

Review Article

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Effect of Tillage with Organic and Inorganic Fertilizer Management Practices on Soil Aggregation and Aggregate Associated Carbon Fractions to a Sub-tropical Soil under Rice-Wheat Rotation: A Review

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ABSTRACT

Soil tillage can affect the stability and formation of soil aggregates by disrupting soil structure. Frequent tillage deteriorates soil structure and weakens soil aggregates, causing them to be susceptible to decay. Different types of tillage systems affect soil physical properties and organic matter content, in turn influencing the formation of aggregates. The objective of this review study was to evaluate the effect of tillage and fertilization on soil aggregates and associated organic carbon fractions to a subtropical soil and to identify the optimal conservation tillage in this system. The average concentration of particulate organic carbon (POC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in organic manure plus inorganic fertilizer treatments (NP+S and NP+FYM) in 0–60 cm depth were increased by 64.9–91.9%, 42.5–56.9%, and 74.7–99.4%, respectively, over the CK treatment. 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 F₁ control treatment the RDF+FYM treatment sequestered 0.28 Mg C ha⁻¹ yr⁻¹ whereas the NPK treatment sequestered 0.13 Mg C ha⁻¹ yr⁻¹. As tillage intensity increased there was a redistribution of SOC in the profile, but it occurred only between ZT and PRB since under CT, SOC stock decreased even below the plow layer. Increased SOC stock in the surface 50 kg m⁻² under ZT and PRB was compensated by greater SOC stocks in the 50-200 and 200-400 kg m⁻² interval under residue retained, but SOC stocks under CT were consistently lower in the surface 400 kg m⁻². Over the last 16 years, CT lost 0.83 ± 0.2 kg of C m⁻² while ZT gain 1.98 ± 0.3 and PRB gain 0.97 ± 0.2 kg of C m⁻² in the 1200 kg of soil m⁻² profile. However increasing the quantity of C input could enhance soil C sequestration or reduce the rate of soil C loss, depending largely on the local soil and climate conditions. SOC can be best preserved by crop rotations with conservation tillage practices such as no or reduced tillage, and with additions of residues, chemical fertilizers and manure SOC change was significantly influenced by the crop residue retention rate and the edaphic variable of initial SOC content. Soil disturbance by tillage leads to destruction of the protective soil aggregate. This in turn exposes the labile C occluded in these aggregates to microbial breakdown. A higher amount of macro-aggregates along with greater accumulation of particulate organic C indicates the potential of conservation tillage for improving soil carbon over the long-term in rice-wheat rotation in North India.

Keywords

Tillage management, aggregates, aggregate associated Carbon, soil organic carbon

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Introduction

Agro-ecosystem represents around 40% of all land on earth (Schmidt *et al.*, 2015) which is critical for maintaining agricultural sustainability, environmental stability, and long-term terrestrial carbon (C) sequestration (Dalal *et al.*, 2013; Ding *et al.*, 2015). Soil organic carbon (SOC) plays an important role in cycling plant nutrients, increasing grain yield and improving the physical, chemical properties of soils (Manna *et al.*, 2007). Fertilization as an agricultural management strategy is being used to promote soil C storage (Malhi *et al.*, 2011; Silveira *et al.*, 2013), which could directly or indirectly increase the SOC inputs and thereby change the availability of nutrients and soil turnover (Schmidt *et al.*, 2015).

For instance, inorganic nitrogen (N) fertilizer may indirectly enhance the SOC storage by increased crop residue input to soils (Malhi *et al.*, 2011; Tian *et al.*, 2015), whereas application of organic manure could influence soil organic matter (SOM) owing to the directly inputs of processed organic materials to soils (Hai *et al.*, 2010; Ryals *et al.*, 2014). In contrast, application of organic fertilizers would result in a higher level of soil C and N mineralization than inorganic fertilizers (Zhou *et al.*, 2013; Xie *et al.*, 2014; Sun *et al.*, 2015). The combined application of inorganic and organic fertilizers has been shown to improve SOM better than the simple addition of inorganic fertilizer (Sun *et al.*, 2015).

