



## Changes in soil organic carbon pools after 15 years of Conservation Agriculture in rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system of eastern Indo-Gangetic plains

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### ABSTRACT

The present study was carried out at Dr. Rajendra Prasad Central Agricultural University, Samastipur, Bihar during 2021–2023 to focus on examining alterations in SOC pools resulting from conservation agriculture (CA) practices in R-W system in the eastern IGP, following the collection of soil samples from a long-term trial that was initiated in rainy (*khari*) season 2006. The trial included eight combinations, namely: conventional tilled rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) (CTR-CTW); CT rice and zero till wheat (CTR-ZTW); direct seeded rice (DSR) and wheat on permanent raised beds (PBDSR-PBW); ZTDSR and CT Wheat (ZTDSR-CTW); ZTDSR and ZT wheat without residue (ZTDSR-ZTW -R); ZTDSR-ZT wheat with residue (ZTDSR-ZTW +R); unpuddled transplanted rice-ZTW (UpTR-ZTW) and ZTDSR-sesbania brown manure-ZTW (ZTDSR-S-ZTW). Results revealed that implementing zero tillage (ZT) combined with residue retention in rice and wheat cultivation led to enhanced levels of soil organic carbon (SOC) across all four fractions, namely very labile (CVL), labile (CL), less labile (CLL), and non-labile (CNL), in comparison to the continuous and rotational tillage practices. The tillage and residue management options significantly affected the lability index (LI) and C pool index (CPI), with zero-tillage and residue retention leading to lower LI and higher CPI values. The management practices significantly affected the C management index (CMI), with zero-tillage and residue retention showing the highest CMI values. Findings showed the potential of CA practices for enhancing soil C quality as well as C sequestration in soil of the Eastern IGP of India.

**Keywords:** Carbon management index, Conservation agriculture, Soil organic carbon fractions, Zero-till

It is widely accepted that soil organic carbon (SOC) is a crucial indicator of soil quality, as it plays an important role in sustaining soil health and meet the nutritional requirements of the plants (Lal 2004, Sainju *et al.* 2017, Morris *et al.* 2018). In recent times, the importance of SOC in climate change mitigation has increased due to the fact that soils store a significant amount of terrestrial carbon, which

is twice that of the atmosphere. As much as 24% of global CO<sub>2</sub> emissions can be attributed to agriculture, emphasizing the increasing importance of finding solutions that decrease emissions and sequester carbon in soil (IPCC 2014).

The adoption of conservation agriculture (CA), which involves limiting soil disturbance and preserving surface residue, has been proven to have a significant positive impact on the sequestration of SOC (Parihar *et al.* 2018, Dey *et al.* 2020). It is crucial to understand the dynamics of sequestered SOC, given the impact that management practices can have on the SOC pools. The quantitative measurements of total SOC alone may not be sufficient to fully understand the impact of management practices; thus, SOC is sub-divided into different fractions/pools, i.e. labile or active pool and recalcitrant or passive pool. The proportional distribution of these pools in soil determines soil C quality (Chan *et al.* 2001).

Blair *et al.* (1995) proposed C management index (CMI) as an integrated approach to evaluate the quality of C in soil management systems. By considering both labile

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C and total SOC, it offers a useful metric for assessing soil C modifications and sequestration resulting from the implementation of management practices (Hazra *et al.* 2018). The assessment of soil quality in management systems in north-western IGP has been successfully carried out using this index (Das *et al.* 2016). However, studies using this index in the eastern IGP are scarce. This study aims to analyse the active and passive pools of SOC and assess soil quality using the CMI under different conservation agriculture practices in the rice-wheat cropping system on a calcareous soil of the eastern IGP. In this study, we hypothesized that the reduction of tillage intensity and the incorporation of crop residues into the field would lead to an increase in all oxidizable organic C components and a consequent enhancement of the soil CMI.

#### MATERIALS AND METHODS

The present experiment was conducted at the experimental farm of the Dr. Rajendra Prasad Central Agricultural University, Samastipur, Bihar during 2021–23. The dominant climate in this area is a subtropical, with 70% of its average annual precipitation of 1350 mm occurring between July and September. Across the year, the range of the average monthly maximum and minimum temperatures falls between 23.8–36.9°C and 9.1–27.3°C, respectively. The soil falls under the Typic Calciorthent classification in the USDA soil taxonomy due to its calcareous composition (Soil Survey Staff 1975). At the start of the experiment, the soil of the experiment contained an average SOC content of 6.8 g/kg, and pH was 8.6.

