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Water-Stable aggregates and soil organic carbon fractions in a sub-tropical RWCS under variable tillage and precision nutrient management: A review

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Abstract

The effects of tillage and precision nutrient water management on water stable aggregates and soil organic carbon fractions can vary spatially and temporally, and for different soil types in rice-wheat cropping system. Surface soil (0–15 cm) was fractionated into aggregate sizes (>4.76 mm, 4.76–2.00 mm, 2.00–1.00 mm, 1.00–0.25 mm, 0.25–0.053 mm, <0.053 mm) under different tillage regimes. Tillage significantly reduced the proportion of macro-aggregate fractions (>2.00 mm) and thus aggregate stability was reduced by 35% compared with (ridge with no tillage) RNT, indicating that tillage practices led to soil structural change for this subtropical soil. The highest SOC was in the 1.00 – 0.25 mm fraction (35.7 and 30.4 mgkg^{-1}for RNT and CT, respectively), while the lowest SOC was in micro-aggregate (<0.025 mm) and silt + clay (<0.053mm) fractions (19.5 and 15.7 mgkg^{-1} for RNT and CT, respectively). Labile C fractions: particulate organic C (POC), microbial biomass C (MBC) and dissolved organic C (DOC) were all significantly higher in NT and ST than in CT in the upper 15 cm. Higher SOC content of 19.44 gkg^{-1} of soil was found in zero tilled residue retained plots followed by 18.53 g kg^{-1} in permanently raised bed with residue retained plots. Whereas, the lowest level of SOC content of 15.86 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots. The application of chemical fertilizers (NP) alone did not alter labile C fractions and SOC mineralization rate from those observed in the CK treatment. Whereas the use of straw in conjunction with chemical fertilizers (NPS) became an additional labile substrate supply that decreased C limitation and resulted in 53% higher cumulative mineralization of C compared to that of CK. Microbial biomass carbon significantly increased with the integrated application of organic manure (FYM@10 tonnes ha^{-1}) and mineral fertilizer (100% NPK) over control. Development of management practices that favour C sequestration or prevent further losses will help to reduce the potential SOC decline due to the climate change and because of the importance of SOC to soil health and plant productivity, maintenance or restoration of SOC will help to reduce the threats of food security due to climate change. The labile part of organic carbon has been suggested as a sensitive indicator of changes in soil organic matter. Enhancing the soil organic carbon pool also improves agro-ecosystem resilience, eco-efficiency, and adaptation to climate change.

Keywords: Labile SOM dynamics, Conservation tillage, Soil Organic Carbon, SOC storage

1. Introduction

In agro-ecosystems, soil aggregation formation is considered an important process in soil organic carbon (SOC) stabilization by hindering decomposition of SOC and its interactions with mineral particles (Gunina and Kuzyakov, 2014). Generally, a more rapid loss of SOC may occur from macro-aggregates than from micro-aggregates (Eynard *et al*., 2005). The SOC change under agricultural management may owe to the aggregate stability index (Nascente *et al*., 2015). Thus, soil aggregated fractionation has been widely applied to evaluate the SOC stability under contrasting tillage systems. Tillage and, particularly, mold board plow (MP) have been reported as a disruption compared to a no-tillage (NT) system (Anders *et al*., 2010).

cause for macro-aggregate In contrast, NT can promote soil surface macro-aggregation and improve structural stability due to lower soil disturbance and higher SOC, arbuscular mycorrhizal fungi, and microbial biomass and glomalin, which are more important driving factors for aggregate stability, and consequently enhance C retention (Zhang *et al*., 2013)[14]. The increased SOC concentration and SOC stock in surface soil under NT may be not only due to higher amount of C-rich macro-aggregates, but also to a higher content of humic and fulvic acids under NT (Tang *et al*., 2011). Hayes and Clapp (2001) reported that humic and fulvic acids are relatively recalcitrant to microbial attack and, hence, are considered a SOC pool with high stability. Some studies have revealed that humic and fulvic acids are significantly linked to SOC stock (Ma *et al*., 2008). This provided some evidence that maintaining good soil humic and fulvic acids status favours SOC accumulation. Therefore, knowledge of the humic and fulvic acids distribution within an aggregate is useful to understand the stability mechanisms of C sequestration in soil under NT.

The soil carbon is capable of enhancing agricultural sustainability and serving as a potential sink of atmospheric CO_2. Carbon dioxide abundance in the atmosphere along with other greenhouse gases caused global warming and climate change. Sequestration of carbon in soils may potentially mitigate the negative effect of global warming on agriculture. Intensified rice based cropping systems consume more inputs and thereby release more CO_2 and sequester less carbon in soil (Bhatia *et al*., 2011) [5]. Soil and cop management practices and organic materials that increase the stocks of soil carbon may have profound effects on climate mitigation (Soderstorm *et al*., 2014) [45]. Because of large pool sizes and inherent spatial variability, soil organic C (SOC) and total N (STN) (slow or non-labile fractions) change slowly with management practices. Therefore, measurements of SOC and STN alone may not adequately reflect changes in soil quality and nutrient status (Ghimire *et al*., 2012) [15].

Formation and stability of soil structure is also considerably influenced by weather dynamics. In the course of individual years, or even within the seasons, the soil aggregates stability varies due to the influence of climatic conditions. The main weather factors include temperature and precipitation, influencing expansion and shrinkage, freezing and thawing of soil matter (Abiven *et al*. 2009) [1]. Caravaca *et al*. (2004) [6] state that natural soils have evidently greater aggregate stability than cultivated soils. The difference in aggregate stability in different forms of soil exploitation is mainly due to the intensity of disturbance of soil and its cultivation. Inappropriate use of soil leads to dissolution of unstable aggregates, and production of finer and more easily transportable particles and micro-aggregates (Zhang *et al*. 2008) [57]. The resistance of an aggregate to water depends on its quality, which is determined by the binding elements of the aggregate, i.e. the organic and mineral colloids and their mutual integration. These characteristics are primarily influenced by the quantity and quality of humus, which especially relates to the microbial activity of soil (Bartlová & Badalíková 2010) [3]. The lability–graded fractions of total organic carbon (TOC) provide valuable able information related to the quality and persistence of soil organic carbon (Venkatesh *et al*., 2013). Primarily, tillage induces disruption of macro–aggregates and thus accelerates the SOC loss (Andruschkewitsch *et al*., 2014a). Protection of organic carbon within stable soil aggregates is crucial for carbon stabilization and its persistence in soils. Thus, this review study on water-stable aggregates strategic for soil organic carbon fractions, particularly in sub-tropical rice-wheat soils, where native C stock is usually low.

Water stability of soil aggregates

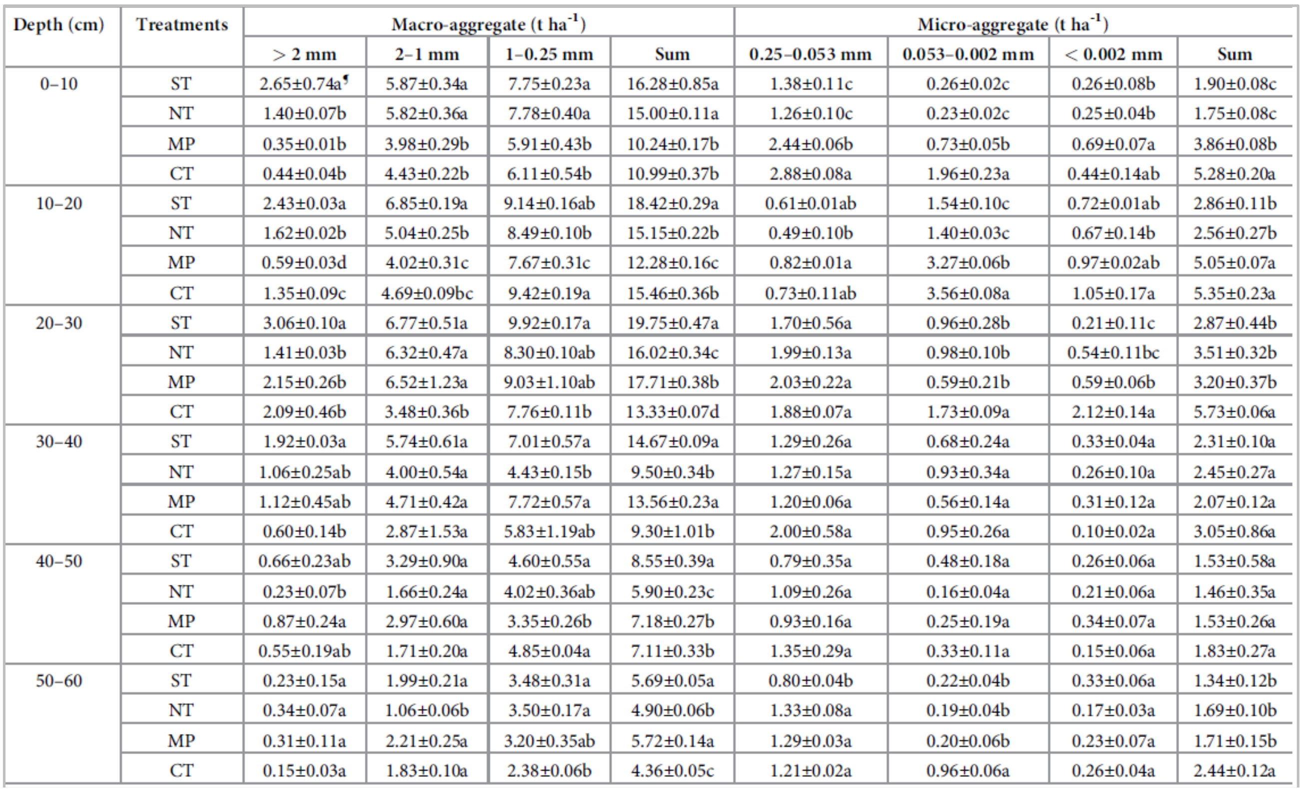
Zhang-liu *et al*. (2013) [14] showed that NT and RT treatments significantly increased the proportion of macro-aggregate fractions (>2000 μm and 250-2000 μm) compared with the MP-R and MP+R treatments. For the 0-5cm depth, the total amount of macro-aggregate fractions (>250μm) was increased by 65% in NT and 32% in RT relative to the MP+R. Averaged across all depths, the macro- aggregate fraction followed the order of NT (0.39) > RT (0.30) > MP+R (0.25)=MP–R (0.24). Accordingly, the proportion of micro-aggregate fraction (53-250 μm) was increased with the intensity of soil disturbance. In the 0-5 and 5-10cm depths, NT and RT had significantly higher total soil C concentration than that of MP−Rand MP+R in all aggregate size fractions. However, in the 10-20cm depth, conservation tillage system reduced total C concentration in the macro-aggregate fraction (>250μm) but not in the micro-aggregate and silt plus clay fractions. The greatest change in aggregate C appeared in the large macro-aggregate fractions where aggregate-associated C concentration decreased with depth. In the 0-5cm depth, the >2000μm fraction had the largest C concentration under NT, whereas the <53μm fraction had the lowest C concentration under the MP−R treatment. Similar trend was also observed in the > 2000μm and 25-2000μm fractions (23 vs. 24 g C kg^{-1} aggregates) in the 5-10cm depth. The large macro-aggregate (>2000μm) had relatively lower C concentration than that in the >250-2000μm fraction in the 10-20cm depth. Averaged across soil depths, all aggregate size fractions had 6-9% higher total soil C concentration in NT and RT than in MP−R and MP+R, except for the 53-250 μm fraction. Again mould-board plough showed slightly higher soil C concentration than the conservation tillage systems in the 53-250μm fraction.

