGs from field crop production include crop establishment practices (Alam et al., 2016), SOC (Duby and Lal, 2009) and N nutrient status (Gupta et al., 2009) and irrigation provision (Tarlera et al., 2016). Kasmaprapruet et al. (2009) found cultivation to be responsible for most of the GWP (almost 95%), while harvesting and seed processing contributed 2% each of a GHG of rice. In the irrigated *boro* rice study by Alam et al. (2016), the GHG emissions from fuel use for irrigating the field and preparing land and harvesting the crop comprised 14–19% of the emissions from the on–farm life cycle stage. That irrigation provision for rice production consumes most energy was also found by Islam et al. (2013). On the contrary, the present study did not require any irrigation application and saved those GHGs. But the present study contrasted with the study by Thanawong et al. (2014) who found almost double the amount of CH_4 emissions with irrigated rice relative to rain-fed rice and hence irrigated rice produced higher emissions at on-farm stage compared to rainfed rice. While the present rice crop was grown in the monsoon (rainy) season and reliant on rainfall only, the on-farm GHG could be substantially increased if periods of low in-season rainfall necessitated the running of an irrigation pump.

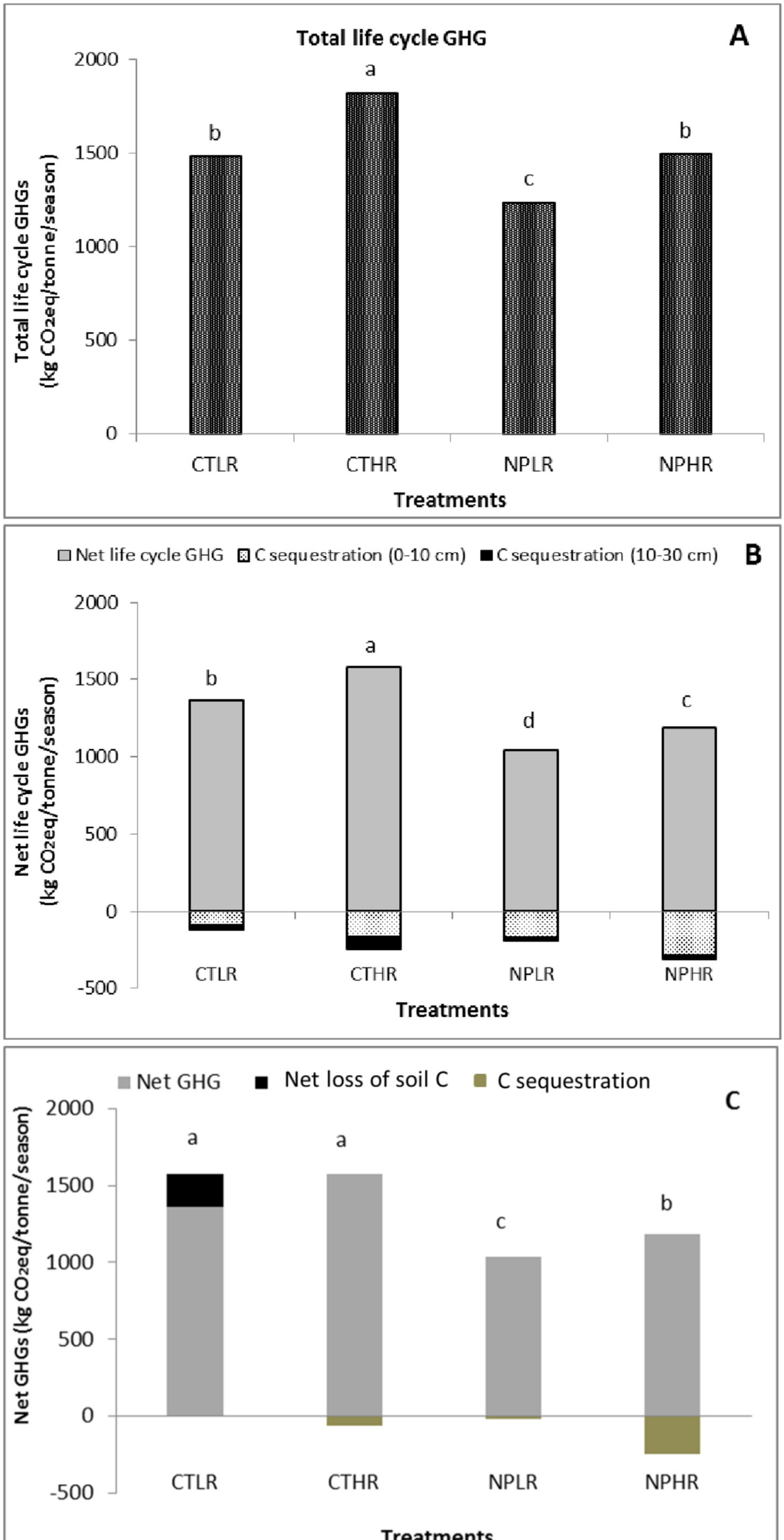
4.2. Identification of hotspots

In the present monsoon paddy rice LCA, the key hot-spots in order of priority were on–farm methane emissions (62.5–66.6%), CO_2 emissions from soils due to heterotopic respiration (16.9–18%), production and transportation of inputs and N_2O emissions from the field (Fig. 4). Alam et al. (2016) and Blengini and Busto (2009) in their LCAs of rice in the EGP-Bangladesh and Italy, respectively, recognised that CH_4 emissions from soil and CO_2eq emissions by farm machinery operations and fertilizer applications during on-farm stage of LCA boundary were the leading hotspots, in that order of priority.