*Treatments, experimental design, and crop management:* In the rainy (*khari*) season of 2006, a long-term experiment was undertaken to investigate the effect of CA in a rice-wheat rotation. The testing was conducted on the following eight combinations of tillage, crop establishment, and residue management practices. CTR–CTW, Conventionally transplanted rice-conventional tilled wheat; CTR–ZTW, Conventionally transplanted rice-zero tilled wheat; PBDSR–PBW, direct seeded rice on permanent beds-zero-tilled wheat on permanent beds; ZTDSR–CTW, zero-tilled direct seeded rice-conventional tilled wheat; ZTDSR–ZTW–R, zero-tilled direct seeded rice-zero-tilled wheat with all residue removed; ZTDSR–ZTW+R, zero-tilled direct seeded rice-zero-tilled wheat with residue retained of both crops; UpTR–ZTW, unpuddled transplanted rice-zero-tilled wheat; and ZTDSR–S–ZTW, zero-tilled direct seeded rice-sesbania brown manuring-zero-tilled wheat. The experiment was conducted using a completely randomized block design with three replications. Both the rice and wheat crops were supplied with recommended dose of N, P and K fertilizers and irrigation as and when required. The crop management practices for each treatment are thoroughly described by Jat *et al.* (2014).

*Soil sampling and analysis:* After 15 years of experimentation, the soil samples were collected from five places in each plot at three depths (0–5, 5–15, and 15–30 cm). Samples were composited for each plot, air-dried, ground,

and passed through a 250 µm sieve before being placed in plastic bags. Total C was analyzed using dry combustion in a CHNS-O elemental analyzer (EuroVector, EA3000). Soil samples were subjected to dilute HCl digestion, and the remaining HCl was titrated with dilute NaOH to determine the amount of total inorganic carbon (SIC) present. The total organic carbon (TOC) content was then calculated by subtracting the SIC concentration from the total carbon concentration.

The study was conducted to determine the different fractions of SOC, we used the Modified Walkley and Black Method (Chan *et al.* 2001) and treated the soil samples with concentrated sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) at three different ratios: 0.5:1, 1:1, and 2:1, corresponding to acid strengths of 12 N, 18 N, and 24 N H<sub>2</sub>SO<sub>4</sub>, respectively. Through the use of acids of different strengths for oxidation, soil organic C can be separated into four distinct fractions based on decreasing oxidizability. The calculation for each fraction is as follows:

- The very labile C (C<sub>VL</sub>) fraction, consisting of highly labile carbon, was oxidized using 12 N H<sub>2</sub>SO<sub>4</sub>.
- The labile C (C<sub>L</sub>) fraction is equal to the difference between the C oxidized under 18 N H<sub>2</sub>SO<sub>4</sub> and the oxidizable C under 12 N H<sub>2</sub>SO<sub>4</sub>.
- The less-labile C (C<sub>LL</sub>) fraction is equal to the difference between the C oxidized under 24 N H<sub>2</sub>SO<sub>4</sub> and the oxidized C under 18 N H<sub>2</sub>SO<sub>4</sub>.
- While determining the non-labile C (C<sub>NL</sub>) fraction, the amount of C that is oxidized under 24 N H<sub>2</sub>SO<sub>4</sub> is subtracted from the total organic C.

By using the four fractions described above, we can calculate the active and passive C pools, which are indicative of the soil's carbon oxidizability. The active carbon (C) pool comprises CVL and CL, representing the labile and easily oxidizable portion, whereas the passive C pool includes CLL and CNL, which are recalcitrant and less reactive, and require more effort to extract and oxidize.

The lability index (LI), carbon pool index (CPI), and carbon management index (CMI) were calculated according to the below -mentioned equations (Sahoo *et al.* 2019).

$$LI = \frac{L_{\text{sample soil}}}{L_{\text{reference soil}}}$$

$$\text{Lability of carbon (L)} = \frac{(C_{CVL} + C_L)}{(C_{CLL} + C_{NL})}$$

$$CPI = \frac{\text{Sample total SOC}}{\text{Reference total SOC}}$$

In this study, we used conventionally managed system (CTR–CTW) as reference.

$$CMI = LI \times CPI \times 100$$

*Statistical analysis:* One-way analysis of variance (ANOVA) was used to compare the impact of various treatments on SOC fractions and different indices, including LI and CMI. Post-hoc analysis was performed using Tukey's Honest Significant Difference (HSD) test for randomized complete block design (RCBD) to compare means. The

statistical software R (version 4.2.2) was used to perform all statistical analyses (R Core Team 2021).

