

## Review Article

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## Variability in Soil Aggregation and Depth Distribution of Aggregate Associated Organic Carbon Fractions Relevance to Different Agricultural Practices in Agro-ecosystems of North-West India: A Review

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### ABSTRACT

Soil aggregates and organic matter are considered to be important indicators of soil quality. The objective of this review study was to determine agricultural practices effects on the distribution of soil organic carbon (SOC) associated with aggregate-size fractions. Depth distribution of soil organic carbon (SOC) fractions depends on the efficiency of agro- technical managements. The SOC stocks to 1-m depth were 172.3 Mg C ha<sup>-1</sup> under Forest and the lowest 89.3 Mg C ha<sup>-1</sup> under home-garden. No significant differences were noted in SOC within the silt + clay fraction (< 53 μm) beyond 60 cm depth under Forest and other shaded AFS. Moreover, depth, aggregate size and treatment had significant interaction effects on SOC stocks. The reports show that deep rooted, crop-based systems, have higher total soil C stocks and more C in the smallest (< 53 μm) soil fractions indicating the recalcitrant (longer-term storage) nature of C and implying consequent ecosystem benefit of reduced chances for soil C release back to the atmosphere. Moreover, the mean stratification ratio (SR) (i.e. a ratio of the concentrations of SOC in the soil surface to those in a deeper layer) of SOC for 0–5:5–10, 10–15, 15–20, 20–25 and 25–30 cm were found higher (> 2) under CA practices compared to intensive tillage-based conventional agricultural practice. The fractions of aggregates, aggregate SOC and aggregate EOC in grassland and forestland were generally higher than those in farmland. Furthermore, because conventional cultivation destroyed aggregates, the dominant aggregate size fractions were < 0.5 mm for farmland and > 0.5 mm for other land uses. Compared to the corresponding values in farmland, the mean weight diameter (MWD) in forestland and grassland increased by 808%–417%, and the stability ratio of water-stable aggregate (WSAR) increased by 920%–553%. Aggregate formation and its dominant size fraction were associated closely with its carbon fractions. SOC and EOC in farmland tended to be concentrated in smaller-sized aggregates, whereas SOC and EOC under other land uses tended to concentrate in larger-sized aggregates. The MBC concentration was the highest in minimum tillage (MT) system, at 15 to 30- cm depth and PMC concentration was highest with MT at 45–60 cm. The highest DOC was at 0 to 15- cm depth. The highest stratification ratio (SR) of PMC was under MT with at 0–15:15–30 and POC was under tine cultivator (TC) and moldboard plow (MP) at depths of 0–15:45–60 cm. The highest SR for DOC was under MP at 0–15:45–60 cm and HCl insoluble C was under MT at 0–15:45–60. In broad- spectrum, labile organic fractions revealed differential sensitivity, and POC stocks are also a sensitive indicator to detect the short-management effects.

### Keywords

Soil organic carbon fractions, Soil aggregate, Stratification ratio, Conservation tillage, Carbon stocks

### Article Info

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## Introduction

On a global scale, soil organic carbon (SOC) reservoir is approximately twice as large as that of the atmosphere, and approximately three times that resides within the vegetation (Smith *et al.*, 2008). Even subtle changes in the overall mass of global SOC pools could trigger immense fluctuation in the concentration of CO<sub>2</sub> in the ambient atmosphere. One potential modification of the SOC pool may occur due to the changes in microbial decomposition of organic matter in the soil. The stability of SOC against microbial degradation is thought to be contingent on various interactions between SOC chemistry, soil climate, soil fauna, and soil structure (Davidson and Janssens, 2006). Of these factors, the effects of soil structure and/or aggregation on SOC dynamics remain one of the least understood, particularly in natural ecosystems. Water-stable aggregation rate has been recognized as one of the standard features of soil quality that affects SOC dynamics (Pulleman *et al.*, 2005; Bu *et al.*, 2012).

Soil organic matter may be protected from temperature fluctuations via micro-aggregation (53–250 µm) within macro-aggregates (250–2000 µm), physical binding with soil clay and silt particles, and the biochemical formation of recalcitrant SOC compounds (Plante *et al.*, 2011).

Conventional tillage practices induce the disruption of soil aggregates due to soil disturbance by plowing and removing crop residues from the field, as has been reported widely (Andruschkewitsch *et al.*, 2014). The disruption of soil aggregates results in enhanced SOC decomposition and transformation rates (Zotarelli *et al.*, 2007). Some studies have reported that conservation tillage can improve SOC stabilization (Nath and Lal, 2017). Compared with conventional

tillage, which can accelerate the regeneration of macro-aggregates, conservation tillage can yield greater macro-aggregate content and sequester more SOC in agricultural land (Alvaro Fuentes *et al.*, 2008). However, most studies of the effects of tillage and straw retention on soil aggregates have focused on plowing depth (0–20 cm) (Liu *et al.*, 2015), while deep soil degradation is becoming a serious limitation to crop yield and soil quality (Hartmann *et al.*, 2008). Accordingly, it is necessary to conduct studies of deep soil (Zhu *et al.*, 2017).

Subsoil C storage may be achieved by increasing C inputs to deep soil layers, decreasing the rate of SOC mineralization, or a combination of both. Carbon inputs are delivered to deep layers through root growth, bioturbation or mechanical incorporation of surface litters, and transport of dissolved organic C from surface layers (Rumpel and KögelKnabner, 2011). Management practices designed to increase subsoil C stocks have focused primarily on increasing root C inputs at depth (Paustian *et al.*, 2016) for at least three reasons. First, the similarity of root and SOC vertical distributions across biomes suggests that root C inputs are a dominant control on deep SOC stocks. Second, root-derived C has a longer residence time than shoot-derived C potentially because it is more biochemically resistant to mineralization (Ahmad *et al.*, 2014) and more likely to become protected through occlusion within soil aggregates than is shoot C (Kong and Six, 2010). And third, variation exists in root system size and depth within and among crop species, which can potentially be exploited for deep C delivery (Lynch and Wojciechowski, 2015). A better understanding of the impact of agricultural management on root inputs, and the effects of enhanced root inputs on subsoil C storage, will be required if deep-rooting cropping systems are to be widely adopted for C storage (Paustian *et al.*, 2016).

The objectives of the review study were to ascertain the effects of long-term conservation tillage and residue retention on: (1) aggregate distribution and stability in the vertical direction in soil; and (2) variations in aggregate-associated and sub-fraction-associated OC in a deep soil. It was hypothesized that: (1) compared to conventional tillage, conservation tillage would yield more SOC and stable macro-aggregates in the deep soil layer; (2) conservation tillage would result in more SOC in soil macro-aggregates than conventional tillage; and (3) mineral-associated OC (mSOC) was the main form of SOC accumulated.

### **Effect of Agricultural Practices on SOC and EOC**

Tan *et al.*, (2007) revealed that across soil depths, significant difference was observed among treatments with respect to SOC concentration. The light fraction accounted for 12.0%, 10.8% and 5.7% of the total soil mass in forest, NT and CT soils, respectively. Averaged across all treatments, light fraction decreased with depth from 11% in the 0–5 cm to 8.8% in the 10–20 cm depth. In the CT soil, however, variation with depth was minor probably due to homogenization and mixing effect of plowing. A higher mass proportion of light fraction was observed by Wander and Traina (1996), which may be due to greater light fraction recovery resulting from the use of a higher density SPT solution (1.85 g mL<sup>-1</sup> versus 1.65 g mL<sup>-1</sup>). Chen *et al.*, (2016) reported that the SOC concentration decreased with soil depth. In both 0–10 and 10–20 cm, the SOC concentration in the RP treatment was significantly greater than that in the other four treatments, yet no significant differences were found among the other four. In 20–30 cm, there were in general no significant differences among all the rotation systems.

Zheng *et al.*, (2018) reported that across treatments, aggregate-associated C at a depth of 0–10cm was higher in the NT and ST treatments than in the MP and CT treatments. The advantage of the NT treatment weakened with soil depth, while the amount of aggregate-associated C remained higher for the ST treatment. There were more macro-aggregates in the ST and NT treatments than in the MP and CT treatments, while the MP and CT treatments had more micro-aggregates. The sum of macro-aggregate contributing rates for soil organic C (SOC) was significantly superior to that of the micro-aggregates. Mahajan *et al.*, (2019) reported that the increased SOC stock in the surface 50 kg m<sup>-2</sup> under ZT and PRB was compensated by greater SOC stocks in the 50–200 and 200–400 kg m<sup>-2</sup> interval under residue retained, but SOC stocks under CT were consistently lower in the surface 400 kg m<sup>-2</sup>.