The hotspots which the present study found are similar to the LCA studies conducted for irrigated rice in the EGP (Alam et al., 2016) and for monsoon rice in Indo-Gangetic Plain (Pathak and Wassmann, 2005) where CH_4 contributed around 60% of GHG emission. There is also a body of LCA studies conducted on the cultivation of wetland rice in temperate climates in Japan (Hatcho et al., 2012), in France (Drocourt et al., 2012) and Italy (Bacenetti et al., 2016) that identified CH_4 emission during the on-farm stage as the major GWP contributor. Even though the studies mentioned above identified CH_4 as the main source of GHG, the current assessment had higher total CH_4 emissions relative to other assessments (63–67% of total GHG or 0.93–1.2 tonne CO_2eq per tonne rice production in CTLR and CTHR, respectively; 63% of total GHG or 0.78 tonne CO_2eq in NPLR and 66% of total GHG or 0.99 tonne CO_2eq in NPHR for each tonne rice production). The present study verifies that CH_4 synthesised through the process of organic matter decomposition under anaerobic soil condition occurs in the profile of non-puddled submerged fields as well as in puddled soils, and regardless of retained residue levels. Alternative mitigation options for CH_4 emissions include DSR under conventional tillage (CT-DSR) or zero tillage-DSR under dryland soil condition which have the potential of reducing CH_4 emissions, while favouring CH_4 oxidation, though such soil conditions also increase the emission of N_2O (Liu et al., 2014). In addition, Adviento-Borbe and Linquist (2016) suggested localised fertilizer-N application to reduce both CH_4 and N_2O losses. Therefore, the high net GWP for conventional wetland rice cultivation could be potentially lower with alternative rice establishment practices (Adviento-Borbe and Linquist, 2016) including the non-puddled soil treatment of the present study and Alam et al. (2016). Pesticides and fertilizers comprised the major share of the chemicals because rice crop required these inputs at high rates while chemicals such as urea, TSP, MoP and glyphosate were imported, thus increasing the emissions from transportation (Alam et al., 2016).