## RESULTS AND DISCUSSION

**Active carbon pools:** Active pools of soil C expressed significant variation with respect to different tillage, crop establishment, and residue management options at different depths (Table 1). Zero-tillage in both the crops, i.e. rice and wheat (PBDSR-PBW, ZTDSR-ZTW-R, ZTDSR-ZTW+R and ZTDSR+S-ZTW) improved the very labile fraction of C ( $C_{VL}$ ) in both rice and wheat crops compared to continuous tillage (CTR) and rotational tillage (ZTDSR-CTW, CTR-ZTW). Residue retention along with zero-tillage (ZTDSR-ZTW+R) and inclusion of sesbania (ZTDSR+S-ZTW) had the highest  $C_{VL}$  values (5.30 and 5.31 g/kg) at 0-5 cm soil depth, with about 100% increase in  $C_{VL}$  pools over CTR-CTW. Puddling of rice leads to the lowest  $C_{VL}$  values in CTR-CTW and CTR-ZTW treatments (2.65 and 2.87 g/kg, respectively).  $C_{VL}$  is an easily decomposable fraction of carbon that provides essential nutrients to plants and serves as an early indicator for comparing soil management (Hazra *et al.* 2018). Differences in the  $C_{VL}$  pool are associated with organic residue supply in the soil. Long-term zero-tillage treatments increase soil porosity and microbial activity, resulting in cooler and wetter soils with more labile C pools. Reduced tillage systems have been shown to have higher active C pools compared to more intensive tillage practices (Dey *et al.* 2020, Tigga *et al.* 2020).

The  $C_L$  pool also showed a similar effect, with rice puddling and transplanting (CTR-CTW and CTR-ZTW) decreased the labile soil C pool (0.98 and 1.38 g/kg, respectively) (Table 1). Keeping the previous crop residue (PBDSR-PBW and ZTDSR-ZTW+R) on the soil surface significantly ( $P<0.05$ ) improved the labile pool at 0–5 cm depth. At 5–15 and 15–30 cm soil depth ZTDSR-ZTW+R and inclusion of sesbania (ZTDSR+S-ZTW) significantly ( $P<0.05$ ) improved the CL content and was at par with each other.  $C_{VL}$  and  $C_L$  pool sizes decreased with increasing soil depth across all treatments. Das *et al.* (2016) and Dey *et al.* (2020) also observed a pronounced reduction in levels

of active C pool with increase in depth. Conservation agriculture practices help in SOC build-up through less mechanical disturbance, surface-retained crop residues (Parihar *et al.* 2018, 2019), higher plant biomass production (Jat *et al.* 2014), better soil hydro-physical conditions (Patra *et al.* 2023). Reintroducing plant-derived C into the soil increases the concentration of active C fractions, stimulating soil microorganisms and providing mineral nutrients for plant growth, leading to more C returned to the soil and an active soil C pool (Ghosh *et al.* 2016).

**Passive carbon pools:** Zero-tillage with residue retention on flat soil surface (ZTDSR-ZTW+R) and on raised beds (PBDSR-PBW) significantly improved  $C_{LL}$  (4.33 and 3.74 g/kg, respectively) at 0–5 cm depth, by 386% and 320% compared to conventionally managed systems (CTR-CTW) (Table 2). Puddled rice (CTR-CTW and CTR-ZTW) reduced soil C at 5–15 and 15–30 cm layers.

Zero-tillage with residue retention had the highest  $C_{NL}$  pool size (6.25 g/kg) at 0–5 cm depth. At 5–15 and 15–30 soil depths, CTR-CTW had the lowest  $C_{NL}$  pool size (0.92 and 0.97 g/kg, respectively). Conservation tillage (zero-tillage) increased C stabilization in the passive pool ( $C_{LL}$  and  $C_{NL}$ ). C mineralization leads to more resistant C compounds which are less likely to oxidize (Singh *et al.* 2005). Partially decomposed plant material can also contribute to an apparent increase in passive C pool by forming mineral-humus complexes that protect it from microbial activity and slow decomposition. Straw residue's higher content of less oxidizable polysaccharide and lignin effectively improves the recalcitrant C pool, which persists in the soil for a longer period.

