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Conservation agriculture impacts on soil carbon sequestration under a cotton (*Gossypium hirsutum*)-wheat (*Triticum aestivum*) system in the Indo-Gangetic plains

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ABSTRACT

Despite many studies reporting conservation agriculture (CA) impacts on soil organic carbon (SOC) sequestration, the impacts of long-term permanent bed planting under CA on SOC sequestration are rarely reported. Hence, this study assessed the permanent bed planted CA impacts on SOC sequestration rates in 0–30 and 30–60 cm soil depths under a cotton (*Gossypium hirsutum* L.)-wheat (*Triticum aestivum* L.) system in the Indo-Gangetic Plains (IGP). The treatments comprised diverse combinations of tillage and residue retention (R), viz. conventional tillage (CT), narrow bed, narrow bed + R, broad bed, broad bed + R, flat bed + R and flat bed. Results indicated that the total SOC stock was ~32, 31 and 29% higher in CA plots than in CT plots (farmers' practice), in 0–30 cm soil depth. The SOC sequestration rate (over CT plots) in the CA plots was ~0.76 Mg C/ha/yr. The broad bed + R, narrow bed + R and flat bed + R plots had appreciably high total SOC sequestration (~0.24 Mg C/ha/yr) compared to CT plots in deep soil layer (30–60 cm). The yield data (2-year mean basis) was recorded highest in the broad bed + R (3.48 tonnes/ha and 8.11 tonnes/ha for cotton and wheat, respectively) and flat bed + R (3.38 tonnes/ha and 8.46 tonnes/ha for cotton and wheat, respectively) treatments showing a positive impact of the adoption of long-term CA in the IGP. Thus, adopting raised beds with residue retention has great potential for higher carbon sequestration and improving yields and can be recommended for sustainable intensification of arable lands in the region.

Keywords: Carbon sequestration rate, Residue retention, Yield, Zero tillage

The soil degradation is primarily attributed to conventional farming practices, characterised by intensive mowing, inadequate residual retention, and limited incorporation methods. These unsustainable methods have led to a decline in soil quality and health. Unfortunately, the consequences of such practices extend beyond soil degradation alone. The overall efficiency of agricultural land utilisation is now jeopardised by a combination of factors, including soil degradation, diminishing water resources, heightened climate variability, and the occurrence of extreme events triggered by climate change. These multifaceted challenges collectively impede the expansion of arable land and pose significant constraints on agricultural productivity (Das *et al.* 2021). In the Indo-Gangetic Plains (IGP), an agricultural region where continuous intensive farming practices have resulted in the decline of groundwater levels and the deterioration of soil health, conservation Agriculture (CA) emerges as a promising alternative farming system (Das *et al.* 2021).

Carbon (C) sequestration presents a promising approach to mitigate soil deterioration and sustain agricultural yields (Bhattacharyya *et al.* 2015). The concentration of soil organic carbon (SOC), particularly in the topsoil, is significantly influenced by the retention of crop residues (Modak *et al.* 2019). This approach minimises soil disturbance, fostering soil aggregation and providing a protective shield for SOC against microbial decomposition. Consequently, residue decomposition rates are significantly reduced compared to conventional and intensive tillage practices. Soil organic carbon is composed of various fractions that exhibit different decomposition rates, such as labile and stable fractions. In assessing the impact of land use changes on soil quality and health, initial indicators often manifest in the unstable organic carbon components, as suggested by Yang *et al.* (2005). Among these components, water-soluble carbon (WSC) plays a crucial role in preserving and stabilizing SOC. WSC consists of microorganisms, soluble carbohydrates, and other simple compounds, albeit accounting for a small proportion of the overall SOC (Sparling *et al.* 1998). Within

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the soil ecosystem, soil microbial biomass represents the active portion of soil organic matter (SOM) and plays a decisive role in nutrient cycling and crop production. Microbial activity significantly influences the stabilization of SOM (Bhattacharyya *et al.* 2021), and changes in microbial biomass carbon due to the adoption of CA are typically observed in the topsoil (Modak *et al.* 2019).