To date, positive (Hyvönen *et al.*, 2008; Wang *et al.*, 2015) negative, and no obvious effects (Zhou *et al.*, 2013; Sun *et al.*, 2015; Chen *et al.*, 2012) have been reported under fertilization on soil C sequestration for agro-ecosystems. Soil is considered the 'skin' of the earth with soil organic carbon (SOC) as the protein that protects the 'skin' (Dou *et al.*, 2011). SOC is a key indicator of soil quality

(Bronick and Lal, 2005), is the basis of soil fertility and function (Pan and Zhao, 2004; Huang *et al.*, 2012), and is important for cementing substances as part of the formation of soil aggregates. SOC affects the number and distribution of differently sized soil aggregates (Zheng *et al.*, 2011).

Soil aggregates are the basic 'cells' of the soil structure and play an important role in improving soil carbon sequestration and fertility (Zhou *et al.*, 2009). Stable soil aggregates not only reduce soil erosion induced SOC loss, but also inhibit microbial and enzymatic decomposition of SOC through coating and isolation effects (Humberto and Lal, 2004; Six *et al.*, 2000). Physical fraction is widely used to study the storage and turnover of soil organic matter (SOC), because it incorporates three levels of analysis by examining three sizes of aggregate.

Application of manure could increase SOC, and the nutrient input could improve soil fertility and soil structure (Mikha and Rice, 2004). Jiao *et al.*, (2006) found that aggregate stability (>2 mm) and nutrient retention were improved when manure and mineral fertilizer were applied in combination at a rate of 30 Mgha⁻¹, as compared to mineral fertilization alone. Many studies have shown that balanced application of inorganic fertilizers or organic manure plus inorganic fertilizers can increase SOC and maintain soil productivity (Powelson *et al.*, 2012).

However, SOM is not sensitive to short-term changes of soil quality with different soil or crop management practices due to high background levels and natural soil variability Haynes, 2005. Labile soil organic carbon pools like dissolved organic C (DOC), microbial biomass C (MBC), and particulate organic matter C (POC) are the fine indicators of soil quality which influence soil function in specific ways and are much more sensitive to

change in soil management practices (Xu *et al.*, 2011). Recently, many studies have reported responses of labile SOC pools to management practices (Liang *et al.*, 2011 and Nayak *et al.*, 2012), though limited to tillage practices (Dou *et al.*, 2008). Challenges for irrigated farming in western Uttar Pradesh, India are low SOC and nutrient retention (Naresh *et al.*, 2015).

However, little is known about the long-term application of inorganic fertilizers either alone or with organic manure on SOC and the distribution of labile organic C fractions at different profile depths. Thus, it is crucial for collected SOC data from in order to understand and estimate the contribution of manure and fertilizer to soil C dynamics. This review study provided a unique opportunity to examine the effects of manure and fertilizer on soil aggregation and aggregate associated carbon fractions for sub-tropical climatic conditions.

Our objective was to study the nutrient, crop residue and tillage management on SOC and SOC fractions in rice-wheat rotation and to explain the relationship between different SOC fractions and SOC concentrations. Improved understanding of labile organic matter fractions will provide valuable information for establishing sustainable fertilizer management systems to maintain and enhance soil quality.

Size distribution of aggregates

Soil aggregates have three major effects on soil. They regulate and maintain water, fertilizer, gas, and heat in the soil, affect the types and activity of the soil enzymes, and also maintain and stabilize the loose arable layer. Almost 90% of SOC exists in the form of aggregates in the topsoil. Therefore, study of intra-aggregate C is of great significance to the influence of human disturbance on SOC

(Zheng *et al.*, 2013). Upendra *et al.*, (2009) reported that No-till increased aggregate proportion compared with tilled treatments in the continuous spring wheat system in the 4.75-to 2.00-mm size class at 0 to 5 cm and in the 2.00-to 0.25-mm size class at 5 to 20 cm.

These resulted in subsequent increases in aggregate proportions in smaller aggregates. No-till increases soil aggregation by reducing soil disturbance and increasing soil organic matter content and the growth of fungi that bind the soil particles and micro-aggregates together. Aulakh *et al.*, (2013) revealed that the proportion of macro-aggregates in the size class of 0.25 to >2 mm was higher as compared to micro-aggregate in the size class 0.11-0.25 mm.