The distribution of active and passive pools is presented in Fig 1. The rice puddling and conventional tillage in wheat (CTR-CTW) had a higher percentage of active pools (61.1%) at 0–5 cm soil layer compared to the zero-tilled and residue retained plots (ZTDSR-ZTW+R) which had 46.5% active pools. The ZTDSR-ZTW+R treatment recorded the lowest percentage of active C pools at 15–30 cm soil depth (39.2%) among all the treatments. Though, the contribution of active pools to total SOC (61.1%) was

Table 1 Impact of different tillage and residue management methods on very labile ( $C_{VL}$ ) and labile ( $C_L$ ) pools (g/kg) of SOC

Treatment	0–5 cm		5–15 cm		15–30 cm	
	$C_{VL}$	$C_L$	$C_{VL}$	$C_L$	$C_{VL}$	$C_L$
CTR-CTW	2.65±0.10c	0.98±0.09e	1.46±0.04c	0.38±0.02d	1.21±0.14b	0.43±0.06b
CTR-ZTW	2.87±0.14c	1.38±0.08de	1.73±0.14bc	0.78±0.07abc	1.43±0.08ab	0.33±0.02b
PBDSR-PBW	4.35±0.45ab	3.10±0.24ab	2.27±0.12ab	0.73±0.05bc	1.77±0.11ab	0.40±0.04b
ZTDSR-CTW	3.56±0.22bc	2.76±0.24bc	2.07±0.13bc	0.68±0.04c	1.59±0.10ab	0.36±0.01b
ZTDSR-ZTW-R	4.64±0.42ab	2.70±0.08bc	2.17±0.05abc	0.95±0.05ab	1.54±0.15ab	0.39±0.01b
ZTDSR-ZTW+R	5.30±0.18a	3.82±0.20a	2.91±0.17a	1.00±0.06a	1.81±0.12 a	0.82±0.03a
UpTR-ZTW	3.47±0.18bc	2.45±0.08bc	2.06±0.14bc	0.89±0.02abc	1.75±0.13ab	0.25±0.02b
ZTDSR+S-ZTW	5.31±0.32a	2.15±0.13cd	2.22±0.32abc	0.99±0.05a	1.77±0.13ab	0.65±0.07a

Treatment details are given under Materials and Methods. The mean values ± standard error at the same soil depth, indicated by the same lowercase letter, are not significantly different ( $P>0.05$ ) according to Tukey's HSD test.