Bartlova *et al*. (2015) [4] observed that the different values of WSA were found according to different methods of tillage, both in topsoil (0–0.30 m) and subsoil (0.30–0.60 m). In contrast to the other two tillage methods, the ploughing variant showed a statistically provable reduction in WSA. The same results were obtained by Hůla *et al*. (2010) [21], who found that, after three years, the ploughing variant showed worsened soil structure in comparison to reduced tillage. Cultivation of land leads to changes in the chemistry of carbon intake in soils. These changes in chemical composition are generally apparent in organic material inside aggregates, whereas changes in organic material linked to clay particles are only slight (Golchin *et al*. 1995) [17]. Dhaliwal *et al*. (2018) [12] revealed that the mean SOC concentration decreased with the size of the 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%). Lal (2004a) [27] found that the rate of SOC increase attains the maximum effect 5–20 years after adoption of management practices aimed at increasing SOC stocks. Tang and Nan (2012) [46] estimated that no-tillage and high residue incorporation techniques have the potential to increase SOC sequestration by up to 0.4 $tha^{-1}yr^{-1}$. However, with reduced or no-tillage, less litter is moved from the soil surface deeper into soil profile. Hence, the increased SOC concentration is very likely to be constrained to topsoil layers that are still mixed by direct seeding (Liu *et al*., 2014) [31], and balanced out by a decline in the soil profile not subject to tillage anymore. Yu *et al*. (2013) [56] also found that the simulations, including changes in climate and agricultural management, suggest that aggregate national mineral SOC stocks will continuously increase at varying rates from 2011 to 2050 across all scenarios. However, trends in carbon sequestration vary among the scenarios. We found a decrease in carbon sequestration under S_0, a slight increase under S_1 and a significant increase under S_2. The carbon sequestration rates under S_0, S_1 and S_2 are estimated to be 30.4 Tg C yr^{-1}, 30.6 Tg C $\mathrm{yr}^{-1}$and 30.9 TgC yr^{-1}, respectively, by 2011. By 2050, carbon sequestration decreases to20.3 TgC yr^{-1}under S0 but increases to 50.5 TgC yr^{-1} under S_1 and increases to 88.4 TgC yr^{-1}under S_2.

Zheng *et al*., (2018) [59] also found that the SOC storage in macro-aggregates under different treatments significantly decreased with soil depth [Table 1]. However, no significant variation was observed in the micro-aggregate associated C storage with depth. SOC storage increased with aggregate size from 1±2 to >2mm and decreased with a decrease in aggregate size. The SOC storage in macro-aggregates of all sizes from 0-30cm depth was higher in the ST treatment than in other treatments. From 30-60cm, trends were less clear. SOC storage in micro-aggregates showed the opposite trend, with significantly higher levels in the CT treatment from 0-30cm, and no significant differences between treatments below this depth. Using suitable tillage and increasing the soil organic matter can improve the formation of soil aggregates and increase their stability (Li *et al*., 2008) [28]. The no-tilling (NT) method promotes the formation of soil aggregates in the topsoil (0-10cm depth) and improves the aggregate stability due to the presence of high stubble. However, the MP and CT treatments strongly disturb the soil, which can reduce the aggregate degree and stability of soil aggregates at the tillage depth of 0-20cm due to erosion and rainfall. Another demonstrated advantage of deep tillage was the 34.49% increase in the number of water-stable aggregates under the ST treatment compared to the other treatments, which could improve the formation of soil aggregate structure in the black soil of North-eastern China. Furthermore, spacing tillage (ST) promoted the enrichment of > 0.25mm water-stable aggregates, thereby improving the soil structure. Our study showed a greater influence of tillage treatment on macro- and micro-aggregates at 0±10, 10±20, and 20±30cm layers than at other depths, suggesting an aggregate stratification phenomenon. This is due to the result of different operations of the secondary tillage. An additional reason may be the difference in the straw returned to soil under the different tillage systems.

The WAS under ZT without residue retention (93.4%) significantly increased by 4%compared to CT system (89.7%). A similar trend was observed under fertilizer management practices where control (91.7%) significantly increased WAS by 2.3% compare to 100% VC (93.9%). The 50%RDF +50%VC and 75%RDF +25%VC decreased WAS by 4% compared to under 100% RDF system. The study reported that mechanical tillage increased the breakdown of soil macro-aggregates and that CT disrupted soil macro-aggregates into micro-aggregates or individual particles. In addition, soil under CT system distributed aggregates during the plowing event by bringing protected aggregates to the soil surface. The degree of macro-aggregation in this soil was much lower than in most other agricultural systems, due primarily to the puddling of soil which tends to destroy aggregates. The ZT system likely improved the physical protection of organic carbon from decomposition and therefore, generally had higher SOC. In contrast, CT disrupts aggregates and exposing them to microbial decomposition (Saygn *et al*., 2017) [43].

Table 1: Distribution of soil organic carbon storage in water-stable aggregates in different soil layers and tillage treatments [Zheng *et al*., 2018] [59]



