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Minimal soil disturbance and increased residue retention increase soil carbon in rice-based cropping systems on the Eastern Gangetic Plain

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ABSTRACT

The adoption of conservation agriculture (CA) in the intensive triple-cropping, rice-based systems of the Eastern Gangetic Plain (EGP) alters the dynamics of carbon (C) in the soil, but the nature of these changes is poorly understood. Our aim was to determine whether CA in these systems involving non-puddled transplanting of wetland rice and strip planting of dryland crops plus increased residue retention would increase the C storage in soils relative to conventional crop establishment practices. Long-term field experiments were studied in two locations of northwestern Bangladesh to determine C turnover as well as examining C cycling under three levels of soil disturbance (conventional tillage (CT), strip planting (SP) and bed planting (BP)) in combination with low residue (straw) retention (LR, the current practice) and increased residue retention (HR) in Calcareous Brown Floodplain soil (Alipur) and Grey Terrace soil (Digram). The total nitrogen (N), organic C, microbial biomass C (MBC) and water-soluble C (WSC) values were measured in soil samples from 0 to 10 cm depth collected at different stages during the growth of the 13th and 14th crops at Alipur and the 12th and 13th crops at Digram since the treatments commenced. At each location, SP and BP with either LR or HR retained more soil organic C (0–10 cm) from C inputs than CT with HR and LR. In general, the CO_2 emissions relative to the stored soil organic C in the soils (0–10 cm) under SP with LR and HR were approximately 13 to 59% lower than those under CT and BP with LR and HR. The higher levels of C mineralization were associated with higher WSC contents in the soil. In contrast, the MBC contents in the HR treatments followed the order SPHR > BPHR > CTHR. Similarly, in SPLR and SPHR, the potentially mineralizable C (PMC) was higher, while the decay rate constant was lower. Increased residue retention with minimal soil disturbance practices (SP and non-puddled transplanting) after 14 crops at Alipur and 13 crops at Digram modified the C cycle by decreasing C emissions and increasing the levels of total organic C in the soil. The application of both minimal soil disturbance and increased residue retention enhanced soil organic C (0–10 cm) concentrations in the two soils under intensive rice-based cropping systems on the EGP.

1. Introduction

The FAO (2009) estimated that a 40% increase in rice production is needed by the end of 2030 to satisfy the rising demand from a growing population, but the land area for production is predicted to increase by only 14%. Hence, while increased grain yield is required to supply the increased demand for rice, traditional practices, such as soil puddling for wetland rice establishment and intensive soil disturbance in rice-upland cropping systems, have resulted in declining soil fertility and low levels of soil organic C (SOC; Kirk and Olk, 2000; Sahrawat, 2005; Zhou et al., 2014). In addition, rice production in wetland soils accounts for 55% of the global agricultural greenhouse gas emissions (IPCC, 2013). Production systems such as conservation agriculture (CA) may serve to increase the rice yield while also improving soil fertility and SOC status and mitigates the effects of rice-based cropping systems on climate change (Alam et al., 2016a; Haque et al., 2016; Powlson et al., 2016).

One of the important areas of intensive rice-based cropping is the EGP, which is characterized by wetland rice (*Oryza sativa*L.) rotated with upland crops. This rotation results in short fallow periods and periodic drying-wetting of the soils between crops. Adoption of CA practices by growers in the intensive rice-based triple-cropping systems

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on the EGP is increasing (Haque et al., 2016; Taneja et al., 2014). A novel rice establishment practice called non-puddled transplanting (NP) has been developed to accommodate CA requirements in rice-based cropping on the EGP (Alam et al., 2016a; Haque et al., 2016). With NP practice, narrow strips (2–4 cm wide) are tilled to 4–5 cm depth while preserving about 80% of untilled soil. A locally-made attachment to 2-wheel rotary–tiller is used after irrigation or seasonal rain-fall to prepare strips so that transplanting can be performed without puddling soil; or the land is kept fully undisturbed until the surface soil is soft enough to transplant the rice seedling in untilled and non-puddled conditions. The CA practice involving minimal soil disturbance and the retention of more residues will alter the dynamics of C in the soil on the EGP, but the nature of these changes is poorly understood.

Carbon accumulation appears to decline over time in most rice-upland crop systems, such as rice-wheat systems (Witt et al., 2000). For paddy-upland crop rotations, the decreased amount of C stored in the soil was attributed to high doses of chemical fertilizers, excessive disturbance of the soil and removal/burning of residues in the fields (see Zhou et al., 2014). Kirk and Olk (2000) found that the decomposition of residues and the mineralization rates of residues and native soil organic matter (SOM) are considerably retarded under submerged soil conditions relative to aerobic (upland) conditions. On the other hand, the process of drying and rewetting of soils controls the decomposition of the retained residues and consequently modifies the C and N dynamics in rice-based intensive cropping systems (Kirk and Olk, 2000). Microbial activity increases during drying and rewetting cycles of soils, resulting in increased SOM decomposition (Orchard and Cook, 1983). Moreover, whatever benefits of C sequestration may accrue by following CA in upland cropping will be destroyed by puddling for wetland rice cropping (Sapkota et al., 2017).

Crop establishment practices and residue management are important factors in C cycling in complex paddy rice-upland rotations (Kirk and Olk, 2000; Zhou et al., 2014). With conventional tillage (CT), crop residues are incorporated into the soil which accelerates C mineralization, and as soil is disturbed heavily by the practice, it exposes the C associated with macro–aggregates to greater decomposition by microorganisms (Six et al., 2000), whereas with minimal soil disturbance, crop residues remain at the soil surface (Curtin et al., 2008), standing or lying, and are less susceptible to microbial breakdown (Verhulst et al., 2013). However, the individual and collective effects of minimal soil disturbance and increased residue retention on the C dynamics and C cycling in rice-based cropping systems on the EGP are not well understood (Sisti et al., 2004).

The chosen crop sequence determines the type and amount of residue added to the soil (Alam et al., 2016b). Crop rotation (Baldock, 2007), residue retention, (Franzluebbers et al., 1994) and soil disturbance associated with tillage (Zhou et al., 2014) alter the C dynamics, which are important in the sequestration of C and N (Balota et al., 2004). Larson et al. (1972) reviewed evidence from laboratory and field studies and suggested that the decomposition rates of plant material added to soil are proportional to the amount added and time of application. Generally, small amounts of crop residues decompose more rapidly than large amounts (Novak, 1974). Current cropping systems on the EGP retain limited amounts of crop residue (Alam et al., 2016a); hence, it is important to assess the impact of increased residue retention on SOC when CA practices are adopted.

Due to the complexity of the soil C cycle, models can be an effective approach for predicting the likely consequences of changes in agricultural land use. The potentially mineralizable C (PMC) in soil is considered the standard measure of the soil mineralizable C (Murwira et al., 1990; Stanford and Smith, 1972). The size of this pool is usually estimated, along with mineralization rate constant, from long-term incubation experiments using kinetic models that fit the increase in cumulative soil C and soil inorganic N release with time (Griffin, 2008). Among the wide variety of kinetic models, the first-order model (Raiesi, 2006) and the parallel first- and zero-order kinetic models (e.g., Van Kessel et al., 2000) are the most commonly used. The parallel first- and zero-order kinetic models assume that the SOM consists of an easily mineralizable pool of C that is mineralized exponentially according to first-order kinetics and a more resistant fraction that is not depleted significantly during a short incubation period. Few modeling studies have examined the differences in C cycling rates between field conditions characterized by minimal soil disturbance with upland crops and non-puddled transplanting of rice crops and those characterized by conventional practices with heavy soil disturbance (Raiesi, 2006; Mulvaney et al., 2010). The main objective of this study was, therefore, to determine the effect of crop establishment with minimal soil disturbance and increased residue retention on C storage in soils and to understand the C dynamics in soils under CA practices for rice and upland crops in rice-upland crop rotations.

2. Materials and methods

2.1. Study site and experimental design

The long-term effects of SP or BP along with two levels of residue retention on C dynamics were studied in northwestern Bangladesh at two locations (Alipur village, Durgapur upazila, Rajshahi division in the agro-ecological zone known as the Level Barind Tract (LBT) and Digram village, Godagari upazila, Rajshahi division in the agro-ecological zone known as the High Barind Tract (HBT)) (FRG, 2012). The experimental sites are located at about 24°28′ N north latitude and 88°46′ east longitude. The LBT and HBT regions feature low (relative to other parts of Bangladesh), unevenly distributed annual rainfall amounts (1370 ± 323 mm) that vary widely from year to year and large temperature ranges (maximum: 42.9 °C in June 2014; minimum: 6.2 °C in January 2014). The texture class of the experimental soil (measured by hydrometer method; Black, 1965) of Alipur was silt loam (24% sand, 53% silt and 23% clay), and the bulk density ranged from 1.38 g cm^{-3}in strip planting (SP) with increased residue retention (HR) to 1.49 g cm^{-3} in conventional tillage (CT) with low residue retention (LR). The texture class of the experimental soil of Digram was silt clay loam (26% sand, 46% silt and 29% clay), and the bulk density ranged from 1.40 g cm^{-3}in SP with HR to 1.52 g cm^{-3}in CT with LR. The soils were slightly acidic and were categorized as Calcareous Brown Floodplain (*Aeric Eutrochrept*; USDA soil classification system; USDA-SCS, 1975) and Grey Terrace soils (*Aeric Albaquepts*; USDA-SCS, 1975) at Alipur and Digram, respectively. The Alipur site was moderately well drained (water can drain gradually after heavy rainfall or seasonal inundation) and the Digram site was very well drained, as it was located above the flood level (SRDI, 2005).

The field study in 2014 examined three soil disturbance practices (CT, SP or NP and bed planting (BP/NP)) and two residue retention levels (increased residue retention, HR, and low residue retention, LR) in four replicates of the treatments (Table 1) in an experiment established in 2010 (Islam, 2016). At Alipur, main plot size was 7.5 m long × 14 m wide and sub-plot was 7.5 m long × 7 m. wide and; the main plot was 8.5 m long × 14 m wide and sub-plot was 8.5 m long × 7 m wide at Digram. For stip planting, 2–4 cm (wide) × 4–5 cm (depth) area was mechanically tilled leaving the inter-row or soil management zone undisturbed and protected by residue cover, while raised beds (BP) were formed by moving soil laterally from the furrows to form a raised. In the BP, the furrow facilitated irrigation, drainage and wheel traffic. Once developed, the bed was not destroyed or displaced but it was renovated each season. Conventional tillage practice involved disturbing soil by 2-wheel rotary tillage up to 10–12 cm depth followed by levelling or a further rotary tillage operation to pulverize or level soil, while puddling of soil was done by several wet tillage operations followed by leveling. For CT. the seeds of non-rice crops were broadcasted for sowing before the final land leveling operation.

The experimental design, followed for the previous 14 crops (three crops per year since 2010) at Alipur and 13 crops at Digram, used a

Table 1
The present study involves the following field treatments at the Alipur and Digram sites.

