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Soil organic carbon changes after seven years of conservation agriculture in a rice–wheat system of the eastern Indo-Gangetic Plains

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Abstract

Sequestration of soil organic carbon (SOC) is an important strategy to improve soil quality and to mitigate climate change. To investigate changes in SOC under conservation agriculture (CA), we measured SOC concentrations after seven years of rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) rotations in the eastern Indo-Gangetic Plains (IGP) of India under various combinations of tillage and crop establishment methods. The six treatments were as follows: conventional till transplanted rice followed by conventional till wheat (CTR-CTW), CTR followed by zero-till wheat (CTR-ZTW), ZT direct-seeded rice followed by CTW (ZTDSR-CTW), ZTDSR followed by ZT wheat both on permanent raised beds with residue (PBDSR-PBW+R), and ZTDSR followed by ZTW both with (ZTDSR-ZTW+R) and without residues (ZTDSR-ZTW). We hypothesized that CA systems (i.e. ZT with residue retention) would sequester more carbon (C) than CT. After seven years, ZTDSR-ZTW+R and PBDSR-PBW+R increased SOC at 0–0.6 m depth by 4.7 and 3.0 t C/ha, respectively, whereas the CTR-CTW system resulted in a decrease in SOC of 0.9 t C/ha. Over the same soil depth, ZT without residue retention (ZTDSR-ZTW) only increased SOC by 1.1 t C/ha. There was no increase in SOC where ZT in either rice or wheat was followed by CT in the next crop (i.e. CTR-ZTW and ZTDSR-CTW), most likely because the benefit of ZT is lost when followed by tillage. Tillage and crop establishment methods had no significant effect on the SOC stock below the 0.15-m soil layer. Over the seven years, the total carbon input from above-ground residues was ca. 14.5 t/ha in ZTDSR-ZTW+R and PBDSR-PBW+R, almost sixfold greater than in the other systems. Our findings suggest that the increased biomass production achieved through a combination of ZT and partial residue retention offers an opportunity to increase SOC whilst allowing residues to be used for other purposes.

Keywords: Soil organic carbon, tillage, crop residue, India, agricultural sustainability

Introduction

The rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) (RW) cropping system occupies about 13.5 million hectares of the Indo-Gangetic Plains (IGP) and contributes to the employment, income and livelihood of millions of people in the region (Regmi *et al*., 2002; Jat *et al*., 2014). In this system, rice is grown in summer by transplanting seedlings into puddled (wet tillage) soil and wheat is grown in the winter season. Farmers generally perform multiple tillage operations to prepare the field for rice and wheat planting. The intensive tillage in RW systems requires much labour, water and energy, which are becoming more expensive, thus increasing the cost of production resulting in decreased profitability (Aryal *et al*., 2015). Also, farmers remove and/or

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burn crop residues to facilitate good seedbed preparation. Such practices deteriorate soil quality through loss of soil carbon and cause environmental problems leading to low productivity of RW cropping systems (Ghimire *et al.*, 2011; Bhattacharyya *et al.*, 2012), which poses a serious threat to the sustainability of this important cropping system (Gathala *et al.*, 2013).

Recently, conservation agriculture (CA), an approach based on the principles of minimum soil disturbance, retention of crop residues or any other soil surface cover combined with appropriate crop rotation, has emerged as an important management strategy to address many of the pressing challenges confronting intensive RW systems in the IGP. CA not only increases farm productivity by reducing the cost of production (Aryal *et al.*, 2015) and increasing yield (Sapkota *et al.*, 2015), but also brings favourable changes in soil properties which affect the delivery of ecosystem services including climate regulation through carbon sequestration and greenhouse gas emissions (Palm *et al.*, 2013). ZT has been reported to increase soil organic carbon (SOC) by 270 kg/ha/yr (Gangwar *et al.*, 2006) to as high as 501 kg/ha/yr (Pandey *et al.*, 2012), whereas retention of crop residues has been reported to increase SOC by 90 kg/ha/yr (Gami *et al.*, 2009) to 440 kg/ha/yr (Nayak *et al.*, 2012). By analysing the tropical data set, Powlson *et al.* (2014, 2016) argued that the rate of SOC increase in ZT systems in the IGP could be ca. 300 kg/ha/yr in 0- to 0.3-m soil layer. Variations in crops, climate and soils are probably the major reasons for the range of values reported in different studies. In almost all studies in the IGP, the effect of tillage, residues and crop diversification on SOC was tested individually (Powlson *et al.*, 2016).