4.3. Overall GHG emissions

The net GHGs t^{-1} of monsoon rice varied from 1.36 to 1.69 in CTLR, from 1.58 to 1.75 in CTHR, from 1.04 to 1.22 in NPLR and from 1.18 to 1.24 in NPHR after accounting for sequestered C in soil with either the LCA or C balance approaches, respectively. The total GHGs t^{-1} rice production without taking C sequestration data into account were 1.48, 1.82, 1.23 and 1.49 tonne CO_2eq for the CTLR, CTHR, NPLR and NPHR, respectively (Figs. 5 and 6). The total GHG in the present life cycle study for rice production in the EGP were higher than the study conducted by Alam et al. (2016) who found 1.11–1.19 tonne CO_2eq in NPLR and NPHR and 1.3–1.6 tonne CO_2eq in CTLR and CTHR, respectively, for the production of each tonne irrigated rice, even though they did not account for soil sequestered


Total life cycle GHG
A
Total life cycle GHGs (kg CO2eq/tonne/season)
2000
1500
1000
500
0
a
b
b
c
CTLR
CTHR
NPLR
NPHR
Treatments
Net life cycle GHG
C sequestration (0-10 cm)
C sequestration (10-30 cm)
B
Net life cycle GHGs (kg CO2eq/tonne/season)
2000
1500
1000
500
0
-500
b
a
d
c
CTLR
CTHR
NPLR
NPHR
Treatments
Net GHG
Net loss of soil C
C sequestration
C
Net GHGs (kg CO2eq/tonne/season)
2000
1500
1000
500
0
-500
a
a
c
b
CTLR
CTHR
NPLR
NPHR
Treatments

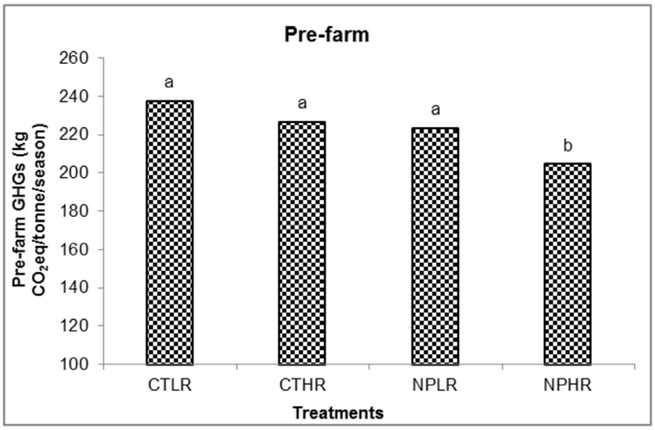


Fig. 6. Pre-farm life cycle greenhouse gas (GHG) emissions produced per season for one tonne of rice production as influenced by crop establishment techniques and residue retention ($p < 0.05$). Bars with the same letter above them are not significantly different at $p < 0.05$. Comparisons are made among emissions converted to CO_2eq according to global warming potentials of CO_2, CH_4 and N_2O over 100-year time horizons. [Legend: CT—Conventional puddled transplanting of rice; NP—Non-puddled transplanting of rice; LR—Low residue retention level; HR—Increased residue retention level].