Among the macro-aggregates, 0.25 -0.50 mm fraction constituted the greatest proportion followed by 0.5 -1.0, 1.0 - 2.0, and >2 mm fraction constituted the least proportion in both 0 - 5 cm and 5 -15 cm soil layers under both CT and CA system. Integrated use of organic and inorganic fertilizers significantly increased total WSA which was highest in all the macro-aggregate size fractions in 0 - 5 cm and 5 - 15 cm soil layer. Das *et al.*, (2014) reported that the higher LM was recorded in T₇ and T₈ in 0–7.5 (34–36%), 7.5–15 (19%) and 15–30 (17%) cm layers.

These treatments had proportionally less SM and significantly lower amounts of mi and sc fractions. The T₅ has significantly higher SM and lower LM in 0–7.5 and 7.5–15 cm layers, while higher mM contents were recorded in T₆, T₇ and T₈ (70.17, 74.34 and 74.76 g 100 g⁻¹ of soil, respectively) in the layer 0–7.5 cm compared to zero and 100% inorganic N treatments. In rest of the layers, T₈ had larger effects while other organic treatments had nearly similar impacts as in inorganic N application.

The cPOM and scM contents did not show significant variation among the treatments. Zhang-liu *et al.*, (2013) showed that NT and RT treatments significantly increased the proportion of macro-aggregate fractions (>2 000 and 250-2 000 μm) compared with the MP-R and MP+R treatments. Averaged across all depths, mean weight diameters of aggregates (MWD) in NT and RT were 47 and 20% higher than that in MP+R.

The concentration of bulk soil organic C was positively correlated with MWD and macro-aggregate fraction in the 0-5 cm depth. In the 0-20 cm depth, comparing with MP+R, total C occluded in the >2 000 μm fraction was increased by 9 and 6% under NT and RT, respectively. Devine *et al.*, (2014) reported that the <53 mm aggregate fraction had lower total SOC concentrations when expressed on a sand-free basis.

Under FS from 0–15 cm, there were no other significant differences among the size classes >53 mm. Under no tillage (NT), in the upper 15 cm both the large macro-aggregates and the <53 mm fractions were SOC depleted relative to the small macro-aggregates (250–2000 mm) and micro-aggregates. This was similar under conventional tillage (CT) from 0–5 cm where the small macro-aggregates (250–2000 mm) were significantly elevated in total SOC.

Under CT from 5–15 cm, both the small macro-aggregates and micro-aggregates were elevated in total SOC compared to the large macro-aggregates but only the small macro-aggregates were significantly elevated compared to the large macro-aggregates. From 15–28 cm, the large macro-aggregates were the most carbon rich under all land uses, having significantly greater total SOC and fine C concentrations compared to the <250 mm size fractions.

Ou *et al.*, (2016) reported that the tillage systems obviously affected the distribution of soil aggregates with different sizes. 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. There was no significant difference in the total amount of all the aggregate fractions between NT+S and NT-S in both the 0.05-0.20 and 0.20-0.30 m layers.

NT+S and NT-S showed higher proportions of >2 mm aggregate and lower proportions of <0.053 mm aggregate compared to the MP system for the 0.00-0.20 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. However, NT system did affect the SOC stock distribution in the soil profile but not the total quantity.

Tillage regimes obviously influenced soil aggregation distribution in the soil profile. In the upper 0.00-0.05 and 0.05-0.20 m layers, the NT system improved the formation level of the >2 mm aggregate but reduced the formation level of <0.053 mm aggregates, compared to the MP system, suggesting that mechanical operation reduced large-macro-aggregate formation and disrupted soil macro-aggregates into individual particles (Jiang *et al.*, 2011).

Zheng *et al.*, (2018) reported that the number and size of water-stable aggregates decreased with increased soil depth from 0-60cm under all tillage treatments. Moreover, 0.25-1 and 1-2mm aggregates dominated the soil throughout the 0-60cm depth, accounting for 36.3-55.4% and 19.2-35.4% of total aggregates, with the exception of the 1-2mm aggregates in the no tillage treatment at the 50- 60cm depth. Macro-aggregate-associated

C content was highest in the ST treatment at the 0-10, 10- 20, and 20-30cm depths for all sizes of macro-aggregates, and at the 30-40 and 40-50cm depths for macro-aggregates on average. For each depth 0-60cm, the micro-aggregate-associated C was highest in the ST treatment for water-stable aggregates of each size.

The contributing rate was 34.7%-45.7%, with that of the ST and NT treatments significantly higher than that of MP and CT. The < 0.002mm aggregates contributed the least to SOC, with a contributing rate of 1.5%-13.4%; and those of the ST and NT treatments were significantly lower than those of MP and CT. The total contributing rate of SOC at all depths in macro-aggregates was in the order NT>ST>CT>MP, while that for micro-aggregates was MP>ST>CT>NT.