Crops and Location	Soil management	Residue management
Mustard (13[a]) (Alipur)	● Conventional tillage (CT) ● Strip tillage (SP) ● Bed Planting (BP)	● Low residue retention (LR) ● Increased residue retention (HR)
Irrigated rice (14[a]) (Alipur)	● Conventional puddling (CT) ● Non-puddling (NP) followed by SP ● Non-puddling (NP) followed by BP	● LR ● HR
Wheat (12[a]) (Digram)	● CT ● SP ● BP	● LR ● HR
Jute (13[a]) (Digram)	● CT ● SP ● BP	● LR ● HR

[a] The number indicates the crop number of the cropping systems followed in the experimental fields.

split-plot layout in which the soil disturbance practices were assigned to the main plots and residue retention levels to the subplots. The LR treatment in the current study, which approximated the current farming practice in this region, involved retaining approximately 20% (by height) of the standing rice crop residue in the field after harvesting the crops. The HR treatment retained approximately 50% by height of the standing rice residue after harvesting. The same residue retention levels were followed for wheat crops at Digram. For the previous lentil, mung bean and mustard crops in the rotation at Alipur (followed for up to 9 crops) and the previous jute and chickpea crops at Digram (for up to 7 crops), the LR treatment involved complete removal, whereas the HR treatment returned all crop residues to the plot. The cereal residues were left standing under SP and BP, while they were incorporated into soil under CT practice. The cropping sequence followed for the first three years at Alipur was lentil (Lens culinaris L.)–mung bean (Vigna radiata L.)–rainfed monsoon rice. At Digram, the rotation involved wheat–jute–monsoon rice up to 2012, then chickpea–jute–monsoon for 2013-14. In 2014-15 at Alipur, the monsoon rice was followed by mustard (Brassica campestris L.) then dry-season irrigated rice. In 2014-15 at Digram, the monsoon rice was followed by wheat then jute. Pesticides and the recommended dose of fertilizers were applied to all the crops at rates typical of the local farming practices. The fertilizer dose for mustard was 85 (HR)-90 (LR), 21, 64, 20, 4 and 1.5 kg ha^{-1} N, P, K, S, Zn and B, respectively; fertilizer dose for irrigated rice 115 kg (HR)-125 (HR), 53, 81, 11, 3 and 2.5 kg ha^{-1} N, P, K, S, Zn and B, respectively; for wheat 110 (LR)-120 (HR), 26, 50, 20, 1.5 and 1.5 kg ha^{-1} N, P, K, S, Zn and B, respectively; and for jute 35(LR)-40(HR), 8, 20, 8, and 1 kg ha^{-1} N, P, K, S and Zn, respectively.

2.2. Soil sampling and parameters determined

Soil samples were collected from the field experiments between November 2014 and June 2015 by means of a push-type auger (2.5 cm diam.). For the soil sampling, three quadrats from each subplot were pre-marked, from which all soil samples were collected. As the tillage practices did not disturb soils more than 10 cm by depth, the soil sampling was done only up to 10 cm depth. The sampling was done at 1, 15, 30, 45, 60, 75, 90 and 100 days after sowing (DAS) for mustard; at 1, 15, 30, 45, 60, 75, 90 and 100 days after transplanting (DAT) for rice; at 1, 15, 30, 45, 60, 75, 90, 105 and 120 DAS for wheat, and at 1, 15, 25, 40, 55, 70, 85 and 95 DAS for jute. These samples were kept separate for individual extraction. The field-moist soil was then quickly cleaned of leaves, roots, weeds, decayed branches, etc. and immediately extracted according to the methods described below and then filtered for collection of extracts. For each sample, 15 g of soil was also used for moisture content measurement. All measurements (bulk density, particle density, soil moisture, water soluble C, SOC, pH, total N and microbial biomass C) were carried out in triplicate.

2.3. Temperature data collection

Air and soil temperature data were collected using automated temperature sensors (Maxim's i-Button sensors recording temperature with accuracy; $< \pm 0.5$ °C; Haight, 2009) placed at a height of 60 cm and at a soil depth of 4–5 cm, respectively. All sensors were set to record instantaneous values of temperature every 6 h, starting at midnight each day. All air temperature sensors were positioned under shallow polystyrene lids and covered with aluminum foil so that they were protected from direct solar radiation. Similarly, the sensors set in the soil were placed in waterproof polyethylene bags.

2.4. CO_2 and CH_4 measurements

Three inverted circular chambers of known volume (100 cm height × 20 cm diameter) were established in each plot. Vials containing 35 ml of 0.5 M NaOH were used to trap evolved CO_2, and these vials were replaced every 2–3 days for up to 15 days after establishment. After this period, the rate of CO_2 evolution decreased, and the amount and concentration of NaOH were reduced to 30 ml of 0.25 M and the vials were replaced every 5–7 days. The trapped CO_2 was measured via the $BaCl_2$ method (Anderson, 1982). The CO_2 in the control treatment (a vial containing 35 ml of 0.5 M NaOH placed in an inverted chamber without soil) was subtracted from the calculated amount of CO_2 released under each practice (treatment).

To measure CH_4 in the paddy field, transparent chambers (dimensions: 60 cm length × 30 cm width × 100 cm height) constructed from 5 mm thick acrylic sheets, were placed over six plants (Alam et al., 2016a). To allow pressure adjustments in the chamber during chamber set-up and gas sampling, a lightweight plastic bag was fixed inside. A digital electronic thermometer was attached inside the chamber within a silicon cork. Samples were collected from 10:00–16:00 h on every sampling day according to the life cycle of the crop. Two samples for CH_4 emission from each chamber were taken; one at the time of chamber placement and the other one after an interval of 10 min, 30 min or 1 h). The samples were triplicated. Samples were collected using a 50 ml polypropylene syringe at 0 and 60 min after sealing the chamber. The syringe was made airtight with a three-way stopcock, and gas was transferred into a 35 ml bottle and, when required, transferred into a 400 ml Tedlar bag through a silicon tube attached to the top of the chamber. The gas samples were analyzed for CH_4 using gas chromatography with a hydrogen flame ionized detector (Alam et al., 2016a). The CH_4 flux was calculated using the equation of Yagi and Miami (1993).

2.5. Description of models used

A simple model was used to predict the rate of C changes in the soil (Stevenson, 1982):

$$C_t = Co\ (1 - e^{-kt}) \tag{1}$$

where k is the decomposition (decay rate) constant (mg C [g C]$^{-1}$ day^{-1}), Co is the potentially mineralizable C, a measure of easily decomposable C (PMC; mg C g^{-1} C), and C_t is the carbon mineralized after time t (days). The model was run in SPSS (software package version 21).

2.6. Soil and crop residue analysis

The methods of Jahan et al. (2014) and Goering and Van Soest (1970) were used to analyze cellulose (Ce), hemicellulose and lignin (Li) in mustard, rice, wheat and jute straw. The total C and N values in

Table 2
Dry weight of residues added according to treatment for different crops of the rotations at Alipur (Monsoon rice-12th crop; Mustard-13th crop; Irrigated dry season rice-14th crop) and Digram (Monsoon rice-11th crop; Wheat-12th crop; Jute-13th crop). Values represent the mean of four replicates for each crop.

Treatments/crops	CTLR	CTHR	SPLR	SPHR	BPLR	BPHR	$LSD_{0.05}$ (tillage × residue retention)
Low Barind Tract (Alipur, Rajshahi)							
Monsoon rice ($t\ ha^{-1}$)	1.28	2.21	1.39	2.43	1.29	2.61	0.37**
Mustard ($t\ ha^{-1}$)	0.48	1.24	0.53	1.45	0.55	1.48	0.13**
Irrigated rice ($t\ ha^{-1}$)	1.41	2.70	1.38	2.65	1.50	2.86	0.39**
High Barind Tract (Digram, Rajshahi)							
Monsoon rice ($t\ ha^{-1}$)	0.95	2.02	1.17	1.84	1.20	2.14	0.40*
Wheat ($t\ ha^{-1}$)	0.92	1.63	1.02	1.64	0.91	1.36	0.32*
Jute (leaf litter) ($t\ ha^{-1}$)	1.87	2.35	1.96	2.35	1.81	2.33	0.14**

Legend: BP – bed planting, CT – conventional tillage, and SP – strip planting; HR – high residue retention and LR – low residue retention.

plants were determined using a CHNS analyzer (Shimadzu, Japan). The element P content was determined using the molybdate blue ascorbic acid method by spectrophotometry (Olsen and Sommers, 1982), while K was determined from the digest made with a 2:1 HNO_3: $HClO_4$ mixture directly by atomic absorption spectrophotometer at 766.5 ηm wavelength (Model No. VARIAN SpectrAA 55B, Australia). The bulk density (BD) and particle density were measured according to Karim et al. (1988) and were used to calculate porosity (Alam et al., 2016b). Soil moisture content was measured by the gravimetric method (Black, 1965). Bulk density was measured by the core sampler method, with a 5 cm long and 2.8 cm radius core; three samples from each subplot were randomly collected; then the samples for each 5 cm depth taken one below the other (Karim et al., 1988). The total organic carbon (TOC) content was calculated from the OC concentration which was determined by the wet oxidation method (Jackson, 1973). Total organic carbon (TOC) stock was determined following Eq. (2)

$$\text{TOC}\ (t\ ha^{-1}) = 10,000\ m^2\ \text{in}\ (1\ ha) \times \text{soil depth} \times \text{BD} \times \text{OC} \quad (2)$$

where BD is the bulk density in $g\ cm^{-3}$ and OC is the percentage of organic C (Ellert and Bettany, 1995). The BD values presented in Tables 5 and 6 were used to compute C stocks.

Water-soluble C (WSC) was extracted following the methods of Tirol-Padre and Ladha (2004) and measured via the Walkley and Black wet oxidation method (Walkley and Black, 1934). The correction factor for WSC calculation was 60%, in line with conversion factors for top soil (Tivet et al., 2012). Microbial biomass C (MBC) was determined via the chloroform fumigation–incubation method (Jenkinson and Powlson, 1976).

2.7. Crop residues retained in the fields

The total amounts of residues added during one year in the SPHR, SPLR, BPHR, BPLR, CTHR and CTLR treatments were 6.15, 3.3, 6.95, 3.34, 6.15, 3.17 $t\ ha^{-1}$, respectively, at Alipur and 5.83, 4.15, 5.83, 3.92, 6.0 and 3.74 $t\ ha^{-1}$, respectively, at Digram (Table 2).

2.8. Statistical analysis

The effects of soil disturbance (SP, BP, and CT) and residue retention (LR and HR) on BD, total N (TN), total C (TC), MBC, Ce, Li, Ce/Li, Li/TN, Ce/TN, (Ce + Li)/TN, TC/TN, WSC, cumulative C emission, PMC and C mineralization rates were analyzed via a two-factor analysis of variance using a split-plot model. All data were statistically assessed with the SPSS software package version 21 (SPSS Inc., Chicago, IL, USA). The tests of normality of the parameters in the manuscript were also done with SPSS software and all were normally distributed. Means were compared using least significant difference (LSD) at $p < 0.05$.

3. Results

3.1. Growing season conditions

During the experimental years, April and January were the warmest and coldest months, respectively. In general, maximum temperatures at Alipur and Digram range from 15 to 38 °C and from 17 to 39 °C, respectively. The minimum temperatures at Alipur and Digram were 9.5 and 10 °C, respectively. Very little rain fell in November, December and January. The rainfall was below average in February, March and April 2015 but was above average in May and June at both sites. The rainfall in April and May was the highest (Table 3). The temperatures and rainfall were comparable to the long-term averages for the High Barind Tract agro-ecological zone (AEZ) and the Level Barind Tract, AEZ. The long-term mean annual rainfall is 1285 mm in the south of the High Barind Tract, whereas the level Barind Tract has the minimum rainfall 700 mm and the maximum rainfall 1450 mm.

At Alipur, the mustard crop was irrigated twice, and the boro rice was irrigated 10 times. At Digram, the wheat was irrigated three times, and the jute was irrigated only once. More rain fell during the early monsoon period (mid-March to May; > 501 mm at Alipur and 443 mm at Digram) than during the winter (November to mid-March; < 118 mm at Alipur and 85 mm at Digram). Solar radiation was highest during the months of April (21.2 and 21.8 $MJ\ m^{-2}$ at Alipur and Durgapur, respectively) and May (21.5 $MJ\ m^{-2}$ and 22.6 $MJ\ m^{-2}$ at Alipur and Durgapur, respectively) which were followed by March and June. The relative humidity recorded during the experimental duration (November 2014- June 2015) ranged from 64.7% in March to 85.7% in June and 64.6% in March to 85.6% in June at Alipur and Digram, respectively (Table 3).

