



Effects of crop residue retention on soil carbon pools after 6 years of rice–wheat cropping system

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Abstract

Enhancing soil organic carbon (SOC) is an important strategy to sustain and improve the soil quality, mitigate climate change and increase crop productivity under intensive tillage-based rice–wheat (RW) system in the Indo-Gangetic Plains (IGP) of South Asia. Therefore, the effects of tillage, crop establishment, and residue management practices on total as well as different pools of SOC in a sandy loam after 6 years of RW system were studied. The imposed three main plot treatments to the rice plots were: (1) ZTDSR, zero till dry seeded rice; (2) CTDSR, conventional till dry seeded rice; and (3) PTR, conventional puddled transplanted rice, and the three sub-plot treatments in succeeding wheat were (i) CTW – R, conventional tillage (CT) wheat with both rice and wheat residues removed; (ii) ZTW – R, zero tillage (ZT) wheat with both the residues removed and (iii) ZTW + R, ZT wheat with rice residue. Total soil organic content increased by 6.5–12.5% and 3.1–12.9% in different soil layers up to 0–60 cm depth in ZTDSR followed by ZTW + R over PTR followed by CTW – R practices, respectively. The corresponding increase of the oxidizable C was 4.2–28.2% and 8.2–8.5%, respectively. Significant enhancement in all the carbon pools (non-labile, less labile, labile, very labile pools, water soluble and microbial biomass carbon) and glomalin content were also recorded in ZTW + R treatment. The carbon management index was significantly higher in ZTW + R than ZTW – R and CTW – R treatments. In conservation-based agriculture systems, the principal component analysis revealed that passive pools of SOC and microbial biomass carbon were the most promising and reliable indicators for assessing soil quality. This study showed that adoption of ZTDSR followed by ZTW + R was the better crop production strategy for increasing C-sequestration, improving and sustaining the soil quality and crop productivity in the RW system. This practice also provides an opportunity to retain crop residues as an alternative to burning, which causes severe air pollution in the RW system in the IGP of South Asia.

Keywords ZT, zero tillage · Residue · DSR, direct seeded rice · RW, rice–wheat

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Introduction

Rice–wheat (RW) is one of the most widely practiced cropping systems in the Indo-Gangetic Plains (IGP) of South Asia. In India, it covers an area of about 10 million hectares (M ha) and produces about 50% of the total food grains consumed in the country (Ladha et al. 2009; Singh et al. 2014). A number of problems (e.g., over-exploitation of groundwater, degradation of soil quality, decline in nutrient supply capacity of soil, environment pollution due to residue burning, low profit margin, etc.) have cropped-up with the adoption of conventional RW system for the last four decades, and are threatening the sustainability of this important cropping system (Humphreys et al. 2010; Dwivedi et al. 2012; Bhattacharyya et al. 2013; Yadvinder-Singh et al. 2014; Parihar et al. 2016). To address these challenges, various soil and

crop management practices such as crop rotations, tillage and crop establishment, residue retention and site-specific nutrient management are being developed and promoted to enhance productivity and profitability (Gathala et al. 2013; Jat et al. 2016).

Combine harvesting of both rice and wheat is now a common practice with farmers in northwestern India which leaves large amounts of residues on the field. These residues interfere with the normal tillage practices. While wheat residues are collected by a special machine for use as animal fodder, rice residue has no economical use which remains scattered in the field are generally burnt by the majority of the farmers. Annually about 24 million tons (Mt) of rice residues are burned in North-West India, and are causing loss of SOC and essential plant nutrients (mainly N and S) and posing the serious threat to soil and environmental health (Mandal et al. 2007; Yadvinder-Singh and Sidhu 2014) and decreased microbial diversity (Zhang et al. 2014). In contrast, surface retention/incorporation of crop residues returns the much needed carbon (C) and plant nutrients back to the soil and thus increases soil organic carbon (SOC) and soil quality (Yadvinder-Singh et al. 2014; Bera et al. 2017; Jat et al. 2018). Tillage is known to adversely affect both soil microbial population (Vaughan et al. 2011; Choudhary et al. 2018) and mineralizable carbon because it allows fast breakdown of SOC (Franzluebbers 2005). The conservation agriculture (CA)-based practices have the ability to change the C storage capacity of agricultural soils depending upon regional climate and soil type (Halvorson et al. 2002; Lal 2004; Russell et al. 2005).

Soil organic carbon plays an important role in improving all major indicators of soil quality (structure, water relations, chemical fertility, biodiversity and enzyme activity) (Loveland and Webb 2003). The SOC content consists of different pools which are generally characterized by different physical, chemical and biological methods. The active fractions of SOC such as labile are subjected to rapid change due to management compared with non-labile pools (Paul et al. 2001). Thus, measurement of labile fractions of SOC can provide a more sensitive appraisal and indication of the effects of tillage and residue management practices on soil quality (Franzluebbers and Arshad 1997). Another important soil quality indicator is glomalin content which also contributes to C pools by slowing down the SOC decomposition rate in the soils (Rillig et al. 2003; Lovelock et al. 2004) and could even be involved in C-sequestration (Rillig et al. 1999). Additionally, it is important in forming and stabilizing aggregates which play significant roles in water infiltration, water retention and linkage between levels of soil disturbance and the types and amounts of photo synthetically derived carbon going belowground, especially as it relates to the plant–mycorrhizal relationship (Wright and Anderson 2000). Carbon management index (CMI) has also proposed

as a sensitive measure of the rate of change in the soil C dynamics of a system relative to a more stable reference soil and is useful in monitoring the differences in C dynamics between treatments on long-term basis (Blair et al. 1995).

While a considerable amount of research related to changes in C has been conducted under CA based practices on soil C sequestration, CMI and C pools in different soils and cropping systems in developing countries, especially in South Asia. Earlier studies from IGP of India showed that both zero tillage (ZT) and residue retention/incorporation resulted in higher soil C retention and thus, sustained crop productivity (Das et al. 2014). It is important to assess changes in C pools and CMI for specific climate, soil and cropping systems in order to draw site-specific conclusions. Limited information is available on the effect of CA-based practices on C pools and CMI in soil under RW production system. Therefore, present study was conducted to quantify the effects of tillage, crop establishment and residue management practices with respect to distribution of carbon pools of varying lability, glomalin content and CMI on a sandy loam soil after 6 years of RW system in the IGP.