Zou *et al.*, (2016) also found that the soil EOC content ranged from 7.98–11.23 g kg<sup>-1</sup> for S<sub>400</sub>, 8.80–13.47 g kg<sup>-1</sup> for S<sub>800</sub>, 7.92–10.02 g kg<sup>-1</sup> for S<sub>1200</sub> and 7.58–9.42 g kg<sup>-1</sup> for S<sub>1600</sub>. The EOC contents in the S<sub>800</sub> treatment were the highest, and the EOC contents in the CK were the lowest at each soil depth. Some appreciable differences were observed between the straw return in the different treatments, which decreased in the following order: S<sub>800</sub> > S<sub>400</sub> > S<sub>1200</sub> > S<sub>1600</sub> > CK (Fig. 1a). The deep soil (depth of 20–40 cm) had the lowest EOC content compared with the other two depths. In the control treatment, the soil EOC decreased as the soil depth increased from 0–10 cm to 10–20 cm. In the straw return treatments, the soil EOC was higher at 10–20 cm than at 0–10 cm. However, the soil LFOC in the different straw return treatments ranged from 223.12–280.37 mg kg<sup>-1</sup> for S<sub>400</sub>, 235.67–300.32 mg kg<sup>-1</sup> for S<sub>800</sub>, 233.78–301.32 mg kg<sup>-1</sup> for S<sub>1200</sub>, and 218.44–268.77 mg kg<sup>-1</sup> for S<sub>1600</sub>. The ranges of soil LFOC in all treatments decreased as

follows:  $S_{1200} > S_{800} > S_{400}$ ,  $CK > S_{1600}$  at 0–10 cm,  $S_{800}$ ,  $S_{1200} > CK$ ,  $S_{400} > S_{1600}$  at 10–20 cm, and  $S_{800}$ ,  $S_{1200} > S_{400} > S_{1600} > CK$  at 20–40 cm (Fig. 1b).

Conforti *et al.*, (2016) observed that the maximum value (214.5 Mg ha<sup>-1</sup>) of SOC stock was observed in the A horizons accounting for about 30% of the estimated total SOC stock along soil profile. The significant lowest values were recorded in the organic horizon, which stored approximately 2% of total SOC stock. Vertical distribution of SOC stock highlighted that even though there was less variability in SOC stock across A-Bw horizons, a significant decrease with depth was observed towards BC and especially Cr layers. The results revealed that the sampling thickness of 20 cm for Cr layers can be considered reliable because of the above quoted decreasing trend of SOC stock in depth. This behavior is consistent with the evidence that 96% of SOC was stored in the overlying soil horizons. In addition, a similar decreasing trend of the weathering degree of the parent rock down-profile suggests a possible corresponding decrease in the storage capacity of SOC. FB. At 0–5 cm and 5–10 cm depths in PRB, the concentration of TOC was significantly higher than the corresponding depths in FB and TT (PRB > FB > TT). However, at 10–20 and 20–40 cm, no significant differences were observed in TOC concentration between treatments. At 40–60 cm, TT tillage had the highest TOC concentration (5.5gkg<sup>-1</sup>) which differed significantly from FB (4.6gkg<sup>-1</sup>); the trend in TOC concentration was TT > PRB > FB.

Zhao *et al.*, (2014) also found that the contents of SOC, TN, POC and LOC responded differently as the change of soil depth (Fig. 2a). In all land use types, contents of SOC, TN, POC and LOC in top soil (0–10 cm) were 3.26–7.86 gkg<sup>-1</sup>, 0.39–0.72 gkg<sup>-1</sup>, 0.65–1.31 gkg<sup>-1</sup> and 0.76–1.07 gkg<sup>-1</sup>,

respectively, which were significantly higher than other soil layers. The contents of SOC, TN, POC and LOC decreased significantly in soil depth of 10–40 cm while the decreases trended to be flatter in subsoil (40–100 cm). Additionally, the differences in contents of SOC, TN, POC and LOC in deep subsoil (100–200 cm) were negligible. The differences in contents of SOC, TN, POC and LOC between three types (RP, CK and AB) and SC are shown in Fig. 2b. The differences in SOC, TN, POC and LOC of RP and SC in soil depths of 0–10 cm and 100–200 cm were significantly higher than that between other land use types and SC. The differences in SOC and TN of RP were 33.78% and 45.97% larger than that of CK and 54.13% and 67.28% larger than that of AB in soil depth of 0–10 cm while the differences in POC and LOC were 32.8%, 54.0% higher than that of CK, and 23.3% and 45.0% higher than that of AB. Moreover, the differences in SOC, TN, POC and LOC of RP were 25.05–85.29% higher than that of CK, and 61.78–90.70% higher than that of AB in soil depth of 100–200 cm.

Gu *et al.*, (2017) revealed that SOC concentration in all treatments decreased with soil depth. The significant differences of SOC among treatments were solely at depths of 0–40 cm, where soil physicochemical properties changed. Further changes would have occurred following activity by microorganisms. Average SOC content at depths of 0–40cm in ST and GT were 6.26 g kg<sup>-1</sup> and 6.59 g kg<sup>-1</sup> respectively, significantly higher than that of 5.44 g kg<sup>-1</sup> in CK. The use of ST and GT increased SOC by 15.15% and 21.14%, respectively. In the course of the growing season, SOC concentrations in all treatments presented substantial changes with seasons. Liu *et al.*, (2019) reported that macro-aggregate proportion under cropland was significantly lower than under abandoned cropland and

native vegetation land at the 0–20 cm depth. Micro-aggregate proportions under abandoned cropland and native vegetation land were significantly lower than under cropland in the soils at the 0–30 cm depth. Silt + clay-sized fraction proportion under cropland was larger than under abandoned cropland and native vegetation land in the soils at the 0–10 cm depth. Macro-aggregates accounted for 63–83% of all sized aggregates. Furthermore, macro-aggregates were generally more sensitive to land management than smaller sized aggregates.

Patra *et al.*, (2018) reported that the soil bulk densities ( $\rho_b$ ) increased significantly with increase in soil depth under all treatments. However, no statistically significant differences were observed for depths beyond 15 cm under all treatments. The  $\rho_b$  ranged from 1.43 (0–5 cm depth) to 1.70 (15–20 cm depth)  $\text{Mg m}^{-3}$  under NT-MWMB, 1.46 (0–5 cm depth) to 1.68 (10–15 cm and 15–20 cm depths)  $\text{Mg m}^{-3}$  under NT-RWMB, 1.42 (0–5 cm depth) to 1.70 (15–20 cm depth)  $\text{Mg m}^{-3}$  under RT-RWMB and 1.45 (0–5 cm depth) to 1.69 (10–15 cm and 15–20 cm depths)  $\text{Mg m}^{-3}$  under CT-RW. Among the treatments, lowest  $\rho_b$  (1.42  $\text{Mg m}^{-3}$ ) was observed in the topsoil layer (0–5 cm) under RT-RWMB followed by NT-MWMB (1.43  $\text{Mg m}^{-3}$ ), CT-RW (1.45  $\text{Mg m}^{-3}$ ) and NT-RWMB (1.46  $\text{Mg m}^{-3}$ ) [Fig.3a]. Therefore, the depth distributions of concentrations of SOC are shown in (Figure 3b). Values decreased with increase in soil depth under all treatments and depth distribution of SOC also differed among the different treatments. Values ranged from 10.65 (0–5 cm depth) to 3.04 (25–30 cm depth)  $\text{g kg}^{-1}$  under NT-MWMB, 10.27 (0–5 cm depth) to 3.30 (25–30 cm depth)  $\text{g kg}^{-1}$  under NT-RWMB, 7.86 (0–5 cm depth) to 2.36  $\text{g kg}^{-1}$  (25–30 cm depth) under RT-RWMB and 5.90 (0–5 cm depth) to 2.64  $\text{g kg}^{-1}$  (20–25 cm depth) under CT-RW. The highest concentrations of SOC were observed

under NT-MWMB at 0–5 cm depth, whereas at 5–10, 10–15 and 15–20 cm soil depths, the highest SOC concentrations were observed under RT-RWMB. At 20–25 and 25–30 cm soil depths NT-RWMB contained the highest concentrations of SOC. The topsoil (0–5 cm depth) SOC concentrations differed significantly from the lower layers under NT-MWMB and NT-RWMB, whereas, the same was not detected under RT-RWMB and CT-RW. The concentrations of SOC did not differ significantly from each other in the lower soil layers (>10 cm depth) under NT-MWMB and NT-RWMB. However, under RT-RWMB and CT-RW, values did not differ significantly in the lower layers only beyond 20 cm of soil depth. The concentrations of SOC at 0–5 cm depth under NT-MWMB and NT-RWMB were not significantly different from each other. At the same depth, SOC values also did not differ significantly under RT-RWMB and CT-RW. However, the topsoil (0–5 cm) SOC concentrations differed significantly between the no-till treatments (NT-MWMB and NT-RWMB) and the treatments having tillage operations (RT-RWMB and CT-RWMB). At 5–10 and 10–15 cm soil depths, the SOC concentrations under RT-RWMB varied significantly from other treatments.