Table 3
Mean monthly climatic variables at the Level Barind Tract (Alipur) and High Barind Tract (Digram) experimental areas in.2014–2015.

Month of the year	Solar radiation ($MJ\ m^{-2}$)		Precipitation (mm)		Relative humidity (%)	
	Alipur	Digram	Alipur	Digram	Alipur	Digram
November	14.6	14.9	25.6	24.0	80.8	80.7
December	11.8	12.6	6.0	4.0	80.1	79.9
January	13.1	13.8	17.6	11.9	79.1	78.9
February	16.8	17.2	35.0	16.8	73.0	72.9
March	19.1	19.5	33.8	28.3	64.7	64.6
April	21.2	21.8	50.2	41.4	67.6	67.4
May	21.5	22.6	215.0	171.5	77.0	76.8
June	18.1	18.6	236.0	230.3	85.7	85.6

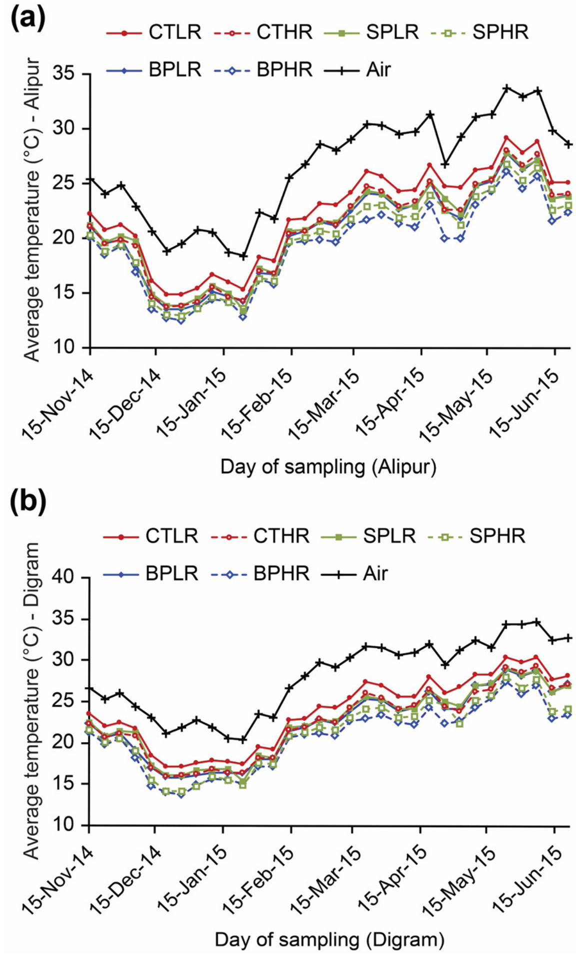

Fig. 1. Air and soil temperature of Alipur-(a) and Digram-(b) recorded at a height of 60 cm in the air and at a soil depth of 4–5 cm, respectively. [Legends: BP – bed planting, CT – conventional tillage, and SP – strip planting; HR – increased residue retention and LR – farmers' practice].

The maximum, minimum and mean soil temperatures recorded at a soil depth of 4 cm at both the Alipur and Digram sites were different among all treatments throughout the experiment. The temperatures were highest and lowest in the CTLR and BPHR treatments, respectively (Fig. 1a, b). At both sites, CTLR had soil temperatures that were 2.5–4.6 °C higher than those of all other treatments throughout the growing seasons. Both SPLR and SPHR exhibited higher minimum, maximum and mean soil temperatures than the respective BPLR and BPHR treatments during the growing seasons in both the experimental seasons (Fig. 1a, b). Soil under mustard and boro rice had a lower mean temperature than soil under wheat and jute crops. The difference between air and soil temperatures under jute crops was lower than that under wheat crops. Like air temperatures, the soil temperatures were lower in winter than in summer.

3.2. *Crop residues retained in the fields*

At Alipur, rice residues comprised 85, 80, 84, 78, 84 and 79% of the all residues retained in the CTLR, CTHR, SPLR, SPHR, BPLR and BPHR treatments, respectively. At Digram, non-rice residues represented the major fraction of the retained residues, accounting for 75, 66, 72, 68, 69 and 63% of the total residues in the CTLR, CTHR, SPLR, SPHR, BPLR and BPHR treatments, respectively. For monsoon rice, the increases in retained residues at Alipur and Digram were 1.04 and 0.67 t ha^{-1}, respectively, for SPHR, 1.32 and 0.94 t ha^{-1}, respectively, for BPHR and 0.93 and 1.07 t ha^{-1}, respectively, for CTHR relative to corresponding values for SPLR, BPLR and CTLR (Table 2). The mustard plots at Alipur and the wheat plots at Digram retained 0.92 and 0.62 t ha^{-1} more crop residues under SPHR, respectively, 0.93 and 0.45 t ha^{-1} more crop residues under BPHR, respectively, and 0.76 and 0.71 t ha^{-1} more crop residues under CTHR, respectively, than under the corresponding LR treatments. The BP with HR treatment, followed by SPHR, had the highest total retained residue values at both sites (Table 2).

3.3. *Chemical characteristics of the added residues*

The TC values were significantly higher in rice residue (486 g kg^{-1}) than in mustard residue (428 g kg^{-1}) (Table 4). The rice residue also

Table 4
Chemical composition of residues of different crops of the cropping systems at the Alipur and Digram sites of Rajshahi, Bangladesh.

Characteristics and crops	Location							
	Alipur, Durgapur, Rajshahi (LBT)				Digram, Godagari, Rajshahi (HBT)			
	Rice (straw)	Mustard (straw)	Irrigated Rice (straw)	*P*	Rice (straw)	Wheat (straw)	Jute (leaves and roots)	*P*
Cellulose (Ce, g kg^{-1})	576 (56)	434 (28)	587 (67)	***	581 (67)	391 (12)	343 (13)	*
Lignin (Li, g kg^{-1})	66 (7)	215 (19)	63 (6)	***	65 (6)	187 (15)	175 (8)	**
Total carbon (TC, g kg^{-1})	471 (14)	428 (28)	486 (16)	*	470 (16)	528 (18)	532 (14)	ns
Total nitrogen (TN, g kg^{-1})	5 (0.3)	9.1 (0.8)	4.9 (0.3)	***	4.7 (0.3)	7.4 (0.3)	14 (0.7)	***
Ce/Li	8.73 (0.6)	2.02 (0.4)	9.32 (0.95)	***	8.93 (0.8)	2.1 (0.3)	1.96 (0.2)	***
Li/TN	13.2 (1.4)	23.6 (2.9)	12.8 (0.9)	**	13.8 (0.5)	25.3 (1.4)	12.5 (0.8)	**
Ce/TN	115 (5.3)	47.7 (2.3)	120 (4.3)	***	124 (6.9)	52.8 (2.8)	24.5 (1.6)	***
(Ce + Li)/TN	128 (5.2)	71.3 (4.1)	133 (6.1)	**	137 (5.8)	78.1 (3.9)	37 (2.0)	***
TC/TN	94.2 (7.5)	47.01 (4.6)	99.2 (8.2)	***	100 (4.1)	71.3 (4.3)	38 (2.9)	**

ns, not significant. Each value represents a mean (n = 4), Standard Error of Mean ((S.E.M (±)) are included in parentheses.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

Table 5
Selected characteristics of the 0–10 cm soil layer of the studied area at Alipur after five years of varied soil disturbance practices and residue retention. Values are means of four replicates.

Treatments	Characteristics					
	Bulk density ($g\ cm^{-3}$)	Porosity (%)	pH (H_2O)	Total N ($g\ kg^{-1}$)	Total organic C ($t\ ha^{-1}$)	Microbial biomass C ($mg\ kg^{-1}$)
CTLR	1.49	41.3	6.4	0.53	6.56	125
CTHR	1.41	43.6	6.4	0.65	7.90	164
SPLR	1.47	42.1	6.6	0.64	9.11	112
SPHR	1.37	45.6	6.8	0.86	10.8	168
BPLR	1.46	42.5	6.5	0.71	7.45	111
BPHR	1.43	43.7	6.6	0.79	10.02	142
$LSD_{0.05}$ (tillage × residue retention)	0.08*	0.78*	ns	0.08*	0.84*	19.9*

Legend: BP – bed planting, CT – conventional tillage, and SP – strip planting; HR – high residue retention and LR – low residue retention.

had significantly higher cellulose content than the mustard residue, whereas the latter had higher lignin (215 $g\ kg^{-1}$) and TN (9.1 $g\ kg^{-1}$) contents than the former ($p < 0.05$). In the Digram soils, the cellulose ($p < 0.05$) and lignin ($p > 0.05$) concentrations were higher in the wheat residue than in the jute leaf and root residues. The TN, P and K concentrations were significantly higher in the jute residues than in the wheat residues, whereas the TC concentrations were similar ($p > 0.05$). The Ce/Li, TC/TN, (Li + Ce)/TN and other ratios followed the same pattern as the TN concentrations in the monsoon rice, boro rice and wheat residues (Table 4).

3.4. *Selected soil properties influenced by tillage practices and residue retention*

After five years of CA practices, the effect of tillage on the BD of the soils at Alipur and Digram varied significantly with residue retention ($p < 0.05$) (Tables 5 and 6). The lowest BD at both Digram and Alipur was in the HR treatments and varied among the different tillage treatments with the following order: SP < CT < BP. The SP with HR treatment reduced the BD by 0.12 $g\ cm^{-3}$ at both Alipur and Digram relative to the CT with LR treatment (Tables 5 and 6). At Alipur, the application of increased residue retention in the SP, BP and CT treatments increased porosity values by 4.3%, 2.4% and 2.3%, respectively, relative to the CTLR treatment (Tables 5 and 6). At Digram, the SPHR, BPHR and CTHR treatments had the highest porosity values, which were 4.6%, 2.1% and 2.6% higher than that of the CTLR treatment, respectively.

The pHs at Alipur and Digram were unaffected by residue and tillage. The TN content in the Alipur soils after 14 crops varied among the tillage practices ($p < 0.05$) and between the crop residue retention practices ($p < 0.01$; Table 5). Among the tillage practices, SP, followed by BP, had the greatest improvement on the N status. Increased residue retention improved the TN status in both the Alipur and Digram soils (0.76 $g\ kg^{-1}$ and 0.66 $g\ kg^{-1}$, respectively) compared to the LR TN values (0.63 and 0.55 $g\ kg^{-1}$, respectively). The effects of SPHR on TN in the Alipur and Digram fields were significantly higher than the other treatment combinations (the TN values of SPHR were 62, 34, 21, 32 and 9% higher than those of CTLR, SPLR, BPLR, CTHR and BPHR, respectively). The TN values ranged from 0.53 to 0.86 $g\ kg^{-1}$ at Alipur and from 0.49 to 0.75 $g\ kg^{-1}$ at Digram.

3.5. *MBC under different tillage practices and residue retentions*

In the Alipur soils, MBC varied due to tillage practices and residue retention levels ($p < 0.05$). At Alipur, the CT, SP and BP treatments under HR had similar MBC values ($p > 0.05$; Table 5). At Digram, the SPHR and CTHR treatments had similar but significantly higher amounts of MBC than other combined treatments of tillage practices and residue retentions. The MBC values ranged from 111 to 168 $mg\ kg^{-1}$ soil at Alipur and from 79 to 142 $mg\ kg^{-1}$ soil at Digram. The lowest MBC values were invariably measured in BP plots with LR at both Alipur and Digram (Tables 5 and 6).

3.6. *TOC under different tillage practices and residue retentions*

The tillage practices and residue retention levels affected the TOC content in the soils of Alipur and Digram ($p < 0.05$; Tables 5 and 6). At both Alipur and Digram, the SPHR treatment had a significantly higher TOC content than the other treatment combinations. At Alipur, the SPHR values were 65, 45, 37 and 19% higher than those of CTLR, BPLR, CTHR and SPLR, respectively, whereas the BPHR values were 52, 26, 10 and 34% higher than those of CTLR, CTHR, SPLR and BPLR, respectively. At Digram, the SPHR TOC levels were 68, 38, 30 and 19% higher than those of CTLR, CTHR, BPLR and SPLR, respectively, while the BPHR values were 54, 24, 9 and 18% higher relative to those of CTLR, CTHR, SPLR and BPLR, respectively.