Although these benefits of CA in RW cropping systems are well documented in the western IGP, in the eastern IGP, they are confined mainly to ZT in wheat. Eliminating wet tillage in the rice component of RW systems benefits the following wheat crop because of better germination and rooting due to improved soil physical properties (Gathala *et al.*, 2011b; Jat *et al.*, 2014). Therefore, to realize the full potentials of CA in RW systems, not only should crop residues be retained as a surface mulch but rice should also be grown under ZT (Gathala *et al.*, 2013). With these considerations in mind, a long-term experiment was established in 2006 to evaluate the effect of various combinations of tillage, crop establishment methods and crop residue management on crop productivity, economic profitability and SOC changes in an RW system in the eastern IGP of India. Results for agronomic productivity and economic profitability have been published elsewhere (Jat *et al.*, 2014); in this study, we present the SOC changes after seven years of experimentation. We hypothesized that crop residues retained on the soil surface in combination with ZT would increase carbon (C) sequestration. To test this, it was necessary to separate the individual effects of ZT and residues as well as their combined effects on SOC accumulation, and compare them with a CT system.

Materials and methods

Research site

The experimental site was located at the research farm of Rajendra Agricultural University, Samastipur, Bihar, India (25°35′N, 85°24′E). The soil of the experimental site was classified as Illitic Ustic Typic Calciorthent according to the soil taxonomy of USDA (Soil Survey Staff, 1975). At the time of establishing the experiment, the soil had 0.41% SOC in the upper 60 cm layer and was slightly alkaline (soil pH = 8.6). The available nitrogen (N), Olsen phosphorus (P) and 1 N NH_4OAc-extractable potassium (K) contents of the soil were 112, 14 and 60 mg/kg, respectively. The climate was characterized by hot and humid summers and cold winters with an average annual rainfall of 1344 mm, 70% of which falls between July and September. The experimental area had been under an intensive tillage-based RW system for more than 50 yr.

Treatments and experimental design

The long-term experiment was established in summer 2006 involving eight combinations of tillage, crop establishment and residue management practices in a RW rotation. Here, we report on the six treatments shown in Table 1. The whole

Table 1 Treatment details included in the study

Treatment description	Residues removed	Abbreviation
Conventionally tilled puddled transplanted rice followed by conventional tilled wheat	95% both crops	CTR-CTW
Conventionally tilled puddled transplanted rice followed by zero-tilled wheat	95% both crops	CTR-ZTW
Zero-tilled direct dry-seeded rice followed by conventional tilled wheat	95% both crops	ZTDSR-CTW
Zero-tilled direct dry-seeded rice followed by zero-tilled wheat	95% both crops	ZTDSR-ZTW
Zero-tilled direct dry-seeded rice followed by zero-tilled wheat with residue retention	50% rice and 75% wheat	ZTDSR-ZTW+R
Direct dry-seeded rice followed by direct drilling of wheat both on permanent beds with residue retention	50% rice and 75% wheat	PBDSR-PBW+R

experimental area was divided into three blocks of equal sizes. Treatments were imposed in such as a way to keep three replicates of a treatment in the same strip for the ease of management (movement of seed drills). This was possible because the soil in the field was homogeneous and has been under the same management for more than 50 yr.

Tillage, crop establishment and residue management

For CTR, tillage operations included three dry harrowings (about 0.15 m depth) followed by two puddlings (wet tillage) and planking (levelling the field with wooden planks) after ponding with water. Rice seedlings (25 days old) were transplanted manually in a random fashion at a rate of 30 seedlings/m^2. In PBDSR, rice seeds were directly drilled on raised beds (0.1–0.12 m height) in two rows (0.3 m apart) using a multicrop raised bed planter. In ZTDSR, rice seeds were directly drilled at 0.2-m row spacing using a ZT seed-cum-fertilizer planter.