Aggregation indices

Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles. The space between the aggregates provides pore space for retention and exchange of air and water. Soil aggregates are microhabitats for microorganisms, and directly influence microorganisms that live within and are influenced by microorganisms in return. Bhattacharyya *et al.*, (2010) observed that fertilization had little effect on aggregation in sizes below S_3 in all soil depths.

It had no effect on S_5 and S_7 in the 0–15 and 15–30 cm and on S_4 , S_5 , S_6 and S_7 in the 30–45 cm soil layers. Addition of FYM increased the percentages of large sized aggregates (2–4.75 and 1–2 mm) in all soil layers. Proportion of aggregates 2 mm (S_1) was nearly 41% higher under NPK? FYM treated plots than that observed under NPK in the 0–15 cm soil layer.

Johnson *et al.*, (2013) also found that the intensive tillage at the Chisel field showed <20% of the soil covered for all Stover treatments, including full return, where all residues were returned; whereas, NT₂₀₀₅ and NT₁₉₉₅ had at least 45% of the soil covered even in low return. In NT₂₀₀₅, significant increases in aggregates <1 mm and significant decreases in aggregates 5–9 mm were measured in low return compared to full return.

Low Return had 15% and 60% more aggregates in the 0–0.5 and 0.5–1 mm classes, respectively, compared to full return, but full return had 14% more 5–9 mm aggregates compared to low return, with moderate return intermediate. Choudhary *et al.*, (2014) 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.

Tripathi *et al.*, (2014) 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 E_{Ce} as compared with inorganic fertilizer application alone and unfertilized control.

Wang *et al.*, (2017) 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 (<0.25 mm) by 5.9% and SOC contents of two macro-aggregate classes (9.1% for >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) > small macro-aggregates (0.25–1 mm) > micro-aggregates (<0.25 mm). Under both the CK and manuring treatments, all macro-aggregates had higher SOC contents than the micro-aggregates.

Therefore, manuring and aggregate size both had significant effects on SOC contents, However, manuring significantly increased the TN contents of the large macro-aggregates (7.1% for >2 mm) and the bulk soil (10.3%), but not for the micro-aggregates. Nandan *et*

al., (2019) also found that Residue retention treatment increased the content of coarse macro-aggregate and meso-aggregate over residue removal treatment.

The ZT based crop establishment treatments (ZTTPR–ZT and ZTDSR–ZT) had higher content of coarse macro– aggregate and meso–aggregate over CTPR–CT. Subsequently, the MWD and aggregate ratio (AR) were higher in residue retention and zero–till crop establishment treatments. Retention of crop residue increased the WSMacA by 7% over residue removal treatment. The ZT based treatments ZTTPR–ZT, ZTDSR–ZT, and NTPR–ZT increased based crop establishment treatment was significant for MesAC and CMicAC.

Different types of soil carbon

SOC is an important index of soil quality and health and is an important component of the soil fertility of farmlands, as well as being the core of soil quality and function (Pan and Zhao, 2005). SOC content can directly affect soil fertility and crop yield, and greatly affects the formation and stability of the water-stable soil aggregate structure (Cai *et al.*, 2009).

Venkanna *et al.*, (2014) also found that the SOC stocks ranges from 22.68 to 94.83 Mg ha⁻¹ with a mean of 52.84 Mg ha⁻¹ in Alfisols, 34.37 to 73.67 Mg ha⁻¹ with a mean of 51.26 in Inceptisols and 27.80 to 74.20 Mg ha⁻¹ with a mean of 49.33 Mg ha⁻¹ in case of Vertisols and associated soils.

The SIC ranges from 4.14 to 25.54 Mg ha⁻¹ with a mean of 12.39 Mg ha⁻¹ in Alfisols, 7.23 to 34.17 Mg ha⁻¹ with a mean of 17.47 Mg ha⁻¹ in Inceptisols and 9.08 to 71.78 Mg ha⁻¹ with a mean of 22.93 Mg ha⁻¹ in Vertisols and Vertic intergrade. In most of the cases, surface SOC is greater than deeper layers, whereas the reverse trend is observed

for SIC in most of the cases. Total carbon stock ranges from 30.81 to 116.42 Mg ha⁻¹ (mean 65.24 Mg ha⁻¹) in Alfisols, 43.12 to 107.20 Mg ha⁻¹ (mean 68.73 Mg ha⁻¹) in Inceptisols and 39.39 to 145.98 Mg ha⁻¹ (mean 72.26 Mg ha⁻¹) in Vertisols and associated soils. Mazumdar *et al.*, (2015) revealed that Concentration of C was higher in macro-aggregates as compared to micro-aggregates.