Table 6
Selected physical and chemical characteristics of the 0–10 cm soil layer at Digram after five years of varied soil disturbance practices and residue retention. Values are means of four replicates.

Treatments	Characteristics					
	Bulk density ($g\ cm^{-3}$)	Porosity (%)	pH (H_2O)	Total N ($g\ kg^{-1}$)	Total organic C ($t\ ha^{-1}$)	Microbial biomass C ($mg\ kg^{-1}$)
CTLR	1.53	40.5	6.10	0.49	6.43	93
CTHR	1.46	43.1	6.40	0.58	7.83	136
SPLR	1.50	41.9	6.40	0.59	9.00	84
SPHR	1.40	45.1	6.70	0.76	10.22	142
BPLR	1.51	41.3	6.30	0.58	8.31	79
BPHR	1.47	42.6	6.50	0.66	9.85	111
$LSD_{0.05}$ (tillage × residue retention)	0.05*	0.81*	ns	0.08*	0.53*	21.8*

Legend: BP – bed planting, CT – conventional tillage, and SP – strip planting; HR – high residue retention and LR – low residue retention.

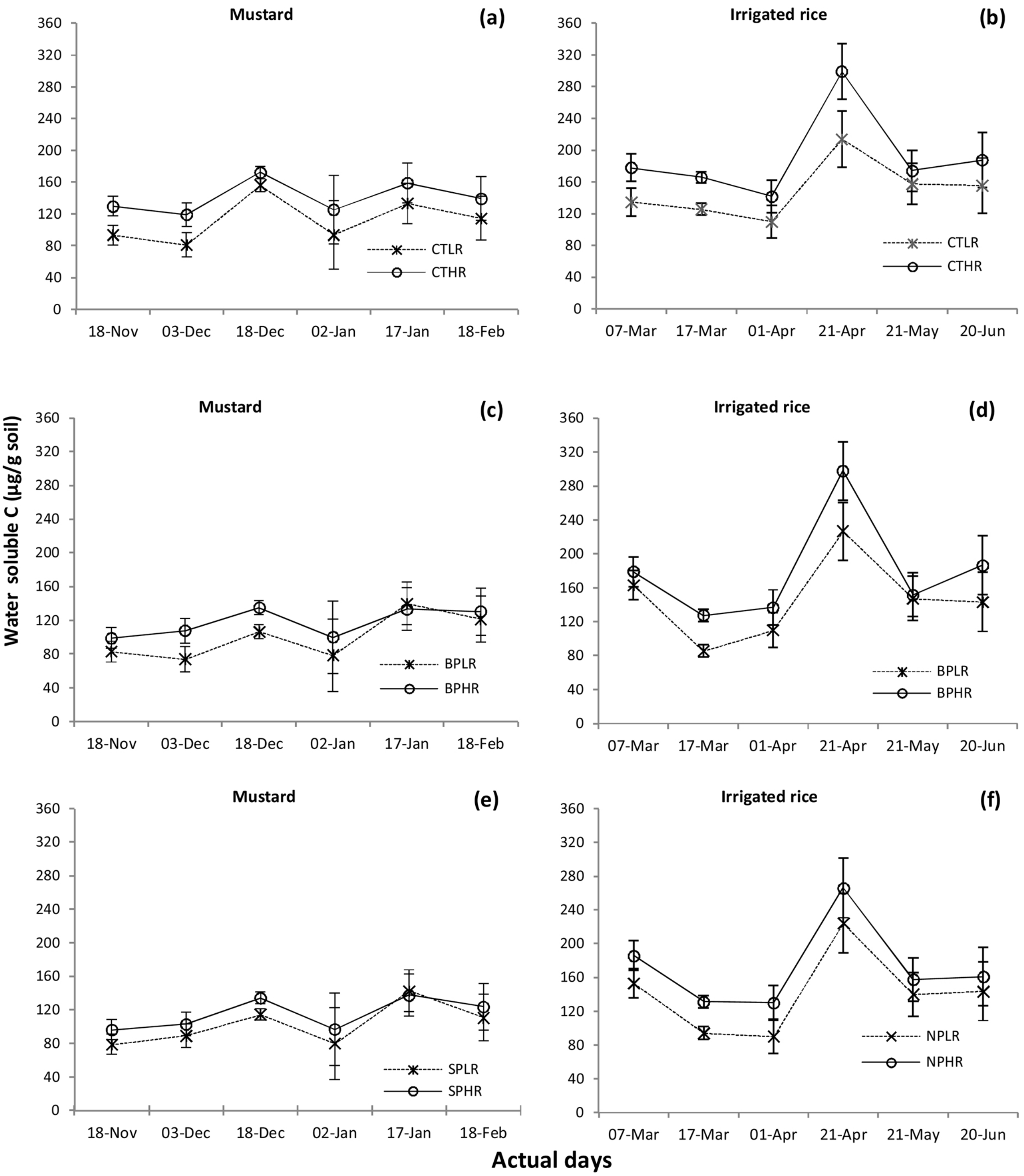

Fig. 2. Water soluble C in soils treated with different soil disturbance practices and residue retention levels. Mustard and irrigated dry season rice were grown at Alipur in winter and early summer seasons, respectively. [Legends: BP – bed planting, CT – conventional tillage, and SP – strip planting; NP – Non-puddling; HR – increased residue retention and LR – farmers' practice. Vertical bars represent LSD ($P < 0.05$). The information provided in the figure regards the 0–10 cm soil depth.

3.7. WSC

Tillage practices altered the WSC content for only the initial three samplings, while residue retention affected the WSC content for all samplings at both sites. The average WSC content in rice soil at the Alipur site (163 mg kg^{-1} soil) was significantly higher than that in the plots of other crops at both sites (Fig. 2). The next highest average WSC contents were associated with jute and mustard soils (124 and 115 mg kg^{-1} soil, respectively). The WSC contents were significantly higher in soils treated with CTHR for 4 years at both the Alipur and Digram sites (166 and 133 mg kg^{-1} soil, respectively). The next highest values were associated with BPHR (148 and 122 mg kg^{-1} soil at Alipur and Digram, respectively) and SPHR (143 and 118 mg kg^{-1} soil at Alipur and Digram, respectively) (Figs. 2 and 3). Significantly higher WSC contents were invariably associated with increased residue retention (153 and 124 mg kg^{-1} soil at Alipur and Digram, respectively) relative to low residue retention (125 and 98 mg kg^{-1} soil at Alipur and Digram, respectively).

3.8. Carbon dioxide emission

3.8.1. Carbon mineralization in soils under mustard and irrigated rice cultivation

The cumulative emission of C as CO_2 and CH_4 per tonne of SOC stored by rice soils in all the treatments increased over the first 55–60 days after sowing or transplanting, at which point the rate of increase

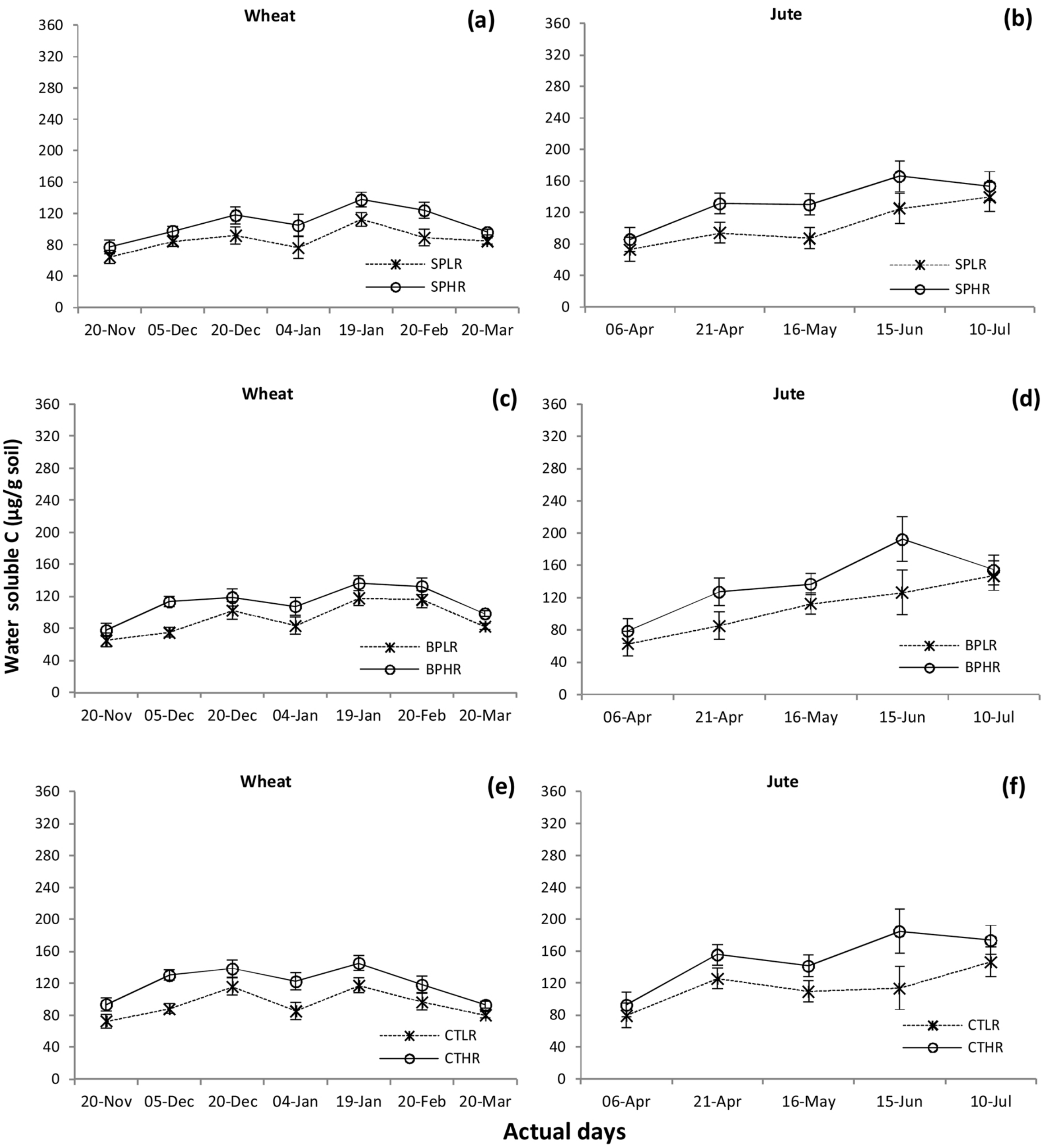

Fig. 3. Water soluble C in soils treated with different crop establishment practices and residue retention levels. Wheat and jute were grown in Digram in winter and early summer seasons, respectively. [Legends: BP – bed planting, CT – conventional tillage, SP – strip planting, NP – Non-puddling; HR – increased residue retention and LR – farmers' practice. Vertical bars represent LSD values ($P < 0.05$). The information provided in the figure regards the 0–10 cm soil depth.

slowed down (Fig. 4). During the cultivation of mustard and rice, the release of C from the soils (in the form of CO_2 and CH_4) with LR treatments was lower than from soils with HR treatments ($p < 0.05$) at different sampling dates up to the harvest (Fig. 4). Again, while the SPLR recorded the lowest respired C as CO_2 and CH_4, the cumulative C mineralization in soils under mustard cultivation was highest in CTHR and CTLR (30.4 and 29.8 kg C t^{-1} SOC) followed by BPLR, BPHR and SPHR, respectively ($p < 0.05$). At the end of the study, the CTHR treatment had emitted 5.4, 9.9, 10.0 and 13.6 more kg C t^{-1} SOC $season^{-1}$, while CTLR treatment had emitted 4.8, 9.3, 9.6 and 13 kg C t^{-1} SOC $season^{-1}$ more than the BPLR, SPHR, BPHR and SPLR treatments, respectively (Fig. 4). In the rice soils, the highest cumulative C mineralization (43.8 kg C t^{-1} $season^{-1}$) was recorded in the CTHR treatment at the end of the study period which was statistically similar to CTLR (40.1 kg C t^{-1} SOC $season^{-1}$; $p > 0.05$). The respired C in the CTHR treatment was followed by that of the BPLR treatment (35.9 kg C t^{-1} SOC; $p < 0.05$), whereas the cumulative mineralized C values of the NPHR and NPLR treatments in rice soils were significantly lower (16.1 and 16.2 kg C t^{-1} SOC) than that of the CTHR value, respectively ($p < 0.05$). The C evolution from rice soils treated with CTHR, CTLR, BPLR and BPHR was significantly higher than NPHR and NPLR practices. The lowest C mineralization was recorded in the SPLR treatment under mustard and rice field soils ($p < 0.05$). In total, the SPHR, SPLR, BPHR, BPLR, CTHR and CTLR treatments mineralized 4.81, 4.44, 5.37, 6.10, 7.42 and 6.99% of the TC present in the soils during the mustard and irrigated rice growing seasons. Overall, the soils containing higher C exhibited more C mineralization, except CTLR and BPLR soils, in which more C was mineralized than in CTHR and BPHR soils, respectively (Table 5 and Fig. 4). Overall, more C was mineralized in the CTHR and CTLR treatments than in the other treatments, which is consistent with the lower C contents of the soils under these treatments.