During the wheat cycle, CTW was established by broadcasting 150 kg seed/ha after two harrowings and one ploughing with the cultivator (about 0.15 m depth) followed by planking at optimum soil moisture content. In the case of ZTW, wheat seed was drilled using a ZT seed-cum-fertilizer planter at 0.2-m row spacing without any preparatory tillage. In PBW, two rows of wheat (0.3 m apart) were directly drilled on each raised bed using a multicrop raised bed planter. Each year, the permanent beds were reshaped during wheat planting.

In ZTDSR-ZTW+R and PBDSR-PBW+R treatments, 50% of rice residues and 25% of wheat residues (by weight) were retained, whereas almost all (95%) the aboveground biomass was removed from the plots in the other treatments (Table 1). The basis for deciding the quantity of the residues retained in ZTDSR-ZTW+R and PBDSR-PBW+R was to minimize the trade-off between their use as a soil mulch and for other purposes such as livestock feed and cooking fuel.

Agronomic management

Irrespective of the treatment, both rice and wheat crops were fertilized at the rate of 150, 60 and 40 kg/ha of N, P_2O_5 and K_2O, respectively. All P_2O_5 plus 15% of N (as di-ammonium phosphate) and all K_2O (as muriate of potash) were applied with a seed-cum-fertilizer drill at sowing in the case of ZT and broadcasted followed by planking in the case of CT. The remaining N (as urea) was top-dressed in two equal splits at 20–25 and 40–45 days after seeding/transplanting. In the PB and ZT plots, weeds present prior to the seeding of rice and wheat were controlled by a preplanting application of glyphosate (1.25 g a.i./ha), but no herbicide was applied in CT plots. Later, weeds in the experimental plots were controlled using pre- and post-emergence herbicides as required. Normally, seeding of DSR was performed in June by utilizing *in situ* moisture following pre-monsoon showers. The DSR plots were irrigated only when no rain fell for 10 consecutive days after seeding. The DSR plots were irrigated at the same time as the CTR plots for puddling and transplanting operations. The total number of irrigations in rice ranged from 6 to 8 depending upon the frequency of rainfall and moisture status in different years. Wheat received four irrigations during its growth period at 20–25, 45–50, 75–80 and 95–100 days after sowing. Both rice and wheat were irrigated (with about 0.05 m of water) using the flood irrigation method.

Harvesting and biomass measurement

Aboveground residue (straw) yield in each plot was determined by harvesting the crops from three randomly selected quadrats of 5 m^2. The dry residue returned to the soil was calculated as a fraction of straw yield returned to the field. The carbon (C) input was estimated assuming a concentration of 0.45 kg C per kg dry matter of rice and wheat residue (Johnson *et al*., 2006).

Soil sampling and laboratory analysis

Initial soil sampling was performed by taking six cores at random from the experimental field after wheat harvest just before the start of the experiment in 2006; these were analysed for basic soil properties such as soil texture, pH, available NPK, bulk density and SOC. Soil sampling for this study was undertaken in 2013 after the wheat harvest, to determine the effect of treatments on bulk density and SOC. In each plot, three subsamples were taken from four soil depths, *viz*. 0–0.05, 0.05–0.15, 0.15–0.3 and 0.3–0.6 m with a 0.038 m i.d. core sampler (Eijkelkamp, the Netherlands). For the permanent bed treatment (PBDSR-PBW+R), two subsamples from the ridge and one subsample from the furrow were collected to represent the proportional area covered by ridge and furrow. The soil bulk density was calculated as the ratio between the oven-dried (105 °C for 24 h) weight and bulk volume of the soil. For SOC determination, the subsamples were mixed thoroughly to create a bulk sample. Upon arrival at the laboratory, the soil samples were air-dried, ground and sieved with 2-mm mesh for subsequent analysis of SOC by chromic acid wet oxidation (Walkley & Black, 1934). The SOC stock in each depth was calculated from the SOC concentration and soil bulk density using equation (1).

$$\mathrm{SOC\ (t/ha)} = \{\mathrm{SOC\ concentration\ (\%)} \times \mathrm{bulk\ density\ (t/m^3)} \times \mathrm{depth\ (m)} \times 100\} \quad (1)$$

The SOC stock for 0- to 0.6-m soil profile was obtained by summing up the SOC stock for all four layers.