The cotton (*Gossypium hirsutum* L.)-wheat (*Triticum aestivum* L.) system has recently emerged as a viable alternative to the conventional rice-wheat (RW) system in the IGP. The RW system is associated with high water usage, high cultivation costs, inefficient input utilization, and the potential emission of greenhouse gases (GHGs). However, there is a lack of comprehensive information regarding the long-term effects of bed planting and residue retention on SOC pools and sequestration under a cotton-wheat system. Consequently, it was hypothesized that implementing bed planting, residue retention, or a combination of both practices would positively affect SOC pools, carbon sequestration, and crop yield after ten years of CA-based cotton-wheat system in the IGP. To address this hypothesis, this study was conducted with two primary objectives. Firstly, to assess SOC stocks under bed planting and evaluate carbon sequestration rates (in comparison to conventional practices) in both surface and sub-surface soil layers. Secondly, to investigate how these long-term CA practices influence the labile and recalcitrant C pools in the surface soil, as well as the overall yield of the crops.

MATERIALS AND METHODS

Experimental site and details: The present study was carried out in an ongoing long-term trial site (block '14B') at the ICAR-Indian Agricultural Research Institute (IARI) in New Delhi during the winter (*rabi)* seasons of 2020 and 2021. The research region is located in the Indian Trans-Gangetic Plains Zone, which has a semi-arid environment with cold winters and dry summers. The surface (0–15 cm) soil of the experimental site had *p*H 7.7, Walkley-Black C 5.2 g/kg, available N 182.3 kg/ha, 0.5 M $NaHCO_3$ extractable P 23.3 kg/ha, and 1 N NH_4OAc extractable K 250.5 kg/ha when the experiment was initiated. The sand, silt and clay proportions in the 0–15 cm soil layer were 49.6, 23.2, and 27.2, respectively. The experimental treatments consisted of conventional tillage (CT), narrow bed (40 cm wide bed and 30 cm wide furrow), broad bed (per 100 cm wide bed and 40 cm wide furrow), narrow bed with residue (narrow bed + R), broad bed with residue (broad bed + R), zero tillage with residue (flat bed + R) and flat bed. The treatments were arranged in a randomized block design with three replications for each treatment. Cotton and wheat residues were taken out of all non-residue retained plots after harvest. However, in all residue-retained plots, fragile cotton branches and leaves (20% of the total cotton residues) and wheat residues (40% of the total wheat residues) were left on the surface. Das *et al.* (2014) offer further experiment specifics.

Soil sampling and analysis: Following the cotton harvest in both years, soil samples from the experimental location were taken at various depths (0–5, 5–15, 15–30, and 30–60 cm). Each sample was a composite sample from five different spots and removed visible crop residues and gravels. One part was sieved and ground for the 0–5 and 5–15 cm samples, while the other was refrigerated for soil microbial biomass C analysis. The total OC levels and organic carbon pools were calculated using the processed soil samples. The sample from the depths of 15–30 cm and 30–60 cm was air-dried before being tested for total SOC.

The amount of organic carbon in the soil was quantified following the dichromate oxidation method (Walkley and Black 1934). According to Tirol-Padre and Ladha (2004), the content of $KMnO_4$-C in bulk soils was evaluated using 33 mM $KMnO_4$, and hot water soluble carbon (WSC) was obtained from samples by Sparling *et al.* (1998). The quantity of C oxidized by 18 N H_2SO_4 was measured in order to assess the labile SOC in bulk soils. By deducting labile C from the total SOC across all soil fractions, recalcitrant SOC was calculated (Chan *et al.* 2001). The amount of carbon as microbial biomass C (MBC) was estimated as given by Jenkinson and Powlson (1976). A CHNS analyzer was utilized to find out the total SOC. The equation that follows was applied to get the SOC sequestration rate:

$$\text{Total SOC sequestration rate (Mg C/ha/yr)} = (\text{SOC}_{\text{treatment}} - \text{SOC}_{\text{control}}) / \text{Number of experiment year}$$

Where, CT treatment was the control. The harvest index was calculated by dividing the economic yield by the biological yield and expressed as a percentage:

$$\text{Harvest index (HI)} = (\text{Economic yield})/(\text{Biological yield}) \times 100$$

Statistical analysis: The statistical analyses of the experimental data were done by the randomized block design-specific analysis of variance (ANOVA). Using SAS software and the guidelines provided by Gomez and Gomez in 1984, the analysis was carried out. The significance level was gauged using the Tukey's HSD test with a p-value of 0.05.