Yu *et al.*, (2020) reported that –10 cm depth and the lowest value (1.370  $\text{g kg}^{-1}$ ) in the SUA treatment at the 40–50 cm depth. The range of the SOC concentrations across the soil profile was 10.970, 7.230, 6.937, 4.408, and 6.025  $\text{g kg}^{-1}$  for the LEY, PUC, ECH, SUA, and CHL treatments, respectively. Vegetation type had significant effects on the SOC concentration. The SOC concentration at 0–10 cm depth was ranked in the order of LEY > ECH > PUC > CHL > SUA. Compared with the SUA and CHL treatments, SOC concentrations in LEY and ECH treatments were significantly higher at the 10–20 cm depth. At 20–50 cm depth, significantly higher SOC concentrations were

found in treatments with LEY  $\approx$  ECH  $>$  PUC  $\approx$  CHL  $>$  SUA (Fig. 9a). The average SOC concentration at 0–50 cm depth was 7.418, 5.268, 6.350, 3.308, and 4.876 g kg<sup>-1</sup> for the LEY, PUC, ECH, SUA, and CHL treatments, respectively. The SOCS under LEY, PUC, ECH, SUA, and CHL was 34.180, 25.923, 26.850, 15.493, and 22.040 Mg ha<sup>-1</sup>, respectively, at the 0–20 cm depth and 22.256, 15.438, 22.313, 10.919, and 16.318 Mg ha<sup>-1</sup>, respectively, at the 20–50 cm depth.

### **Total carbon stocks in the fractions and layers up to a 1-m depth**

Devine *et al.*, (2014) observed that 0–5 cm, NT and FS aggregate size fractions were significantly elevated for SOC and fine fractions compared to CT. In POC, increasing C from CT>NT>FS was evident in all aggregate sizes but significant at 0.05 for only the >2000  $\mu$ m. From 5–15 cm, there were no significant differences between CT and NT for any of the size class and C fraction combinations, while the two largest aggregate size classes were significantly elevated in FS with respect to NT for SOC and all three classes were greater for POC. FS also exceeded CT but only in the small and micro aggregate fractions for POC. There were no significant differences for any of the size class and C fraction combinations from 15–28 cm.

Mangalassery *et al.*, (2014) revealed that zero tilled soils contained significantly more soil organic matter (SOM) than tilled soils. Soil from the 0–10 cm layer contained more SOM than soils from the 10–20 cm layers in both zero tilled (7.8 and 7.4% at 0–10 cm and 10–20 cm respectively) and tilled soils (6.6% at 0–10cm and 6.2% at 10–20 cm). Wang *et al.*(2018) reported that tillage system change influenced SOC content, NT, ST, and BT showed higher values of SOC content and increased 8.34, 7.83, and 1.64 MgCha<sup>-1</sup>, respectively, compared with CT. Among the

changed tillage systems, NT and ST showed a 12.5% and 11.6% increase in SOC content then BT, respectively. Tillage system change influenced SOC stratification ratio values, with higher value observed in BT and NT compared CT but ST. Therefore, in loess soil, changing tillage system can significantly improve SOC storage and change profile distribution.

Dhaliwal *et al.*, (2018) revealed that the mean SOC concentration decreased with dry stable aggregates (DSA) and water stable aggregates (WSA). In DSA, the mean SOC concentration was 58.06 and 24.2% higher in large and small macro-aggregates than in micro-aggregates respectively; in WSA it was 295.6 and 226.08% higher in large and small macro-aggregates than in micro-aggregates respectively in surface soil layer. The mean SOC concentration in surface soil was higher in DSA (0.79%) and WSA (0.63%) as compared to bulk soil (0.52%). Zhao *et al.*, (2014) observed that SOC distribution in soil aggregate fractions of different vegetation types was shown in Figure 4. Micro-aggregates (< 0.25 mm) of five vegetation types had higher SOC content than macro-aggregates. However, SOC contents in macro-aggregates (> 0.25 mm) of Rr, Po, Pt, and Ab were greater than that of Sc, suggesting that the distribution of SOC contents appeared to have shifted from the micro-aggregates (< 0.25 mm) in low C input systems to the macro-aggregates in high C input systems. It was mainly due to micro-aggregate formation within macro-aggregates. Micro-aggregates occluded in the macro-aggregates can serve as an indicator for C sequestration.

Zhao *et al.*, (2014) revealed that the SOC, TN, POC and LOC stocks of RP were significantly increased which were 0.43–5.8 Mgha<sup>-1</sup>, 0.25–4.70 Mgha<sup>-1</sup>, 0.44–9.14 Mgha<sup>-1</sup> and 1.49–11.38 Mgha<sup>-1</sup> higher than that of SC in soil layers of 0–10, 10–40, 40–100 and

100–200 cm, respectively. Moreover, the stocks of SOC, TN, POC and LOC in soil layer of 100–200 cm of RP were higher than that of CK and AB by 15.4–32.1% and 21.8–43.1%, respectively (Fig. 5).

Zhao *et al.*, (2015) also found that the concentrations of SOC decreased with increasing soil depth, and the depth distribution of SOC differed among treatments in both the wheat and maize seasons. At the wheat harvest, the SOC concentrations were the highest under NT at the 0–5 and 5–10 cm depths, but the highest under PT at the 10–20, 20–30, and 30–50 cm depths. Furthermore, the SOC concentrations under RT fell between those for PT and NT at all soil depths except 5–10 cm. At the maize harvest, a similar trend as for the wheat harvest was observed among the treatments. Comparing to the maize harvest, the SOC concentrations under NT increased by 12.17%, 17.13%, and 5.56% at the 0–5, 5–10 and 10–20 cm depths, respectively, but decreased by 6.97% at the 20–30 cm depth at the wheat harvest. Similar trends were also observed under RT and PT, for which SOC increased at the 0–5, 5–10 and 10–20 cm depths and decreased or remained constant for the 20–30 and 30–50 cm depths.

Naresh *et al.* (2018) reported that conservation tillage practices significantly influenced the total soil carbon (TC), Total inorganic carbon (TIC), total soil organic carbon (SOC) and oxidizable organic carbon (OC) content of the surface (0–15 cm) soil. Wide raised beds transplanted rice and zero till wheat with 100% ( $T_9$ ) or with 50% residue management ( $T_8$ ) showed significantly higher TC, SOC content of 11.93 and 10.73 g kg<sup>-1</sup>, respectively in  $T_9$  and 10.98 and 9.38 g kg<sup>-1</sup>, respectively in  $T_8$  as compared to the other treatments. Irrespective of residue incorporation/retention, wide raised beds with zero till wheat enhanced 53.6%, 33.3%, 38.7% and

41.9% of TC, TIC, SOC and OC, respectively, in surface soil as compared to conventional tillage with transplanted rice cultivation. Simultaneously, residue retention caused an increment of 6.4%, 7.4%, 8.7% and 10.6% in TC, TIC, SOC and OC, respectively over the treatments without residue management. Concerning the organic carbon storage, SOC<sub>s</sub> varied between 31.9 Mg·ha<sup>-1</sup> and 25.8 Mg·ha<sup>-1</sup> under NT, while, in tilled treatments, SOC<sub>s</sub> ranged between 28.8 Mg·ha<sup>-1</sup> and 24.8 Mg·ha<sup>-1</sup>.

Wang *et al.*, (2019) reported that the silt +clay fraction accounted for 9%–13% and the large macro-aggregates accounted for 0%–10%. In the 0–10 and 10–20 cm layers, the NT treatment produced the highest proportion of large and small macro-aggregates, with mean values of 6% and 33%, respectively, whereas the proportion of large and small macro-aggregates under CT was 0% and 21%, respectively (Fig. 6a). The positive effects of the RT and NT treatments were mainly concentrated on the small macro-aggregates. Compared with CT, the mass proportions of small macro-aggregates were higher in the 10–100 cm layer, accounting for 11%–36% under RT and 7%–40% in all layers under NT. Except for some individual values, CT soil had the highest proportion of the micro-aggregate and silt +clay fractions. Moreover, the different aggregates, the highest OC contents were found in the small macro-aggregates in the 0–60 cm layer, with a range of 37–88 g Ckg<sup>-1</sup> aggregate, which was significantly higher than that of the large macro-aggregates, micro-aggregates, and the silt +clay fraction (Fig. 6b). Compared with CT, the NT treatment significantly increased the OC contents in the upper 10-cm layer in the large macro-aggregates, micro-aggregates, and the silt +clay fraction by 31%, 30%, and 36%, respectively (Fig. 6b). In the 10–100 cm layer, OC contents under NT decreased compared with those under CT, except for the

silt +clay fraction in the 40–60 cm layer. The RT treatment increased OC contents in the small macro-aggregates mainly from the 0–10 cm to the 60–80 cm layers, with a 1%–58% improvement compared to CT. In the large macro-aggregates, RT significantly increased OC contents in the 0–10 and 40–60 cm soil layers by 58% and 51%, respectively. In the silt +clay fraction, RT significantly increased OC contents in the 10–20, 20–40, and 40–60 cm layers by 31%, 34%, and 52%, respectively. The differences in OC contents in micro-aggregates between the RT and CT treatments were only significant in the 40–60 cm layer.