The amount and rate of SOC sequestration were calculated as follows:

$$\text{Sequestered SOC (t/ha)} = \text{SOC}_f - \text{SOC}_i \quad (2)$$

$$\text{SOC sequestration rate (t/ha/year)} = \text{sequestered SOC/years of experimentation} \quad (3)$$

where SOC_f and SOC_i indicate the SOC stocks in April 2013 (current) and those at the start of the experiment (in May 2006), respectively.

Statistical analysis of data

Biomass yield, soil bulk density and SOC data were subjected to analysis of variance (ANOVA) for a randomized complete block design using CoStat software (CoHort, 2012). Before analysis, the Bartlett test was performed to test the homogeneity of the error variances. Differences between treatment means were compared using Tukey's HSD test at $P < 0.05$ (Gomez & Gomez, 1984). The tillage effect on SOC was determined by deducting the SOC concentration of CT plots from that of ZT plots. Similarly, the combined effect of tillage and residue on SOC was determined by deducting the SOC concentration of CT from that of ZT+R treatment.

Results

Residue yield and carbon input

Tillage and crop establishment method both had a significant effect on total crop residue production. In the first year, the highest residue yield was under CTR-CTW (Figure 1). Thereafter, the residue yield was higher in treatments where at least one crop was under ZT. Treatment ZTDSR-ZTW+R produced significantly lower residue yield than CTR-CTW in the first year, but it out-yielded the CT system in the fourth year and thereafter (Figure 1). In the 6th and 7th years, total residue yield was the highest in ZTDSR-ZTW+R followed by PBDSR-PBW+R. Total cumulative residue production was also highest in ZTDSR-ZTW+R and ZTDSR-CTW and lowest in CTR-CTW and CTR-ZTW (Figure 1). The variation in residue yield together with variations in the proportion of residue returned to the system resulted in differential carbon input to the soil over seven years (Table 2). Seven years' cumulative carbon inputs from aboveground residues were almost three times higher in ZTDSR-ZTW+R and PBDSR-PBW+R compared with the other treatments (Table 2).

Bulk density

Significant effects of treatments on soil bulk density were visible only up to 0.3 m depth (Table 3). In the surface 0–0.05 m, bulk density was significantly higher ($P = 0.009$) in CTR-CTW compared with all other treatments except ZTDSR-ZTW and ZTDSR-CTW (Table 3). At 0.05–0.15 and 0.15–0.3 m soil depths, bulk density was, in general, significantly lower in ZTDSR-ZTW+R and PBDSR-PBW+R than in the other tillage and crop establishment methods. Treatment effects on bulk density were also statistically significant when averaged over the whole 0.6 m depth.

Soil organic carbon concentration

Treatments had a significant effect on SOC concentrations at different soil depths (Figure 2). Variation in the SOC