RESULTS AND DISCUSSION

Total soil organic carbon (SOC) stock: The overall SOC stocks were considerably greater in the residue-maintained plots than in their equivalent residue removal plots. The CA plots (broad bed + R, narrow bed + R and flat bed + R) in the surface soil stratum (0–30 cm) had ~39, 31 and 29% higher SOC stocks, respectively, than the conventional tillage (CT) plots (Fig 1 a). Also, the adoption of zero tillage had increased carbon stock by 15% over CT plots in a decade. According to Jat *et al.* (2014), maintenance of crop leftovers on surfaces, higher biomass addition in the plots and a slower pace of decay of organic matter because of low turmoil to the soil may all have contributed to the higher SOC concentration in surface soil stratum under CA plots compared to CT plots. The SOC sequestration rates over the CT plots in the surface soil stratum (0–30 cm) were similar for the CA plots (Fig 1b), and the mean value was ~0.76 Mg/

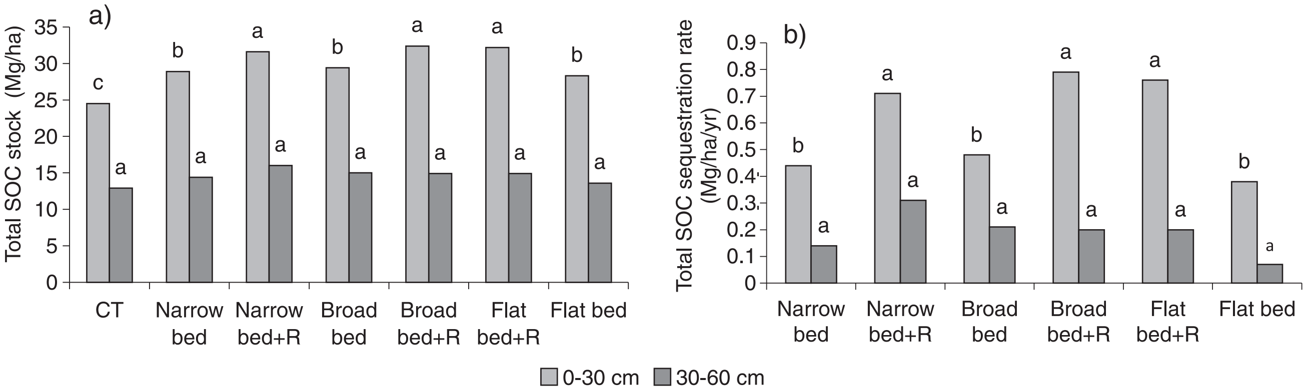

Fig 1 a) Total SOC stock (Mg/ha) and b) Total SOC sequestration rate (Mg/ha/yr) in surface layer (0–30 cm) and deep layers (30–60 cm) as influenced by long-term conservation agriculture under a cotton-wheat cropping system in an Inceptisol. According to Tukey's HSD test at P<0.05, means with distinct lowercase letters are statistically different. Treatment details are given under Materials and Methods.

ha/yr. The SOC sequestration rate was significantly higher than the mean SOC sequestration rate of the CT plots (~0.44 Mg/ha/yr) of this stratum's broad bed, narrow bed and flat bed plots. The CA plots (broad bed + R, narrow bed + R and flat bed + R) had higher SOC sequestration rates than broad bed, narrow bed and flat bed plots, in that order. In the deep layer (30–60 cm), the narrow bed + R plots had the highest SOC sequestration rate (Fig 1b). The broad bed + R, narrow bed + R and flat bed + R plots had appreciably high total SOC sequestration compared to CT plots in deep soil stratum (30–60 cm). The SOC sequestration rate was better in the elevated beds with residue (CA plots), and it could be due to higher C inputs along with the effect of flat bed that had positively affected the physicochemical condition of soils. Higher C accumulation and storage in 30–60 cm soil stratum in the narrow bed + R plots could be due to higher root density and slower decomposition rates in deeper depth (Paustin *et al.* 2019).

Walkley-Black carbon (WBC), labile and recalcitrant C: The treatments under permanent beds with residue retention had considerably higher WBC (by 31–32%) than CT plots and were similar with the conclusions of Jat *et al.* (2019). Residue retention had a significant impact in increasing WBC in the topsoil, with narrow bed + R had more WBC than narrow bed, broad bed + R had higher WBC than broad bed and flat bed + R having more WBC compared with flatbed. However, in the 5–15 cm soil stratum, broad bed + R treatment exhibited the highest WBC concentration and was substantially higher than narrow bed + R and flat bed + R plot (Table 1). Plots under broad bed + R had ~54% more WBC than CT plots (Table 2). Like the data trends in the 0–5 cm, residue retention had significantly more WBC than residue removal plots in the 5–15 cm soil stratum (Table 2).