### Storage of SOC

Zhao *et al.*, (2015) reported that the SOC storage under NT was significantly higher than that under PT in the surface soil (top 10 cm) by 10.82% and 8.16% at the 0–5 and 0–10 cm depths, respectively. However, no statistically significant differences were observed among the three treatments in the 0–50 cm soil profile in the maize season, and the SOC storage in this soil layer was 3.82% and 6.28% higher than that under NT and RT, respectively. Additionally, the SOC storage was greater under RT than that under PT in the 0–5 cm layer by 6.53%, but no statistically significant differences existed between the two treatments in the 0–10, 0–20, 0–30, and 0–50 cm layers. In the wheat season, the SOC storage was still higher under NT than that under PT in the 0–5 cm and 0–10 cm layers by 7.19% and 4.26%, respectively. Furthermore, the SOC storage increased more under PT when the soil depth increased from the 0–5 to 0–50 depth than that under NT or RT. For the 0–50 depth, the SOC storage was significantly greater under PT by 5.54% than that under NT and by 6.98% than that under RT. Moreover, the SOC storage was significantly higher under NT than that under RT at 0–5 and 0–10 cm; however, no

significant differences existed at the 0–20, 30, and 50 depths.

Patra *et al.*, (2018) observed that the SOC storage at 0–10 cm soil depth was the highest under NT-MWMB (12.49 Mg ha<sup>-1</sup>) followed by NT-RWMB (12.12 Mg ha<sup>-1</sup>), RT-RWMB (11.52 Mg ha<sup>-1</sup>) and CT-RW (8.57 Mg ha<sup>-1</sup>). No statistically significant difference existed among NT-MWMB, NT-RWMB and RT-RWMB treatments. However, storage of SOC at 0–10 cm depth was significantly lower under CT-RW compared to other treatments. The storage of SOC at 0–25 cm depth was the highest under RT-RWMB followed by NT-RWMB, NT-MWMB and CT-RW. However, it was only significantly higher than under CT-RW. At 0–30 cm soil depth, NT-RWMB stored the highest amount of SOC (25.32 Mg ha<sup>-1</sup>) and it differed significantly only from that under CT-RW (20.83 Mg ha<sup>-1</sup>). However, there were no statistically significant differences among NT-MWMB, NT-RWMB and RT-RWMB and NT-MWMB, RT-RWMB and CT-RW. The TN storage at 0–5 cm depth followed the order of NT-MWMB > NT-RWMB > RT-RWMB > CT-RW. However, the trend was different with an increase in soil depth. At 0–15 cm, 0–20 cm, 0–25 cm and 0–30 cm soil depths, the storage of TN was the highest under RT-RWMB followed by NT-MWMB, NT-RWMB and CT-RW. At these soil depths, the TN storage under RT-RWMB differed significantly only from that under CT-RW. For the storage of TN at 0–30 cm, there was no significant difference among the different treatments.

Wang *et al.*, (2019) also found that the SOC contents in all treatments displayed a decreasing trend from topsoil (0–10 cm) to deep soil (80–100 cm). RT resulted in the highest SOC content in all layers except the 80–100 cm layer. Compared with the CT treatment, RT significantly increased SOC

contents in the 0–10, 10–20, 20– 40, 40–60, and 60–80 cm layers, with values of 59%, 28%, 29%, 77%, and 24%, respectively. NT significantly increased SOC contents in the 0–10, 10–20, 20–40, and 40–60 cm layers, with values of 20%, 19%, 3%, and 23%, respectively. There was no significant difference in the SOC content between RT and CT in the 80–100 cm layer. In the deep soil of the 60–80 and 80–100 cm layers, the SOC content in NT soil was significantly lower than that in CT soil. Yu *et al.*, (2020) also found that the greater SOCS was observed in the LEY treatment as compared

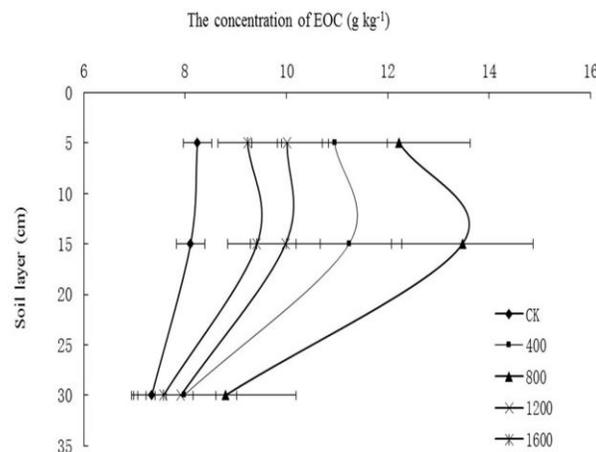
to PUC ≈ ECH > CHL > SUA treatments at 0–10 cm depth. At the 10–20 cm depth, SOCS in the LEY, PUC and ECH treatments was significantly higher than that in the SUA and CHL treatments. Similar to the SOC concentration, SOCS at 20 to 50 cm depth was ranked as LEY ≈ ECH > PUC ≈ CHL > SUA (Table 1). The SOCS under LEY, PUC, ECH, SUA, and CHL was 34.180, 25.923, 26.850, 15.493, and 22.040 Mg ha<sup>-1</sup>, respectively, at the 0–20 cm depth and 22.256, 15.438, 22.313, 10.919, and 16.318 Mg ha<sup>-1</sup>, respectively, at the 20–50 cm depth.

**Table.1** Storage of SOC under different vegetation types

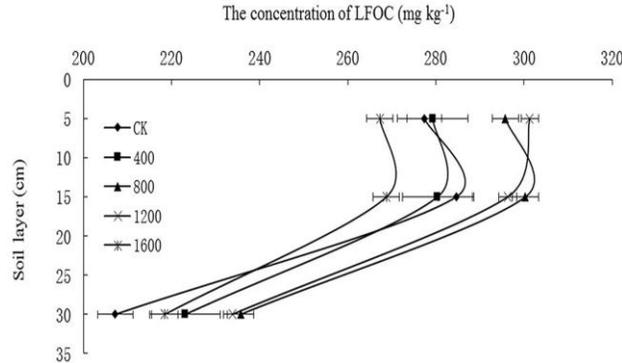
Soil Depth (cm)	Storage of Soil Organic Carbon (Mg ha <sup>-1</sup> )				
	LEY	PUC	ECH	SUA	CHL
0-10	20.625 (±0.465) Aa	14.453 (±0.632) Ba	15.275 (±0.181) Ba	9.035 (±0.209) Da	13.225 (±0.109) Ca
10-20	13.555 (±0.739) Ab	11.470 (±1.599) Ab	11.575 (±0.464) Ab	6.458 (±0.653) Bb	8.815 (±0.240) Bb
20-30	9.838 (±0.400) Ac	6.785 (±0.495) Bc	9.390 (±0.380) Ac	5.058 (±0.380) Cc	6.525 (±0.455) Bc
30-40	7.208 (±0.197) Ad	4.973 (±0.099) Bcd	7.453 (±0.361) Ad	3.578 (±0.241) Cd	5.460 (±0.202) Bd
40-50	5.210 (±0.304) ABe	3.680 (±0.298) Bd	5.470 (±0.399) Ae	2.283 (±0.151) Ce	4.333 (±0.299) Be
0-50	56.436 (±1.038) A	41.361 (±1.928) C	49.163 (±0.804) B	26.412 (±0.858) D	38.358 (±0.738) C

*Leymus chinensis* (LEY), *Puccinellia tenuiflora* (PUC), *Echinochloa phyllopogon* (ECH), *saline seepweed* (SUA), and *Chloris virgata* Swartz (CHL)