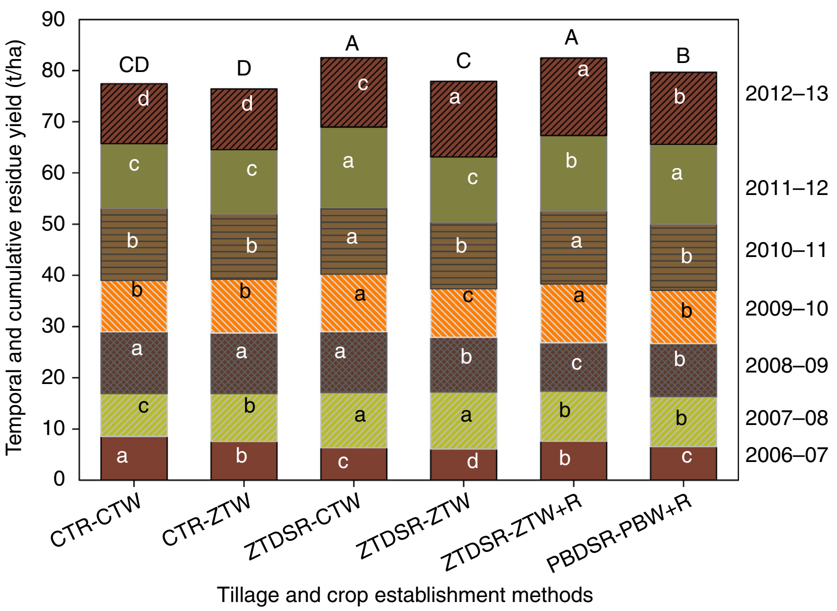

Figure 1 Total residue yield of RW system as affected by different tillage and crop establishment methods. Total residue yield is the summation of straw yield of the RW system in each year of experimentation stacked above each other to present the cumulative yield over seven years. Within crop year, means bearing different lowercase letters are significantly different from each other, and seven year cumulative means bearing different uppercase letters are significantly different from each other based on Tukey's HSD test ($P = 0.05$). Refer to Table 1 for treatment descriptions. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 2 Estimated total carbon input (t/ha) from aboveground biomass over seven years under different treatments

	Carbon input from residue retention		
Tillage and crop establishment method[a]	Rice	Wheat	Total
CTR-CTW	1.97	1.14	3.10
CTR-ZTW	1.98	1.14	3.12
ZTDSR-CTW	1.98	1.38	3.35
ZTDSR-ZTW	1.84	1.37	3.21
ZTDSR-ZTW+R	10.73	3.91	14.64
PBDSR-PBW+R	10.84	3.55	14.38

[a]Refer to Table 1 for treatment descriptions.

Table 3 Soil bulk density across different soil depths under different tillage and crop establishment methods

Tillage and crop establishment method[a]	Depth (m)				
	0–0.05	0.05–0.15	0.15–0.3	0.3–0.6	0–0.6
	Bulk density (t/m^3) [b]				
CTR-CTW	1.55a	1.58a	1.58a	1.55	1.56a
CTR -ZTW	1.46b	1.58ab	1.57a	1.53	1.55a
ZTDSR-CTW	1.47ab	1.54bc	1.58a	1.53	1.54ab
ZTDSR-ZTW	1.50ab	1.58ab	1.56ab	1.54	1.55a
ZTDSR-ZTW+R	1.46b	1.51c	1.52b	1.51	1.51bc
PBDSR-PBW+R	1.45b	1.52c	1.51b	1.52	1.50c
MSD	0.04	0.05	0.05	0.04	0.03
Treatment effect (*P*-value)	0.009	<0.001	0.002	0.21	<0.001

[a]Refer to Table 1 for treatment descriptions. MSD, minimum significant difference. [b]Means in each column followed by different letters differ significantly from each other based on Tukey's HSD test ($P = 0.05$).

concentration between different treatments was highest in the top 0.15 m of soil, with values generally declining with depth (Figure 2). On average, ZTDSR-ZTW+R and PBDSR-PBW+R had 86, 32 and 13% higher SOC concentrations than CTR-CTW at 0–0.05, 0.05–0.15 and 0.15–0.3 m soil depths, respectively, but 5% less than that of CTR-CTW at the lowest soil depth (Figure 2). ZTDSR-ZTW had 50 and 26% higher SOC concentrations than CTR-CTW at 0–0.05 and 0.05–0.15 m soil depths, but 5 and 10% lower concentrations than CTR-CTW at 0.15–0.3 and 0.3–0.6 m soil depths, respectively.

Soil organic carbon stock

Treatment effects on SOC stock were significant at 0–0.05 and 0.05–0.15 m soil depths only (Table 4). At 0–0.05 m, ZTDSR-ZTW+R and PBDSR-PBW+R, on an average, had significantly higher SOC stocks, that is 2.4 t/ha more than CTR-CTW (Table 4). ZTDSR-ZTW, ZTDSR-ZTW+R and PBDSR-PBW+R had a similar improvement in total SOC at 0.05–0.15 m, which was significantly higher (by about 2.0 t/ha) than for CTR-CTW (Table 4). All the treatments had similar SOC stocks at 0.15–0.3 m and 0.3–0.6 m soil depths. Calculations for the whole 0–0.6 m depth showed that ZTDSR-ZTW+R and PBDSR-PBW+R contained 5.6 t and 3.9 t/ha more SOC than CTR-CTW, respectively.