Materials and methods

Description of the experimental site and climate

A long-term field experiment on irrigated system was started in 2010 at the experimental farm of the Punjab Agricultural University, Ludhiana, Punjab (30°56'N and 75°52'E) in the IGP of NW India. The soil of the experimental field is a Typic Ustochrept sandy loam (1.30% clay, 15.0% silt and 72.0% sand). Surface layer (0–15 cm) of soil at the initiation of experiment was non-saline (electrical conductivity 0.36 dS m⁻¹) with pH (1:2 soil: water) 7.88 and contained 4.5 g oxidizable carbon kg⁻¹ of soil (Walkley and Black 1934), 8.2 mg kg⁻¹ 0.5 M NaHCO₃-extractable P (Olsen et al. 1954) and 50.4 mg kg⁻¹ of soil 1 N NH₄OAc-extractable K (Knudsen et al. 1982). The region has a sub-tropical climate, with hot, wet summers and cool dry winters. Annual mean rainfall is 760 mm, about 80% of which occurs from June to September. The long-term average (30 years) mean minimum and maximum temperatures in wheat (November–April) are 6.7 °C and 22.6 °C while in rice (June–October) are 18 °C and 35 °C, respectively. The weather conditions at the experimental location during rice and wheat growing seasons were quite variable in all the 6 years of experimentation (Table 1). This showed uncertainty of weather and hence climate resilient management practices are very crucial for sustainable production.

Table 1 Mean monthly meteorological observations during 2010 through 2015

Parameters	June	July	August	September	October	November	December	January	February	March	April	May
2010–2011												
Max temp (°C)	36.9	33.1	33.2	31.9	31.9	28.6	20.8	15.6	20.0	27.4	32.4	38.0
Min temp (°C)	26.0	27.2	26.5	23.9	20.3	13.8	5.7	5.0	8.3	13.0	16.7	23.0
Rainfall (mm)	193.9	223.4	112.2	118.5	8.8	0.0	17.6	5.4	44.2	6.5	24.7	40.4
2011–2012												
Max temp (°C)	37.4	33.2	32.6	32.2	32.8	28.8	22.1	16.6	19.3	24.4	31.4	35.9
Min temp (°C)	24.9	26.5	26.1	25.4	21.0	13.5	7.1	5.9	6.2	9.6	16.0	19.8
Rainfall (mm)	258.5	218.8	507.0	183.5	0.0	0.0	11.4	52.6	1.2	0.0	23.2	16.7
2012–2013												
Max temp (°C)	40.3	38.5	34.6	34.4	32.4	27.8	20.2	17.5	21.0	28.2	34.2	40.3
Min temp (°C)	24.0	27.4	27.3	26.0	19.3	11.6	7.5	5.7	9.4	13.9	18.3	23.4
Rainfall (mm)	0.0	22.1	138.5	193.1	27.1	1.0	17.4	30.8	71.8	35.6	4.4	1.2
2013–2014												
Max temp (°C)	36.3	34.7	33.1	33.4	30.6	25.8	19.8	17.5	19.6	25.3	32.7	37.6
Min temp (°C)	27.0	27.7	26.3	24.0	18.2	9.7	7.4	6.9	8.0	12.5	16.6	22.8
Rainfall (mm)	296.7	159.1	205.1	59.9	13.2	4.6	13.2	4.5	5.8	8.5	10.1	9.3
2014–2015												
Max temp (°C)	40.6	35.5	34.1	31.3	31.2	26.9	17.8	15.6	22.2	25.5	32.6	39.6
Min temp (°C)	27.1	27.9	26.9	23.4	18.9	10.9	7.0	7.1	10.5	13.1	19.5	23.7
Rainfall (mm)	16.3	6.3	7.4	7.7	6.0	7.1	4.2	3.2	5.6	7.7	8.5	17.0

Experimental layout and treatments

The field experiment was laid out in a split plot design with three replications. Treatments consisted of three systems of rice establishment (CTDSR, conventional till dry seeded rice; ZTDSR, zero till dry seeded rice; and PTR, conventional till puddled transplanted rice) in main plots and three combinations of tillage and residue management (CTW – R, CT wheat with residues of both the crops removed; ZTW – R, ZT wheat with residues of both the crops removed and ZTW + R, ZT wheat with rice residue in sub-plots in the subsequent wheat crop. The sub-plot size was 5.4 m × 20.0 m. The treatments were assigned to the same experimental plots in all the study years. The treatment details are summarized in Table 2.

Soil and crop management

Tillage and crop establishment

All the plots after wheat harvest remained fallow until pre-sowing irrigation for rice planting was applied in first week of June. In PTR, preparatory tillage included disking twice followed by two cultivator operations in standing water to puddle the soil followed by planking. ZTDSR was planted in a single operation using zero-till-fertilizer cum seed drill at 20 cm row spacing. In CTDSR, plots were prepared by two harrowings + two passes of tyne plough

followed by planking. In PTR, rice (variety PR 115) was transplanted manually using 30-day-old seedlings spaced at 15 cm × 20 cm in the second week of June each year during each year. DSR was seeded in the first week of June in rows at 20 cm row to row spacing using a seed rate of 20 kg ha⁻¹. Rice was harvested manually at ground level in – R treatments and whole of the residue was removed from the plots. Combine harvester fitted with straw spreader was used in + R plots and entire amount of the rice residue was retained in the field. Turbo Happy Seeder (THS) capable of sowing wheat in heavy loads of rice residue was used for planting wheat in + R plots (Sidhu et al. 2015). Wheat (variety HD 2967) was seeded with THS in rows at a distance of 20 cm between rows in all the plots during first fortnight of November in different years of experimentation. Rice plots were harvested between 10th and 20th October, and wheat plots were harvested between 18th and 24th April in different years of the study.

Fertilizer and water management

Rice received a uniform dose of 150 kg N ha⁻¹ as urea, 13 kg P ha⁻¹ as diammonium phosphate, 25 kg K ha⁻¹ as muriate of potash and 10 kg Zn ha⁻¹ as zinc sulphate (21% Zn). Whole amounts of P, K and Zn were applied at planting on all the plots. Fertilizer N to PTR was applied in three equal splits at transplanting and at 3 and 6 weeks after transplanting. In CTDSR and ZTDSR plots, fertilizer N was applied

Table 2 Description of treatments used in the study

Treatment detail	Abbreviation	Method of crop establishment
A. Rice (main plot treatments)		
Conventional till direct dry seeded rice	CTDSR	Residue of preceding wheat was removed. Tillage for DSR included two passes of harrows and two passes of tyne plough followed by leveling. The DSR was sown using inclined plate multi-crop planter ^a in rows 20 cm apart
Zero till direct dry seeded rice	ZTDSR	Residue of preceding wheat was removed. Zero till DSR was sown using inclined plate multi-crop planter ^a in rows 20 cm apart
Conventional till puddled transplanted rice	PTR	Residue of preceding wheat was removed. Pre-puddling tillage operations included two discings and two harrowings followed by plankings. Puddling (wet tillage) was done twice in 6–8 cm of standing water using a tractor-mounted puddler followed by planking. Rice seedlings were manually transplanted at 15 × 20 cm spacing
B. Wheat (sub-plot treatments)		
Conventional till wheat after removal of rice residue	CTW – R	Residue of previous rice crop was removed. Tillage operations included two passes of harrows and two passes of tyne plough followed by plankings. After pre-sowing irrigation, seed bed was prepared by two passes of tyne plough followed by planking. Wheat was sown using seed cum fertilizer drill in rows 20 cm apart
Zero till wheat after removal of rice residue	ZTW – R	Residue of previous rice crop was removed. Wheat was direct seeded in the no till plots in rows 20 cm apart using zero till seed cum fertilizer drill
Zero till wheat with 100% rice residue as mulch	ZTW + R	Residue of previous rice crop was retained. Wheat was direct seeded in rows 20 cm apart into rice residues using Turbo Happy Seeder (Sidhu et al. 2015) ^b