C. The higher emissions in the present study can be attributed to lower relative yield and continuous submergence of paddy rice soil during monsoon season which caused lower soil redox potential (Takai and Kamura, 1966) and stimulated higher CH_4 emissions (Yu and Chen, 2004). The LCA study of Hokazono et al. (2009) conducted in Japan estimated GHG for 1 tonne of rice production under conventional soil puddling was 1.5 tonne CO_2eq. Farag et al. (2013) found even higher GHGs (1.9 tonne CO_2eq tonne^{-1} rice) with the system boundary up to the farm gate (due to higher CH_4 emission, increased input use especially N and rice straw burning after harvest). Additionally, in the analysis of Ryu et al. (2013), the C footprint t^{-1} rice production under CT practice (puddling) was 2.2 tonne CO_2eq up to the farm gate boundary (due to increased CH_4 emission for continuous flooded condition, increased use of inputs especially N, use of diesel fuel as feedstock). In the current study, the total GHGs (1.48–1.82 tonne CO_2eq tonne^{-1} rice) for the production of rice under puddled transplanting practice were in close proximity to values estimated for rice production under similar practice in other locations and in different climates. As for example, Hokazano and Hayashi (2012) estimated the life cycle GHG up to farmgate to be 1.46, 1.58 and 2.0 tonnes of CO_2eq emission for conventional, environment-friendly and organic rice farming, respectively, while Wang et al. (2010) within the same boundary showed the estimate of GHG of traditional monsoon rice establishment in the rice-wheat system was 1.50 tonnes of CO_2eq t^{-1} of rice. The GHG including milling of paddy rice in the study of Blengini and Busto (2009) in Italy for traditional rice crop establishment was 2.52–2.66 t of CO_2eq t^{-1} of rice. Up to farmgate boundary, the GHG as estimated by Thanawong et al. (2014) in the North East Thailand ranged from 2.97 to 5.55 for tonnes of CO_2eq t^{-1} of rice produced by dry seeding, wet seeding or transplanting (nursery). The comparatively higher emission was attributed to lower yield in spite of using increased amounts of inputs. On the contrary, the studies conducted by Ecoinvent Centre (2008), Brodt et al. (2014) in USA (California) and Bautista and Saito (2015) in Philippines up to farmgate boundary found a lower range of GHGs (from 0.47 to 1.09 tonnes CO_2eq t^{-1} rice) than the GHGs recorded in our present study despite using traditional wetland rice production methods.

4.4. Importance of accounting for soil sequestered C under long-term cropping systems

The majority of LCAs of agricultural products have not accounted for possible changes in soil C sequestration which may occur when new soil and crop management practices are implemented. While agricultural ecosystems can emit C as CO_2 and CH_4 they can also simultaneously sequester C (Zhang et al., 2017). Accounting for SOC sequestration in the present study adds important insights to the LCA for monsoon rice. The amount of SOC sequestration varied with rice cropping system. While monsoon rice is a high CH_4 emitter this can be offset in part by high C sequestration. The net GHG emissions of the current practice of rice crop establishment was similar to that of total GHG of the CA practice, non-puddled transplanting of rice with increased crop residue retention (NPHR) ($p < 0.05$; Fig. 5). However, after accounting for SOC sequestration, the GHG of NPHR was significantly lower than the net GHG of CTLR. The NPHR had 15.5% lower net GHG, while NPLR had 32% lower emissions due to the reduced contribution of CH_4 emission and the C sequestration in soil ($p < 0.05$; Fig. 5). Alam et al. (2016) studied the LCA of irrigated rice production in the EGP under novel non-puddled transplanting of rice relative to traditional rice cultivation without taking soil C sequestration into account. Similarly, Cheng et al. (2011, 2015) used input data from national inventory of agriculture to assess the C footprint of grain crop production but did not include data of SOC sequestration. On the other hand, Goglio et al. (2015) and Petersen et al. (2013) found that accounting for soil sequestered C in a long-term cropping system study is critically important for finding net GHGs for any crop production practices. The present findings support Marble et al. (2011) who proposed that all sectors of agriculture need to examine alternative management practices that can reduce GHG emissions and sequester C without decreasing productivity or profits.

4.5. Further research and practical implications

While there is no evidence that the present results are unreliable, further refinement and enhancement of the LCA could be achieved by follow-up studies. The present study used manual chambers to estimate seasonal fluxes of GHGs. The gas sampling was considered frequent enough to assess GHG emissions in the wetland rice (Harada et al., 2007). However, the use of automated chambers with continuous measurement of GHG emissions is recognised for its accuracy for characterizing temporal variation in GHG fluxes for the LCA study (Butterbach-Bahl et al., 2013). In addition to measurement of GHGs for estimating the LCA of monsoon rice, future refinements of the estimates may include measurements of N losses (via ammonia volatilization and nitrate leaching) (Kasmaprapruet et al., 2009).