Between 2006 and 2013, ZTDSR-ZTW+R increased the total SOC stock in the 0–0.6 m soil depth by 17.5% corresponding to a gain of 0.7 t SOC/ha/yr. In contrast, CTR-CTW and CTR-ZTW decreased SOC by 1–3% in the same depth corresponding to a loss of 0.13–0.06 t SOC/ha/yr. Similarly, PBDSR-PBW+R and ZTDSR-ZTW increased SOC by 11.3 and 4.4% corresponding to a gain of 0.4 and 0.2 t SOC/ha/yr, respectively (Table 4). The rate of SOC increase with the CA-based practices was highest in the top 0- to 0.05-m soil layer, that is 69, 52 and 37% in ZTDSR-ZTW+R, PBDSR-PBW+R and ZTDSR-ZTW, respectively. Tillage and crop establishment methods had no significant effect on the SOC stock in the 0.15–0.6 m soil depth.

In the RW system, ZT in wheat alone increased SOC stocks by 0.07 t/ha/yr at the 0.6 m soil depth compared with the conventional control (CTR-CTW), whereas ZT in rice alone increased SOC stock by 0.15 t/ha/yr (Figure 3). ZT in both crops increased SOC stock by 0.29 t/ha/yr compared with the CT system; this further increased to 0.8 t/ha/yr with the retention of residues in the ZT system (Figure 3).

Discussion

The increase in SOC concentration at 0.15 m soil depth in ZT systems compared with the other treatments (Figure 2) could be due to (i) surface retention of crop residues (or stubbles in the case of no residue), (ii) higher plant biomass production (Jat *et al.*, 2014) leading to large amounts of root residues left in the system and (iii) a lower rate of organic matter decomposition due to minimum soil disturbance. Higher SOC concentrations in surface soils under ZT compared to CT system have been also reported in the northwestern IGP of India by Gupta Choudhury *et al.* (2014) and were attributed to less disruption of macro-aggregates which protected SOC against oxidation. Our study demonstrated that CT with residue removal resulted in SOC decline in an RW system (Table 4). CTR-ZTW without residue retention, which is adopted by the majority of farmers in the region, also led to a net loss of 0.4 t SOC/ha corresponding to a loss of 0.06 t SOC/ha/yr over seven years. ZT in both crops without residue retention led to slightly less SOC below 0.15 m but significantly higher SOC at 0.15 m depth than under CT systems, corresponding to a net gain of 1.09 t SOC/ha over seven years. Retention of crop residue with both crops under ZT as well as bed

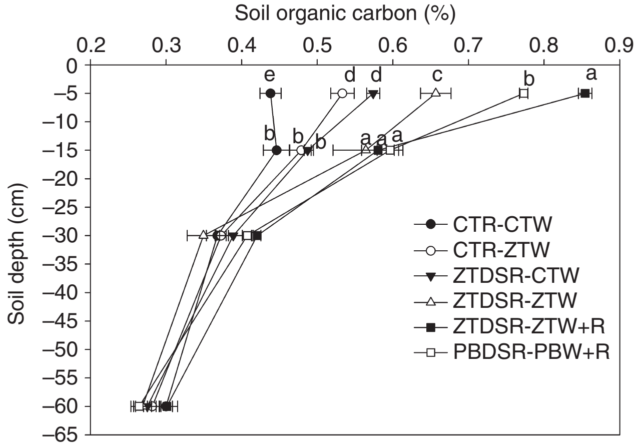

Figure 2 Organic carbon content (%) in different soil layers as affected by tillage and crop establishment methods. For each layer, values are presented at the bottom depth (e.g. −5 cm represents 0- to 5-cm soil layer). Within each layer, means bearing different lowercase letters are significantly different from each other based on Tukey's HSD test (P = 0.05). Horizontal bars are the standard errors of the means. Refer to Table 1 for treatment descriptions.

planting systems significantly increased SOC stocks compared with no residue retention (Table 4). Increased SOC stock under ZT with residue retention was mainly due to greater carbon inputs with crop residues (Table 2).