Depth (cm)	Treatments	Macro-aggregate (t ha^{-1})				Micro-aggregate (t ha^{-1})			
		> 2 mm	2–1 mm	1–0.25 mm	Sum	0.25–0.053 mm	0.053–0.002 mm	< 0.002 mm	Sum
0–10	ST	2.65±0.74a¶	5.87±0.34a	7.75±0.23a	16.28±0.85a	1.38±0.11c	0.26±0.02c	0.26±0.08b	1.90±0.08c
	NT	1.40±0.07b	5.82±0.36a	7.78±0.40a	15.00±0.11a	1.26±0.10c	0.23±0.02c	0.25±0.04b	1.75±0.08c
	MP	0.35±0.01b	3.98±0.29b	5.91±0.43b	10.24±0.17b	2.44±0.06b	0.73±0.05b	0.69±0.07a	3.86±0.08b
	CT	0.44±0.04b	4.43±0.22b	6.11±0.54b	10.99±0.37b	2.88±0.08a	1.96±0.23a	0.44±0.14ab	5.28±0.20a
10–20	ST	2.43±0.03a	6.85±0.19a	9.14±0.16ab	18.42±0.29a	0.61±0.01ab	1.54±0.10c	0.72±0.01ab	2.86±0.11b
	NT	1.62±0.02b	5.04±0.25b	8.49±0.10b	15.15±0.22b	0.49±0.10b	1.40±0.03c	0.67±0.14b	2.56±0.27b
	MP	0.59±0.03d	4.02±0.31c	7.67±0.31c	12.28±0.16c	0.82±0.01a	3.27±0.06b	0.97±0.02ab	5.05±0.07a
	CT	1.35±0.09c	4.69±0.09bc	9.42±0.19a	15.46±0.36b	0.73±0.11ab	3.56±0.08a	1.05±0.17a	5.35±0.23a
20–30	ST	3.06±0.10a	6.77±0.51a	9.92±0.17a	19.75±0.47a	1.70±0.56a	0.96±0.28b	0.21±0.11c	2.87±0.44b
	NT	1.41±0.03b	6.32±0.47a	8.30±0.10ab	16.02±0.34c	1.99±0.13a	0.98±0.10b	0.54±0.11bc	3.51±0.32b
	MP	2.15±0.26b	6.52±1.23a	9.03±1.10ab	17.71±0.38b	2.03±0.22a	0.59±0.21b	0.59±0.06b	3.20±0.37b
	CT	2.09±0.46b	3.48±0.36b	7.76±0.11b	13.33±0.07d	1.88±0.07a	1.73±0.09a	2.12±0.14a	5.73±0.06a
30–40	ST	1.92±0.03a	5.74±0.61a	7.01±0.57a	14.67±0.09a	1.29±0.26a	0.68±0.24a	0.33±0.04a	2.31±0.10a
	NT	1.06±0.25ab	4.00±0.54a	4.43±0.15b	9.50±0.34b	1.27±0.15a	0.93±0.34a	0.26±0.10a	2.45±0.27a
	MP	1.12±0.45ab	4.71±0.42a	7.72±0.57a	13.56±0.23a	1.20±0.06a	0.56±0.14a	0.31±0.12a	2.07±0.12a
	CT	0.60±0.14b	2.87±1.53a	5.83±1.19ab	9.30±1.01b	2.00±0.58a	0.95±0.26a	0.10±0.02a	3.05±0.86a
40–50	ST	0.66±0.23ab	3.29±0.90a	4.60±0.55a	8.55±0.39a	0.79±0.35a	0.48±0.18a	0.26±0.06a	1.53±0.58a
	NT	0.23±0.07b	1.66±0.24a	4.02±0.36ab	5.90±0.23c	1.09±0.26a	0.16±0.04a	0.21±0.06a	1.46±0.35a
	MP	0.87±0.24a	2.97±0.60a	3.35±0.26b	7.18±0.27b	0.93±0.16a	0.25±0.19a	0.34±0.07a	1.53±0.26a
	CT	0.55±0.19ab	1.71±0.20a	4.85±0.04a	7.11±0.33b	1.35±0.29a	0.33±0.11a	0.15±0.06a	1.83±0.27a
50–60	ST	0.23±0.15a	1.99±0.21a	3.48±0.31a	5.69±0.05a	0.80±0.04b	0.22±0.04b	0.33±0.06a	1.34±0.12b
	NT	0.34±0.07a	1.06±0.06b	3.50±0.17a	4.90±0.06b	1.33±0.08a	0.19±0.04b	0.17±0.03a	1.69±0.10b
	MP	0.31±0.11a	2.21±0.25a	3.20±0.35ab	5.72±0.14a	1.29±0.03a	0.20±0.06b	0.23±0.07a	1.71±0.15b
	CT	0.15±0.03a	1.83±0.10a	2.38±0.06b	4.36±0.05c	1.21±0.02a	0.96±0.06a	0.26±0.04a	2.44±0.12a

*Data are represented as meand ± S.D., and data with the same letters within each column indicate no significant difference at $P = 0.05$ level.

Distribution of soil aggregates with different sizes

Jiang *et al*. (2011) [23] reported that the aggregate-associated SOC concentration in different soil layers was influenced by tillage systems. In the 0.00-0.05 m layer, SOC concentration in macro-aggregates showed the order of NT+S>MP+S = NT-S>MP-S, whereas the NT system was superior to the MP system. However, the NT system significantly reduced the SOC concentration in the 2.00-0.25 mm fraction in the 0.05-0.20 m layer. A similar trend was observed in the 0.25-0.053 mm fraction in the 0.20-0.30 m layer. Across all the soil layers, there was no difference in the <0.053 mm fraction between NT-S and MP-S, as well as between NT+S and MP+S, indicating that the NT system did not affect the SOC concentration in the silt + clay fraction. In average across the soil layers, the SOC concentration in the macro-aggregate was increased by 13.5% in MP+S, 4.4% in NT-S and 19.3% in NT+S, and those in the micro-aggregate <0.25mm were increased by 6.1% in MP+S and 7.0% in NT+S compared to MP-S. For all the soil layers, the SOC concentration in all the aggregate size classes was increased with straw incorporation, by 20.0, 3.8 and 5.7% under the MP system, and 20.2, 6.3 and 8.8% under the NT system.

Tripathi *et al*. (2014) [48] also found that the aggregate size distribution was significantly affected by the application of FYM and inorganic fertilizers compared to unfertilized control. An aggregate fraction of 0.25–0.5 mm made up the largest (27.36–31.36%) whereas 0.1–0.053 mm fraction made the least contribution (2.10–3.87%) in total WSA percentage at two sampling depths. Application of FYM alone or in combination with inorganic fertilizers significantly improved the formation of macro and meso-aggregates compared to unfertilized control at both sampling depths. The incorporation of FYM alone increased the occurrence of macro-aggregates (5–2 mm) by 165.33% whereas meso-aggregates increased by 130.68% in 2–1 mm fraction, by 282.83% in 1–0.5 mm fraction over unfertilized control in 0–15 cm soil layer. The proportion of micro-aggregates (0.25–0.1 mm and 0.1–0.053 mm) was less in FYM + inorganic fertilized plots than the plots applied with inorganic fertilizer alone. The application of FYM decreased the micro-aggregate fraction of 0.25– 0.1 mm by 0.35 to 9.94% and micro-aggregate fraction of 0.1–0.053 by 0.4–30.63% compared to unfertilized control in the surface soil. The increase in the proportion of water stable macro-aggregates (>2 mm) by FYM + inorganic fertilizer application could be attributed to the input of additional organic residues and available C to the soils and increase in ECe as compared with inorganic fertilizer application alone and unfertilized control. Ou *et al*. (2016) reported that the proportion of the >2 mm aggregate fraction in NT+S was 7.1% higher than that in NT-S in the 0.00-0.05 m layer. The proportion of >0.25 mm macro-aggregate was significantly higher in MP+S than in MP-S in most cases, but the proportion of <0.053 mm aggregate was 11.5-20.5% lower in MP+S than in MP-S for all the soil layers.

Naresh *et al*. (2018) [39] 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^{-1}, respectively in T_9 and 10.98 and 9.38 g kg^{-1}, 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.

Aggregate-associated SOC concentration

Yang *et al*. (2005) [54] observed that soil PMOC, LFOC, and POC under water regime of continuous water-logging decreased by 30.6, 8.3, and 10.6 % in wheat straw treatment, respectively, as compared to the water regime of alternative wetting and drying. This confirmed that the adoption of soil water regimes is an important factor to improve the transformation of soil organic carbon pools after the addition of rice straw. Yang *et al*. (2012) [55] showed that LFOC, POC, and PMOC were improved by 2.25, 1.84, and 2.15 times after the addition of wheat straw or maize stalk in a silt clay loam soil. They also mentioned that PMOC was higher in wheat straw or maize stalk-amended soil than the control could be explained by the higher labile organic carbon inputs, which associated with the straw and stalk. Wagner *et al*. (2007) [49] also found that in the surface soil, the mean yields of water-stable macro-aggregates were significantly higher under MT and NT than under CT treatment. Statistically significant differences below 5 cm were only found in 25-40 cm soil depth under NT. The carbon content of the micro-aggregates within macro-aggregates was higher under reduced tillage treatments, indicating increased macro-aggregate turnover under CT. However, in contrast, in 5-25 and 25-40 cm soil depth no negative effect by CT was found on yields of macro-aggregates and carbon contents within macro-aggregates assume that the soil mixing and litter incorporation in higher soil depths by CT might lead to a flush of microbial activity, producing binding agents as nucleation sites for macro-aggregates, probably counteracting the physical impact of tillage. Jiang *et al*. (2010) [22] revealed that tillage significantly reduced the proportion of macro-aggregate fractions (>2.00 mm) and thus aggregate stability was reduced by 35% compared with RNT, indicating that tillage practices led to soil structural change for this subtropical soil. The highest SOC was in the 1.00–0.25mm fraction (35.7 and 30.4mg/kg for RNT and CT, respectively), while the lowest SOC was in micro-aggregate (<0.025mm) and silt + clay (<0.053mm) fractions (19.5 and 15.7mg/kg for RNT and CT, respectively). Choudhury *et al*. (2014) [8] revealed that compared to conventional tillage, water stable macro-aggregates in conservation tillage in wheat coupled with direct seeded rice (DSR) was increased by 50.13% and water stable micro-aggregates of the later decreased by 10.1% in surface soil. Residue incorporation caused a significant increment of 15.65% in total water stable aggregates in surface soil (0–15 cm) and 7.53% in sub-surface soil (15–30 cm). In surface soil, the maximum (19.2%) and minimum (8.9%) proportion of total aggregated carbon was retained with >2 mm and 0.1–0.05 mm size fractions, respectively. Zhu *et al*. (2014) [60] observed that the contents of soil TOC and labile organic C fractions, where PD generally had the highest contents of TOC, DOC, MBC and EOC at the three soil depths. Crop straw return treatments (PR, PW, PD, RR, RW, RD) had consistently higher amount of TOC and labile organic C fractions at the three soil depths than without crop straw return treatments (PN, RN). Moreover, PN had significantly lower TOC, DOC, MBC and EOC at 0–7 cm and 7–14 cm, and RN had the lowest TOC and MBC at 14–21 cm compared to other treatments. Wang *et al*. (2017) [51] observed that compared with the CK, the manuring significantly increased the portion of large macro-aggregates (>2 mm) by 2.4% and reduced the portion of micro-aggregates (2 mm, and 12.4% for 0.25–1 mm) and of the bulk soil (15.2%). Under both the CK and manuring treatments, the percentage of different aggregate classes decreased in following order: large macro-aggregates (>2 mm)>moderate macro-aggregates (1–2 mm)> smallmacro-aggregates (0.25–1mm)>micro-aggregates.