While the present study only estimated GHG emissions up to the farmgate boundary, a LCA considering cradle to grave boundary can also be estimated so that the contribution of processing the rice

Fig. 5. Total (A-top) and net GHG (B-middle & C-below) emissions produced per season for one tonne of rice production as influenced by crop establishment techniques and residue retention ($p < 0.05$). Net GHGs were calculated by subtracting the CO_2eq for soil organic carbon sequestered at 0–30 cm of soil during the monsoon rice crop, and by subtracting C sequestration (see Materials and methods for the methods of calculation). Bars with the same lower case or capital letter above them are not significantly different at $p < 0.05$. Comparisons are made among emissions converted to CO_2eq according to global warming potentials of CO_2, CH_4 and N_2O over 100-year time horizons. Legend: See Fig. 4.

and rice foods can be assessed. The LCA up to grave boundary estimates environmental burdens associated with all rice production stages from raw material extraction for inputs and delivering them to paddock, on-farm emissions and activities, post-harvest rice processing through boiling and milling, by-products handling, distribution, cooking and disposal or recycling (ISO 14044, 2006). The emissions associated with fuel use for transport of paddy rice to processing ground, milled rice to market and boiling and milling might be important besides emissions from on-farm stages from soil and fuel use (Roy et al., 2007).

In rice-based systems of the EGP, a range of upland crops are grown in the cool-dry season (from mid-October to middle March). The emissions reported here and by Alam et al. (2016) need to be combined with those for the upland crops to complete LCAs of the cropping systems with diversified crops that are typical of the EGP (Alam et al., 2019).

Conservation agricultural practices have been reported to increase C in soil in some studies (West and Post, 2002; Salahin, 2017; Alam et al., 2018), but not in others (Powlson et al., 2016). Where soil and crop management practices increase sequestered soil C inclusion of the gains in the LCA inventory will improve the LCA tool for determining the net GHG values per functional unit of rainfed rice production. This would enable policy makers to more accurately predict the benefits of CA practices for GWP mitigation. The present study which estimated C footprints of monsoon rice in a rice-based cropping system can inform policy development by Governments in the EGP since wetland rice is the dominant crop in the country and a major contributor to national carbon accounts. The methodology followed for estimating C footprints of rainfed rice production could be used for countries growing rainfed (monsoon) rice and irrigated rice following CA principles. The present results for example suggest that GHG emissions per tonne of rice grain are lower in the *boro* season crop than the monsoon season. By contrast, the irrigation of the *boro* rice crop is depleting groundwater resources in Northwest Bangladesh. Hence, in addition to the simple LCA of rice in the rice-dominant cropping system, there remains scope for conducting other LCAs, namely: attributional LCA which describes the pollution and resource flows within a chosen system attributed to the delivery of a specified amount of the functional unit and; consequential LCA which estimates how pollution and resource flows within a system change in response to a change in output of the functional unit (Thomassen et al., 2008).

5. Conclusions

The C footprint of rainfed wetland rice has been estimated from carbon balances and GHG emissions under non-puddled and puddled establishment practices in a rice-based cropping system in the EGP. Two alternative cropping production systems were identified as cleaner production strategies than the conventional rice production system. The modified production techniques of CA cropping offer environmental benefits by saving fuels, improving productivity and reducing GHG emissions. Non-puddling for rice establishment with low or high crop residue inputs offers significant GHG savings on both pre-farm and on-farm stages of monsoon rice production (NPLR saved 47 and 20% on-farm GHG emission, respectively, over CTHR and CTLR while NPHR had 17% lower pre-farm emission than CTLR), relative to conventional methods of rice crop establishment in the EGP. The shrinking of the carbon footprint under CA practices for rainfed rice production compared to conventional tillage can be attributed to increased soil C sequestration and reduced CH_4 emissions due to straw retention at soil surface and minimum soil disturbance. The non-puddled transplanting of rice with low residue return was the best option for the mitigation of total GHGs and for net GHGs. The CTLR and CTHR accounted for 1.3 and 1.7 tonne net GHGs. The savings of net GHGs with the best mitigation practices, NPLR and NPHR, were 0.54 and 0.39 t emissions t^{-1} of rice production relative to CTHR and CTLR, respectively.