Our study showed that adopting ZT in both crops in the RW system without residue retention would sequester 0.3 t more SOC/ha/yr than growing both crops under a CT system. This is consistent with findings reported by other researchers from the IGP (Grace *et al.*, 2012; Powlson *et al.*, 2016) as well as other regions of the world (Mazzoncini *et al.*, 2011; Virto *et al.*, 2011; Stockmann *et al.*, 2013; Tian *et al.*, 2013; Powlson *et al.*, 2014). For example, Grace *et al.* (2012) made a regional assessment of the impact of ZT in India using the IPCC (Intergovernmental Panel on Climate Change) methodology and reported that changing wheat-based production from CT to ZT in the IGP could sequester 0.2–0.4 t C/ha/yr. Similarly, Powlson *et al.* (2016) cited a value of 0.3 t C/ha/yr for ZT systems in the IGP based on published data. There are also several studies reporting no measurable increase in SOC under CA compared to CT systems (West & Post, 2002; Ludwig *et al.*, 2011). A few studies have reported higher SOC under CT than ZT when the comparison was made using a deeper soil profile i.e. 1 m or more (Black & Tanaka, 1997; Li *et al.*, 2007). Some researchers have reported increases in SOC in the surface soil but decreases below the plough layer, indicating redistribution of the SOC pool (Baker *et al.*, 2007; Xu *et al.*, 2007). Decline in the SOC pool under NT is mainly related to lower input of biomass carbon into the system either because of low productivity or harvesting of residues (Kim *et al.*, 2009). Similarly, differences in soil moisture and temperature

Table 4 Effect of various tillage and crop establishment methods on soil organic carbon (SOC) stock and its change compared to the initial stock after seven years

	Depth (m)				
	0–0.05	0.05–0.15	0.15–0.3	0.3–0.6	0–0.6
Tillage and crop establishment method[a]	Total SOC (t/ha)[b]				
CTR-CTW	3.5e	7.1c	8.7	7.0	26.2c
CTR-ZTW	3.9d	7.6bc	8.8	6.5	26.7c
ZTDSR-CTW	4.2d	7.5bc	9.2	6.3	27.3c
ZTDSR-ZTW	4.9c	8.9ab	8.2	6.2	28.2bc
ZTDSR-ZTW+R	6.1a	9.0ab	9.8	6.8	31.8a
PBDSR-PBW+R	5.5b	9.3a	9.3	6.0	30.1ab
MSD	0.4	1.7	2.0	1.4	2.49
Treatment effect (P value)	<0.001	0.04	0.158	0.267	<0.001
Initial SOC content	3.6 ± 0.15	8.1 ± 1.39	8.78 ± 1.07	6.7 ± 0.73	27.1 ± 1.21
Change in SOC over seven years (t/ha)					
CTR-CTW	−0.16	−0.99	−0.04	0.28	−0.90
CTR-ZTW	0.28	−0.50	0.01	−0.20	−0.41
ZTDSR-CTW	0.62	−0.57	0.45	−0.34	0.16
ZTDSR-ZTW	1.34	0.84	−0.62	−0.46	1.09
ZTDSR-ZTW+R	2.49	0.96	1.04	0.16	4.66
PBDSR-PBW+R	1.89	1.22	0.51	−0.64	2.98

[a]Refer to Table 1 for treatment descriptions. MSD, minimum significant difference. [b]For total SOC, means in each column followed by different letters differ significantly from each other based on Tukey's HSD test (P = 0.05).