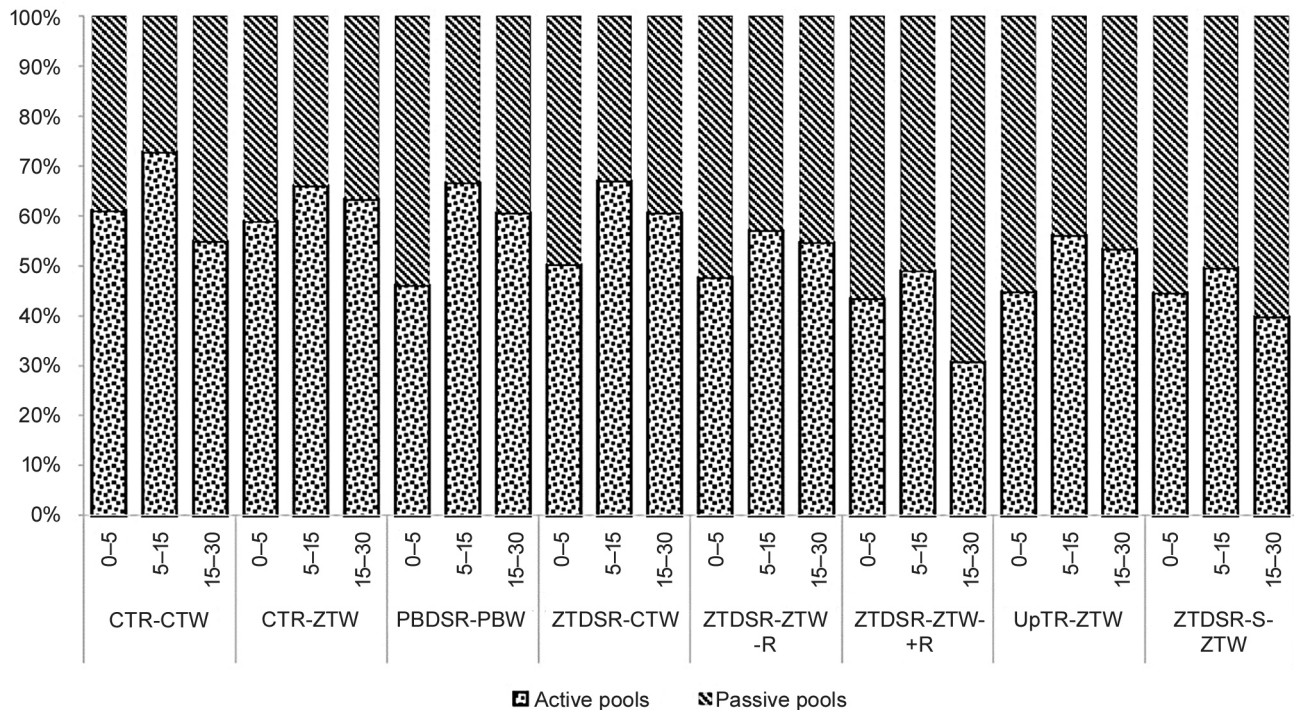


Fig 1 Per cent distribution of active and passive pools of SOC. Treatment details are given under Materials and Methods.

higher in a conventionally managed system (CTR-CTW). However, in absolute terms, the active and passive pools of SOC are larger (9.18 and 10.6 g/kg) in zero-tilled and surface residue retained treatments (ZTDSR-ZTW+R). The intensive tillage disrupts the soil aggregates and exposes the protected C for rapid oxidation through microbial actions (Parihar *et al.* 2018). While surface retained residue in CA decompose more slowly than incorporated residues in soil. Thus provide a slow but steady source of SOC to the soil. Dey *et al.* (2020) also indicated that all oxidizable components of SOC were improved in CA compared to conventional farming in a rice-wheat system.

*Carbon management index and its components:* The LI significantly changed in 0–5 cm soil layer in response to the various tillage and residue management options (Fig 2a). Systems including puddling of rice with continuous tillage (CTR-CTW) or rotational tillage (CTR-CTW) had the significantly ( $P < 0.05$ ) higher LI values compared with the rest of treatments having reduced form of tillage. At 15–30 cm soil layer, zero-tillage along with residue retention (ZTDSR-ZTW+R; 0.46) and brown manuring (ZTDSR-S-ZTW; 0.50) had the significantly lower ( $P < 0.05$ ) LI values compared to the rest of the treatments, which showed no significant effect of residue management and tillage

Table 2 Impact of different tillage, crop establishment, and residue management methods on less labile ( $C_{LL}$ ) and non-labile ( $C_{NL}$ ) pools (g/kg) of SOC in the 0–5, 5–15 and 15–30 cm soil layers

Treatments	0–5 cm		5–15 cm		15–30 cm	
	$C_{LL}$	$C_{NL}$	$C_{LL}$	$C_{NL}$	$C_{LL}$	$C_{NL}$
CTR-CTW	0.89±0.02c	1.43±0.11e	0.31±0.03e	0.92±0.06c	0.19±0.02f	0.97±0.10c
CTR-ZTW	0.86±0.08c	1.61±0.12e	0.81±0.08de	1.48±0.08bc	0.24±0.01ef	1.10±0.12bc
PBDSR-PBW	2.22±0.07b	5.01±0.30b	1.39±0.08bc	2.02±0.29ab	0.87±0.05bc	1.55±0.10b
ZTDSR-CTW	1.90±0.11b	3.36±0.17cd	1.14±0.17cd	1.40±0.08bc	0.66±0.05cd	1.11±0.11bc
ZTDSR-ZTW-R	2.41±0.15b	4.40±0.26bc	1.70±0.14ab	1.52±0.14bc	0.48±0.02de	1.14±0.06bc
ZTDSR-ZTW+R	4.33±0.22a	6.25±0.39a	1.74±0.06ab	2.53±0.23a	1.53±0.09a	2.57±0.08a
UpTR-ZTW	2.40±0.12b	3.10±0.21d	1.61±0.12abc	2.03±0.08ab	0.77±0.05c	1.04±0.08c
ZTDSR+S-ZTW	3.74±0.23a	4.54±0.27bc	1.96±0.10a	2.31±0.11a	1.12±0.08b	2.30±0.14a

Treatment details are given under Materials and Methods. The mean values ± standard error at the same soil depth, indicated by the same lowercase letter, are not significantly different ( $P > 0.05$ ) according to Tukey's HSD test.