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^bM/S Kamboj Machinery Manufacturers, Ramdas, Amritsar, Punjab, India

in three equal split doses at 3, 5 and 9 weeks after planting. Wheat received a uniform dose of 120 kg N + 26 kg P + 25 kg K ha⁻¹. One-third of total N and entire amount of P and K fertilizers were drilled at the time of wheat sowing. The remaining 2/3 of N was applied in two equal split doses at just before each irrigation at 3 weeks (crown root initiation) and 7–8 weeks (maximum tillering) after planting. The PTR plots kept flooded (50 mm of standing water) for first 2 weeks, followed by irrigation (50 mm depth) 2 days after the disappearance of standing water from the previous irrigation till 15 days before maturity. To DSR (both CT and ZT), light irrigation (50 mm) was applied at 1 day after seeding to ensure satisfactory germination, and then at every 4–5 days interval until physiological maturity depending on the rainfall events during the growing season. Wheat was irrigated (each of about 75 mm) at critical growth stages (crown root initiation, maximum tillering, panicle initiation and dough) as recommended for the crop in the region.

Soil analysis

Soil sub-samples were collected after wheat harvest in duplicate from each plot from five layers (0–7.5, 7.5–15, 15–30, 30–45 and 30–60 cm) for carbon pools analysis and the surface layer (0–7.5 cm) was also used for analysis of enzyme

activities. After removing visible root debris, the soil samples were mixed and sieved (2 mm). Each sub-sample of 0–7.5 cm layer was divided into two portions. One portion of the sample was stored in a refrigerator for biological analyses and the other portion along with samples from remaining layers were air-dried and stored at room temperature for analysis of chemical pools of carbon.

The content of total SOC was determined by the dry combustion method of Houba et al. (1995). Briefly, a 10-g finely ground soil sample was dry combusted in a muffle furnace at 550 °C for 3 h, and the weight loss was considered as loss of carbon. Different fractions of SOC with varying lability were estimated following the Walkley and Black (1934) method as modified by Chan et al. (2001), which allowed separation of total SOC into the following four fractions of decreasing order of C oxidation as defined by Chan et al. (2001) that include (i) very labile SOC (frac₁) = organic C oxidizable under 6.0 mol L⁻¹ H₂SO₄; (ii) labile SOC (frac₂) = the difference in organic C oxidizable under 9.0 mol L⁻¹ and that under 6.0 mol L⁻¹ H₂SO₄; (iii) less labile SOC (frac₃) = the difference in organic C oxidizable under 12.0 mol L⁻¹ and that under 9.0 mol L⁻¹ (12.0 mol L⁻¹ H₂SO₄ is equivalent to the standard Walkley and Black method), and (iv) non-labile SOC (frac₄): the difference in total SOC and organic C oxidizable under 12.0 mol L⁻¹ H₂SO₄.

Water-soluble organic carbon (WSOC) was determined by shaking 10 g soil with 20 mL deionized water for 1 h (McGill et al. 1986). The OC content in the extracts was determined by wet digestion method. Humus fractions were estimated as outlined by Schnitzer (1982). Glomalin was estimated as described by Wright and Upadhyaya (1998). Microbial biomass carbon (MBC) was determined at the end of incubation by the chloroform fumigation extraction method (Vance et al. 1987) using a recovery factor of 0.41.

Carbon management index (CMI)

First step included computation of lability index (LI) for the SOC using three SOC pools (C frac₁, C frac₂ and C frac₃) as described above. The C frac₁, C frac₂ and C frac₃ have been designated as very labile, labile and less labile and are given weighting of 3, 2 and 1, respectively. Subsequently, their actual values were transformed to a proportional amount of TSOC and weighed with the weighing factor to get an LI for the organic carbon content in each of the soils under different depths (Blair et al. 1995):

$$LI = [(Cfrac_1/TSOC) \times 3 + (Cfrac_2/TSOC) \times 2 + (Cfrac_3/TSOC) \times 1]. \quad (1)$$

Second step included calculation of carbon pool index (CPI) using the formula:

$$CPI = \frac{\text{sample total C (mg kg}^{-1}\text{ of soil)}}{\text{reference total C (mg kg}^{-1}\text{ of soil)}}, \quad (2)$$

where reference total carbon is the total carbon content (mg kg⁻¹) of control plots (Blair et al. 1995). The CMI was calculated as follows:

$$CMI = CPI \times LI \times 100. \quad (3)$$

Carbon input calculations

Grain and straw yields were recorded over 5 years starting from the year 2010–2011. Amount of crop residue added in each plot was calculated using the database available in literature (Bronson et al. 1998; Mandal et al. 2007; Benbi and Brar 2009; Das et al. 2013) taking into consideration the yield data during the entire period of experimentation. The rhizodeposition of carbon in rice and wheat crops was taken as 15.0 and 12.6% of the total aboveground biomass (grain + residue) at harvest, respectively (Bronson et al. 1998). Similarly, root biomass of rice and wheat was taken as 17.7 and 13.5% of the total aboveground biomass, respectively, as calculated from the root:shoot ratios. The stubble biomass left in field was estimated at 10 and 4% of the residue biomass of rice and wheat, respectively. Stubble and root C concentrations were taken as 33.5 and 35.0% for rice and

41.9 and 39.3% for wheat, respectively (Mandal et al. 2007). The C concentration in rhizodeposition (74%) as reported by Benbi and Brar (2009) was considered for calculating total C input. Rice residue C concentration was assumed as 42% (Sharma et al. 2015). The cumulative C inputs to the soil were taken as the summation of biomass C input through stubble, root, rhizodeposition and C input through residue retention as per treatment combinations (Table 7).

Statistical analysis

All the data sets were analyzed using analysis of variance (ANOVA) and differences among treatments were compared at $p=0.05$ level of significance using the IRRISTAT package (IRRI 2000). To reveal the similarities and differences between samples and to assess the relationships between the observed variables, principal component analysis (PCA) (Wold et al. 1987) is used to create a minimum data set (MDS) to reduce the indicator load in the model and avoid data redundancy. The number of variables was reduced by excluding those that were less than 50% explained by the significant components in PCA. All the original observations (untransformed data) of each variable were included in the PCA model using SPSS, version 21.0 (SPSS 2014).