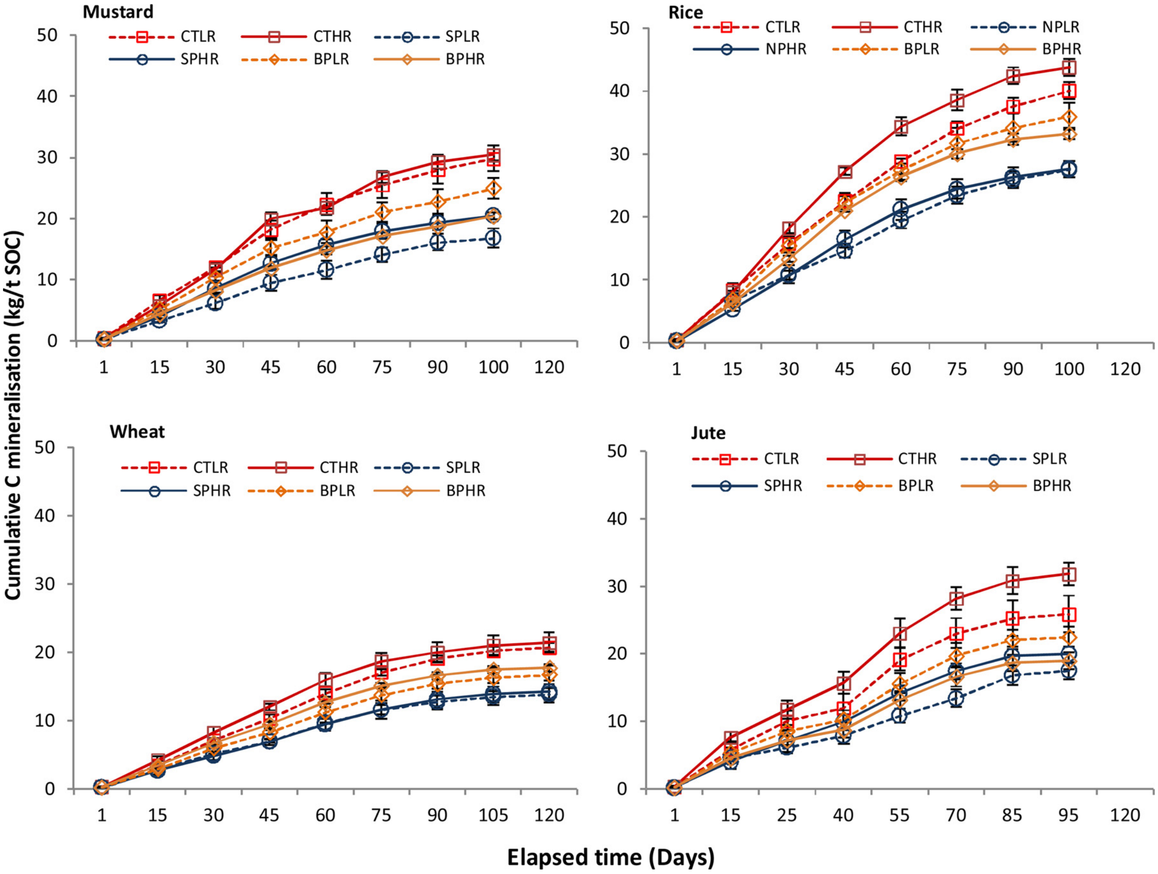

Fig. 4. Cumulative CO_2 emissions in soils (kg respired CO_2 per tonne of SOC) treated with different soil disturbance practices and residue retention levels in two fields in two seasons. Mustard and Irrigated dry season rice were grown at Alipur in winter and early summer season, respectively, while wheat and jute were grown in Digram in winter and early summer seasons, respectively. [Legends: BP – bed planting, CT – conventional tillage, and SP – strip tillage, NP – Non-puddling; HR – increased residue retention and LR – farmers' practice. Each marker point represents mean (n = 3) and vertical bars indicate S.E.M. (±). The soils studied were Calcareous Brown Flood Plain soil (*Aeric Eutrochrept*) at Alipur and Gery Terrace soil (*Aeric Albaquepts*) at Digram. The information provided in the figure regards the 0–10 cm soil depth.

3.8.2. Carbon mineralization in soils under wheat and jute cultivation

Significantly more cumulative C was mineralized in the CTHR and CTLR treatments (21.4 and 20.7 kg C t^{-1} SOC, respectively) for soils under wheat cultivation than in other treatments ($p < 0.05$), while similar amounts of C were mineralized in the BPHR and BPLR treatments ($p > 0.05$). However, in terms of C mineralized in soils under jute cultivation, the CTHR treatment (31.9 kg C t^{-1} SOC) had significantly more mineralized cumulative C than the other treatments. At the end of the wheat growing season (winter), the SPLR soils had emitted 7.5, 6.8, 3.9 and 2.9 kg C t^{-1} SOC less than the CTHR, CTLR, BPHR and BPLR soils, respectively. Again, SPHR soil had mineralized 7.1, 6.4, 3.5 and 2.4 kg less C t^{-1} SOC than the CTHR, CTLR, BPHR and BPLR soils, respectively. Overall, SPLR at the end of the jute season had 14.3, 8.4 and 5 kg lower C emitted t^{-1} SOC under jute soils than CTLR and BPLR, respectively. Likewise, at the end of the jute growing season, SPHR soils had emitted 11.9, 5.9 and 2.5 kg C t^{-1} SOC less than with CTHR, CRLR and BPLR treatments, respectively (Fig. 4). In both cases, the lowest cumulative C mineralization was also found in SPLR ($p < 0.05$). During the wheat and jute growing seasons, Digram soils under SPHR, SPLR, BPHR, BPLR, CTHR and CTLR mineralized 3.43, 3.14, 3.99, 3.93, 5.35 and 4.68% of the TC present in the respective soils. Similar to the Alipur results, the Digram soils with higher TOC contents also released higher amounts of C as CO_2. The BPLR soils were also the exception at Digram, as they exhibited more C mineralization than the BPHR soils (Table 6 and Fig. 4).

3.8.3. Carbon dynamics

The C mineralization values as a function of time and the fitted single-exponential model for the different soil disturbance practices and residue retention levels are shown in Table 7. In general, the R^2 values were all close to 1, and the standard errors were very low (Table 7), indicating that the selected model satisfactorily describes the C mineralization process.

3.8.4. Potentially mineralizable C pool (Co) and mineralization rate constant (mg C [g C]$^{-1}$ day^{-1})

Overall, the CTLR treatment produced the smallest potentially mineralizable C pool (Co) under the mustard crop at Alipur, whereas the SPHR treatment (followed by BPHR and SPLR) produced the largest Co ($p < 0.05$; Table 7). Between the residue retention practices, soil with more residue had the higher Co (Table 7). However, the decay rate was significantly higher for the CT treatments (0.017 mg C [g C]$^{-1}$ day^{-1}) than for the SP and BP treatments, which had the same decay rate (0.011 mg C [g C]$^{-1}$ day^{-1}). Between the residue retention practices, greater residue retention resulted in a significantly higher decay rate (Table 7). Low decay rates and high PMC values were found in soils under the mustard crop in the SP treatment, while high decay rates and low PMC values were observed in the CT and BP treatments.

In the Alipur soils under irrigated rice, the SP and BP (each using NP) treatments produced the highest Co value ($p < 0.05$; Table 7), while CT (using traditional puddling), had the lowest Co value. Increased residue retention resulted in 15% higher Co values (Table 7). The lowest Co value was observed in BPLR, while the highest was

Table 7
Potentially mineralizable C (Co) and decay rate (K) of soil organic carbon accumulated in different crop-growing conditions (mustard, rice at Alipur and wheat and jute at Digram) during two different seasons (mustard and wheat during the winter season and jute and rice during the early summer season) under soil disturbance and residue retention practices.

Treatments/ dynamic parameters	Alipur						Digram					
	Mustard			Rice			Wheat			Jute		
	C_0 (mg C g^{-1} C)	K (mg *C* [g *C*]$^{-1}$ day^{-1})	R^2	C_0 (mg C g^{-1} C)	K (mg *C* [g *C*]$^{-1}$ day^{-1})	R^2	C_0 (mg C g^{-1} C)	K (mg *C* [g *C*]$^{-1}$ day^{-1})	R^2	C_0 (mg C g^{-1} C)	K (mg *C* [g *C*]$^{-1}$ day^{-1})	R^2
BPHR	326	0.012	0.997	468	0.019	0.9973	236	0.012	0.990	427	0.010	0.989
BPLR	299	0.010	0.995	390	0.010	0.9953	206	0.010	0.990	363	0.008	0.988
CTHR	308	0.017	0.993	484	0.014	0.9943	216	0.018	0.988	442	0.016	0.987
CTLR	278	0.015	0.997	443	0.012	0.9970	189	0.013	0.987	259	0.011	0.985
SPHR	343	0.015	0.994	514	0.011	0.9947	258	0.009	0.990	434	0.010	0.989
SPLR	322	0.008	0.996	443	0.010	0.9973	211	0.011	0.989	347	0.008	0.990
S.E.M (±)	18.2	0.0018	0.002	28.6	0.001	0.001	14.0	0.002	0.003	32.5	0.001	0.002
LSD	29.4*	0004*	Ns	40.0*	0.003*	ns	28.2**	0.004*	ns	69.1*	0.003*	ns

Legend: BP – bed planting, CT – conventional tillage, and SP – strip planting, NP – non-puddling; HR – high residue retention and LR – low residue retention (farmers' practice). LSD – least significant difference; S.E.M. – standard error of means. *indicates significant at the 5% level of significance, and **indicates significant at the 1% level of significance. The information provided here is only valid for 0–10 cm soil depth.

recorded in SPHR. The BP and SP with HR under rice soil represented the highest Co values (Table 7). However, the decay rate was significantly higher in BP (0.014 mg *C* [g *C*]$^{-1}$ day^{-1}) than in SP (0.009 mg *C* [g *C*]$^{-1}$ day^{-1}), while CT closely followed BP. The decay rates of high retention levels (0.014 mg *C* [g *C*]$^{-1}$ day^{-1}) were significantly higher than those of low retention levels (0.01 mg *C* [g *C*]$^{-1}$ day^{-1}). The BPHR treatment in rice soils had the highest decay rate (0.019 mg *C* [g *C*]$^{-1}$ day^{-1}) (Table 7).