Tiwari *et al*. (2018) [47] also found that 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. In contrast, LFOC and DOC are useful indicators for subsoil. Reduced proportions of fine POC, LFOC, DOC and microbial biomass to soil organic C reflected the decline in soil organic C quality caused by tillage and straw Management practices. Average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+FYM treatment. Compared to F_1 control treatment the RDF+FYM treatment sequestered 0.33 Mg C ha^{-1} yr^{-1} whereas the NPK treatment sequestered 0.16 Mg C ha^{-1} yr^{-1}.

SOC storage in different aggregate size fractions

Du *et al*. (2013) [14]; Conceicao *et al*. (2015) [9] reported that the NT system resulted in stratification of SOC, while the MP system resulted in a more homogeneous distribution in the 0.00-0.20 m layer. When considering the whole 0.00-0.30 m layer, however, the differences in SOC stock were not significant between NT-S and MP-S as well as between NT+S and MP+S. This indicates that the NT system did affect the SOC stock distribution in the soil profile but not the total quantity. Lihua Zhang *et al*. (2014) [60] reported that the significant increases (31.83%)in the SOC concentrations were observed at AG compared with Al at a depth of 0–10 cm, with no significant effect at a depth of 10–100 cm. SOC in the profile showed an increasing trend from AL to AAL and from DG to AL, with amplitudes of 20.09% and 6.23% at the depth of 0–10 cm. It displayed a decreasing trend of 17.12–44.35% from DG to AW. The difference in SOC content was significant between the depths of 0–10, 10–20 and20–100cmforeachlandusetype.The influence of land use and soil depth on SOC content was all significant. Consistent with the accumulation of SOC, POC content at the 0–100 cm depth at AG showed significant enrichment compared with AL. The increase (92.83%) was most obvious at the 0–10 cm depth. The ratio of POC/SOC in the soil profile showed a higher trend at AG relative to AL. LOC in the profile showed an increasing trend after conversion of DG to AL, while POC tended to increase at the 0–40 cm depth and to decrease at the 40–100cm depth. Su (2007) found SOC and POC at the 0–5 cm depth increased by 35% and 52.4% following the same LUC. Li *et al*. (2009) reported that SOC and POC in the 0–10 cm layer increased 22% and 44%, respectively, under perennial grass of 4years on former cropland. This suggests that accumulated SOC might occur primarily in the POC fraction, and POC and LOC may serve as sensitive indicator for the impact of short-term land use and management practices on SOC. The increment of LOC (23.17–23.67%) was greater than that of POC (0.17–10.0%). POC/SOC showed a decreasing trend

Wang *et al*. (2015) [50] reported that on average, the SOC densities of the entire wheat-growing areas in each decade were27 (±22%, 95%) Mg ha−1during the 1960s, 24 (±17%) Mg ha^{-1}during the 1970s, 22 (±18%) Mg ha^{-1}during the 1980s, 21 (±14%) Mg ha^{-1}during the 1990s, and 20 (±15%) Mgha^{-1}during the 2000s, respectively. Although average SOC densities decreased over the study period, the rate loss of SOC is declining, with more SOC lost in the first 30 years than in the last 20 years. Averaging for each decade, the rate of SOC loss was estimated to be approximately 6.4, 3.7, 2.5, 1.4 and 1.6 Tgyr^{-1}in the 1960s, 1970s, 1980s, 1990s and 2000s, respectively. Summing up the yearly changes in SOC over the period from 1960 to 2010, the loss of SOC in wheat-growing areas was estimated to be 156 Tg C, with a range from 86 to 222 Tg C at the 95% confidence level. It is noteworthy that after the decline in the first few years, SOC seemed to reach a new, steady state in the mid-2000s, followed by a decrease in the following several years.

Guo *et al*. (2016) [20] reported that NT treatments significantly increased SOC concentration of bulk soil, >0.25 aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer by 5.8%, 6.8% and 7.9% relative to CT treatments, respectively. S treatments had higher SOC concentration of bulk soil (12.9%), >0.25 mm aggregate (11.3%), and <0.25 mm aggregate (14.1%) than NS treatments. Compared with CT treatments, NT treatments increased MBC by 11.2%, 11.5%, and 20%, and dissolved organic carbon (DOC) concentration by 15.5%, 29.5%, and 14.1% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively. Compared with NS treatments, S treatments significantly increased MBC by 29.8%, 30.2%, and 24.1%, and DOC concentration by 23.2%, 25.0%, and 37.5% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively.

Naresh *et al*. (2017) [37] reported that the highest SOC concentration was obtained for 0–5 cm depth and decreased with sub surface depth for all treatments. The SOC concentration in 0–5 and 5– 15 cm depths increased significantly by farmyard manure or GM/SPM application. At the 0–5 and 5–15 cm soil depths, SOC was highest in 50% RDN as CF+50% RDN as FYM (F_5) followed by 50% RDN as CF+50% RDN as GM/SPM (F_6) treatments and the least in Control (no manure and fertilizer) F_1 treatment. The total SOC stocks in the 0-15 cm layer was 35.17 Mgha^{-1} for 50% RDN as CF+50% RDN as FYM-treated soils compared with 28.43 Mgha^{-1} for 100% RDN as CF-treated plots and 26.45 Mg ha^{-1} for unfertilized control plots. Soil organic C content in the 0–15 cm soil layer in the plots under 50% RDN as CF+50% RDN as FYM treatment was 16% higher than that under 75% RDN as CF+25% RDN as FYM treated plots. The TOC in surface soil were in the order of 50% RDN as CF+50% RDN as FYM (23.65 g kg^{-1})> 50% RDN as CF+50% RDN as GM/SPM (21.47 g kg^{-1})>1/3rd N as CF+1/3rd N as FYM+1/3rd N as GM/SPM (21.40 gkg^{-1}) >75% RDN as CF+25% RDN as FYM (19.64 gkg^{-1}) > unfertilized control (10.99 gkg^{-1}).

Poeplau *et al*. (2017) [42] also found that the difference in NPP between the unfertilised treatments and the high N rates increased only in the first decade and remained relatively constant thereafter. However, the SOC stocks in both the RR and RI treatments were not influenced by N level which did not interact with residue management. The difference in SOC stock between RI and RR at the highest N rate (240N) was 2.9Mgha^{-1}, while the difference at the lowest N level (0N) was 3.1Mgha^{-1}, despite the difference in annual C input between RI and RR for these two N extremes being 0.43Mgha^{-1} yr^{-1}. The coarse fractions SA and POM and the liquid DOC fraction contributed only 4%, 2.3% and 1.7% respectively to the total SOC stock. Furthermore, 93% of the total surplus of SOC due to 40 years of residue incorporation was found in the SC fraction. Within the SC fraction, the greatest change in SOC stock occurred in the more active SC-rSOC fraction, while the more passive rSOC on average did not change at all.

Soil organic carbon pool

Mamta Kumari *et al*. (2011) [32] reported that macro-aggregates increased under a ZT rice (direct-seeded or transplanted) and wheat rotation with the 2- to 4-mm fraction greater than that of the 0.25- to 2-mm fraction. Bulk and aggregate associated C increased in ZT systems with greater accumulation in macro-aggregates. The fine (0.053–0.25 mm) intra-aggregate particulate organic C (iPOM-C), in 0.25- to 2-mm aggregates, was also higher in ZT than conventional tillage. A higher amount of macro-aggregates along with greater accumulation of particulate organic C indicates the potential of ZT for improving soil carbon over the long-term in rice-wheat rotation. Grandy and Robertson, (2006) [18] also found that the iPOM-C is physically better protected than other POM-C fractions in soil. A significantly higher amount of fine iPOM-C mostly associated with small macro-aggregates indicated slower turnover under ZT, resulting in the formation and stabilization of fine intra-aggregate C particles. The increased fine iPOM-C could be regarded as a potential indicator of increased C accumulation.

Dikgwatlhe *et al*. (2014) [13] compared with PTO and PT, significantly higher SOC and N concentrations were observed in surface layer (0-10 cm depth) under NT and RT. In 2004, the SOC stocks were lower under NT and RT than under PT and PTO, however, the opposite trend was observed in 2012. Compared with 2001, the net profile (0-30 cm) SOC sequestration rate was 10.60, 13.95, 13.65, and 14.92 Mg ha^{-1} in 2012 under PTO, PT, RT, and NT, respectively. As for stocks in the 0-50 cm profile, no significant differences were observed among NT, RT, and PT. The trends in N stocks in profile (0-30, 0-50 cm depth) were NT>TR>PT>PTO in both the years. Naresh *et al*. (2018) [39] revealed that the highest SOC stock of 72.2Mg C ha^{-1} was observed in F_6 with T_6 followed by that of 64Mg C ha^{-1} in F_4 with T_2> that in F_3 with T_4 (57.9Mg C ha^{-1})> F_5 with T_1 (38.4Mg C ha$^{–1}$) = F_7 with T^5 (35.8Mg C ha^{-1}), and the lowest (19.9Mg C ha^{-1}) in F_1 with T_7. Relatively higher percentage increase of SOC stock was observed in F_6 with T_6 treatment (56.3Mg C ha$^{–1}$) followed by F_4 with T_2 (51.4Mg C ha$^{–1}$) and F_3 with T_1 (48.4Mg C ha$^{–1}$). Majumder *et al.*, (2008) [25] reported 67.9% of C stabilization from FYM applied in a rice–wheat system in the lower Indo-Gangetic plains.