Following a decade of CA methods, broad bed + R contained 33% more labile C in the 0–5 cm of soil depth than CT plots (Table 2). Pool of labile carbon responds quickly to the management practices, while recalcitrant C indicates C retention and is a potential sign of enhanced C sequestration in soil under various management techniques

Table 1 Walkley-Black carbon (WBC), labile C and recalcitrant C as influenced by long-term conservation agriculture under a cotton-wheat cropping system in an Inceptisol in the 0–5 and 5–15 cm soil depth (2-year mean basis)

Treatment	0–5 cm			5–15 cm		
	WBC (g/kg)	Labile C (g/kg)	Recalcitrant C (g /kg)	WBC (g /kg)	Labile C (g/kg)	Recalcitrant C (g/kg)
CT	4.78	2.85	3.44	3.76	2.28	2.75
Narrow bed	5.08	3.21	3.52	4.90	2.88	3.66
Narrow bed + R	6.28	3.73	4.49	5.51	3.35	3.84
Broad bed	5.71	3.42	3.87	4.97	2.77	3.54
Broad bed + R	6.32	3.80	4.58	5.80	3.41	4.19
Flat bed + R	6.16	3.57	4.57	4.97	3.24	3.51
Flat bed	5.54	3.25	4.03	4.07	2.42	3.02
SEm±	0.101	0.118	0.109	0.051	0.106	0.085
LSD (P<0.05)	0.314	0.368	0.338	0.158	0.331	0.264

Treatment details are given under Materials and Methods.

Table 2 Permanganate-oxidizable carbon (POXC), water soluble carbon (WSC) and microbial biomass carbon (MBC) as influenced by long-term conservation agriculture under a cotton-wheat cropping system in an Inceptisol in surface soil layers (2-year mean basis)

Treatment	0–5 cm			5–15 cm		
	POXC (g/kg)	WSC (mg/kg)	MBC (mg/kg)	POXC (g/kg)	WSC (mg/kg)	MBC (mg/kg)
CT	0.313	32.0	389.5	0.212	22.9	283.9
Narrow bed	0.336	82.4	436.7	0.269	73.9	383.4
Narrow bed + R	0.430	103.9	569.4	0.304	80.0	440.2
Broad bed	0.391	89.1	502.3	0.293	78.0	401.3
Broad bed + R	0.439	107.4	595.4	0.326	104.4	466.1
Flat bed + R	0.446	96.0	562.7	0.314	48.5	409.9
Flat bed	0.319	50.4	510.5	0.248	36.3	315.2
SEm±	0.005	6.84	12.5	0.007	2.33	15.2
LSD (p<0.05)	0.015	21.3	38.9	0.020	7.27	47.3

Treatment details are given under Materials and Methods.

(Bhattacharyya *et al.* 2012). The raised beds with residue retained plots exhibited significantly alike recalcitrant C in the topsoil. The plots under broad bed + R, narrow bed + R and flat bed + R had ~33, 30 and 33% more recalcitrant C, respectively, than farmers' practice plots in the 0–5 cm soil stratum. The treatments under residue retention exhibited ~52, 39 and 28% more recalcitrant C concentration than plots under farmers' practice in the sub-surface layer. But, the recalcitrant C concentration in this layer was lesser in flat bed + R than in the raised beds with residue-removed treatments (Table 2).

Permanganate-oxidizable carbon (POXC), microbial biomass carbon (MBC) and water soluble carbon (WSC): The flat bed+R treatment had higher amounts of POXC among all treatments (Table 2) in the 0–5 cm depth. Adopting long-term CA practices (broad bed + R, narrow bed + R and flat bed + R) improved the POXC in the topsoil with ~40, 37 and 42% more POXC than farmers' practice. Also, the residue-retained plots exhibited ~11, 13 and 26% more POXC concentrations than their respective residue removed plots. While the broad bed + R had the highest POXC concentration in the 5–15 cm stratum (Table 2), CT practice considerably decreased the POXC concentration in the 5–15 cm stratum. In that layer, the plots under broad bed + R, narrow bed + R and flat bed + R exhibited more POXC concentrations (by ~53, 43 and 48%) than the farmers' practice plots, respectively. Also, residue retention significantly increased the POXC concentrations over residue-removed plots (Table 2).