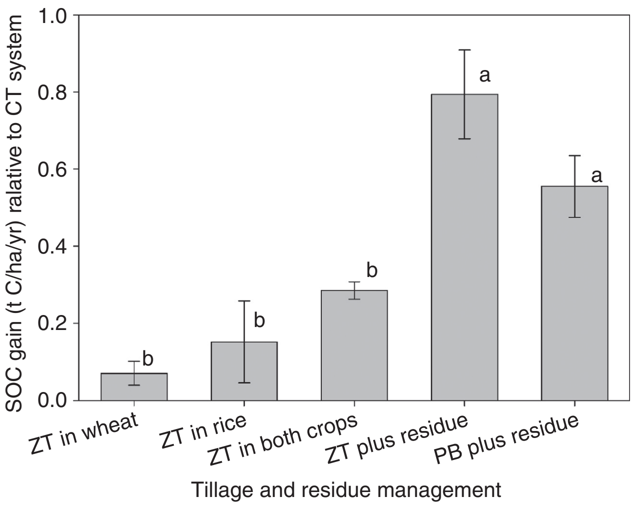

Figure 3 Gain in organic carbon stock in 0 to 0.6 m soil layer due to adoption of various components of CA over conventional control in a RW system. Values are means of difference in soil organic carbon (SOC) change between respective treatments and conventional system (CTR-CTW). ZT is zero tillage, and PB is permanent bed. The bars bearing different lowercase letters are significantly different from each other based on Tukey's HSD test (P = 0.05).

regimes, and susceptibility to erosion are some of the factors explaining the variations in SOC sequestration under CA versus CT (Lal, 2015). Marked stratification of SOC in the surface layer under ZT than CT can be attributed to application of crop residues and other biomass on the surface in ZT and incorporation within the plough layer in CT systems. Therefore, it is important to identify which management systems are suitable for enhancing carbon sequestration under different soil types and agroecosystems.

In our study, residue yield was always higher under ZT systems from the first year of the experiment (Figure 1) and carbon input from crop residues was almost four times higher in ZT with residue retention treatments (Table 2) compared with CT treatments. Residue retention under ZT system substantially increased SOC stocks (by about three times) compared with no residue retention (Figure 3), corroborating the earlier findings which suggested that SOC gains are largely determined by the quantity of organic matter returned to the soil (Giller *et al*., 2009; Virto *et al*., 2011). Surface placement of crop residues coupled with ZT reduced the rate of decomposition and carbon loss due to limited contact of residue with soil and suboptimal moisture content, thereby increasing SOC content (Yadvinder-Singh *et al*., 2010).

The loss of SOC through the disruptive effect of tillage under CT systems is well known. The treatments with one crop under ZT in RW system showed intermediate changes in SOC (i.e. higher than both crops under CT but lower than both crops under ZT) with ZT in rice being more effective in terms of increasing SOC compared to ZT in wheat (Table 4). This is probably because of the major disruption of soil macro- and microaggregates during puddling (CT) for rice (Gathala *et al*., 2011b) exposing SOC to microbial decomposition compared to CT for wheat. The cumulative carbon input from aboveground biomass after 7 yr was about three times greater in ZTDSR-ZTW+R and PBDSR-PBW+R than the other treatments, which increased total SOC by 4.7 and 3.0 t/ha at 0–0.6 m depth, respectively. Higher net SOC gain under the ZTDSR-ZTW+R than in PBDSR-PBW+R (Table 4) was due to higher biomass C input (Table 2), coupled with less disturbance compared to bed planting. The permanent beds were reshaped once a year during wheat seeding which resulted in the incorporation of about 30% of surface residues, probably leading to enhanced mineralization and loss of SOC compared with ZT where the residues were on a flat surface.

Our study suggests that crop residues need to be retained to achieve sizable gains in SOC under ZT. The importance of livestock in the mixed farming systems typical of the study area and the competing use of residues for livestock feed is, therefore, a major disincentive for CA adoption by farmers. Substituting cereal residues with nutrient-rich feed for animal diets or increasing total residue production so that a portion of the residue can be returned to the field without compromising livestock feed may incentivize CA adoption. Further research with variable quantities of crop residue retention under CA is necessary to understand and quantify trade-offs between the benefit of crop residue retention to future crop productivity and soil quality, versus its value as a livestock feed in the study area.

Conclusion

This study compared changes in SOC in a CA-based RW system and its variants with a conventional RW system over a seven-year period. To our knowledge, this is first long-term experiment in eastern IGP comparing various combinations of tillage and crop establishment methods examining SOC sequestration in an RW system. The results showed that ZT combined with partial residue retention increased SOC stock at 0.6 m depth. Given the importance of crop residues as livestock feed in the mixed farming system of the study area, increased residue production under ZT and permanent bed with residue retention could provide an opportunity to retain a portion of crop residues in the field without compromising its uses elsewhere. Retaining crop residues in ZT system will not only reduce environmental pollution from residue burning but also improve soil quality.

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