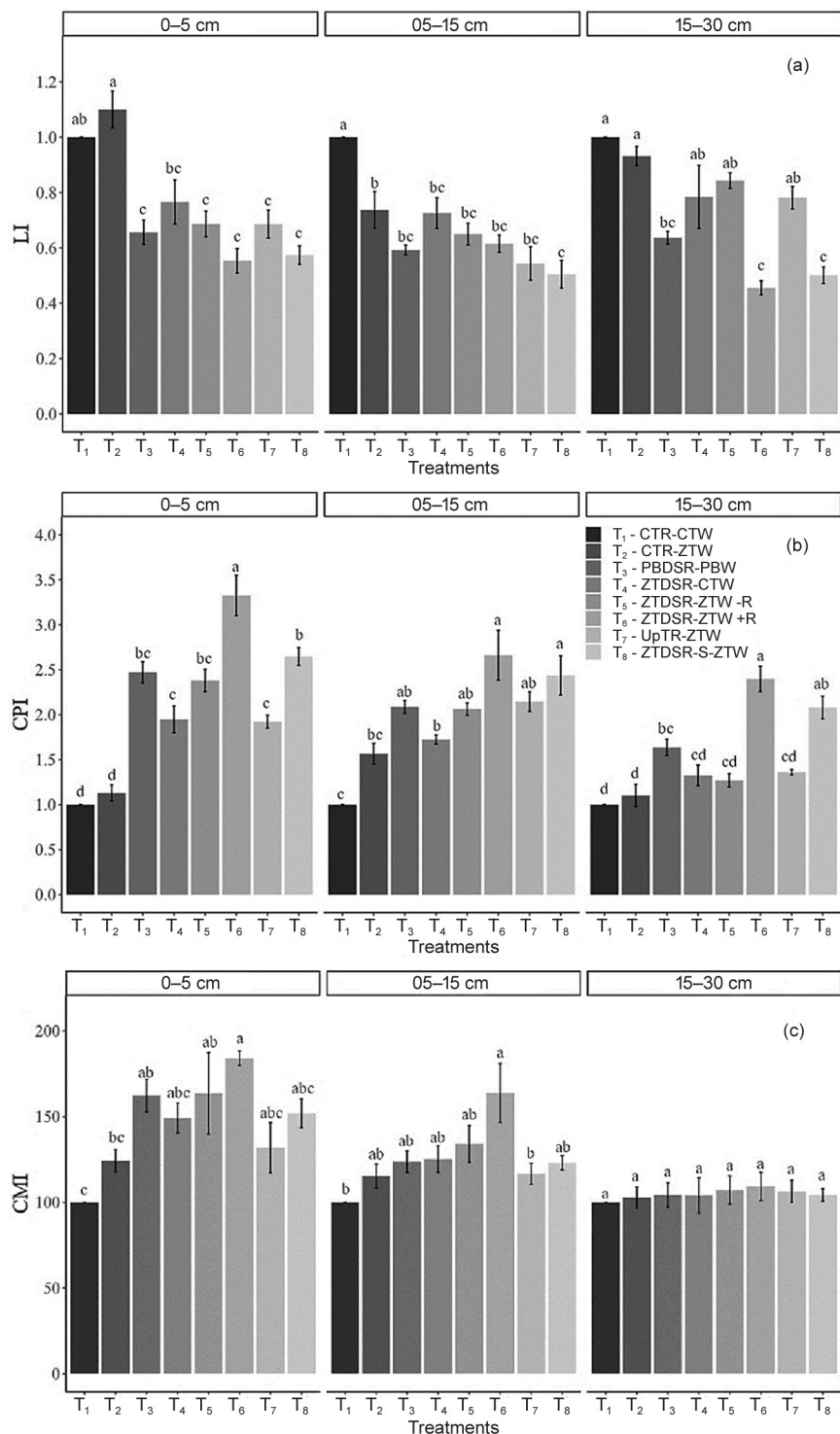


Fig 2 (a) LI, (b) CPI, and (c) CMI under various tillage, crop establishment, and residue management methods. Error bars indicate standard errors. Within the same soil depth, treatments that are labelled with the same lowercase letter are not significantly different (P>0.05) based on Tukey's HSD test. Treatment details are given under Materials and Methods.