The Co values under wheat were higher in association with higher residue retention rates than with lower residue retention rates (Table 7). The Co values for CTLR and BPLR were 37 and 25% lower than those for SPHR. The SPHR Co values were also 19 and 9% higher than those of CTHR and BPHR. However, CTHR had the highest decay rate (0.018 mg *C* [g *C*]$^{-1}$ day^{-1}) while SPHR had the lowest decay rate (0.009 mg *C* [g *C*]$^{-1}$ day^{-1}).

In soils under jute, the Co value of the HR treatment was 111 mg C g^{-1} C higher than that of the LR treatment. Among the interaction effects, CTHR had the highest Co value (442 mg C g^{-1} C), which was closely followed by the values for SPHR (434 mg C g^{-1} C) and BPHR (427 mg C g^{-1} C). The lowest Co value corresponded to CTLR (258 mg C g^{-1} C). The mineralization rate constant (decay rate) in soils under jute crop cultivation varied with the interaction effects of tillage and residue retention levels ($p < 0.05$). While BPLR and SPLR exhibited the lowest decay rates (0.008 mg *C* [g *C*]$^{-1}$ day^{-1}), BPHR and SPHR had lower decay rates (0.009 mg *C* [g *C*]$^{-1}$ day^{-1}) than CTHR, which had the highest overall decay rate constant (Table 7).

4. Discussion

4.1. Effects of soil disturbance and residue retention practices on soil C

Minimal soil disturbance with SP in combination with increased residue retention over 5 years sequestered more C from C inputs in the 0–10 cm soil layer at both sites. The increase in SOC can be attributed to 1) surface retention of the crop residues of three crops over the course of a year as cover (Table 2) and as additional C from the increased biomass production; 2) decreased disturbance of SOC and plant root residues when establishing upland crops and transplanting rice crops; and 3) following crop rotation with species that produce different qualities of residues. At Alipur, soil C accumulation under SPHR was 65% higher than the current practice (CTLR). Even SPLR plots had 39 and 22% higher SOC values than the CTLR and BPLR plots, respectively, suggesting that minimizing soil disturbance, even without increasing residue retention is beneficial in this cropping system for soil C accumulation. The TOC contents in SPHR were only 8% higher than in BPHR. In the treatments with the least soil disturbance (SP) and greater surface residue retention, the patterns of SOC increase were similar for both Alipur and Digram, despite differences in rotation crop types and soil types.

An extra of 1.90 and 1.39 t C ha^{-1} with HR can be attributed to increased residue input at Alipur and Digram sites, respectively, relative to LR. Though the HR treatment doubled the amount of residue added relative to the current LR practices (Table 2), lower CO_2-eq emission t^{-1} of SOC was recorded with the SP with either LR or HR and BPHR (except for wheat) which also resulted in increased C storage in comparison with C inputs to each practice. In other words, the practices capable of retaining more organic C from the inputs had lower CO_2-eq emission. Thus, overall the SOC sequestration was greatest in the SPHR treatment (Fig. 4). Six et al. (2002) found that SOC contents increased by ∼212 to ∼438 kg C ha^{-1} year^{-1} under zero tillage (ZT) relative to CT in tropical and temperate systems. Sapkota et al. (2017) found a three-fold increase in SOC stocks under residue retention and minimum tillage compared to no residue retention and CT practices. In Indo-Gangetic Plains, SOC storage increased at a rate of between 0.16 and 0.49 t C ha^{-1} yr^{-1} with minimum disturbance of soil and residue retention compared to CT practice (Powlson et al., 2016). Other studies also showed SOC increases related to retention of more than 30% of crop residues and minimal disturbance of the soil (Virto et al., 2011).

Previous study found that soil C accumulation peaks at rates of 430–710 kg C ha^{-1} year^{-1} within 5–10 years of the implementation of CA (Ghimire et al., 2014; West and Post, 2002). But the benefits of following CA are undone by soil puddling for wetland rice (Sapkota et al., 2017), if CA practices are applied only to the upland crops in rice-upland crop rotations (Hobbs et al., 2008). On the contrary, residue decomposition under anaerobic soil conditions is slower than decomposition under aerobic conditions (Kirk and Olk, 2000). However, current research has found that following SP for upland crops and SP followed by NP for rice together with HR retention for all crops in the rice-upland cropping systems increased C stocks in the soil after 5 years to values that were almost double that achieved via the CT, soil puddling and residue removal. Moreover, the SPLR and SPHR treatments also outperformed the BPLR and BPHR treatments in conserving C in soils. This difference can be attributed to the higher degree of soil disturbance (Haque et al., 2017) and to more frequent wetting and drying episodes for the raised beds during irrigation and rainfall. The permanent shallow raised beds were reshaped two or three times in a year which incorporated nearly 30–40% of the residues left on the surface, and enhanced the mineralization and loss of SOC compared to the SP/NP treatment with surface residue retention. Similar results were obtained by Sapkota et al. (2017) for rice wheat double-cropping systems.

The increase in soil C was associated with lower levels of cumulative release of C as CO_2 and/or CH_4 in the rice-based cropping systems in both soil types (Tables 5 and 6 and Fig. 4). At the end of the study, the cumulative C mineralization in the soils in the SPLR, SPHR and BPLR, BPHR treatments were lower compared to those of the CTLR and CTHR soils. Seven years of direct seeding in ZT plots or on permanent raised beds for rice-wheat cropping was also associated with an increase in soil C accumulation together with a significant decrease in soil C mineralization (Sapkota et al., 2017). The higher PMC values under SP/NP with HR are consistent with the increased SOC content in these soils, as the higher PMC is an indication of the slow decomposition of SOM and the eventual SOC accumulation (Raiesi, 2006). However, the higher MBC values in the current study under SP/NP with HR soils were also positively related to the high SOC contents in the soils. Liu et al. (2012) and Song et al. (2016) found similar results, i.e., increased organic C and MBC contents in soils in association with increased residue retention and minimal soil disturbance. Hence, the increased PMC, MBC and lower WSC and CO_2-eq emission under the SP and SP followed by NP together with increased residue retention appear to lead to stabilization and accumulation of SOC in these rice-based cropping systems. Either minimum disturbance or increased residue increased SOC, i.e. the two CA principles acted independently to increase SOC.

In addition to the direct effects of minimal soil disturbance and HR on C sequestration, material retained on surface lowered the soil temperature (Fig. 1a, b), which probably further contributed to the reduced C mineralization (Lal et al., 2007). Conventional tillage practices resulted in a mean soil temperature that was on average 1.3–1.9 °C higher during winter and early summer seasons relative to the SP practices. The average soil temperature was slightly higher in SP than in BP from the planting of mustard through the harvesting of rice in June at Alipur. Similarly, in Digram, the average soil temperature was slightly higher in SP relative to BP throughout the wheat and jute growing period, regardless of the residue retention practices. Naresh et al. (2011) also reported a similar result for BP and suggested that tillage systems that leave most residue on the soil surface result in lower soil temperatures. Green and Lafond (1999) reported that the soil temperature during summer was higher under CT than under minimal tillage with surface-retained residue. In our case, the lower temperatures recorded under SP and BP might help reduce the C loss through reduced mineralization. On the other hand, the effect of lower temperature under BP than SP on SOC was probably counterbalanced by the additional soil disturbance under BP.

Tillage and residue retention effects on soil C sequestration also varied among different soil types. In the current study, the higher soil moisture, improved N status, decreased BD, more favorable pH and higher porosity (Tables 5 and 6) might be responsible for the increased C mineralization in the silty loam soil at Alipur than in the silty clay loam soil at Digram. However, the higher C storage values recorded in the Alipur soils are also attributable to the larger amounts of C retained in soils from added C inputs by 14 crops than at Digram (13 crops). In addition, there may have been a contribution from greater in-season biomass C added to the soil due to algal growth in the rice flood water (Roger and Watanabe, 1984).

4.2. CO_2 emissions

The increases in soil C with SP and HR were associated with decreases in the cumulative release of C as CO_2 and/or CH_4 (i.e., CO_2-eq) in the rice-based cropping systems on both soil types (Tables 5 and 6 and Fig. 4). During the mustard growing season at Alipur, the emissions from soils under SPHR were 48.5, 45.6 and 21.9% lower t^{-1} of SOC than those under CTHR, CTLR and BPLR, respectively. During the wheat growing season at Digram, the emissions from soils under SPHR were 50, 44.9 and 24.2% lower t^{-1} of SOC than those of CTHR, CTLR and BPHR, respectively. During the jute growing seasons at Digram, the emissions from soils under SPHR were 59.3, 29.5 and 12.5% lower t^{-1} of SOC than those under CTHR, CTLR and BPLR, respectively. The incorporation of the NP method in the rice–based cropping system offers potential reductions in terms of the CO_2–eq releases t^{-1} SOC stored from inputs (SPHR decreases CO_2–eq releases t^{-1} of SOC by 58, 45 and 30% over CTHR, CTLR and BPLR, respectively) and accordingly helps sequester more C in the soil relative to the conventional puddling method. Both the SPLR and SPHR offer the greatest savings (almost similarly) in terms of CO_2-eq emissions t^{-1} SOC stored from inputs. Rice and jute, which are grown during the early monsoon period, were associated with higher C releases relative to other crops grown in the same fields during the winter period (Fig. 4).

Minimal disturbance of the soil and surface application of residue probably maintained a low WSC level throughout the growing seasons by regulating the microbial activities and decomposition of residues. The higher WSC values recorded under CTHR and BPHR during the growing season for all crops might also cause higher CO_2-eq releases from these soils. Sainju et al. (2012) found a positive relationship between WSC and SOM mineralization, and the methods of application and the amount of added residue also affect the WSC and C mineralization values. In our study, the repeated and increased residue incorporation (three times a year) in the CT practices resulted in higher WSC values and higher CO_2-eq emissions compared to minimal soil disturbance and retention of residue on the soil surface.

Continuous minimal disturbance of soil together with increased residue retention practices resulted in higher MBC contents than tillage practices with low residue retention practices. The higher MBC values in soils under CT, SP and BP with HR might be attributed to substrates with more residue retained from three crops per year. The greater crop or biomass productivity under tillage practices with HR (Table 2 and Haque et al., 2016) also may be responsible for the increased MBC and SOC levels in the soils (Liu et al., 2016). Soil MBC, microbial activity, SOC and C mineralization can all be increased via the addition of organic amendments under conventional tillage practices; however, the minimal tillage practices in our experiments, particularly SP, retain residues on the surface or standing, and the poor microbial colonization due to less contact with soil probably retards residue mineralization (Broder and Wagner, 1988).