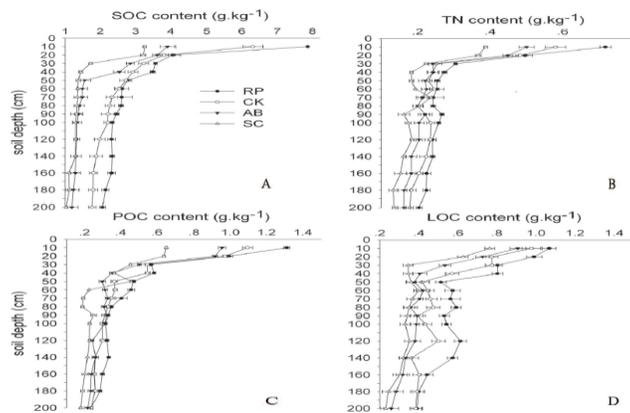
**Fig.1a** Effects of straw return to deep soil on the easily oxidized organic carbon (EOC) contents at three soil depths



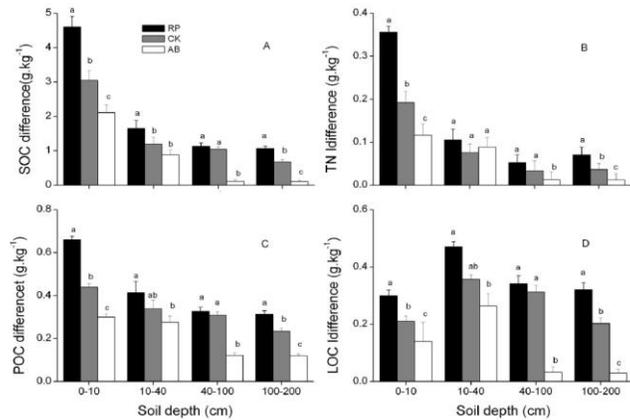
**Fig.1b** Effects of returning straw to deep soil on the soil light fraction organic carbon (LFOC) at three soil depths



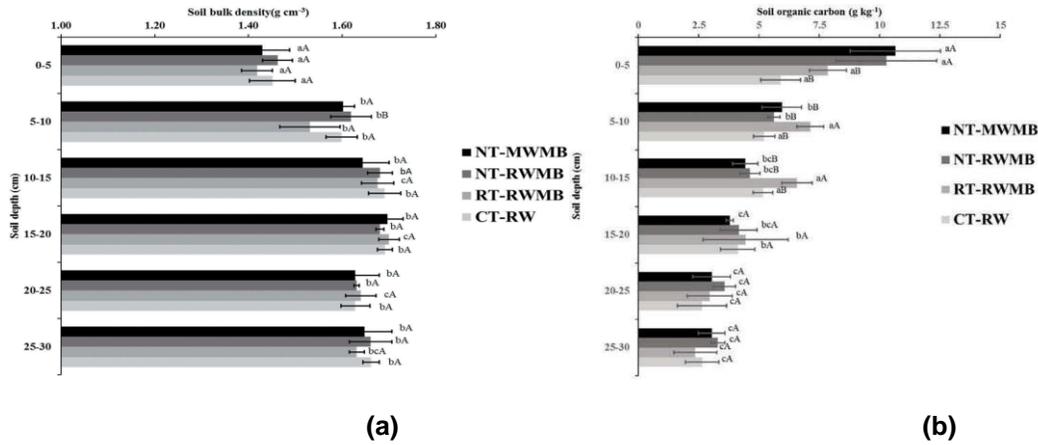
**Fig.2a** Distribution of soil organic carbon (SOC, A), total nitrogen (TN, B), particulate organic carbon (POC, C), and labile organic carbon (LOC, D) contents of different land used types in soil depth of 0–200 cm



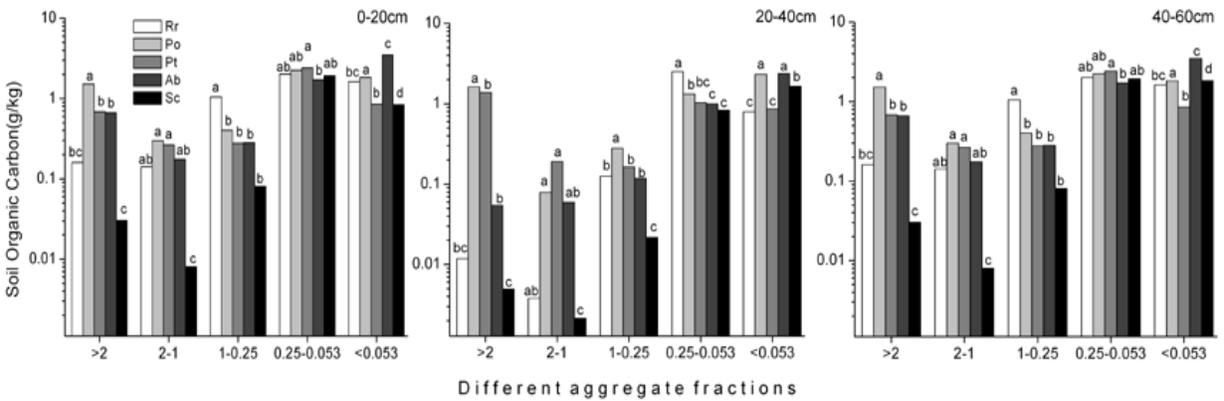
**Fig.2b** Differences in soil organic carbon (SOC, A), total nitrogen (TN, B), particulate organic carbon (POC, C), labile organic carbon (LOC, D) contents between SC and RP, CK or AB (RP/CK/AB - SC)



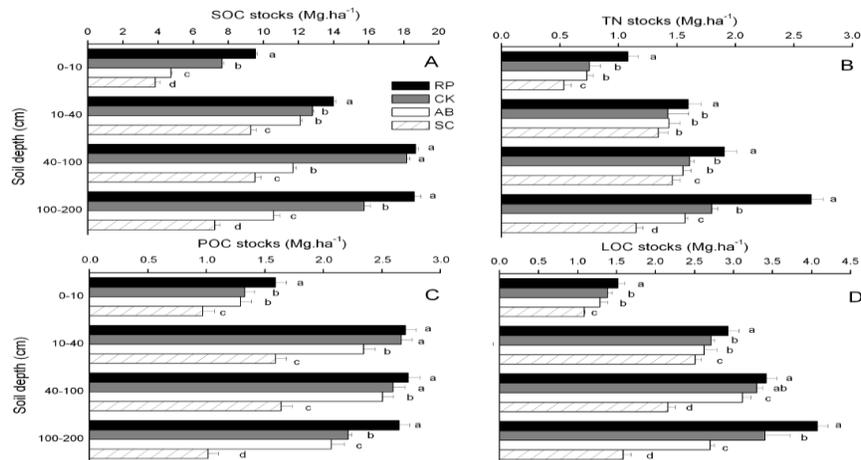
**Fig.3a** Depth distribution of soil bulk density ( $\rho_b$ ) under different treatments **Fig.3b** Depth distribution of the concentrations of soil organic carbon (SOC) under different treatments



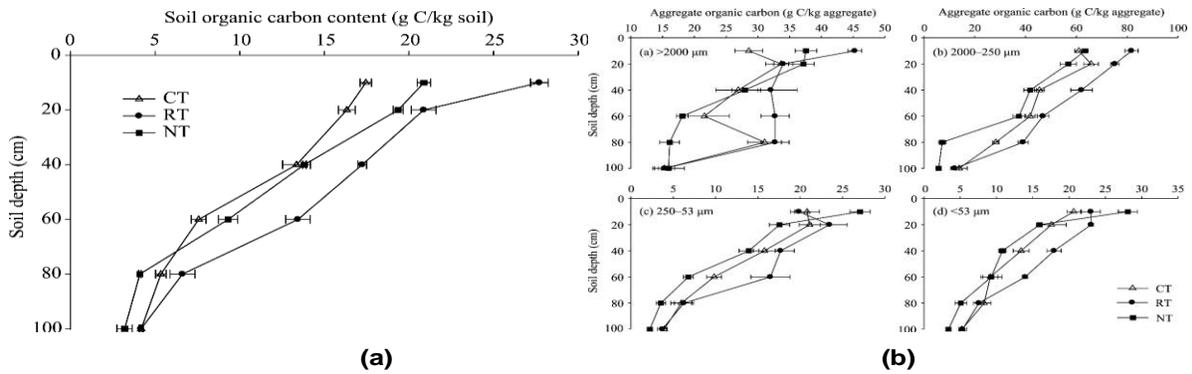
**Fig.4** Distribution of soil organic carbon of different vegetation types