Results

Total and oxidizable organic carbon content

After 6 years of experimentation, significant variation was observed in depth-wise distribution of total SOC content under different imposed treatments in rice and wheat (Table 3). Among rice establishment methods, total SOC content in surface soil layer (0–7.5 cm) was significantly higher in ZTDSR than in CTDSR and PTR. On an average, ZTDSR showed 2.8% and 8.7% increase in total SOC content over CTDSR and PTR practice, respectively (Table 3). Similarly, CTDSR recorded 5.6% increase in total SOC content over PTR practice. The relative preponderance of oxidizable carbon content under different tillage practices was recorded in the order of: ZTDSR > CTDSR > PTR. Irrespective of tillage and rice establishment methods, there was considerable vertical variation in oxidizable carbon content. At 0–15 depth, oxidizable SOC content in ZTDSR was 4.7% and 7.4% higher compared with CTDSR and PTR, respectively. However, the differences were not significant at deeper soil depths (Table 3). Total SOC content in wheat under ZTW + R, irrespective of different methods of rice establishment was higher compared with ZTW – R, which has significantly higher than CTW – R (Table 3). In ZTW + R, total SOC content was increased by 2.3% and 3.2% compared with ZTW – R and CTW – R, respectively.

Table 3 Effect of tillage and cropping system on total soil organic carbon and oxidizable carbon in different soil layers after 6 years of rice–wheat cropping system

Treatment	Soil depth (cm)				
	0–7.5	7.5–15	15–30	30–45	45–60
Total soil organic carbon (g kg ⁻¹)					
Rice treatments					
ZTDSR	9.62	7.76	6.30	4.60	3.49
CTDSR	9.35	7.91	6.06	4.49	3.39
PTR	8.85	7.15	5.60	4.32	3.22
LSD (0.05)	0.30	0.20	0.44	0.15	NS
Wheat treatments					
CTW – R	9.19	7.42	5.47	4.13	3.25
ZTW – R	9.27	7.45	5.88	4.52	3.34
ZTW + R	9.48	7.69	6.22	4.74	3.55
LSD (0.05)	0.29	0.26	0.34	0.50	NS
Oxidizable carbon (g kg ⁻¹)					
Rice treatments					
ZTDSR	6.77	5.26	4.22	3.55	3.00
CTDSR	6.45	5.19	4.21	3.45	3.01
PTR	6.30	4.86	4.05	3.24	2.34
LSD (0.05)	NS	0.22	NS	NS	0.30
Wheat treatments					
CTW – R	6.43	4.87	3.98	3.24	2.57
ZTW – R	6.50	5.10	4.17	3.43	2.84
ZTW + R	6.80	5.35	4.31	3.66	3.04
LSD (0.05)	NS	0.26	0.24	NS	NS

Similarly, ZTW + R recorded significantly higher oxidizable carbon compared with ZTW – R which was significantly higher than CTW – R. The oxidizable carbon in ZTW + R treatment was 4.6% and 7.4% higher compared with ZTW – R and CTW – R, respectively.

Fractions of soil organic carbon

In surface (0–7.5 cm) and subsurface soil layers (7.5–15, 15–30, 30–45 and 45–60 cm), non-labile SOC content is the largest, followed by very labile, labile and less labile pools (Table 4). The rice establishment methods had greater impact on the very labile pool of total SOC in all the soil layers up to 60 cm depth. Compared with PTR, very labile C content increased with the adoption of ZTDSR or CTDSR. Residue retention ZTW + R plots increased very labile C content over ZTW – R and CTW – R at all the soil depths, but the increase was significant only at 7.5–15.0 cm depth. Under ZTW + R, 20.7% increase in very labile C content was observed over CTW – R plots in the 7.5–15.0 cm soil layer. Very labile C pool fraction under ZTW + R was significantly higher compared with ZTW – R and CTW – R. Distribution of labile C content also followed nearly similar pattern as

that for very labile SOC content at all the sampling depths and the significant effect of rice and wheat treatments on labile SOC content was observed only up to 0–30 cm soil layers (Table 4). ZTDSR treatment had significantly higher labile C content compared with PTR, irrespective of wheat treatments. Like very labile C content, labile and less labile C contents were generally significantly higher under ZTW + R compared with ZTW – R and CTW – R at 0–30 cm depth with few exceptions. The DSR (CT/ZT) plots had significantly higher less labile C content up to 45 cm depth compared with PTR. In wheat, ZTW + R had significantly higher less labile content compared with CTW – R at all the soil depths except at 0–7.5 cm and 30–45 cm depths. Non-labile C pool increased in ZTDSR compared with PTR at all the soil depths, however the differences were significant only at 0–7.5 cm and 15–30 cm depths (Table 4). ZTW + R showed a similar increasing trend in non-labile C content compared with ZTW – R and CTW – R at all the soil depths. Total amount of non-labile C content up to 60 cm depth was 7.26 and 9.50 g kg⁻¹ under CTW – R and ZTW + R, respectively.

Active and passive pools of carbon

Across the treatments, larger proportion of active and passive carbon pools were found in the surface soil layer (up to 0–7.5 cm depth) compared with subsurface soil layers (Table 5). Rice treatments showed no effect on active C pool at all the soil depths (up to 60 cm). The distribution of active C pool in soil varied significantly with different treatments applied to wheat up to 30 cm depth (Table 5). Passive pool of SOC was significantly affected by rice treatments at all the soil depths, except at 30–45 cm depth (Table 5). Both CTDSR and ZTDSR had significantly higher passive C pool compared with PTR. The increase in passive pool under ZTDSR was 18.4, 27.6, 42.5, 40.4 and 62.6% compared with PTR at 0–7.5 cm, 7.5–15.0 cm, 15–30 cm, 30–45 cm and 45–60 cm, respectively. Among the imposed wheat treatments, active and passive pools of SOC were significantly higher under ZTW + R compared with ZTW – R and CTW – R up to 30 cm and 60 cm depths, respectively (Table 5). In surface layer, active pool under ZTW + R was 8.6% and 13.2% higher compared with ZTW – R and CTW – R, respectively. The corresponding increases for passive C pool in ZTW + R were 10.2% and 19.8%.