4.3. Forms of C and C cycling

Residue retained in the rice-wheat-jute and rice-mustard-rice cropping systems had significant differences in C turnover rates that may be related to quantity, litter quality and soil aeration conditions. Both the cropping systems added similar amounts of residues (by weight) to the soil per year, but higher C mineralization occurred in the rice-dominated cropping systems. If a rotation is rice dominated, similar to the one followed at Alipur, the soils remain underwater for more than eight months a year. In contrast, the soils under the more diverse crop rotation at Digram remain underwater for only four months. Additionally, rice residues contain higher levels of phenolic compounds (Olk et al., 1998). Collectively, the degradation of the compounds in mustard and rice residues is expected to be slow and incomplete due to the submerged conditions and the slow lignin and phenol degradation, even in aerated soils (Olk et al., 1998). Current evidence suggests that retaining residues under prolonged anaerobic (submerged) conditions reduce decomposition and mineralization of the residues compared to those under aerobic conditions (Liping and Erda, 2001). However, the monsoon and irrigated rice crops cultivated at Alipur have higher cellulose contents, lower lignin contents and lower (Ce + Li)/TN and C/N ratios than the monsoon rice-wheat, and -jute crops at Digram. These factors all favor faster decomposition (Table 4). Mustard residues have 11 and

15% higher cellulose and lignin contents, respectively, than wheat residues, while rice residues have 71% higher cellulose contents and almost three times lower lignin contents than jute residues (Table 4). In addition, at Alipur, mustard residues with higher lignin contents and rice crop residues with higher cellulose contents were retained in the wet soils under irrigated rice. The slowly degradable phenolic compounds, cellulose and lignin from frequently applied residues might increase the C stocks by resisting degradation through heterotrophic respiration over the 5-year study period. Although the wheat and jute residues retained at Digram soils contain higher levels of lignin, more complete decomposition of the residues may occur than at Alipur due to the prolonged aerated conditions. However, these findings were not reflected in our results for WSC and CO_2 emissions, possibly because the present study did not account for the additional organic matter added by algae and aquatic weed biomass to the flooded soils (Roger and Watanabe, 1984) or the rice root exudates (Bacilio-Jiménez et al., 2003) that increase the overall level of WSC and the emissions of CO_2 and CH_4. Additionally, repeated episodes of wetting and drying of the rice soils might expedite the decomposition of residues retained in rice-dominant cropping systems, thereby enhancing the emission-based WSC and C losses. The potential role of wetting and drying in SOC mineralization are discussed below.

In both soil types and for all crops, the cumulative C mineralization and mineralization rates were highest during the first two months (50–65 days) of crop growth; thereafter, the mineralization rate decreased (Fig. 4). Therefore, the Co remaining after 50, 60, 55 and 65 days for mustard, wheat, rice and jute, respectively, was increasingly inaccessible to microbial decomposition in all soils (Chaudhary et al., 2014; Murphy et al., 2007). The cumulative CO_2-eq evolution from soils treated with tillage practices and previous crop residues was well described using a first-order exponential model, with an R^2 ranging from 97 to 99.9% (Table 7). The decomposition of the retained residues was faster in the conventionally tilled than that in the minimally tilled soils (Tables 5 and 6). Relative to conventionally cultivated soils under mustard cultivation, the SP soils exhibited higher Co values, probably because of the higher C contents, as well as the lower decay rate (Table 7). Hence, it would be worth assessing whether soils treated with SP for five years form more micro- and macro-aggregates that physically and chemically protect aggregate-enclosed organic C (Six et al., 2000; Song et al., 2016). The Co values of the BPHR and BPLR soils were also greater than those of CTHR and CTLR soils, respectively, while the decay rates were lower in the BP soils relative to the CT soils (Table 7). However, the lowest Co value in the rice soil was estimated for the BPHR treatment. The higher decay rate for Co may be the result of the frequent wet-dry cycles of the soils in raised bed wetland rice plots (Table 7). The decay rate of the resistant pool of C was also higher under rice with the BP treatment. The reshaping of the bed before sowing each new crop disturbs the soils (Haque et al., 2017) and might also disrupt the aggregates, thereby increasing the decay rate of PMC.

In wheat and jute fields, the lowest Co values were recorded in soils under the CTHR and CTLR treatments, possibly due to the low C contents and high PMC decay rates (Table 7). Similar to rice, soils under jute had high Co values. The CTHR, SPHR and BPHR soils had similar Co values, but the highest PMC decay rate was recorded for CTHR. This decay rate can be attributed to the soil disturbance during the CT jute establishment and the corresponding loss of SOC due to increased total soil porosity as found in our study (Table 5 and 6; Raiesi, 2006). Even a small increase in soil porosity in the cultivated soils might be responsible for higher rates of C mineralization (Raiesi, 2006).The high Co values found in the jute soils in the current study (Table 7) indicate the potential increases in the SOC levels associated with jute cultivation due to the large input of high-quality litterfall that occurs before jute reaches maturity.

4.4. Implications of increasing SOC contents via novel practices (strip planting and non-puddling of soil)

Notwithstanding the barriers to fitting CA in rice–based cropping systems in the EGP and in other rice growing areas of the world (Friedrich et al., 2012), the SPHR treatment has outperformed the conventional practices (intensive soil disturbance and residue removal) in terms of yield, soil health, profitability and greenhouse gas emission mitigation (Alam et al., 2016a; Haque et al., 2016). The yield of rice, lentil and wheat under SPHR were 6.2, 23 and 9% higher than under CT, respectively (Alam et al., 2016a; Islam, 2016). For boro rice, the CA practice (SPHR) saved 19% of the LCA GHG emissions relative to emissions estimated for CT (Alam et al., 2016a), while total variable cost can also be decreased by the CA practice by 22% relative to CT (Haque et al., 2016). If we apply the C sequestration performance of our 4–5–year experiments at Alipur and Digram to the rice-based cropland of the EGP, the conversion from conventional cropping to CA (SP/NP with HR) could sequester an extra 131–145 million t CO_2–eq. These values exceed several other estimates of soil C sequestration and greenhouse emissions from altered soil management practices in the EGP. After seven years, ZT rice and ZT wheat with residue in permanent raised beds increased the SOC contents in the 0–10 cm depth by 2.97 t C ha^{-1} (103 million t CO_2–eq in EGP) and 2.5 t C ha^{-1} (87 million t CO_2–eq in EGP), respectively (Sapkota et al., 2017). In accordance with the methodology of the Intergovernmental Panel on Climate Change, Grace et al. (2012) assessed the regional impact of ZT on the Indo-Gangetic Plain (IGP) and reported that changing wheat-based production from CT to ZT on the IGP could sequester 0.2–0.4 t C ha^{-1} yr^{-1} (7–14 million t CO_2–eq yr^{-1} in EGP). Furthermore, on the basis of published data on ZT in the IGP, Powlson et al. (2016) estimated a value of 0.3 t C ha^{-1} yr^{-1} (10 million t CO_2–eq yr^{-1}) could be accumulated in the soil of the EGP via ZT. With these amounts of SOC sequestered in the soil of the EGP, additional co–benefits can be expected with regard to soil fertility, cost savings and crop productivity due to improvements in the physical, chemical and biological soil properties (Krull et al., 2004).

5. Conclusions

Increased residue retention with minimal soil disturbance using SP (and NP for rice) after 14 consecutive crops at Alipur (Level Barind Tract, Calcareous Brown Floodplain soil) and after 13 consecutive crops at Digram (High Barind Tract, Grey Terrace soil) altered the C cycling by reducing C emissions, WSC and the decay rates of PMC and by increasing PMC and MBC. The net effect was an increase in the TOC levels in the soils of 0–10 cm depth. The greatest increases in SOC contents achieved with HR together with SP practices were 4.24 and 3.79 t ha^{-1} higher at Alipur and Digram, respectively, than those of the current practices (CTLR). With the lower decay rate of PMC values, the SP with HR had greater PMC than other practices. The rice soils had even higher PMC values under SPHR (514 mg C g^{-1} C) than any other crops studied which contributed to increased SOC under the rice-dominated rotation at Alipur. The decline in WSC values and CO_2 emissions and the increase in MBC values in soils under SPHR are consistent with greater soil C sequestration under the practice. Overall, the rice-dominant rotation accumulated more SOC than rice-anchored cropping system. Crop establishment practices involving strip planting for upland crops and non-puddling for rice minimize the SOC losses relative to current crop establishment practices. In conclusion, after 4–5 years of consecutive crops, the SPHR treatment altered the C cycling by slowing the in-season turnover of C by reducing the soluble C in the soil available to microorganisms during the growing season and by increasing the TOC content in the 0–10 cm layer of soil.

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Conflicts of interest

The manuscript authors hereby profess that there are no conflicts of interest for any reasons, such as personal, institutional and financial relationships, academic competition, or intellectual passion. Gender issues were also avoided in publishing this manuscript.

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Appendix A. Supplementary data

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References

Alam, M.K., Biswas, W.K., Bell, R.W., 2016a. Greenhouse gas implications of novel and conventional rice production technologies in the Eastern-Gangetic plains. J. Clean. Prod. 112, 3977–3987. http://dx.doi.org/10.1016/j.jclepro.2015.09.071.

Alam, M.K., Salahin, N., Islam, S., Begum, R.A., Hasanuzzaman, M., Islam, M.S., Rahman, M.M., 2016b. Patterns of change in soil organic matter, physical properties and crop productivity under tillage practices and cropping systems in Bangladesh. J. Agric. Sci. 155, 216–238. http://dx.doi.org/10.1017/s0021859616000265.

Anderson, J.P.E., 1982. Soil respiration. In: 2nd ed. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Agronomy Monograph, vol. 9. ASA and SSSA, Madison, WI, pp. 831–871.

Bacilio-Jiménez, M., Aguilar-Flores, S., Ventura-Zapata, E., Pérez-Campos, E., Bouquelet, S., Zenteno, E., 2003. Chemical characterization of root exudates from rice (*Oryza sativa*) and their effects on the chemotactic response of endophytic bacteria. Plant Soil 249, 271–277. http://dx.doi.org/10.1023/a:1022888900465.

Baldock, J.A., 2007. Composition and cycling of organic carbon in soil. In: Marschner, P., Rengel, Z. (Eds.), Nutrient Cycling in Terrestrial Ecosystems. Springer, Berlin Heidelberg, pp. 1–35.

Balota, E.L., Filho, A.C., Andrade, D.S., Dick, R.P., 2004. Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil Till. Res. 77, 137–145. http://dx.doi.org/10.1016/j.still.2003.12.003.

Black, C.A., 1965. Method of Soil Analysis Part-I and II. American Society of Agronomy, Madison, Wis, USA, pp. 1965.

Broder, M.W., Wagner, G.H., 1988. Microbial colonization and decomposition of corn, wheat, and soybean residue. Soil Sci. Soc. Am. J. 52, 112–117. http://dx.doi.org/10.2136/sssaj1988.03615995005200010020x.

Chaudhary, D.R., Chikara, J., Ghosh, A., 2014. Carbon and nitrogen mineralization potential of biofuel crop (*Jatropha curcas* L.) residues in soil. J. Soil Sci. Plant Nutr. 14, 15–30. http://dx.doi.org/10.4067/S0718-95162014005000002.

Curtin, D., Francis, G.S., McCallum, F.M., 2008. Decomposition rate of cereal straw as affected by soil placement. Soil Res. 46, 152–160. http://dx.doi.org/10.1071/SR07085.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75, 529–538.

FAO, 2009. Food and Agricultural Organization of the United Nations, 2009. OECD-FAO Agricultural Outlook. FAO, pp. 2011–2030.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1994. Seasonal changes in soil microbial biomass and mineralizable C and N in wheat management systems. Soil Biol. Biochem. 26, 1469–1475. http://dx.doi.org/10.1016/0038-0717(94)90086-8.

FRG, 2012. Fertilizer Recommendation Guide, vol. 1215. Bangladesh Agricultural Research Council (BARC), Farmgate, Dhaka, pp. 274.

Friedrich, T., Derpsch, R., Kassam, A., 2012. Overview of the global spread of conservation agriculture. J. Field Actions 6, 1–17.

Ghimire, R., Norton, J.B., Stahl, P.D., Norton, U., 2014. Soil microbial substrate properties and microbial community responses under irrigated organic and reduced-tillage crop and forage production systems. PLoS One 9, e103901. http://dx.doi.org/10.1371/journal.pone.0103901.

Goering, H.K., Van Soest, P.J., 1970. Forage Fibre Analysis (Apparatus, Reagents, Procedures and Some Applications). Agricultural Handbook No. 379. Agricultural Research Service-United States Department of Agriculture, Washington, DC.

Grace, P.R., Antle, J., Aggarwal, P.K., Ogle, S., Paustian, K., Basso, B., 2012. Soil carbon sequestration and associated economic costs for farming systems of the Indo-Gangetic Plain: a metaanalysis. Agric. Ecosyst. Environ. 146, 137–146.