Zhang *et al*. (2019) [58] showed that the percentages of the remaining GM C in the soil after one year of decomposition averaged 26% and 33% for the above-ground and below-ground residues. Thus, the 5-yr growth of GM legumes continuously significantly improved the SOC and easily oxidized organic carbon (EOOC) concentrations, as well as the corresponding stocks compared with the original soil at the 0–20 cm depth. The cumulative dry matter decomposition rates for the roots of the summer legumes followed the same order with the highest for mung bean (69%), the lowest for soybean (58%) and intermediate for Huai bean (68%). The power model fitted well with the cumulative dry matter decomposition patterns of the GM legumes. The cumulative C decomposition rates of the GM legumes were the highest in the mung bean followed by the Huai bean and finally the soybean, similar to the pattern of dry matter decomposition. The per-cent of the mass remaining in the shoots and roots decreased to 23–29% (on average 26%) and 28–43% (on average 33%) of the original value in 374 days. The mean SOC contents under the SW, MW, and HW systems were 10.5%, 12%, and 15.6% greater (on average 12.7%) than those in the FW system. As with the SOC, the mean EOOC contents under the MW, SW, and HW systems were 7.8%, 9.3%, and 15.3% greater than those in the FW system. Compared with the initial SOC and EOOC contents at the 0 to 20 cm depth in 2008, the continuous application of the GM approach for 5-yr significantly increased the corresponding concentrations by 9.0% and 11.4%. The SOC stocks in the FW system ranged from 14.6 to 21.6 Mg C/ha with an average of 19.1 Mg C/ha and a CV of 8.2%, while in the GM systems, it ranged from 14.8 to 24.1 Mg C/ha, with an average of 20.1 Mg C/ha and a CV of 8.3%. The mean EOOC stock in the GM systems (10.8 Mg C/ ha) was 3.5% greater than that in the FW (10.5 Mg C/ha) with a wider range (9.0-4.0 Mg C/ha) and a higher variability (9.5%).

Soil organic carbon distribution

Ghimire *et al.*, (2012) [15] revealed that 9.89% greater SOC in 0–50 cm soil profile under no-tillage than under conventional tillage in a rice-wheat system. The significant fraction of SOC under no-tillage was accumulated in surface soil with 28.3% greater SOC content in 0–5 cm depth of no-tillage system than that in the conventional tillage system. Quintero and Comer ford, (2013)[19] indicated that reduced tillage increased the soil C concentration and average C content in the whole profile (≈117 cm depth) by 50 and 33% (1636 tCha$^{−1}$ vs. 1224 t Cha$^{−1}$), respectively, as compared to conventional farming practices. Carbon content increased 177% in the subsoil (A_2 horizon, 78 - 117 cm depth, from 215 to 596 tha$^{−1}$) although most of the soil C was in the A_1 horizon (between 0 - 78 cm average thickness, 1097 tha$^{−1}$). These increases show that reduced tillage enhances C stores in Andisols which are already high in organic matter. In addition, C in aggregates represented more than 80% of the total organic matter and it was positively affected by conservation practices. The C increase was preferential in the smaller macro-aggregates (<2 mm). The aggregate dispersion energy curves further suggested that C increase was occurring in micro-aggregates within the smaller macro-aggregate fraction. Data suggested that smaller macro-aggregates can be used in these soils to evaluate the influence of field management practices on soil C sequestration. Naresh *et al.*, (2015) [36] reported that average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+ FYM treatment. Compared to F_1 control treatment the RDF+FYM treatment sequestered 0.33 Mg C ha^{-1} yr^{-1} whereas the NPK treatment sequestered 0.16 Mg C ha^{-1} yr^{-1}. Das *et al*. (2017) [11] revealed that the total organic C increased significantly with the integrated use of fertilizers and organic sources (from 13 to 16.03 g kg$^{–1}$) compared with unfertilized control (11.5 g kg$^{–1}$) or sole fertilizer (NPKZn; 12.17 g kg$^{–1}$) treatment at 0–7.5 cm soil depth. Oxidisable organic C fractions revealed that very labile C and labile C fractions were much larger in the NPK+FYM or NPK+GR+FYM treatments, whereas the less-labile C and non-labile C fractions were larger under control and NPK+ CR treatments.

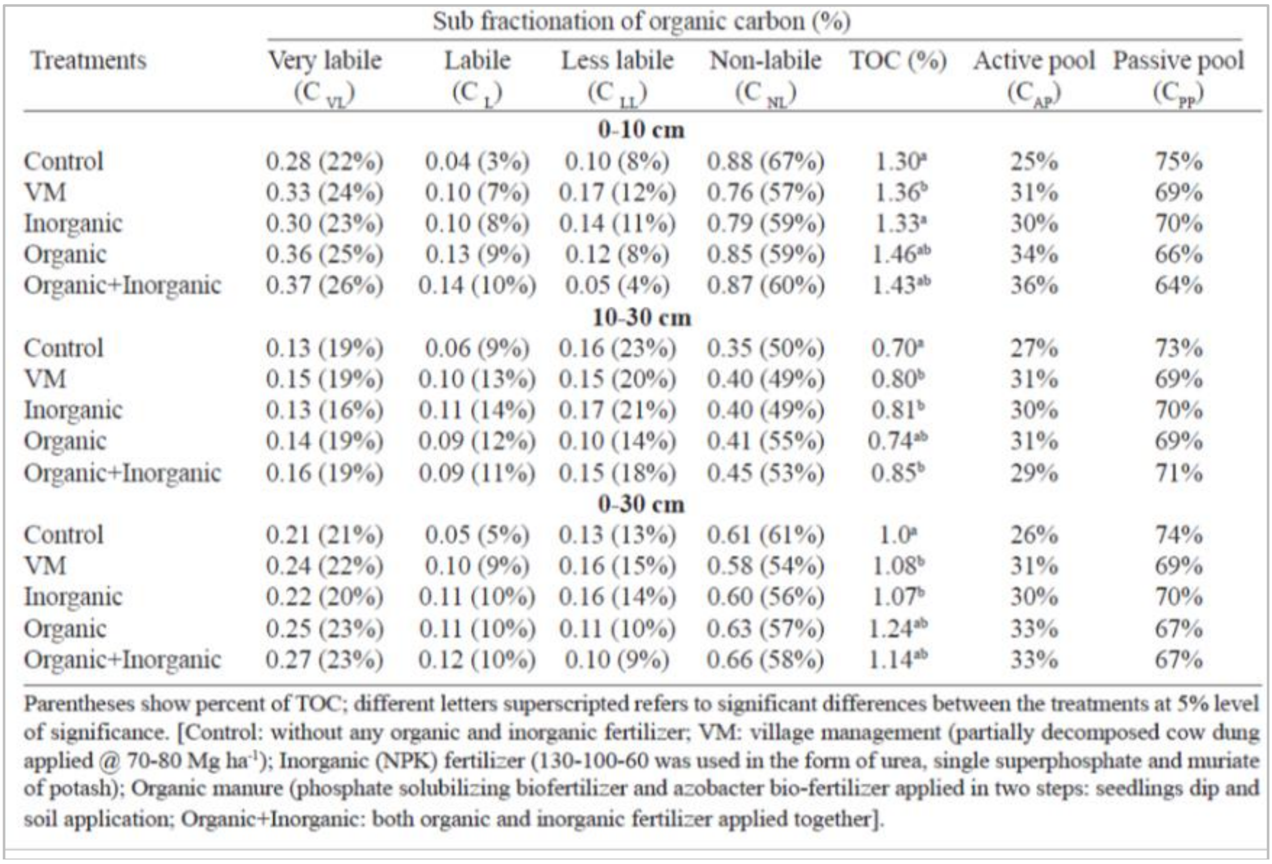
Meenakshi, (2016) [34] revealed that under conventional tillage, the organic carbon content in the surface 0-15 cm soil depth was 0.44, 0.51 and 0.60% which was increased to 0.60, 0.62 and 0.70% under zero tillage practice in sandy loam, loam and clay loam soil. In all the three soils, the organic carbon decreased significantly with depth under both the tillage practices. Under conventional tillage, the amount of organic carbon observed in 0-15 cm found to decrease abruptly in 15-30 cm soil depth as compared to the decrease under zero tillage practice in all the soils. Long term ZT practice in wheat increased the organic carbon content significantly as compared to CT in different depths of all the soils. As expected, the higher amount of organic carbon was observed in relatively heavier textured soil viz. clay loam > loam > sandy loam at both the depths.

Moreover, under conventional tillage, the light fraction carbon, in the surface 0-15 cm soil depth was 0.29, 0.49 and 0.58 g kg^{-1} which increased to 0.43, 0.62 and 1.01 g kg^{-1} under zero tillage practice in sandy loam, loam and clay loam soil. The heavy fraction carbon in the surface 0-15 cm soil layer was 3.8, 4.2 and 4.9 g kg^{-1} which decreased to 2.0, 2.2 and 2.6 g kg^{-1} in 15-30 cm soil layer in sandy loam, loam and clay loam, respectively. The heavy fraction carbon was highest in the surface layer in all the three soils and decreased with depth under both tillage treatments. The zero tillage resulted in an increase in heavy fraction carbon at both the depth. In the surface 0-15 cm, it increased the heavy fraction carbon significantly from 3.8 to 4.9, 4.2 to 4.9 and 4.9 to 5.1 g kg^{-1} and in 15-30 cm soil depth from 2.0 to 2.9, 2.2 to 3.4 and 2.6 to 3.9 g kg^{-1} in sandy loam, loam and clay loam. Relatively higher amount of heavy fraction carbon was observed in heavier textured soil at both the depths. Liang *et al*. (1998) [29] reported that ratios of LF of C and SOC were greater in light-textured soils than in fine-textured soils. LF of C is directly proportional to sand content. The lower disturbance in ZT systems can promote the interaction between clays and slower decomposing C inputs to form soil aggregates. But the DOC content was lowest among all fractions followed by MBC and LFC, and highest amount was of HFC in case of all the three texturally different soils at both 0-15 and 15-30 cm soil depths. The higher amounts of different fractions were observed in relatively heavier textured soil, and under ZT treatment as compared to CT.