Humus fractions

The main effects of rice treatments on different humus fractions, except fulvic-C were significant at 0–7.5 cm depth (Table 6). Non-humic-C (NH-C), fulvic acid-C (FA-C) and humic acid-C (HA-C) content in surface was higher by 36, 35.3 and 19.4% under ZTDSR and 26.5, 15.3 and

Table 4 Soil organic carbon (SOC) pools in different soil layer as affected by tillage, crop establishment and straw management practices after 6 years of rice–wheat system

Treatments	Soil depth (cm)				
	0–7.5	7.5–15	15–30	30–45	45–60
Very labile SOC (g kg⁻¹)					
Rice treatments					
ZTDSR	3.05	2.08	1.71	1.31	1.06
CTDSR	2.93	2.00	1.56	1.20	1.02
PTR	2.48	1.94	1.43	1.08	0.92
LSD (0.05)	NS	NS	NS	NS	NS
Wheat treatments					
CTW – R	2.67	1.83	1.49	1.12	0.86
ZTW – R	2.85	1.93	1.54	1.18	0.98
ZTW + R	2.98	2.21	1.64	1.25	1.05
LSD (0.05)	NS	0.19	NS	NS	NS
Labile SOC (g kg⁻¹)					
Rice treatments					
ZTDSR	2.31	1.78	1.53	1.32	1.10
CTDSR	2.22	1.61	1.37	1.12	0.80
PTR	1.62	1.29	1.05	0.86	0.75
LSD (0.05)	0.33	0.17	0.35	NS	NS
Wheat treatments					
CTW – R	1.89	1.32	1.01	0.86	0.72
ZTW – R	1.90	1.54	1.33	1.09	0.86
ZTW + R	2.17	1.69	1.40	1.18	0.98
LSD (0.05)	0.21	0.23	0.25	NS	NS
Less labile SOC (g kg⁻¹)					
Rice treatments					
ZTDSR	2.06	1.78	1.57	1.36	1.27
CTDSR	1.98	1.75	1.57	1.25	1.11
PTR	1.59	1.36	1.17	0.98	0.76
LSD (0.05)	0.36	0.31	0.23	NS	NS
Wheat treatments					
CTW – R	1.69	1.42	1.24	1.01	0.84
ZTW – R	1.77	1.57	1.47	1.14	0.97
ZTW + R	1.99	1.75	1.57	1.39	1.26
LSD (0.05)	NS	0.17	0.20	NS	0.32
Non-labile SOC (g kg⁻¹)					
Rice treatments					
ZTDSR	2.85	2.72	2.02	1.28	0.60
CTDSR	2.89	2.50	1.91	1.20	0.51
PTR	2.55	2.16	1.35	0.89	0.39
LSD (0.05)	0.26	NS	0.47	NS	NS
Wheat treatments					
CTW – R	2.46	2.27	1.36	0.88	0.29
ZTW – R	2.74	2.44	1.78	1.08	0.50
ZTW + R	2.98	2.54	1.97	1.32	0.69
LSD (0.05)	0.27	NS	0.28	NS	0.26

Table 5 Effect of tillage practices and cropping system on active and passive soil organic carbon pool in different soil layers after 6 years of rice–wheat cropping

Treatments	Soil depth (cm)				
	0–7.5	7.5–15	15–30	30–45	45–60
Active pools (g kg⁻¹)					
Rice treatments					
ZTDSR	5.36	3.86	3.24	2.63	2.16
CTDSR	5.14	3.61	2.92	2.32	1.82
PTR	4.11	3.22	2.48	1.94	1.67
LSD (0.05)	NS	NS	NS	NS	NS
Wheat treatments					
CTW – R	4.55	3.15	2.51	1.98	1.58
ZTW – R	4.74	3.48	2.88	2.27	1.84
ZTW + R	5.15	3.90	3.05	2.43	2.03
LSD (0.05)	0.40	0.63	0.44	NS	NS
Passive pools (g kg⁻¹)					
Rice treatments					
ZTDSR	4.90	4.49	3.59	2.64	1.87
CTDSR	4.87	4.25	3.49	2.45	1.63
PTR	4.14	3.52	2.52	1.88	1.15
LSD (0.05)	0.56	0.14	NS	0.51	0.53
Wheat treatments					
CTW – R	4.15	3.68	2.61	1.89	1.12
ZTW – R	4.51	4.03	3.15	2.22	1.47
ZTW + R	4.97	4.27	3.53	2.71	1.95
LSD (0.05)	0.42	0.45	0.68	0.58	0.41

18.4% under CTDSR compared with PTR, respectively. Irrespective of imposed rice treatments, all humus fractions was significantly affected by the treatments applied to wheat at all the soil depths (Table 6). The NH-C, FA-C and HA-C contents were 55.7, 34.5, and 21.3% higher in ZTW + R 15.8, 16.1 and 14.0% higher under ZTW – R compared with CTW – R, respectively. Among rice treatments, WSOC content in ZTDSR treatment was increased significantly by 10.0% and 15.6% compared with CTDSR and PTR, respectively (Table 6). In wheat treatments, the WSOC under ZTW + R was 22.1% and 58.4% higher compared with ZTW – R and CTW – R, respectively. Among rice treatments, MBC was significantly higher after ZTDSR compared with CTDSR and the lowest after PTR. At surface soil layer, MBC in ZTDSR treatment was increased significantly by 8.4% and 8.2% compared with CTDSR and PTR, respectively. Among wheat treatments, MBC was significantly higher under ZTW + R compared with ZTW – R and CTW – R. At surface soil layer, MBC under ZTW + R was 0.63% and 11.1% higher compared with ZTW – R and CTW – R, respectively.

Table 6 Effect of tillage practices and cropping system on humus and labile microbial fractions of carbon at surface 0–7.5 cm soil layer

Treatments	Non-humic-C (g kg ⁻¹)	Fulvic-C (g kg ⁻¹)	Humic-C (g kg ⁻¹)	WSOC (g kg ⁻¹)	MBC (μg g ⁻¹)
Rice treatments					
ZTDSR	4.20	1.15	3.76	86.0	214.6
CTDSR	3.91	0.98	3.73	78.0	197.8
PTR	3.09	0.85	3.15	74.4	198.3
LSD (0.05)	0.71	NS	0.39	6.7	6.6
Wheat treatments					
CTW–R	3.09	0.87	3.29	61.5	185.7
ZTW–R	3.58	1.01	3.75	79.8	205.1
ZTW+R	4.81	1.17	3.99	97.4	206.4
LSD (0.05)	0.54	0.20	0.24	6.8	4.0

WSOC water-soluble organic carbon, MBC microbial biomass carbon

Glomalin content

Glomalin contents were significantly affected by both rice and wheat treatments (Fig. 1). Among rice establishment methods, easily extractable glomalin (EEG) and total glomalin (TG) contents were lowest in PTR and highest under ZTDSR. The EEG in ZTDSR was 6.5% and 33.5% higher compared with CTDSR and PTR, respectively. The corresponding increase in TG content in ZTDSR was 0.5% and 3.0%. Both EEG and TG contents under ZTW + R, irrespective of different methods of rice establishment, were significantly higher compared with ZTW – R, which was significantly higher than CTW – R. The ZTW + R recorded significantly higher EEG content by 33.3% compared with ZTW – R which had 44.6% higher than CTW – R. Similarly, ZTW + R recorded 11.1% and 21.2% higher TG content compared with ZTW – R and CTW – R, respectively.

Carbon management index

The CMI up to 60 cm depth in ZTDSR was significantly higher by 27.9% compared with PTR (Fig. 2). Wheat treatments also showed significant effect on CMI in different soil layers. The CMI under ZTW + R was significantly higher compared with ZTW – R, which had significantly higher CMI than under CTW – R. The increase in CMI under ZTW + R was 9.8% and 20.9% compared with ZTW – R and CTW – R, respectively.