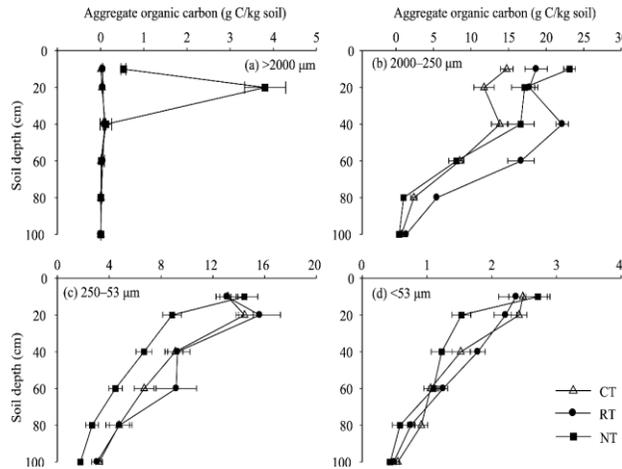
**Fig.5** Stocks of soil organic carbon (SOC, A), total nitrogen (TN, B), particulate organic carbon (POC, C), labile organic carbon (LOC, D) of different land use types



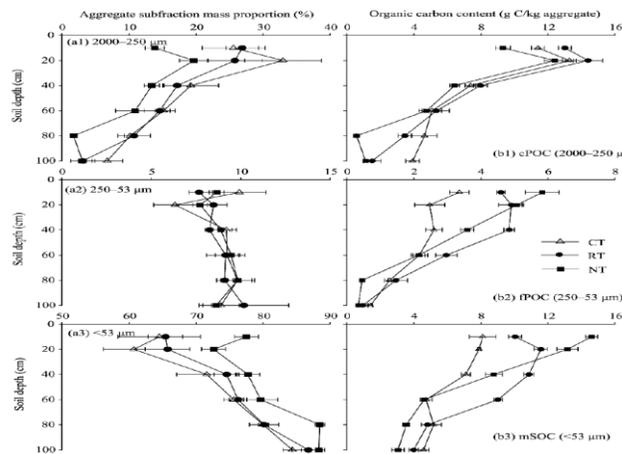
**Fig.6a** Soil organic carbon (SOC) content under conventional tillage with residue removal (CT), reduced tillage with residue incorporated (RT), and no-tillage with residue mulch (NT)  
**Fig.6b** Aggregate-associated organic carbon (OC) content under CT, RT and NT



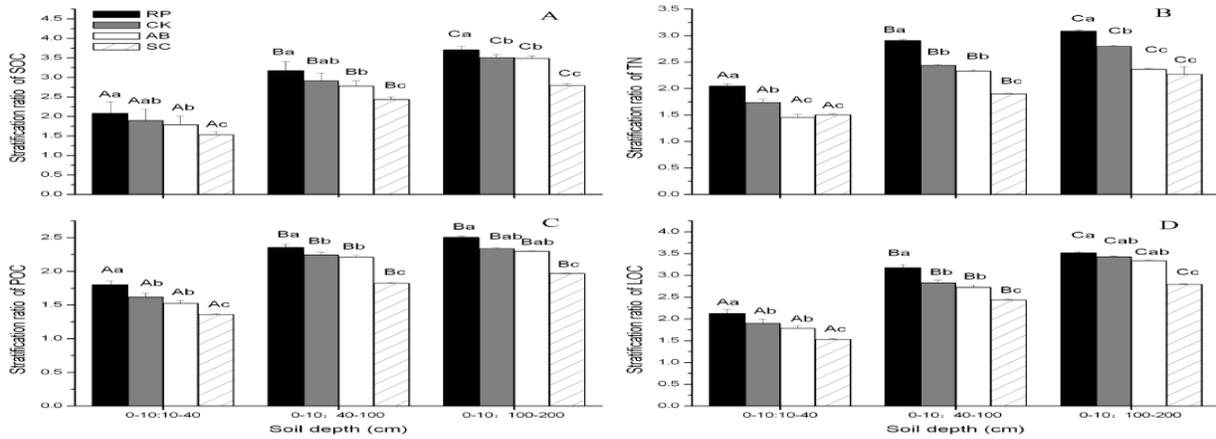
**Fig.7a** Organic carbon content of aggregates in soil under CT, RT and NT



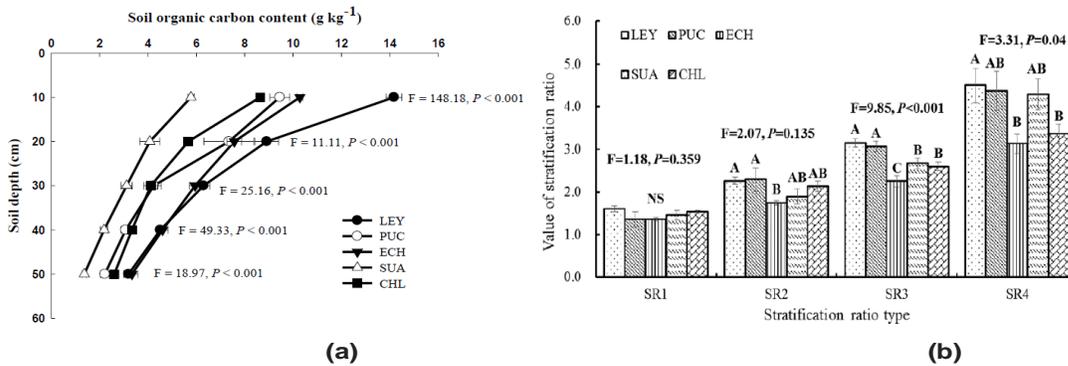
**Fig.7b** Aggregate sub-fraction distribution and associated organic carbon (OC) contents in small macro-aggregates under CT, RT and NT



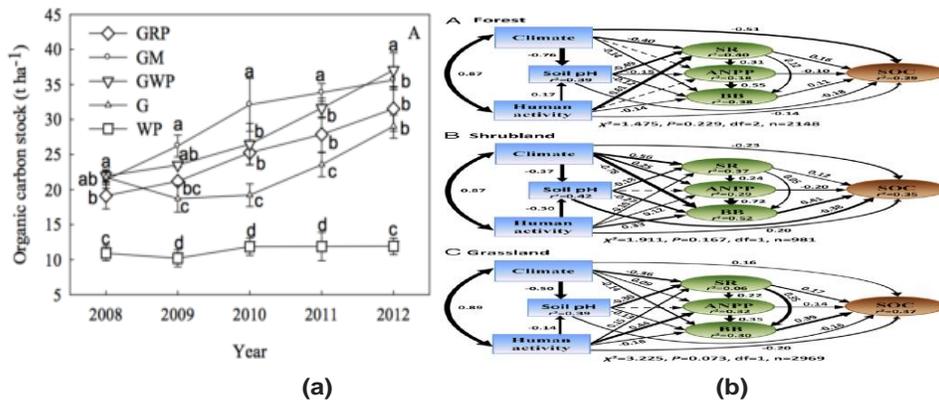
**Fig.8** Comparison of stratification ratio of soil organic carbon (SOC, A), total nitrogen (TN, B), particulate organic carbon (POC, C), labile organic carbon (LOC, D) under different land use types



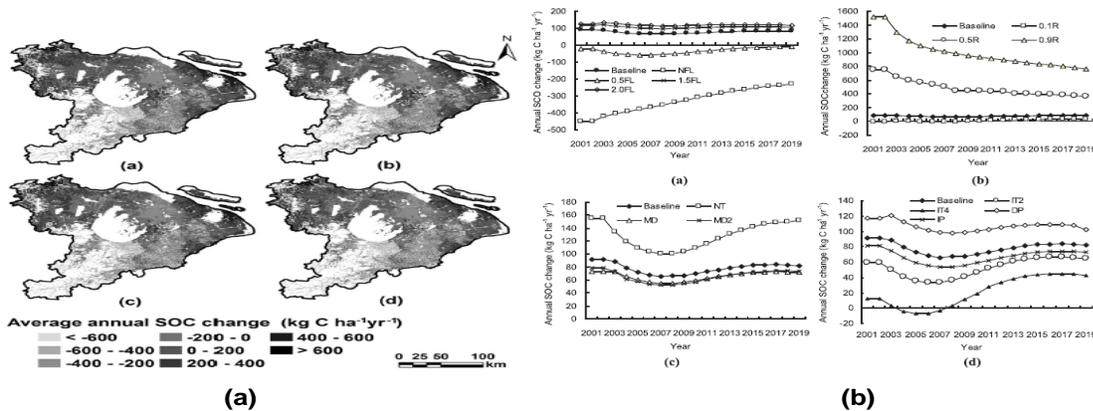
**Fig.9a** Depth distribution of SOC concentration under different vegetation types  
**Fig.9b** The stratification ratio of SOC concentration under different vegetation types



**Fig.10a** Enhanced Soil Carbon Storage under Agro-forestry and Afforestation  
**Fig.10b** SOC storage and the effects of climate, soil, and human activity variables