Irrespective of treatments, C concentration was highest in 1-2 mm followed by 0.5-1mm size of macro-aggregates and the concentration decreased as the aggregates became smaller in size. Incorporation of organic manures induces decomposition of organic matter where roots, hyphae and polysaccharides bind mineral particles into micro-aggregates and then these micro-aggregates bind to form C rich macro-aggregates.

Naresh *et al.*, (2018) showed that, soil organic carbon buildup was affected significantly by tillage and residue level in upper depth of 0-15 cm but not in lower depth of 15-30 cm. Higher SOC content of 19.44 g kg⁻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. Zero tilled residue retained plots sequestered 0.91gkg⁻¹yr⁻¹ SOC in the year 2015-16 which was 22.63% higher over the conventionally tilled residue removed plots after seven seasons of experimentation.

Song *et al.*, (2019) reported that the average topsoil contents of total carbon (TC), SOC and labile organic carbon (LOC) were 12.72 g·kg⁻¹, 11.01 g·kg⁻¹, and 7.13 g·kg⁻¹,

respectively, under the three no-tillage treatments (T₇, T₈, and T₉). These mean values were significantly higher than those under the conventional tillage treatments (T₁, T₂ and T₃), which had average TC, SOC, and LOC contents of 9.87 g·kg⁻¹, 8.56 g·kg⁻¹, and 5.20 g·kg⁻¹, respectively.

The average contents of the three carbon types under rotary tillage were between those under conventional tillage and those under no-tillage. The contents of TC and SOC were significantly lower than those under no-tillage. The subsoil contents of TC, SOC, and LOC under conventional tillage were 9.42 g·kg⁻¹, 7.60 g·kg⁻¹, and 5.97 g·kg⁻¹, respectively, which were 17.16%, 4.25% and 16.83% higher than those under no-tillage.

Furthermore, the influence of tillage, straw return and organic fertilizer also led to variations in soil carbon content among the different treatments. The average topsoil TC contents under straw return (T₂, T₅ and T₈) and organic fertilizer (T₃, T₆ and T₉) were 16.83% and 19.78% higher than those under chemical fertilizer only (T₁, T₄ and T₇), with F = 6.852. Similar results were observed for the SOC and LOC. The average subsoil contents of TC, SOC, and LOC under straw return were 8.82 g·kg⁻¹, 7.61 g·kg⁻¹, and 5.68 g·kg⁻¹, respectively.

The corresponding values under organic fertilizer were 9.33 g·kg⁻¹, 8.15 g·kg⁻¹, and 5.67 g·kg⁻¹, respectively. The subsoil TC and SOC contents under straw return were significantly higher than those under chemical fertilizer only, but no significant differences were observed in the LOC content.

Bhardwaj, *et al.*, (2019) also found that the Oxidizable C was the maximum in FYM followed by GM and crop residue (WS, RS) treatments in the surface 0.15 m soil. At the lower depths (0.15–0.30 m), there was no

significant difference in the oxidizable C for any management. At both depths O and F accumulated least oxidizable C. VLc (very labile C) and LLc (less labile C) fractions constituted a major part of soil organic C, for all managements. GM accumulated the maximum Lc fraction at the surface 0–0.15 m.

The LLc fraction was maximum in FYM which was followed by all other integrated nutrient managements. Management O had least LLc fraction in surface 0.15 m. There was no difference in NLc fraction for any of the treatments, for any measured depth. There was 46 to 65% decrease in oxidizable C, from the surface (0–0.15 m) to lower layer (0.15–0.30 m).

Labile soil organic carbon fractions

Labile organic carbon is the portion of soil organic carbon that can be readily decomposed by soil organisms. Farm productivity is closely linked to soil functions that depend on the amount and quality of labile organic carbon and its turnover rate. Labile organic carbon can be a sensitive indicator of changes in soil health in response to land management change.