Total carbon input

Addition of crop stubble, root and rhizodeposition in general and residue retention in case of CTDSR-ZTW + R and ZTDSR-ZTW + R treatments, resulted in a substantial amount of organic C input to soil (Table 7). But, SOC followed a continuous decline in PTR practice. The amount of rice residue retained and the quantity of major nutrients

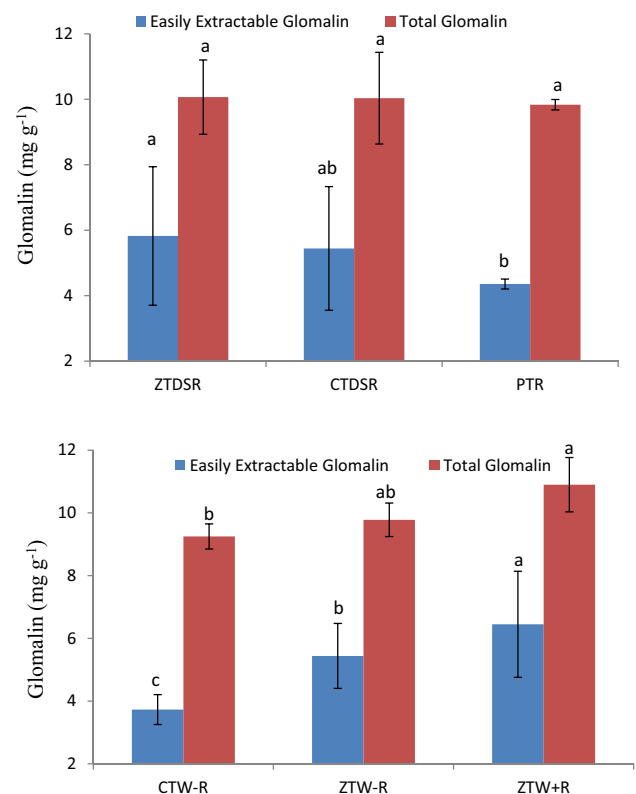


Fig. 1 Effect of tillage practices and cropping system on easily extractable glomalin and total glomalin. ZTDSR zero till direct dry seeded rice, CTDSR conventional till direct dry seeded rice, PTR conventional till puddled transplanted rice, CTW–R conventional till wheat after removal of rice residue, ZTW–R zero till wheat after removal of rice residue, ZTW+R zero till wheat with 100% rice residue as mulch

added through rice residue in different rice establishment methods in different experimentation years. The amount of rice residue added ranged from 7.72 to 8.15 Mg ha⁻¹ during the study period under the three rice establishment

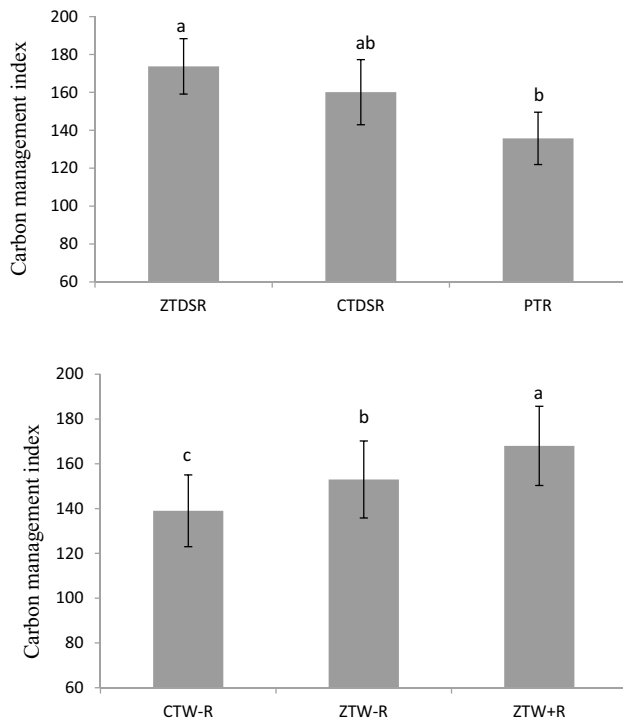


Fig. 2 Effect of tillage practices and cropping system on carbon management index. *ZTDSR* zero till direct dry seeded rice, *CTDSR* conventional till direct dry seeded rice, *PTR* conventional till puddled transplanted rice, *CTW-R* conventional till wheat after removal of rice residue, *ZTW-R* zero till wheat after removal of rice residue, *ZTW+R* zero till wheat with 100% rice residue as mulch

treatments. Total carbon input was found maximum in *CTDSR-ZTW+R* (30.9 Mg ha^{-1}) followed by *PTR-ZTW+R* (30.5 Mg ha^{-1}) and least in *ZTDSR-ZTW+R* (31.0 Mg ha^{-1}).

Table 7 An estimate of total organic inputs to soil under different treatments over 6 years

Treatments	Stubble biomass C (Mg ha^{-1})		Root biomass C (Mg ha^{-1})		Rhizodeposition biomass C (Mg ha^{-1})		Residue biomass C (Mg ha^{-1})	Total carbon input
	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	
							–	
<i>ZTDSR-CTW-R</i>	1.75	0.81	3.24	2.56	5.80	4.49	–	16.90
<i>ZTDSR-ZTW-R</i>	1.50	0.62	2.76	1.96	4.95	3.45	–	13.75
<i>ZTDSR-ZTW+R</i>	1.90	0.81	3.51	2.57	6.28	4.51	13.3	30.97
<i>CTDSR-CTW-R</i>	2.03	0.79	3.76	2.49	6.73	4.38	–	18.14
<i>CTDSR-ZTW-R</i>	1.78	0.66	3.29	2.08	5.90	3.65	–	15.58
<i>CTDSR-ZTW+R</i>	2.05	0.84	3.79	2.66	6.80	4.67	14.1	32.87
<i>PTR-CTW-R</i>	2.13	0.79	3.93	2.51	7.05	4.42	–	18.71
<i>PTR-ZTW-R</i>	1.86	0.69	3.45	2.19	6.17	3.84	–	16.34
<i>PTR-ZTW+R</i>	2.05	0.86	3.80	2.71	6.80	4.79	13.6	32.51

