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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