options. The lability of C ( $C_{VL} + C_L / C_{LL} + C_{NL}$ ) was lower in treatments with zero-tillage and residue retention (ZTDSR-ZTW+R, PBDSR-PBW) and inclusion of brown manuring (ZTDSR-S-ZTW). This may be attributed to the larger passive pool size in comparison to the active pool (Fig 1).

However, a significantly (P<0.05) higher CPI was observed in ZTDSR-ZTW+R treatment (3.32) followed by ZTDSR-S-ZTW (2.65), PBDSR-PBW (2.47) and ZTDSR-ZTW-R (2.38) at 0–5 cm soil depth (Fig 2b). The CPI indicates the buildup of C in soil concerning reference C (in this study C present in CTR-CTW treatment). The puddling of rice along with conventionally tilled wheat (CTR-CTW) or zero-tilled wheat (CTR-ZTW) had the lowest CPI values at all three soil layers. Surface residue retention along with zero-tillage in both the crops (ZTDSR-ZTW+R) increased the CPI values by 232%, 166% and 140% at in comparison to the CTR-CTW at 0–5, 5–15 and 15–30 cm soil depths. The rest of the treatments had the intermediate effects on the CPI values. A higher CPI value indicates a more significant accumulation of SOC in the soil compared to a lower CPI value (Parihar *et al.* 2018). This is due to the greater supply of carbon through crop residues or manuring. The buildup of SOC is influenced by C inputs and mineralization rate (Lal 2018). Physical protection of SOC from microbial decomposition through aggregation under CA practices (Six *et al.* 2000) could have leads to higher CPI values than conventional systems.

In their study, Blair *et al.* (1995) highlighted the relevance of the CMI for evaluating soil quality and the potential for carbon sequestration. This index is widely used to compare and assess different management practices in promoting soil C buildup. The CMI was significantly affected by tillage, residue, and crop establishment methods, except at 15–30 cm soil layer (Fig 2c). Zero-tillage in rice and wheat with residue retention on the soil surface led to the highest CMI values (184 and 164) at 0–5 and 5–15 cm layers. Soils of PBDSR-PBW, ZTDSR-ZTW -R and ZTDSR-S-ZTW, and ZTDSR-CTW had 62%, 63%, 51% and 49% higher CMI values at 0–5 cm soil layer in comparison to CTR-CTW. The increased values of CMI in these treatments may be ascribed to the greater CPI values, pointing towards the accumulation of total SOC. However, the positive effect of zero-tillage adoption diminishes with increasing soil depth, and CMI

variation at 15–30 cm depth was not significant (Fig 2c). The adoption of management practices or cropping systems that lead to higher CMI values indicate their effectiveness in improving soil quality and increasing SOC (Parihar *et al.* 2019). Overall, the results highlighted that the zero-tillage along with residue return is a promising way of improving CMI value and soil quality.

The study found that adopting zero-tillage and residue retention in rice-wheat systems can improve soil health and increase carbon pools, both active and passive, compared with conventional management practices. Tillage and residue management also affected the lability and carbon pool index, with zero-tillage and residue retention showing higher carbon pool index and carbon management index values. These practices can enhance soil carbon quality and promote carbon sequestration in the eastern Indo-Gangetic plains of India and other similar eco-regions worldwide.