Principal component analysis

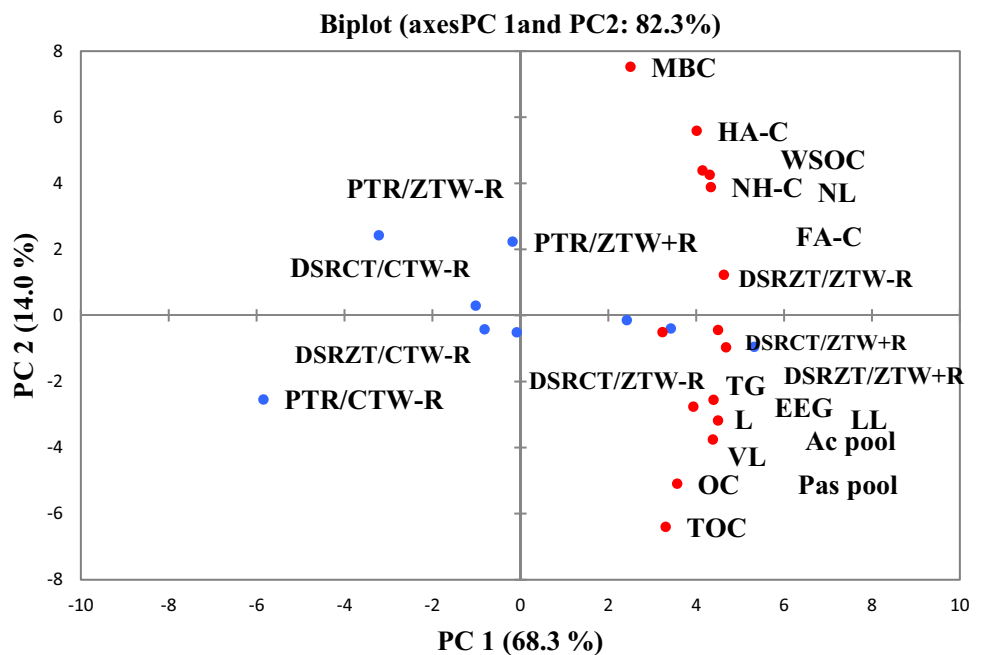
The PCA method was chosen as a data reduction tool to select the most appropriate indicator(s) for evaluation of soil quality. The PCs with high eigen values represented the maximum variation in the dataset. Under a given PC, each variable had corresponding eigen vector weight value or factor loading (Supplementary Table 1). Only the ‘highly weighted’ variables were retained to include in the minimum data set (MDS). The ‘highly weighted’ variables were defined as the highest weighted variable under a certain PC with absolute factor loading value under the same PC. Thus, all the bold-faced and underlined soil parameters were selected in the final MDS (passive pool, fulvic acid and active pool for PC1 and microbial biomass carbon and total soil organic carbon for PC2). However, all the parameters were significantly correlated to each other to determine the correlation coefficients (Supplementary Table 2). The principal component analysis clearly separated the treatments in the factorial space defined by two PCs (Fig. 3). In the surface 0–15 cm soil layer PC1 explained 68.3% of the variation and separated *ZTDSR/CTDSR* and *ZTW+R* treatments combination from rest of the treatments, while PC 2 explained 14.0% of the variability in the dataset.

Discussion

Organic carbon pools

Soil organic carbon is the most important index of soil fertility and sustainability for any soil–crop–climate ecosystem (Tiessen et al. 1994; Reeves 1997). The total SOC content and its fractions are closely associated with a wide range of soil physical, chemical, and biological properties, which play key role in soil processes and functioning, and are

Fig. 3 Principal component analysis of assayed variables at surface soil layer. *ZTDSR* zero-tillage-direct seeding rice, *CTDSR* conventional tillage-direct seeding rice, *PTR* manual transplanting, *ZT* zero tillage, *CT* conventional tillage, *ZTW+R* zero tillage with residues, *CTW-R* conventional tillage without residues, *TSOC* total soil organic carbon, *OC* oxidizable carbon, *VL* very labile, *L* labile, *LL* less labile, *EEG* easily extractable glomalin, *TG* total glomalin, *AC* active, *PAS* passive, *NL* non-labile, *WSOC* water-soluble SOC, *MBC* microbial biomass carbon, *HA-C* humic acid, *FA-C* fulvic acid



probably the most widely acknowledged soil quality indicators (Sa and Lal 2009). In the present study, total SOC content among the rice treatments was the highest in ZTDSR and the lowest in the PTR for all the soil layers (Table 3). The increasing trend of total SOC in ZTDSR compared to CTDSR and PTR include decrease in C mineralization due to reduced tillage and high inputs of roots (data not recorded) and crop residues (Lal 2004; Kaur et al. 2008). The ZTDSR treatment in rice and ZTW + R in wheat were more effective in increasing SOC content compared with PTR and CTW – R, respectively (Table 3). The increase in oxidizable carbon content in surface soil layer in ZTDSR and ZTW + R compared with the other treatments could be due to slow rate of organic matter decomposition due to minimum soil disturbance and surface retention of crop residues (Yadvinder-Singh et al. 2010; Jat et al. 2018), higher plant biomass production (Choudhury et al. 2010; Jat et al. 2014; Yadvinder-Singh et al. 2014) leading to large amounts of root residues left in the system (Singh et al. 2016).

The variation detected in soil carbon fractions is related to dynamic decomposition process. It has been demonstrated that the organic C (fresh or labile) derived from crop residues is first incorporated into labile C pools and subsequently accumulates and becomes stable or recalcitrant carbon in soils (Six et al. 2000; Chen et al. 2014). Irrespective of different methods of rice establishment, ZTW + R recorded significantly higher non-labile, less labile, labile and very labile pools than either ZTW – R or CTW – R practice (Table 4). The increase in labile C pools ranged from 14.5 to 31.0% in the surface soil layer (0–7.5 cm) with ZTW + R than ZTW – R and CTW – R. The lower SOC pool

under CTW – R is mainly because of lesser input of biomass C into the system because of low crop productivity and/or removing of residues (Kim et al. 2009). Similar trend was observed at the other soil depths among different treatments. Possible factors responsible for improving labile C fractions in a particular soil layer include altered root C dynamics (Chabbi et al. 2009) and changes in the quantity and composition of SOC in the soil profile (Kaiser and Kalbitz 2012). Higher SOC in the surface layer under ZTDSR/ZTW + R than those under CTDSR/ZTW – R and PTR/CTW – R systems can be attributed to a combination of less soil disturbance and reduced litter decomposition due to less soil/residue interaction (Dolan et al. 2006; Du et al. 2010). In this study, less soil disturbance under ZTW + R and the presence of mulch layer caused stratification of SOC up to 30 cm or even lower depths as reported by other researchers (Angers et al. 1997; Paustian et al. 1997). Furthermore, the presence of mulch may have improved soil structure by stabilizing aggregates and protecting SOM against microbial degradation and reduced the rate of SOC decomposition (De Gryze et al. 2005). It is well known that the addition of easily decomposable substrates to soil rapidly stimulates the soil micro-flora and determines the proportions of different carbon fractions, resulting in a significant improvement in soil structure (Abiven et al. 2007), redistribution of the SOC pool (Baker et al. 2007).