Green, B., Lafond, G., 1999. Farm Facts: Soil Temperature and Crop Emergence Under Conventional and Direct Seeding. Department of Agriculture and Food, Saskatchewan Government, pp. 4.

Griffin, T.S., 2008. Nitrogen availability. In: In: Schepers, J.S., Raun, W. (Eds.), Nitrogen in Agricultural Systems. Agronomy Monograph, vol. 49. ASA, CSSA, and SSSA, Madison, WI, pp. 613–646.

Haight, C.M., 2009. OneWireViewer and iButton Quick Start Guide. Available at: Available at:. https://www.maximintegrated.com/en/app-notes/index.mvp/id/4373.

Haque, M.E., Bell, R.W., Islam, M.A., Rahman, M.A., 2016. Minimum tillage unpuddled transplanting: an alternative crop establishment strategy for rice in conservation agriculture cropping systems. Field Crops Res. 185, 31–39. http://dx.doi.org/10.1016/j.fcr.2015.10.018.

Haque, M.E., Bell, R.W., Menon, R.K., Mia, N.N., Hossain, M.M., 2017. Comparative levels of soil disturbance under reduced and minimum tillage types with two-wheel tractor planting operations. In: Bell, R.W., Haque, M.E., Vance, W. (Eds.), Proceedings on 2nd Conference on Conservation Agriculture for Smallholders (CASH-II). Mymensingh, Bangladesh. pp. 57–60.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363, 543–555. http://dx.doi.org/10.1098/rstb.2007.2169.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Islam, M.A., 2016. Conservation Agriculture: Its Effects on Crop and Soil in Rice-Based Cropping Systems in Bangladesh, PhD Thesis. School of Veterinary and Life Sciences, Murdoch University, Australia.

Jackson, M.L., 1973. Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi.

Jahan, M.S., Rumee, J.N., Rahman, M.M., Quaiyyum, A., 2014. Formic acid/acetic acid/water pulping of agricultural wastes. Cellul. Chem. Technol. 48, 111–118.

Jenkinson, D.S., Powlson, D.S., 1976. The effects of biocidal treatments on metabolism in soil. A method for measuring soil biomass. Soil Biol. Biochem. 8, 209–213. http://dx.doi.org/10.1016/0038-0717(76)90005-5.

Karim, Z., Rahman, S.M., Ali, M.I., Karim, A.J.M.S., 1988. Soil Bulk Density: A Manual for Determination of Soil Physical Parameters. Soils and Irrigation Division, BARC, Dhaka, Bangladesh.

Kirk, G.J.D., Olk, D.C., 2000. Carbon and nitrogen dynamics in flooded soils. Proceedings of the Workshop on Carbon and Nitrogen Dynamics in Flooded Soils. International Rice Research Institute, Los Baños, Philippines. Makati City (Philippines), pp. 188.

Krull, E.S., Skjemstad, J.O., Baldock, J.A., 2004. Functions of Soil Organic Matter and the Effect on Soil Properties. Grains Research and Development Corporation (GRDC) Australia Project No CSO 00029. ACT, vol. 129 Canberra.

Lal, R., Follett, R.F., Stewart, B.A., Kimble, J.M., 2007. Soil carbon sequestration to mitigate climate change and advance food security. Soil Sci. 172, 943–956. http://dx.doi.org/10.1097/ss.0b013e31815cc498.

Larson, W.E., Clapp, C.E., Pierre, W.H., Morachan, Y.B., 1972. Effects of increasing amounts of organic residues on continuous corn: II. Organic carbon, nitrogen, phosphorus, and sulfur. Agron. J. 64, 204–208. http://dx.doi.org/10.2134/agronj1972.00021962006400020023x.

Liping, G., Erda, L., 2001. Carbon sink in cropland soils and the emission of greenhouse gases from paddy soils: a review of work in China. Chemosphere Global Change Sci. 3, 413–418. http://dx.doi.org/10.1016/s1465-9972(01)00019-8.

Liu, N., Zhang, Y., Chang, S., Kan, H., Lin, L., 2012. Impact of grazing on soil carbon and microbial biomass in typical steppe and desert steppe of inner Mongolia. PLoS One 7, e36434. http://dx.doi.org/10.1371/journal.pone.0036434.

Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J., Jin, Y., Zou, J., 2016. Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. GCB Bioenergy 8, 392–406. http://dx.doi.org/10.1111/gcbb.12265.

Mulvaney, M.J., Wood, C.W., Balkcom, K.S., Shannon, D.A., Kemble, J.M., 2010. Carbon and nitrogen mineralization and persistence of organic residues under conservation and conventional tillage. Agron. J. 102 (5), 1425–1433.

Murphy, D.V., Stockdale, E.A., Poulton, P.R., Willison, T.W., Goulding, K.W.T., 2007. Seasonal dynamics of carbon and nitrogen pools and fluxes under continuous arable and ley-arable rotations in a temperate environment. Eur. J. Soil Sci. 58, 1410–1424. http://dx.doi.org/10.1111/j.1365-2389.2007.00946.x.

Murwira, H.K., Kirchmann, H., Swift, M.J., 1990. The effect of moisture on the decomposition rate of cattle manure. Plant Soil 122, 197–199. http://dx.doi.org/10.1007/bf02851975.

Naresh, R., Gupta, R.K., Satya, P., Kumar, A., Singh, M., Misra, A., 2011. Permanent beds and rice-residue management for rice-wheat systems in the North West India. Int. J. Agric. Sci. 7, 429–439.

Novak, B., 1974. Nitrogen immobilization as affected by straw. Ann. Microb. Enzymol. 24, 151–157.

Olk, D.C., Cassman, K.G., Mahieu, N., Randall, E.W., 1998. Conserved chemical properties of young humic acid fractions in tropical lowland soil under intensive irrigated rice cropping. Eur. J. Soil Sci. 49, 337–349. http://dx.doi.org/10.1046/j.1365-2389.1998.00163.x.

Olsen, S.R., Sommers, L.E., 1982. Phosphorus. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis, 2nd Edition. American Society of Agronomy Madison, USA, pp. 403–427 Part 2.

Orchard, V.A., Cook, F.J., 1983. Relationship between soil respiration and soil moisture. Soil Biol. Biochem. 15, 447–453. http://dx.doi.org/10.1016/0038-0717(83)90010-X.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agriculture. Ecosyst. Environ. 220, 164–174. http://dx.doi.org/10.1016/j.agee.2016.01.005.

Raiesi, F., 2006. Carbon and N mineralization as affected by soil cultivation and crop residue in a calcareous wetland ecosystem in central Iran. Agric. Ecosyst. Environ. 112, 13–20. http://dx.doi.org/10.1016/j.agee.2005.07.002.

Roger, P.A., Watanabe, I., 1984. Algae and aquatic weeds as source of organic matter and plant nutrients for wetland rice. In: Banta, S., Mendoza, C.V. (Eds.), Organic Matter and Rice. International Rice Research Institute., Los Banos Laguna, Philippines, pp. 147–168.

Sahrawat, K., 2005. Fertility and organic matter in submerged rice soils. Curr. Sci. India 88, 735–739.

Sainju, U.M., Lenssen, A.W., Caesar-TonThat, T., Jabro, J.D., Lartey, R.T., Evans, R.G., Allen, B.L., 2012. Tillage, crop rotation, and cultural practice effects on dryland soil carbon fractions. Open J. Soil. Sci. 2, 242–255. http://dx.doi.org/10.4236/ojss.2012.23029.

Sapkota, T.B., Jat, R.K., Singh, R.G., Jat, M.L., Stirling, C.M., Jat, M.K., Bijarniya, D., Kumar, M., Yadvinder-Singh, Saharawat, Y.S., Gupta, R.K., 2017. Soil organic carbon changes after seven years of conservation agriculture in a rice-wheat system of the eastern Indo-Gangetic plains. Soil Use Manage. 33, 81–89. http://dx.doi.org/10.1111/sum.12331.

Sisti, C.P.J., dos Santos, H.P., Kohhann, R., Alves, B.J.R., Urquiaga, S., Boddey, R.M., 2004. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Till. Res. 76, 39–58. http://dx.doi.org/10.1016/j.still.2003.08.007.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103. http://dx.doi.org/10.1016/s0038-0717(00)00179-6.

Six, J., Feller, C., Denef, K., Ogle, S.M., de Moraes, J.C., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils-effects of no-tillage. Agronomie 22, 755–775. http://dx.doi.org/10.1051/agro. 2002043.

Song, K., Yang, J., Xue, Y., Lv, W., Zheng, X., Pan, J., 2016. Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. Sci. Rep. 6. http://dx.doi.org/10.1038/srep36602.

SRDI, 2005. Bhumi and Mrittika sampad Bhavohar Nirdeshika. Gazipur Sadar Upazila, Rajshahi Zila: Bangladesh: Soil Resource Development Institute. Ministry of Agriculture. Government of the People's Republic of Bangladesh (in Bangla).

Stanford, G., Smith, S.J., 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. J. 36, 465–472. http://dx.doi.org/10.2136/sssaj1972.03615995003600030029x.

Stevenson, F.J., 1982. Humus Chemistry: Genesis, Composition, Reactions. John Wiley and Sons, New York.

Taneja, G., Pal, B.D., Joshi, P.K., Aggarwal, P.K., Tyagi, N.K., 2014. Farmers Preferences for Climate Agriculture: An Assessment in the Indo-Gangetic Plain. IFPRI Discussion Paper 01337. International Food Policy Research Institute (IFPRI), New Delhi.

Tirol-Padre, A., Ladha, J.K., 2004. Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. Soil Sci. Soc. Am. J. 68, 969–978. http://dx.doi.org/10.2136/sssaj2004.0969.

Tivet, F., Carlos de Moraes Sà, J., Borszowskei, P.R., Letourmy, P., Briedis, C., Ferreira, A.O., Burkner dos Santos Thiago Massao Inagaki, J., 2012. Soil carbon inventory by wet oxidation and dry combustion methods: effects of land use, soil texture gradients, and sampling depth on the linear model of C-equivalent correction factor. Soil Sci. Soc. Am. J. 76, 1048–1059.

USDA, SCS (United States Department of Agriculture, Soil Conservation Service), 1975. Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Soil Surv. Staff. U.S. Dep. Agric. Handb. pp. 436.

Van Kessel, J.S., Reeves, J.B., Meisinger, J.J., 2000. Nitrogen and carbon mineralization of potential manure components. J. Environ. Qual. 29, 1669–1677. http://dx.doi.org/10.2134/jeq2000.00472425002900050039x.

Verhulst, N., Francois, I., Grahmann, K., Cox, R., Govaerts, B., 2013. Nitrogen use efficiency and optimization of nitrogen fertilization in conservation agriculture. CAB Rev. 8, 53.

Virto, I., Barré, P., Burlot, A., Chenu, C., 2011. Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems. Biogeochemistry 108, 17–26. http://dx.doi.org/10.1007/s10533-011-9600-4.

Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Sci. Soc. Am. J. 66, 1930–1946. http://dx.doi.org/10.3334/CDIAC/tcm.002.

Witt, C., Cassman, K.G., Olk, D.C., Biker, U., Liboon, S.P., Samson, M.I., Ottow, J.C.G., 2000. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. Plant Soil 225, 263–278. http://dx.doi.org/10.1023/a:1026594118145.

Yagi, K., Miami, K., 1993. Spatial and temporal variations of methane emissions from rice paddy fields. In: Oremland, R.S. (Ed.), Biogeochemistry of Global Change. Chapman and Hall, Norwell, MA, pp. 353–368.

Zhou, W., Lv, T.F., Chen, Y., Westby, A.P., Ren, W.J., 2014. Soil physicochemical and biological properties of paddy-upland rotation: a review. Sci. World J. 2014, 856352. http://dx.doi.org/10.1155/2014/856352.