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#### REFERENCES

- Blair G J, Lefroy R D and Lisle L. 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research* **46**(7): 1459–66.
- Chan K Y, Bowman A and Oates A. 2001. Oxidizable organic carbon fractions and soil quality changes in an oxic *paleustalf* under different pasture leys. *Soil Science* **166**(1): 61–67.
- Das D, Dwivedi B S, Singh V K, Datta S P, Meena M C, Chakraborty D, Bandyopadhyay K K, Kumar R and Mishra R P. 2016. Long-term effects of fertilisers and organic sources on soil organic carbon fractions under a rice-wheat system in the Indo-Gangetic Plains of north-west India. *Soil Research* **55**(3): 296–308.
- Dey A, Dwivedi B S, Bhattacharyya R, Datta S P, Meena M C, Jat R K, Gupta R K, Jat M L, Singh V K, Das D and Singh R G. 2020. Effect of conservation agriculture on soil organic and inorganic carbon sequestration and lability: A study from a rice-wheat cropping system on a calcareous soil of the eastern Indo-Gangetic Plains. *Soil Use and Management* **36**(3): 429–38.
- Ghosh B N, Meena VS, Alam N M, Dogra P, Bhattacharyya R, Sharma N K and Mishra P K. 2016. Impact of conservation practices on soil aggregation and the carbon management index after seven years of maize-wheat cropping system in the Indian Himalayas. *Agriculture, Ecosystems and Environment* **216**: 247–57.
- Hazra K K, Ghosh P K, Venkatesh M S, Nath C P, Kumar N, Singh M, Singh J and Nadarajan N. 2018. Improving soil organic carbon pools through inclusion of summer mungbean in cereal-cereal cropping systems in Indo-Gangetic plain. *Archives of Agronomy and Soil Science* **64**(12): 1690–704.
- IPCC. 2014. Climate change 2014: Mitigation of climate change. <https://www.ipcc.ch/report/ar5/wg3/>.
- Jat R K, Sapkota T B, Singh R G, Jat M L, Kumar M and Gupta R K. 2014. Seven years of conservation agriculture in a rice-wheat rotation of Eastern Gangetic Plains of South Asia: yield trends and economic profitability. *Field Crops Research* **164**: 199–210.
- Lal R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* **123**(1–2): 1–22.
- Lal R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Global Change Biology* **24**(8): 3285–301.
- Morris T F, Murrell T S, Beegle D B, Camberato J J, Ferguson R B, Grove J, Ketterings Q, Kyverya P M, Laboski C A, McGrath J M and Meisinger J J. 2018. Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. *Agronomy Journal* **110**(1): 1–37.
- Parihar C M, Parihar M D, Sapkota T B, Nanwal R K, Singh A K, Jat S L, Nayak H S, Mahala D M, Singh L K, Kakraliya S K and Stirling C M. 2018. Long-term impact of conservation agriculture and diversified maize rotations on carbon pools and stocks, mineral nitrogen fractions and nitrous oxide fluxes in inceptisol of India. *Science of the Total Environment* **640**: 1382–92.
- Parihar C M, Singh A K, Jat SL, Ghosh A, Dey A, Nayak H S, Parihar M D, Mahala D M, Yadav R K, Rai V and Satayanaryana T. 2019. Dependence of temperature sensitivity of soil organic carbon decomposition on nutrient management options under conservation agriculture in a sub-tropical Inceptisol. *Soil and Tillage Research* **190**: 50–60.
- Patra S, Parihar C M, Mahala D M, Singh D, Nayak H S, Patra K, Reddy K S, Pradhan S and Sena D R. 2023. Influence of long-term tillage and diversified cropping systems on hydro-physical properties in a sandy loam soil of North-Western India. *Soil and Tillage Research* **229**: 105655.
- R Core Team. 2023. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>.
- Sahoo U K, Singh S L, Gogoi A, Kenye A and Sahoo S S. 2019. Active and passive soil organic carbon pools as affected by different land use types in Mizoram, Northeast India. *PLoS One* **14**(7): 0219969.
- Sainju U M, Lenssen A W, Allen B L, Stevens W B and Jabro J D. 2017. Soil total carbon and crop yield affected by crop rotation and cultural practice. *Agronomy Journal* **109**(1): 388–96.
- Singh Y, Singh B and Timsina J. 2005. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping system in the tropics. *Advances in Agronomy* **85**: 269–407.
- Six J A, Elliott E T and Paustian K. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* **32**(14): 2099–103.
- Soil Survey Staff. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. USDA-SCS. *Agricultural Handbook no 436*.
- Tigga P, Meena M C, Dey A B, Dwivedi B S, Datta S P, Jat H S and Jat M L. 2020. Effect of conservation agriculture on soil organic carbon dynamics and mineral nitrogen under different fertilizer management practices in maize (*Zea mays*)-wheat (*Triticum aestivum*) cropping system. *Indian Journal of Agricultural Sciences* **90**(8): 1568–74.