The on–farm stage had high emission of agricultural GHGs from soil and from use of on-farm machineries and accordingly, contributed 78% (NPLR) to 86% (CTHR) of the total GHG emissions. Irrespective of tillage and crop residue return practices, CH_4 emission was the most prevalent GHG from the on-farm stage for 1 tonne of monsoon rice production under anaerobic soil conditions in the EGP. Relative to the previous studies estimating CH_4 to contribute 40%-60% to the GHG of rice production up to farmgate boundary, the values in the current analysis are higher (62.5–66.6%). Emission of CO_2 from soil was the second highest contributor to GHGs of monsoon rice production.

The exclusion of soil C sequestration overestimated the GHG emissions by 16% for non-puddling with increased residue retention and by 32% with non-puddling with low residue retention relative to their total GHG emphasising the necessity of accounting for soil organic C sequestration in LCA analysis.

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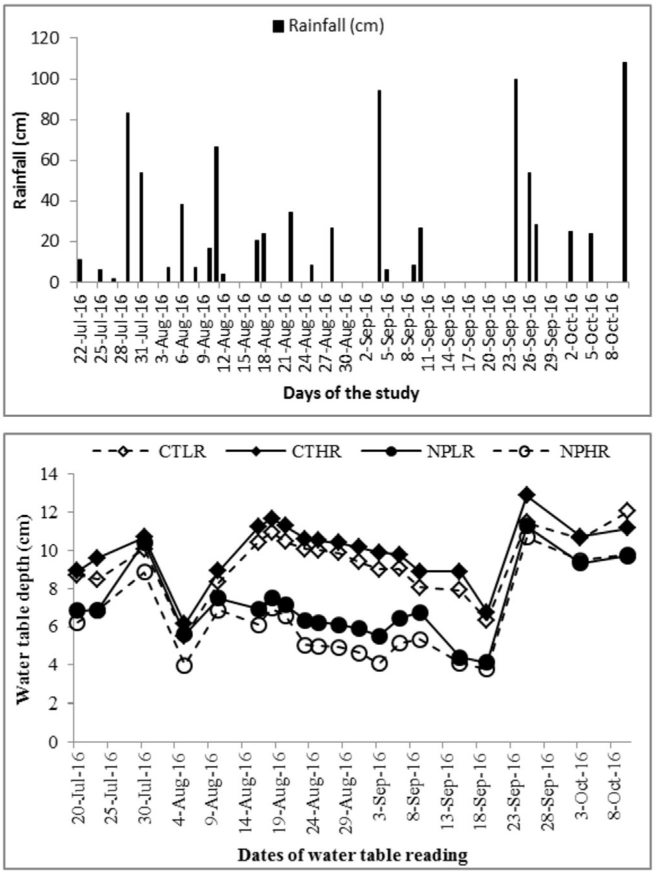
Appendix 1. Rainfall and standing water level in field

The rainfall was evenly distributed over the monsoon growing season. From the day of sowing to 31 July, the amount of rainwater was 155.5 cm, in the next month (August) it was 252.8 cm, in September, the rainfall was 317.4 cm. For the first ten days of October, the rainfall was 157 cm. From 11 September to 23 September was the longest period without rain fall (Appendix 1). The depths of standing water in the field under all treatments reflected the rainfall patterns and distribution, though the water depths were consistently higher with CTLR and CTHR. For example, in July, the water depth with CT was 9.5 cm and 8.5 cm with NP. In August, the CT soils had 9.8 cm and NP had 6.1 cm of standing water (Appendix 1). With the increase in intensity of rainfall, the water table depth increased at the end of the study in October (Appendix 1).



Appendix 1. Rainfall distribution over the season of monsoon rice at Alipur (top); the depth of standing water in field during the monsoon rice growing season (bottom). [CT=Conventional puddling, NP=Non-puddling of rice following strip planting; LR = farmers' practice and HR=Increased residue retention].

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