**Fig.11a** Spatial distribution of average annual SOC change under different climatic scenarios  
**Fig.11b** Annual SOC change from 2001 to 2019 under different management practices



Zhou *et al.*, (2020) concluded that the SOC concentration in the WSA<sub>2-5 mm</sub>, WSA<sub>0.5-1 mm</sub>, WSA<sub>0.25-0.5 mm</sub>, WSA<sub>0.106-0.25 mm</sub>, and WSA<sub><0.106 mm</sub> were all significantly increased by 15.2%, 26.2%, 20.7%, 41.6%, and 28.7% from SC treatment; by 11%, 35.6%, 24.5%, 34.2%, and 33.8% from CS treatment; and by 20.2%, 25.8%, 29.7%, 43.5%, and 27.4% from FS treatment in comparison with the CC treatment, respectively. Simultaneously, compared with CC treatment, CS and FS treatments both significantly increased SOC concentration in the WSA<sub>>5 mm</sub> by 22.4% and 19.4%, as well as SC and CS treatments both significantly increased SOC concentration in the WSA<sub>1-2 mm</sub> by 21.4% and 14.1%, respectively. In addition, the CS and FS treatments both significantly increased SOC concentration by 17.6% and 14.1% compared with the CC treatment in bulk soils. Across all treatments, the SOC stock in the seven aggregates' sizes showed a similar tendency in the SOC concentration, although the bulk density differed a little among the treatments. Bulk density for the five treatments was in the range of 1.12–1.18 g cm<sup>-3</sup>. CS treatment had the highest SOC stock in the WSA<sub>>5 mm</sub>, WSA<sub>0.5-1 mm</sub>, and WSA<sub><0.106 mm</sub> with 8.89 t hm<sup>-2</sup>, 8.59 t hm<sup>-2</sup>, and 3.75 t hm<sup>-2</sup>, respectively. While the FS treatment had the highest SOC stock in the WSA<sub>2-5 mm</sub> (7.64 t

hm<sup>-2</sup>), WSA<sub>0.25-0.5 mm</sub> (7.10 t hm<sup>-2</sup>), respectively. Furthermore, the SC treatment demonstrated the biggest SOC stock in the WSA<sub>1-2 mm</sub> (8.80 t hm<sup>-2</sup>) and WSA<sub>0.106-0.25 mm</sub> (6.64 t hm<sup>-2</sup>), respectively. Except for WSA<sub>0.106-0.25 mm</sub> and WSA<sub><0.106 mm</sub>, the FC treatment documented the lowest SOC stock in all five other aggregate sizes. Furthermore, the SOC stock in the WSA<sub>2-5 mm</sub>, WSA<sub>1-2 mm</sub>, WSA<sub>0.5-1 mm</sub>, WSA<sub>0.25-0.5 mm</sub>, WSA<sub>0.106-0.25 mm</sub>, and WSA<sub><0.106 mm</sub> from the SC treatment, the stock in the WSA<sub>>5 mm</sub>, WSA<sub>0.5-1 mm</sub>, WSA<sub>0.25-0.5 mm</sub>, WSA<sub>0.106-0.25 mm</sub>, and WSA<sub><0.106 mm</sub> from the CS treatment were all significantly ( $P < 0.05$ ) increased by 8%, 19.6%, 29.5%, 18.3%, 63.1%, and 34.7%; and by 16.7%, 43.1%, 20.6%, 40.2%, and 39.4% compared with CC treatment, respectively. Similarly, the SOC stock in the WSA<sub>0.106-0.25 mm</sub> and WSA<sub><0.106 mm</sub> from the FC treatment, and the stock in the WSA<sub>>5 mm</sub>, WSA<sub>2-5 mm</sub>, WSA<sub>0.5-1 mm</sub>, WSA<sub>0.25-0.5 mm</sub>, WSA<sub>0.106-0.25 mm</sub>, and WSA<sub><0.106 mm</sub> from the FS treatment were also significantly increased by 10.7%, and 23.8%; and by 12.3%, 13.8%, 24.7%, 32.4%, 62.3%, and 27.9 in comparison with the CC treatment, respectively.

Wang *et al.*, (2019) observed that the OC content in aggregates was transformed by adding 1 g C kg<sup>-1</sup> aggregate throughout the

bulk soil, a different result for the OC content in aggregates (unit of  $\text{g C kg}^{-1}$  soil) was observed (Fig. 7a). After this transformation, NT significantly increased the OC content in large macro-aggregates down to a soil depth of 20 cm soil and in small macro-aggregates down to a soil depth of 40 cm compared with CT. There was a significant effect of RT on the OC content in small macro-aggregates, which was 27%–129% higher than that in CT soil from the 0–10 to 80–100 cm layers. Differences in the OC content in micro-aggregates and the silt +clay fraction between the RT and CT treatments were not significant at any depth, except for the 40–60 cm layer. However, the CT treatment, the OC content in cPOC was significantly increased by RT only in the 0–10 cm layer (Fig. 7b). Compared with the CT treatment, RT significantly increased the OC content in fPOC and mSOC in the 0–60 cm layers, with improvements of 37%–99% and 24%–90%, respectively. The NT treatment significantly increased the OC content in fPOC and mSOC in the 0–40 cm layers, with improvements of 38%–105% and 23%–80%, respectively. However, the OC content in the sub-fractions under RT and NT was lower than that under CT in the 60–100 cm layers, except for fPOC under RT in the 60–80 cm layer.

### **Stratification of SOC**

Ma *et al.*, (2016) reported that the differences in SMBC were limited to the surface layers (0–5 and 5–10 cm) in the PRB treatment. There was a significant reduction in SMBC content with depth in all treatments. SMBC in the PRB treatment increased by 19.8%, 26.2%, 10.3%, 27.7%, 10% and 9% at 0–5, 5–10, 10–20, 20–40, 40–60 and 60–90 cm depths, respectively, when compared with the TT treatment. The mean SMBC of the PRB treatment was 14% higher than that in the TT treatment. Zhao *et al.*, (2014) concluded that the responses of SR in different land use types

to change of soil depth were different (Fig. 8). The SR values of SOC, TN and LOC differed significantly among different soil depths while the SR values of LOC differed only between 0–10:10–40 cm, 0–10:40–100 cm and 0–10:100–200 cm. Among four land use types, the SR values of SOC, TN, POC and LOC of RP were the highest, but that of SC were the lowest in each soil depth. The SR values of SOC, TN, POC and LOC were in a decreasing order of  $\text{CK} > \text{AB} > \text{SC}$ . The SR values differed significantly between CK and AB with SC while there was no significant difference between CK and AB. Additionally, the ratios of SR values of SOC, TN, POC and LOC in the surface layer (0–10 cm) to that in layer of 10–40 cm were  $> 2.0$ . Wang *et al.*, (2010) this is mainly due to the fact that SOC input into subsoil is largely affected by plant roots and root exudates, dissolved organic matter and bioturbation. In addition, most important factors leading to protection of SOC in subsoil include the spatial separation of SOM, microorganisms and extracellular enzyme activity related to the heterogeneity of C input.

Zhao *et al.*, (2015) observed that the SR of SOC increased significantly with increased soil depth at wheat harvest, the SR of SOC ranged from 1.07 to 3.95, 1.13 to 3.41, and 1.03 to 2.98 for NT, RT, and PT, respectively for 0–5:5–10, 0–5:10–20, 0–5:20–30, and 0–5:30–50 cm. The SR of SOC for 0–5:5–10 cm under RT was significantly higher than that under PT. Compared with the undisturbed soil (NT), RT increased the SR of SOC for 0–5:5–10 cm without statistical significance but significantly decreased the SR of SOC for the other layers (10–20, 20–30, and 30–50 cm). Furthermore, the SRs of SOC for 0–5:5–10, 0–5:10–20, 0–5:20–30, and 0–5:30–50 cm layer followed the order of  $\text{NT} > \text{RT} > \text{PT}$ , indicating that the SR of SOC decreased with increased tillage intensity. At the maize harvest, SR of SOC was significant higher

under NT than that under PT for 0–5:5–10, 0–5:10–20, 0–5:20–30, and 0–5:30–50 cm. The SR ranged from 1.12 to 3.56, 1.10 to 3.18, and 1.01 to 2.51 for NT, RT, and PT, respectively across the depth ratios. When compared with the wheat harvest, the SR at the maize harvest changed little for the 0–5:5–10 and 10–20 cm depths but decreased for the 0–5:20–30 and 0–5:30–50 cm depths. Yu *et al.*, (2020) observed that SR of SOC ranged from 1.355 to 1.603, 1.735 to 2.288, 2.245 to 3.150, and 3.128 to 4.503 for SR<sub>1</sub>, SR<sub>2</sub>, SR<sub>3</sub>, and SR<sub>4</sub>, respectively, among the five vegetation types. Vegetation type had no significant effect on SR<sub>1</sub> and SR<sub>2</sub> due to the narrow range. However, the influences of vegetation types on SR<sub>3</sub> and SR<sub>4</sub> were significant (Fig. 9b). SR<sub>3</sub> of SOC was ranked as LEY  $\approx$  PUC > SUA  $\approx$  CHL > ECH.