Compared to CT plots, CA practices improved the MBC of surface soil by ~44 to 52% (Table 2). In the sub-surface soil layer, a highest MBC level was in the broad bed + R treatment and there was a significant decrease in MBC concentration in other treatments. Under CA practices, the soil is less disturbed and continuous retention of residues increases the microbial biomass as they form the primary energy source for soil organisms (Das *et al.* 2021). The raised beds and flat bed along with adequate mulch improved the MBC content of soils as they positively influenced the soil temperature, moisture content, and the beds' microenvironment. In broad bed + R plots, more residues are retained than other treatments. The impact of tillage and residue retention was more noticeable at this depth. The broad bed + R, narrow bed + R and flat bed + R treatments had 64, 55 and 44% more MBC concentrations than CT treatments, respectively, in the 5–15 cm depth (Table 2). Residue retention increased the WSC by 20, 26 and 90% than the respective residue-removed plots (broad bed + R versus broad bed, narrow bed + R versus narrow bed and flat bed + R versus flat bed). However, the elevated beds with residue (broad bed + R and narrow bed + R) had ~11 and 8% more WSC than flat beds with residue. Unlike the topsoil, retaining residue had no significant effect on WSC, except in broad bed + R treatment (Table 2). The priming effect when adding fertilizers or new organic substances to the soils may have contributed to the increase in WSC by encouraging the breakdown of organic matter via enhanced microbial activity. (Yagi *et al.* 2005). The lower POXC content in CT plots indicates the high carbon loss due to greater disruption to the soil and the absence of leftovers. The WSC contents were meagre in CT plots in both the depths and could be due to less carbon retention in those plots.

The yield data indicate zero tillage and residue (CA) had a discernible impact. The broad bed + R and flat bed + R plots documented the highest crop yields, whereas CT plots had the lowest yields. The economic yields were ~72 and 67% and ~19 and 24% higher in broad bed + R and flat bed + R for cotton and wheat, respectively, compared with CT plots (Table 3). According to Das *et al.* (2014) an adequate growing microclimate with better soil physical and biochemical qualities could be accounted for the increased yield with higher biomass under CA-based systems.

The findings demonstrate the viability of raised bed planting methods with residue retention for C sequestration in the surface (0–30 cm) and deep soil layer (30–60 cm), as well as improving yield in cultivated soils, which agrees

Table 3 Effect of long-term conservation agriculture on yield of cotton-wheat (2-year mean basis)

Treatments	Cotton			Wheat		
	Biological yield (tonnes/ha)	Economic yield (tonnes/ha)	Harvest index	Biological yield (tonnes/ha)	Economic yield (tonnes/ha)	Harvest index
CT	10.2	2.02	20.0	17.8	6.82	38.4
Narrow bed	10.6	2.32	22.0	18.9	7.38	39.0
Narrow bed + R	10.4	2.34	22.6	18.3	7.17	39.3
Broad bed	10.2	2.39	23.6	19.8	7.87	39.7
Broad bed + R	13.4	3.48	26.0	20.7	8.11	39.2
Flat bed + R	15.7	3.38	21.6	20.9	8.46	40.5
Flat bed	12.4	2.78	22.4	19.6	7.96	40.6
SEm±	0.38	0.11	0.50	0.340	0.152	0.947
LSD	1.19	0.33	1.56	1.06	0.474	Ns

Ns, Not significant. Treatment details are given under Materials and Methods.

with the hypothesis. Also, the results indicate that zero tillage and residue (CA) enriched soil's organic carbon pools and microbial biomass. The enhancement of the labile C pool under CA practices shows the positive effects of CA under its long-term adoption in the IGP. Thus, adopting permanent raised beds with residue retention has excellent potential for higher carbon sequestration in deeper layers, which is considered to be a key mechanism for the long-term stabilization of SOC. Farmers, extension specialists, and lawmakers can utilise the study's findings to inform their decisions about tillage and residue management techniques that can increase productivity and enhance C sequestration in the cotton-wheat system of the IGP and comparable agro-ecosystems.

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