Light fraction of carbon

Zou *et al*. (2014) [61] revealed that the soil DOC ranged from 297.83–351.97 g kg^{-1} for S_{400}, 223.08–243.88 g kg^{-1} for S_{800}, 220–254.34 g kg^{-1} for S_{1200} and 311.83–321.43 g kg^{-1} for S_{1600}. Straw return to deep soil significantly decreased the soil DOC. The straw return treatments had significantly lower soil DOC than the CK at each soil depth, except for the S_{400} treatment at depths of 0–10 cm and 20–40 cm. The soil DOC contents were not significantly different between the soil layers in each treatment. Regarding the vertical distribution of soil DOC, the soil DOC decreased with increasing soil depth in all treatments. Nath *et al*. (2015) [40] revealed that the TOC content for all the treatments was high in surface soil (0-10 cm) than in subsurface soil (10- 30 cm). TOC in surface and sub-surface soil was in the order organic > organic + inorganic > VM >inorganic > control and organic > organic +inorganic > inorganic > VM > control respectively [Table 2]. Build-up of higher amount of TOC in surface soil over sub-surface soil is attributed to accumulation of organic matter from root biomass and left over crop residues in the former that decreased with soil depth. Addition of root biomass and root exudates results in such variation in soil depths (Kaur *et al*., 2008) [24]. Application of organic manure alone or in combination with inorganic fertilizer considerably increased TOC in 0-10 cm soil depth than control plot [Table 2].

Table 2: Soil organic carbon (SOC) pools under different management regimes in surface soil (0-10 cm) and subsurface (10-30 cm) paddy growing soils [Nath *et al*., 2015] [40]



Treatments	Sub fractionation of organic carbon (%)						
	Very labile (C_{VL})	Labile (C_L)	Less labile (C_{LL})	Non-labile (C_{NL})	TOC (%)	Active pool (C_{AP})	Passive pool (C_{PP})
0-10 cm							
Control	0.28 (22%)	0.04 (3%)	0.10 (8%)	0.88 (67%)	1.30^a	25%	75%
VM	0.33 (24%)	0.10 (7%)	0.17 (12%)	0.76 (57%)	1.36^b	31%	69%
Inorganic	0.30 (23%)	0.10 (8%)	0.14 (11%)	0.79 (59%)	1.33^a	30%	70%
Organic	0.36 (25%)	0.13 (9%)	0.12 (8%)	0.85 (59%)	1.46^{ab}	34%	66%
Organic+Inorganic	0.37 (26%)	0.14 (10%)	0.05 (4%)	0.87 (60%)	1.43^{ab}	36%	64%
10-30 cm							
Control	0.13 (19%)	0.06 (9%)	0.16 (23%)	0.35 (50%)	0.70^a	27%	73%
VM	0.15 (19%)	0.10 (13%)	0.15 (20%)	0.40 (49%)	0.80^b	31%	69%
Inorganic	0.13 (16%)	0.11 (14%)	0.17 (21%)	0.40 (49%)	0.81^b	30%	70%
Organic	0.14 (19%)	0.09 (12%)	0.10 (14%)	0.41 (55%)	0.74^{ab}	31%	69%
Organic+Inorganic	0.16 (19%)	0.09 (11%)	0.15 (18%)	0.45 (53%)	0.85^b	29%	71%
0-30 cm							
Control	0.21 (21%)	0.05 (5%)	0.13 (13%)	0.61 (61%)	1.0^a	26%	74%
VM	0.24 (22%)	0.10 (9%)	0.16 (15%)	0.58 (54%)	1.08^b	31%	69%
Inorganic	0.22 (20%)	0.11 (10%)	0.16 (14%)	0.60 (56%)	1.07^b	30%	70%
Organic	0.25 (23%)	0.11 (10%)	0.11 (10%)	0.63 (57%)	1.24^{ab}	33%	67%
Organic+Inorganic	0.27 (23%)	0.12 (10%)	0.10 (9%)	0.66 (58%)	1.14^{ab}	33%	67%

Parentheses show percent of TOC; different letters superscripted refers to significant differences between the treatments at 5% level of significance. [Control: without any organic and inorganic fertilizer; VM: village management (partially decomposed cow dung applied @ 70-80 Mg ha^{-1}); Inorganic (NPK) fertilizer (130-100-60 was used in the form of urea, single superphosphate and muriate of potash); Organic manure (phosphate solubilizing biofertilizer and azobacter bio-fertilizer applied in two steps: seedlings dip and soil application; Organic+Inorganic: both organic and inorganic fertilizer applied together].

Sheng *et al*. (2015) [44] also found that the stocks associated with the different LOC fractions in topsoil and subsoil responded differently to land use changes. POC decreased by 15%, 38%, and 33% at 0-20 cm depth, and by 10%, 12%, and 18% at 20e100 cm depth following natural forest conversion to plantation, orchard, and sloping tillage, respectively. Regarding the different POC components, only fPOC stock in 0-20 cm topsoil decreased by 21%, 53%, and 51% after natural forest conversion to plantation, orchard, and sloping tillage, respectively. This implied that the reduction of POC stock after land use change mainly resulted from the loss of topsoil fPOC, which, consequently, could be used as a sensitive indicator to detect SOC changes. Noticeably, fPOC stock in subsoil below 40 cm increased by 11-74% following the land use change, indicating that changes in POC fractions in subsoil may follow the opposite direction to those in topsoil. Loss of LFOC occurred not only in topsoil, but also in subsoil below 20 cm following land use change. The top soil showed a greater reduction in LFOC stock than did subsoil following the conversion of natural forest to orchard and sloping tillage. LFOC appeared to be more sensitive to land use changes than SOC both in top and subsoil. The decrease in ROC stock through the soil depth profile following land use change was smaller than that of LFOC.

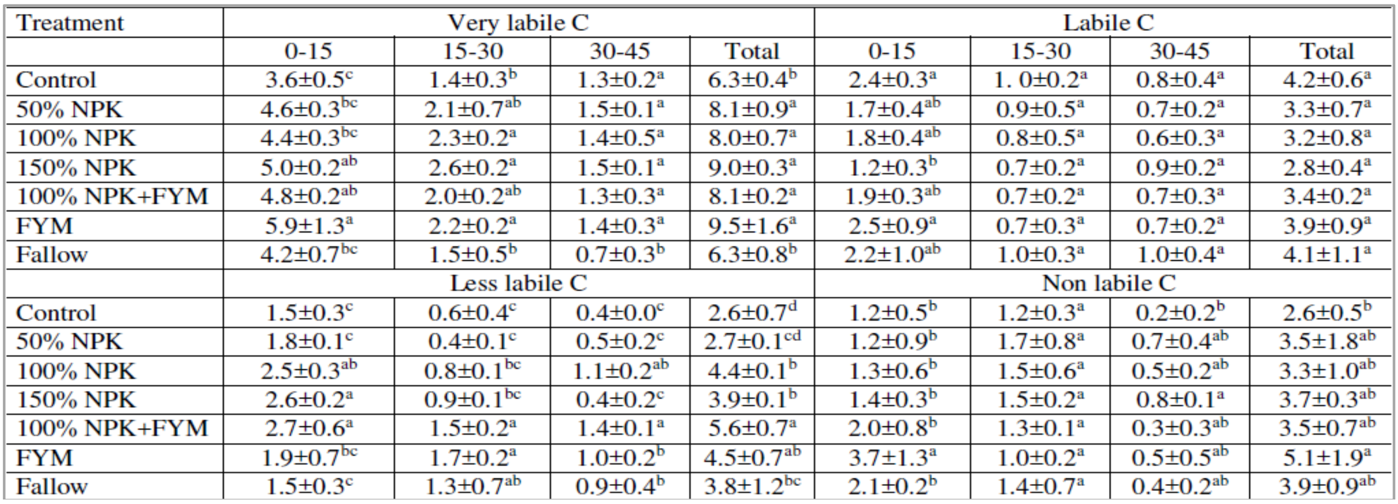
The DOC stock in the topsoil decreased by 29% and 78% following the conversion of natural forest to plantation and orchard, respectively, and subsoil DOC stocks decreased even more dramatically following land use change. MBC stock decline was more pronounced in topsoil (49-86%) than in subsoil (21-61%) following land use change. DOC and MBC were the most sensitive indicators to land use change. However, the sensitivity of LOC fractions to land use change depends on soil depth. In topsoil, fPOC, LFOC, DOC and MBC stocks were more sensitive to land use change than was SOC. In subsoil, on the other hand, only LFOC and DOC are sensitive enough to represent useful indicators of SOC changes. Similar to POC stocks and those of its different components, MBC in subsoil below 40 cm can increase after land conversion indicating that changes of LOC fractions may follow opposite patterns to those in topsoil. In another example, soil C accumulation was almost entirely from LFOC in topsoil (0-7.5 cm), and C loss was mainly from C fractions associated with silt and clay-size particles in the subsoil (35-60 cm) 48 years after the conversion of old fields into secondary forest (Mobley *et al*., 2015) [35]. In the topsoil, the ratios fPOC, LFOC, and MBC to SOC decreased, while those of ROC and cPOC increased following land use change. In subsoil, only the ratio of DOC to SOC decreased, the ratios POC, fPOC and ROC to SOC increased, and those of LFOC and MBC remained constant following land use change. In the topsoil, ratios fPOC, LFOC, DOC and MBC to SOC were more sensitive to conversion from natural forest to sloping tillage than SOC.