Patra *et al.*, (2018) concluded that the SR of SOC increased significantly with increased soil depth under all treatments. Values ranged from 1.80 to 3.50, 1.84 to 3.12, 1.10 to 3.33 and 1.13 to 2.23 for NT-MWMB, NT-RWMB, RT-RWMB and CT-RW, respectively, for 0–5:5–10, 0–5:10–15, 0–5:15–20, 0–5:20–25 and 0–5:25–30 cm soil depths. The SRs of SOC for 0–5:10–15 and subsequent lower layers were significantly different than the top 0–5:5–10 SR under NT-MWMB, whereas, the same was observed only beyond 0–5: 15–20 for NT-RWMB and 0–5:20–25 for RTRWMB and CT-RW, indicating that SRs of SOC varied in response to differential amount of crop residue incorporation and the increased tillage intensity. The treatment-based comparison revealed that the SRs at 0–5:5–10 and 0–5:10–15 were not significantly different from each other under NT-MWMB and NT-RWMB and under RT-RWMB and CT-RW. However, the no-tillage treatments (NT-MWMB and NT-RWMB) differed significantly from the tilled treatments (RT-RWMB and CT-RW). There were no significant differences among

the SRs for lower soil depth ratios (beyond 0–5:10–15 cm) under all treatments.

Tripathi *et al.*, (2014) observed that the significant positive correlations were observed between TOC and organic C fractions (POC and SMBC), illustrating a close relationship between TOC and POC and TOC and SMBC and that SOC is a major determinant of POC and SMBC. The microbial biomass carbon includes living microbial bodies (bacteria, fungi, soil fauna and algae). Divya *et al.*, (2014); it is more sensitive to soil disturbance than TOC. The proportion of SMBC to TOC is evaluation of carbon availability indexes for agriculture soil, which is usually 0.5–4.6%. Nair *et al.*, (2010) also found that there was a correlation between organic carbon concentrations tree density and that soil near trees tended to store more carbon than in soil. SOC levels up to 20 cm in depth and total soil carbon up to 80 cm was greater in all treatments with trees, and lowest in the crop-only system (Fig. 10a). Chen *et al.*, (2018) reported that favorable climate conditions to increase both species richness and belowground biomass, which had a consistent positive effect on SOC storage. Ecosystem management that maintains high levels of plant diversity can enhance SOC storage and other ecosystem services that depend on plant diversity (Fig. 10b).

Malviya, (2014) also indicated that irrespective of soil depth the SMBC contents were significantly higher under RT over CT. This was attributed to residue addition increases microbial biomass due to increase in carbon substrate under RT. Ma *et al.*, (2016) reported that the differences in SMBC were limited to the surface layers (0–5 and 5–10 cm) in the PRB treatment. There was a significant reduction in SMBC content with depth in all treatments. SMBC in the PRB treatment increased by 19.8%, 26.2%, 10.3%,

27.7%, 10% and 9% at 0–5, 5–10, 10–20, 20–40, 40–60 and 60–90 cm depths, respectively, when compared with the TT treatment. The mean SMBC of the PRB treatment was 14% higher than that in the TT treatment. McGonigle and Turner, (2017) concluded that the MBC in cropland increased from 210  $\mu\text{g g}^{-1}$  at 15  $\text{g kg}^{-1}$  SOC to only 530  $\mu\text{g g}^{-1}$  at 45  $\text{g kg}^{-1}$  SOC. In contrast, MBC in grassland increased from 440  $\mu\text{g g}^{-1}$  at 15  $\text{g kg}^{-1}$  SOC to 1190  $\mu\text{g g}^{-1}$  at 45  $\text{g kg}^{-1}$ , thereafter increasing further to 1800  $\mu\text{g g}^{-1}$  at 65  $\text{g kg}^{-1}$  SOC. The slope of increase of MBC in response to increasing SOC was 2.5-fold higher in grassland at 27.2 ( $\mu\text{g g}^{-1}$ )/ ( $\text{g kg}^{-1}$ ) compared to 10.7 ( $\mu\text{g g}^{-1}$ )/ ( $\text{g kg}^{-1}$ ) for cropland.

Zhang *et al.*, (2016) revealed that Average annual SOC changes exhibited different responses to various climate change and management practice scenarios (Figs. 11a and 11b). Under the baseline scenario (CT), 2.32 Mha paddy soils increased 3.44 Tg C from 2001 to 2019, with the annual SOC change of 78  $\text{kg C ha}^{-1} \text{ yr}^{-1}$ . This is mainly associated with the average chemical fertilizer application and farmyard manure incorporation rate of as high as 335  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  and 270  $\text{kg C ha}^{-1} \text{ yr}^{-1}$ , respectively. Applications of nutrients through fertilizers or organic manure increased crop yield and residue accumulation and thus large amount of organic matter is returned to the soil. In addition, SOC decomposition has been reduced in this region by utilizing no-tillage practices in wheat planting, which reduces the physical disturbance and increases the crop residues covered. The average annual SOC changes were –33 and –330  $\text{kg C ha}^{-1} \text{ yr}^{-1}$  for the 0.5FL and NFL scenarios, respectively and the corresponding SOC changes are 142% and 522% lower than the baseline scenario.

In conclusions the SRs of SOC for 0–5:10–15, 15–20, 20–25 and 25–30 cm were all > 2

under no-till-based treatments (NT-MWMB and NT-RWMB). However, the SRs under RT-RWMB and CT-RW were > 2 only below 20 cm soil depth, indicating a comparatively enhanced soil quality improvement under no-till treatments. The storage of SOC (0–30 cm) was observed to be the highest under NT-RWMB followed by NT-MWMB, RT-RWMB and CT-RW. Furthermore, the storages of SOC were significantly related to the SRs of SOC along the soil profile. Hence, SR could be an indicator of SOC storage along the soil profile. The depth distribution of the storage of SOC also suggested 0–30 cm soil depth to be an adequate soil depth criterion for comparing SRs among conventional tillage-based agricultural practices and no-till-based CA practices.

The SOC, TN, POC and LOC contents of RP, CK and AB in soil layer of 100–200 cm were higher than SC, especially for RP plot. Although the SOC, TN, POC and LOC stocks in soil layer of 100–200 cm were lower, there was more than 27.38–36.62%, 25.10–32.91%, 21.59–31.69% and 21.08–26.83% of SOC, TN, POC and LOC stocks were distributed in 100–200 cm soil depth under RP, CK and AB. Meanwhile, the SR of SOC, TN, POC and LOC in the surface to lower depth ratio (i.e., 0–10:10–40 cm) was >2.0 in most of case. Changes in SOC concentration and composition occurred along with changes in structural stability to a depth of 15 cm, consistent with a reduced capacity for tilled soil to physically protect organic matter from decomposition. Although differences in stability were evident from 15–28 cm. SOC content in the surface soils under cropland (30  $\text{g kg}^{-1}$ ) was significantly lower than 45  $\text{g kg}^{-1}$  under native vegetation land, as well as SON content (2.9  $\text{g kg}^{-1}$  /4.4  $\text{g kg}^{-1}$ ), macro-aggregate proportion (63%/82%), and MWD (0.73 mm/0.94 mm). Soil aggregation, soil aggregate stability, and SOC content in surface soils increased following agricultural abandonment.

A significant effect of RT was sustained down to the 60–80 cm layer, while that of NT was sustained down to the 40–60 cm layer. This implies that conservation tillage can increase the SOC content in deep soil compared with CT. The RT treatment significantly increased the amount of small macro-aggregates in the layers from 10 to 100 cm, and the number of small macro-aggregates in the 0–100 cm layers under NT was higher than under CT. In addition, the MWD and GMD under conservation tillage were higher than under CT at a soil depth of 0–80 cm, which suggested a more stable aggregation with conservation tillage, not only in surface soil, but also in deep soil. The maximum enhancement effects were recorded in the minimum tillage along with residue retained treatment. Conventional tillage reduced soil organic C stocks and that of its labile fractions both in top and subsoil (20-100 cm). POC reduction was mainly driven by a decrease in fine POC in topsoil, while DOC was mainly reduced in subsoil. Fine POC, LFOC and microbial biomass can be useful early indicators of changes in topsoil organic C.

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