The labile soil organic C pools were able to distinguish SOC changes due to tillage treatments: MBC, DOC, HWC, $\text{KMnO}_4\text{-C}$, and POC all were significantly higher in the conservation tillage treatments (ST and NT) than conventional tillage in the surface soil, but not in the subsurface layer. Chen *et al.*, (2009);

Sheng *et al.*, (2015) 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 20-100 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). 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.

Day *et al.*, (2016) revealed that significant effect of ZT, green manuring (GM; Green gram residue retention) and brown manuring BM; Dhaincha residue retention) was recorded on very labile SOC in the 0-15 cm soil layer only. Treatments ZT-ZT, ZT-ZT+BM and ZT-ZT+GM increased very labile SOC by 35, 25, and 38%, respectively over conventional practice (CT-CT). There were large differences in portions among the five labile C fractions. Soil microbial biomass C was 2.8–3.9%, DOC was 0.8– 1.0%, HWC was 2.9–4.7%, POC was 33.2–59.6%, and $\text{KMnO}_4\text{-C}$ was 7.1–32.9% of SOC in our study (Rudrappa *et al.*, 2006).

Although the responses of the five labile C fractions to tillage effects were similar, their sensitivities to tillage effects were different.

The magnitude of changes of labile C fractions between conservation tillage treatments and conventional tillage for 0–15-cm depth ranged in the order: $\text{KMnO}_4\text{-C}$ (87.9–158.9%) > POC (42.0–69.2%) > HWC (37.0–47.7%) > DOC (13.1–30.8%) and MBC (21.7–8.4%). So that $\text{KMnO}_4\text{-C}$, POC and HWC were the most sensitive to tillage effects than total SOC which showed 25.6–34.2% enrichment.

Naresh *et al.*, (2017) reported that LFOC were also significantly higher following the treatments including organic amendment than following applications solely of chemical fertilizers, except that the F₅, F₆ and F₇ treatments resulted in similar LFOC contents.

Application solely of chemical fertilizers had no significant effects on LFOC and $\text{KMnO}_4\text{-C}$ fractions compared with unfertilized control plots. Nevertheless, application of F₅ or F₆ significantly increased contents of POC and MBC relative to F₁ (by 49.6% and 40.9% or 70.2% and 63.4%, respectively).

Ghosh *et al.*, (2016) [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).

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) 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 fraction (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) 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 yr⁻¹ is needed to maintain SOC level.

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. However, the contribution of V_L , 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).

Organic carbon in soil aggregates

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. Singh, Kumar, and Pal (2008) studied the influence of cropping sequence and nutrient management on SOC and nutrient status and found that fertilizer along with FYM

application significantly raised SOC from 27.6 to 43.2 per cent. Bharadwaj, Sharma, and Sharma (2010) studied the effect of integrated nutrient management on soil fertility. Maximum OC concentration was noted in combined use of the organic fertilization followed by fertilizers combined with organic sources.

Nalatwadmath *et al.*, (2003) also reported that continuous application of NPK and organic manure decreased the pH significantly over control and increased the soil OC. Zhu *et al.*, (2014) also found that soil TOC and labile organic C fractions contents were significantly affected by straw returns, and were higher under straw return treatments than non-straw return at three depths. At 0–7 cm depth, soil MBC was significantly higher under plowing tillage than rotary tillage, but EOC was just opposite.

Rotary tillage had significantly higher soil TOC than plowing tillage at 7–14 cm depth. However, at 14–21 cm depth, TOC, DOC and MBC were significantly higher under plowing tillage than rotary tillage except for EOC. The reason might be that rotary tillage and plowing tillage mixed crop straw into the deeper soil layer, making SOM well distributed at different depths. Consequently, under short-term condition, rice and wheat straw both return in rice-wheat rotation system could increase SOC content and improve soil quality.

Yang *et al.*, (2012) 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. Zhu *et al.*, Meenakshi, (2016) reported that zero tillage

practice in wheat increased the organic carbon content and carbon stock as compared to conventional tillage in soils. The zero tillage increased dissolved organic carbon, microbial biomass carbon light and heavy fractions of carbon in soils at both the depths.

Microbial utilization of organic carbon is an important characteristic which reflect the quality of the soil, the higher the efficiency, the less energy which required maintaining the same microbial, indicating the soil environment conducive to microbial growth, relatively high quality (Xianli *et al.*, 2006).