Xin *et al*. (2015) [52] revealed that the tillage treatments significantly influenced soil aggregate stability and OC distribution. Higher MWD and GMD were observed in 2TS, 4TS and NTS as compared to T. With increasing soil depth, the amount of macro-aggregates and MWD and GMD values were increased, while the proportions of micro-aggregates and the silt + clay fraction. Accordingly, the average proportions of micro-aggregates and the silt + clay fraction were reduced by 15 and 23%, respectively. In the 5–10 cm depth, the mass proportions of macro-aggregates of 2TS, 4TS and NTS were increased by 12, 11 and 13%, respectively, but there were no significant differences between T and TS. In the 10–20 cm depth, the proportions of macro-aggregates in 4TS and NTS were increased by 8% compared to 4T and NT. Across all soil depths, 2TS, 4TS and NTS had greater proportions of macro-aggregates than T, and this trend was declined with soil depth. In the 0–5 cm layer, compared with T, values of MWD under 4T and NT were increased by 41 and 68%, respectively. Values of MWD under NT in the 5–10 and 10–20 cm depths were increased by 41 and 28% as compared to that under T. The highest GMD value appeared in NTS, while the lowest appeared in T across all soil depths. Additionally, residue retention had pronounced positive effects on MWD and GMD. The average MWD values among crop residue treatments were 30, 15 and 14% higher than the corresponding treatments without crop residues in the 0–5, 5–10, and 10–20 cm depths. The OC concentrations in different aggregate fractions at all soil depths followed the order of macro-aggregates>micro-aggregates>silt + clay fraction. In the 0–5 cm soil layer, concentrations of macro-aggregate associated OC in 2TS, 4TS and NTS were 14, 56 and 83% higher than for T, whereas T had the greatest concentration of OC associated with the silt + clay fraction in the 10–20 cm layer. Soil OC concentrations under 4TS and NTS were significantly higher than that of T in the 0–10 cm layer. Residue retention promoted formation of macro-aggregates, increased macro-aggregate-associated OC concentrations and thus increased total soil OC stock. In the 0–5, 5–10 and 10–20 cm depths, treatments with crop residues had higher macro-aggregate-associated OC concentrations compared to treatments without residues. In the 0–5 cm depth, comparing with that of T, macro-aggregate- associated OC concentrations under 2TS, 4TS and NTS were increased by 14, 56 and 83%, respectively. The greatest increase of micro-aggregate-associated OC concentration among treatments with residue retention was in the 0–5 cm, where OC under 4TS and NTS were 34 and 11% higher compared to that of 4T and NT, respectively. However, in the 10–20 cm, residue retention reduced OC concentration by 42% in the silt + clay fraction.

Ghosh *et al*. (2016) [16] reported that LOC showed significant seasonal changes, where the maximum value occurred during February to March, after which content declined and remained lower prior to October. Lower accumulation of LOC during the period from April to September was possibly attributable to high decomposition of recent organic material inputs, and high loss with runoff at this rainy time (Chen *et al*., 2004) [7]. Mulching practices did not alter these as dynamic changes of LOC, but could increase its content, e.g., in March, ST and GT increased LOC by 167% and 122% respectively. The higher values of LOC in ST and GT can possibly be attributed to the inputs from organic materials and root residues, as well as decreased losses with surface runoff as a result of mulching. Awanish, (2016) [2] reported that the greater variations among carbon fractions were observed at surface layer (0-5 cm). F_1= very labile, F_2 =labile, F_3= less labile and, F_4=non-labile. At this depth, C fraction in vertisols varied in this order: $F_4>F_1>F_2=F_3$. Below 5 cm, the carbon fraction was in the order: $F_4>F_1>F_3>F_2$. For 15-30 cm depth it was in the order $F_4>F_1>F_2>F_3$. At lower depth, almost similar trend was followed as that of 30-45 cm. Regardless of tillage system, contribution of different fractions of carbon (C) to the TOC varied from, 33 to 41%; 9.30 to 30.11%; 8.11 to 26%; 30.6 to 45.20% for very labile, labile, less labile and non-labile fractions, respectively at 0-5cm depth. For subsurface layer (5-15cm), contribution of different fractions to the TOC varied from 27.8 to 40%; 7.80 to 12.40%; 11.11 to 19.0%;

38.0 to 50.0% for very labile, labile, less labile and non-labile fraction, respectively. In general, C contents decreased with increasing depth, mainly for very labile faction (F_1) which was contributing around 40% or more in surface and surface layers (0–5 and 5–15 cm) as compared to deeper layers (15–30 and 30–45 cm). Moreover, less labile and non-labile fractions contribute more than 50% of TOC, indicating more recalcitrant form of carbon in the soil. Krishna *et al*. (2018) [25] reported that the total organic carbon (TOC) allocated into different pools in order of very labile > less labile > non labile >labile, constituting about 41.4, 20.6, 19.3 and 18.7%, respectively. In comparison with control, system receiving farmyard manure (FYM-10 Mg ha^{-1} season-^{1}) alone showed greater C build up (40.5%) followed by 100% NPK+FYM (120:60:40 kg N, P, K ha^{-1}+ 5 Mg FYM ha^{-1}season^{-1}) (16.2%). In fact, a net depletion of carbon stock was observed with 50% NPK (-1.2 Mg ha^{-1}) and control (-1.8 Mg ha^{-1}) treatments. Only 28.9% of C applied through FYM was stabilized as SOC. A minimal input of 2.34 Mg C ha^{-1} y^{-1} is needed to maintain SOC level [Table 3]. The magnitude of carbon pools extracted under a gradient of oxidizing conditions was as follows: C_{VL} >C_{LL}> C_{NL}> C_L constituting about 41.4, 20.6, and 19.3 and 18.7%, respectively, of the TOC [Table 3]. However, the contribution of VL, L and LL pools to SOC was 51.2, 23.1 and 25.5%, respectively. While active pool (C_{VL} + C_L) constituted about 60.1%, passive pool (C_{LL} + C_{NL}) represented 39.9% of the TOC. Among the treatments, 100% NPK+FYM (44.4%) maintained a proportionately higher amount of soil C in passive pools. With an increase in the dose of fertilization, on average, C allocation into passive pool was increased (33.0, 35.3, 40.7% and 39.3% of TOC under control, 50% NPK, 100% NPK and 150% NPK treatments, respectively.

Table 3: Oxidisable organic carbon fractions (very labile, labile, less labile and non-labile) in soils (g kg^{-1}) at different layers (cm) [Krishna *et al*., 2018] [25]



Treatment	Very labile C				Labile C			
	0-15	15-30	30-45	Total	0-15	15-30	30-45	Total
Control	3.6±0.5^{c}	1.4±0.3^{b}	1.3±0.2^{a}	6.3±0.4^{b}	2.4±0.3^{a}	1. 0±0.2^{a}	0.8±0.4^{a}	4.2±0.6^{a}
50% NPK	4.6±0.3^{bc}	2.1±0.7^{ab}	1.5±0.1^{a}	8.1±0.9^{a}	1.7±0.4^{ab}	0.9±0.5^{a}	0.7±0.2^{a}	3.3±0.7^{a}
100% NPK	4.4±0.3^{bc}	2.3±0.2^{a}	1.4±0.5^{a}	8.0±0.7^{a}	1.8±0.4^{ab}	0.8±0.5^{a}	0.6±0.3^{a}	3.2±0.8^{a}
150% NPK	5.0±0.2^{ab}	2.6±0.2^{a}	1.5±0.1^{a}	9.0±0.3^{a}	1.2±0.3^{b}	0.7±0.2^{a}	0.9±0.2^{a}	2.8±0.4^{a}
100% NPK+FYM	4.8±0.2^{ab}	2.0±0.2^{ab}	1.3±0.3^{a}	8.1±0.2^{a}	1.9±0.3^{ab}	0.7±0.2^{a}	0.7±0.3^{a}	3.4±0.2^{a}
FYM	5.9±1.3^{a}	2.2±0.2^{a}	1.4±0.3^{a}	9.5±1.6^{a}	2.5±0.9^{a}	0.7±0.3^{a}	0.7±0.2^{a}	3.9±0.9^{a}
Fallow	4.2±0.7^{bc}	1.5±0.5^{b}	0.7±0.3^{b}	6.3±0.8^{b}	2.2±1.0^{ab}	1.0±0.3^{a}	1.0±0.4^{a}	4.1±1.1^{a}
	Less labile C				Non labile C			
Control	1.5±0.3^{c}	0.6±0.4^{c}	0.4±0.0^{c}	2.6±0.7^{d}	1.2±0.5^{b}	1.2±0.3^{a}	0.2±0.2^{b}	2.6±0.5^{b}
50% NPK	1.8±0.1^{c}	0.4±0.1^{c}	0.5±0.2^{c}	2.7±0.1^{cd}	1.2±0.9^{b}	1.7±0.8^{a}	0.7±0.4^{ab}	3.5±1.8^{ab}
100% NPK	2.5±0.3^{ab}	0.8±0.1^{bc}	1.1±0.2^{ab}	4.4±0.1^{b}	1.3±0.6^{b}	1.5±0.6^{a}	0.5±0.2^{ab}	3.3±1.0^{ab}
150% NPK	2.6±0.2^{a}	0.9±0.1^{bc}	0.4±0.2^{c}	3.9±0.1^{b}	1.4±0.3^{b}	1.5±0.2^{a}	0.8±0.1^{a}	3.7±0.3^{ab}
100% NPK+FYM	2.7±0.6^{a}	1.5±0.2^{a}	1.4±0.1^{a}	5.6±0.7^{a}	2.0±0.8^{b}	1.3±0.1^{a}	0.3±0.3^{ab}	3.5±0.7^{ab}
FYM	1.9±0.7^{bc}	1.7±0.2^{a}	1.0±0.2^{b}	4.5±0.7^{ab}	3.7±1.3^{a}	1.0±0.2^{a}	0.5±0.5^{ab}	5.1±1.9^{a}
Fallow	1.5±0.3^{c}	1.3±0.7^{ab}	0.9±0.4^{b}	3.8±1.2^{bc}	2.1±0.2^{b}	1.4±0.7^{a}	0.4±0.2^{ab}	3.9±0.9^{ab}