Active and passive pools of carbon

It is widely acknowledged that total SOC pool may not be an accurate early indicator of management-induced differences

in soil functions, primarily because the fractions comprising the SOC vary considerably in their physical and chemical properties, and turnover rates (Jenkinson and Coleman 1994). However, active C fractions are strongly influenced by short-term changes in soil management practices compared with recalcitrant C fractions (Ghani et al. 2003) and thus can provide an early indication of changes in soil quality in response to management practices. In the present study, the changes in SOC pools were most pronounced in the surface layer under ZTDSR/ZTW + R and CTDSR/ZTW – R compared with PTR/CTW – R (Table 5). The trends presented here in suggest that changes in SOC resulted from the changes in both active and passive pools. The differences in climatic variables recorded in Table 1 seem to have little effect on dynamics of SOC pools in different treatments under irrigated RW system. Our study showed that SOC gains or losses following tillage practices occur substantially from the active C pools because of their dynamic nature (Sa and Lal 2009; Culman et al. 2012).

Humus fractions

Information about effects of agricultural practice on soil C compounds (humic and non-humic substance) is very scarce (Lopez-Fando et al. 2007). Higher HA-C > NH-C > FA-C contents were recorded in ZTDSR in rice and ZTW + R in wheat compared with PTR and CTW – R (Table 5). The higher humus fractions ZTDSR/ZTW + R and CTDSR/ZTW – R compared with PTR/CTW – R related with humification process and total decomposition of the residue, and in consequence the recalcitrant C would be incorporated in HA molecules, increasing its concentration. Contribution of these labile components to the total SOC influences the biological activity of the soil because of relatively new and fresh C and thus represents a transitory pool between fresh residues and humified stable organic matter (Stine and Weil 2002). The improvement in humic acid-C fractions with ZTDSR/ZTW + R might be due to higher SOC content leading to greater humus formation (Table 5). Gathala et al. (2007) reported that increased in humus fractions due to addition of root residues consequent to higher biomass yield decomposition of added residue to constitute part such as lignin derived phenolic unit, carbohydrates or amino compounds as building blocks or substrate for humus formation. The content of humic acid was higher than fulvic acid regardless of different treatments. Fulvic acids, although primarily considered to be humic acid precursors, may be humic acid degradation products as well. It is probable that fulvic acid can be absorbed on to clay, but the size of their molecules suggested that the force of attraction would be less than those for longer humic acid constituents (Anderson 1979). The increase in WSOC content with the application of ZTW + R compared with ZTW – R/CTW – R could be as

a result of the surface retention of crop residues (Table 6). Our results are in agreement with that of Bera et al. (2017) who reported increased in the soil microbial biomass carbon content and different C fractions in soil under long-term ZT with residue retention in RW system.

Glomalin content

Glomalin production is sensitive to carbon exudates from the plant and soil disturbance. Both glomalin fractions (EEG and TG) differed significantly between rice establishment, tillage and crop residue management practices (Fig. 1). ZTDSR/ZTW + R increased the glomalin content compared with PTR/CTW – R in both fractions, which may be attributed to no soil disturbance in ZT system, improving the amount and the activity of mycorrhizal fungi hyphae in relation to CT (Kabir et al. 1997; Cornejo et al. 2008), and consequently the increase in levels of glomalin content (Kabir 2005). Additionally, the higher amount of AM mycelium under ZT may lead to a more production of glomalin in comparison with CT. On the contrary, CT management and the associated disruption of the hyphal network would likely lead to a reduction of glomalin production (Borie et al. 2000) and reduced aggregate stability (Kabir 2005).

Carbon management index

Compared with TSOC as a single measure, CMI (integration of both carbon pool and C lability) can be used as a more sensitive indicator of the rate of change of SOC in response to changes in cropping system and soil management (Whitbread et al. 1998). In the present study, ZTDSR/ZTW + R had higher CMI over PTR/ZTW – R (Fig. 2). Crop establishment, ZT and crop residue management practices increased the CMI due to the increase in annual C input and the variations in organic matter quality, thus modifying the lability of C to change to an oxidized form (Tirol-Padre and Ladha 2004).

Total carbon inputs

It is well known that the quantity of crop residue on surface soil is strongly impacted by the tillage system and the crop establishment methods (Ernst et al. 2002; Abril et al. 2009). The cumulative carbon input from above ground biomass after 6 years was about three times greater in ZTDSR/ZTW + R than PTR/CTW – R. Consistent with the results of Lopez-Fando et al. (2007), the total residue biomass in different treatments in our study clearly responded on both factors (tillage and rice establishment methods) as well as the time since the new residue deposition. Accordingly, the residue labile C content depends on: (a) the fresh residue chemical composition (Andriulo and Guerif 1999) the time

since residue deposition, and (b) the climatic conditions which modified the microbial activity (Torres et al. 2005; Carranza et al. 2012). Accordingly, the labile C source is the fresh residue composition. Higher net SOC gain under the ZTDSR/ZTW + R than in PTR/CTW – R (Table 7) was due to higher biomass C input coupled with lesser soil disturbance compared with CT.

Principal component analysis

In the factorial space defined by two PCs the data points for ZTDSR in rice and ZT with crop residue in wheat were distinctly separated from data points for PTR in rice and CT without residue treatments in wheat in RW system (Fig. 3). The data point pertaining to these variables are closely positioned to sustainable management practices (i.e., ZTDSR and ZTW + R). This implies that continuous addition of carbon sources through rice residue enhanced the microbial activity and abundance of different microbial communities of soil, nutrient availability and rhizodeposits might be the reasons for high soil carbon pools with ZTW + R. The most influential variables for the first principal component were passive pools, fulvic acid carbon and active pools and for second principal component were microbial biomass carbon and TSOC. This implies that continuous addition of carbon sources through rice residue enhanced the microbial activity and carbon pools. Consistent with the results from our study, Mathew et al. (2012) recorded SOC as the most influential factor for PC 1, confirming its critical role in the ZT system. Bini et al. (2014) observed that PCA clearly separated ZT from CT in the factorial space defined by two PCs which inferred that addition of diversified carbon sources through crop residues enhanced microbial biomass and carbon pools in soil.

Conclusions

The very labile fraction of carbon (C frac₁) contributed the largest percentage of total SOC, leading to the more active carbon pool in the surface soil. Reduction in tillage intensity and residue retention additively increased the SOC under ZTDSR/ZTW + R, in turn achieving the highest total SOC concentration in the soil in RW system. Among tillage and residue management practices, ZTW + R had greater amount of total SOC, active pool of C, passive pool of C, and higher carbon management index and is considered as the best soil management practice in RW system. Principal component analysis identified two most important indicators (passive carbon pool and microbial biomass carbon) of soil quality that provided guidelines to distinguish the most sustainable CA-based practices (e.g., zero tillage and residues retention) in wheat under RW system. Future studies should consider

interrelations between all the parameters of soil quality (physical, chemical and biological) to get an integrated soil quality index for CA-based RW and other cropping systems under different soil and climatic conditions.

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