*values in the same column followed by different letters are significantly different at P>0.001 according to Duncan's Multiple Range test (DMRT) for separation of means, ± indicates the standard deviation values.

Naresh *et al*. (2017) [37] reported that the WSC was found to be 5.48% higher in surface soil than in sub-surface soil. In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to CT, FIRB and ZT coupled with 6tha^{-1} CR increased 35.6% WSC in surface soil and 33.1% in sub surface soil. Among all the treatments, T_6 had significantly higher (19.73%) proportion of WSC than the other treatments compared. Irrespective of tillage practices, residue retention resulted in 22.56% and 25.61% higher WSC as compared to the non-residue treatments in surface and sub-surface soil, respectively. Meena *et al.* (2018) [33] revealed that the WBC decrease in CL and BL was accompanied by mean increase in soil bulk density of 21% compared with FL. The WBC and LOC concentrations from barren land, cultivated land, grass land and forest land significantly varied among the LUS and soil depth form 0–15, 15–30 and 30–45 cm soil depth. The significantly highest WBC and LOC concentrations were observed in the top 0–15 cm depth and decreased with increase in depth. It was observed that FL showed highest WBC concentrations followed by GL, CL and BL of ecosystem. Significantly highest WBC (14.45 g C kg^{-1}) was observed with FL followed by GL (12.54 g C kg^{-1}), CL (9.23 g C kg^{-1}) and significantly lowest was recorded with the BL (6.26 g C kg^{-1}) in the top surface soil 0–15 cm depth. However, among the soil depth the significantly higher WBC (10.62 g C kg^{-1}) was noticed in the 0–15 cm soil depth followed by 15–30 cm soil depth (8.78 g C kg^{-1}) and lowest was recorded with 30–45 cm soil depth (6.81 g C kg^{-1}). Meanwhile, the cumulative effect of soil depth (0–45 cm) 8.74 g Ckg^{-1} WBC under various land use systems.

Carbon restoration in soil profile

Pandey *et al.,* (2014) revealed that no-tillage before sowing of rice and wheat could increase SOC by 0.59 Mg C ha^{-1} yr^{-1}. The rate of SOC sequestration due to reduced- or no-tillage management in rice-based systems in South Asia varied from 0- to 2114 kg ha^{-1} yr^{-1}. Xue *et al.*, (2015) [53] found that over time, CT system generally exhibit a significant decline in SOC concentration due to destruction of the soil structure, exposing SOM protected within soil aggregates to microbial organisms. Thus, the adoption of no-till system can minimize the loss of SOC leading to higher or similar concentration compared to CT. Conforti *et al*., (2016) [10] observed that the maximum value (214.5 Mg ha^{-1}) 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 behaviour is consistent with the evidence that N96% 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 Naresh *et al*. (2018) [39] reported that as compared to the RDF treatment also, the NPK+FYM treatment had higher SOC concentration in all the TCE. The highest increase in SOC in the NPK+FYM treatment was observed in F_6 with TCE T_6. In comparison with the control, the mean rate of SOC build-up during the 18 years of cropping was the highest in F_6 with T_6 (50.63%) and the lowest in F_1 with T_7 (9.79%) [Table4]. It was estimated that 30 per cent of applied C through FYM was stabilized, and the rest (70 per cent) was lost through oxidation. Kuhn *et al*. (2016) also found that the benefit of NT compared to CT on the changes of SOC stocks varied across different soil depths. In topsoil layers (above 20 cm), NT in general had greater SOC stocks than CT but the benefit tended to decline with soil depths, and even turned to be negative in soil layers deeper than 20 cm. In addition, in each soil layer, except for the top 5 cm, the total SOC stocks generally declined with the number of years after NT adoption.

Table 4: Soil organic carbon (SOC) stocks and annual rate of change in multiple soil mass intervals (averaged over tillage crop residue practices and nutrient management rate) in 2000 and in 2018 at Meerut, U.P. [Naresh *et al*., 2018] [39]

Tillage crop residue practices	Soil Organic Carbon (± Standard error)											
	0-400 kg of soil m^{-2} (approx. 0-30 cm)			Annual SOC change rate g of Cm^{-2} yr^{-1}	400-800 kg of soil m^{-2} (approx. 30-60 cm)			Annual SOC change rate g of Cm^{-2} yr^{-1}	800-1200 kg of soil m^{-2} (approx. 60-90 cm)			Annual SOC change rate g of Cm^{-2} yr^{-1}
	2000	2018	Difference		2000	2018	Difference		2000	2018	Difference	
	kgm^{-2}											
T_1	7.46	7.15*	-0.31±0.03	-28.2	5.39	5.65	-0.26 ±0.09	-6.9	3.14	3.12	-0.02±0.01	-1.8
T_2	8.98*	9.77	0.79 ±0.2	66.2	7.03	7.11	0.08 ±0.2	1.5	3.72	3.81	0.09±0.11	8.1
T_3	9.18*	9.87	-0.69 ±0.2	57.4	7.62	7.64	0.02 ±0.2	7.0	5.04	5.08	0.04 ±0.01	1.7
T_4	8.81	8.75	-0.06±0.05	-25.7	5.82	5.31*	-0.51 ±0.2	-4.5	2.93	2.67	-0.26±0.02	-4.7
T_5	8.12	9.11*	0.99 ±0.2	82.1	5.47	5.57	0.10 ±0.09	8.8	3.38	3.47	0.01±0.11	5.4
T_6	9.15	9.29	0.14±0.9	19.6	5.72	5.88	0.16 ±0.09	7.3	4.57	4.58	0.01 ±0.01	0.6
T_7	5.92	5.22	-0.70 ±0.09	-13.4	4.05	3.98	-0.07 ±0.09	-5.5	2.42	2.37	-0.05±0.02	-3.9

*Significant difference between years at *a*=0.05

Conclusion

The conservation tillage (ST and NT) treatments effectively improved the soil structure and strengthened the stability of water-stable soil aggregates. In addition, they increased the SOC content and storage in aggregates of different sizes with comparison of MP and CT. Furthermore, long-term adoption of conservation tillage methods significantly increased the content of water-stable macro-aggregates and of aggregate MWD, and increased the SOC content, ratio of, and storage in the macro-aggregates. In particular, the ST treatment increased the SOC content and enriched the newly formed C in macro-aggregates. In addition, correlation analysis suggested a significant correlation between SOC and aggregate- associated C in differently sized aggregates. The 0.25-1 and 1-2mm aggregates were the main sites of SOC storage and were also the important indices of the soil C pool saturation.

The findings also demonstrate the negative effect of conventional tillage not only on SOC decline, but also the weakening of soil aggregate formation and strength under continuous wet conditions, which can lead to other negative effects such as sediment loss and water quality concerns. The logical consequence is that the micro-aggregate-within-macro-aggregate fraction shows promising potential for early detection of changes in soil C arising from changes in management. A greater percentage of C was found in all aggregate size classes with the conservation tillage treatments than CT at the 0- to 5-cm depth. At the 10– 15-cm depth, however, the highest C percentages were found in aggregates from the CT and RT treatments, again reflecting a probable lower deposition of C due to the NT treatment at the lower depth.

The organic carbon content under no-tillage and reduced tillage system increased compared to conventional tillage due to retention of residues and minimum disturbance in the former system. The no-tillage system showed a trend to accumulate organic carbon near the soil surface layer. 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. In contrast, LFOC and DOC are useful indicators for subsoil. Reduced proportions of fine POC, LFOC, DOC and microbial biomass to soil organic C reflected the decline in soil organic C quality caused by tillage. The LOC fractions to SOC ratios also decreased, indicating a reduction in C quality as a consequence of tillage and residue management. Reduced LOC fraction stocks in subsoil could partially be explained by the decrease in fine root biomass in subsoil, with consequences for SOC stock. However, not all labile fractions could be useful early indicators of SOC alterations due to l tillage and residue management options.

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