Guo *et al.*, (2016) 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) 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 (F₅) followed by 50% RDN as CF+50% RDN as GM/SPM (F₆) treatments and the least in Control (no manure and fertilizer) F₁ 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 g kg⁻¹) > 75% RDN as CF+25% RDN as FYM (19.64 g kg⁻¹) > unfertilized control (10.99 g kg⁻¹).

Tiwari *et al.*, (2018) 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 s for subsoil. Reduced proportions of fine POC, LFOC, DOC and microbial biomass to soil organic useful early indicators of changes in topsoil organic C. In contrast, LFOC and DOC is useful indicator 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 F₁ 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. Song *et al.*, (2019) observed that the

aggregate-associated C content within varied aggregate sizes was significantly higher in the topsoil than in the subsoil. The order was as follows: small macro-aggregates > micro-aggregates > large macro-aggregates, with average values of 25.14 g·kg⁻¹, 23.34 g·kg⁻¹, and 20.54 g·kg⁻¹, respectively.

In contrast to the topsoil, the variation in aggregate -associated C in the subsoil was smaller between the different aggregate sizes. The average contents under the different treatments were from 10.42–11.77 g·kg⁻¹. Under conventional tillage, the average aggregate-associated C contents of the large and small macro-aggregates and micro-aggregates under T₁, T₂, and T₃ were 11.60 g·kg⁻¹, 12.14 g·kg⁻¹ and 12.33 g·kg⁻¹, respectively. These values under organic fertilizer and straw return were significantly higher than those under single chemical fertilizer.

Carbon in bulk soil and aggregates

Jiang *et al.*, (2011) 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.

Mandal *et al.*, (2012) reported that the SOC stock was highest within 0–15-cm soil and gradually decreased with increase in depth in each land use systems. In 0–15 cm depth, highest SOC stock (16.80 Mg ha⁻¹) was estimated in rice– fallow system and the lowest (11.81 Mg ha⁻¹) in the soils of guava orchard. In 15–30 cm, it ranged from 8.74 in rice–rice system to 16.08 Mg ha⁻¹ in mango orchard. In the 30–45-cm soil depth, the SOC stock ranged from 6.41 in rice–potato to 15.71 Mg ha⁻¹ in rice–fallow system.

The total SOC stock within the 0–60-cm soil profile ranged from 33.68 to 59.10 Mg ha⁻¹ among rice-based systems, highest being in soils under rice–fallow system and the lowest for rice–rice system. Das *et al.*, (2014) also found that the bulk soil organic was higher in T₇ (12.42– 18.40 g kg⁻¹ of soil) and T₈ (12.38–15.11 g kg⁻¹ of soil) in all the layers followed by T₄ (8.57–13.98 g kg⁻¹ of soil).

The inorganic N-fertilizer improved soil C - over zero-N, but recorded lower C than the treatments with partial substitutions of N through organic sources. The C contents were higher in LM and followed the order: LM > SM > sc > mi, although substantial variations over the treatments and the soil depths were observed. The LM-and SM-C fractions were higher in T₇, ranging between 9.51 and 18.95 g kg⁻¹ of soil and closely followed by T₈ (8.66– 14.58 g kg⁻¹ of soil).

Furthermore, among various fractions of

macro-aggregates, cPOM contained higher C, especially in 0–7.5 and 7.5–15 cm layers. Significantly higher C in this fraction was found in T₈ in 0–7.5 and 7.5–15 cm layers. All the organic treatments in 0–7.5 cm layer and T₆ and T₇ treatments in 7.5–15 cm layer showed higher cPOM-C concentration compared to T₂ and T₃.

None of the treatments showed significant variation in 15–30 cm layer. Chu *et al.*, (2016) revealed that cropping system increased the stocks of OC and N in total soils at mean rates of 13.2 g OC m⁻² yr⁻¹ and 0.8 g N m⁻² yr⁻¹ at the 0–20 cm depth and of 2.4 g OC m⁻² yr⁻¹ and 0.4 g N m⁻² yr⁻¹ at the 20–40 cm depth.

The stocks of OC and N in this system increased by 45 and 36%, respectively, (with recovery rates of 31.1 OCm⁻² yr⁻¹ and 2.4 gN m⁻² yr⁻¹) at the 0–20 cm depth and by 5 and 6%, (with recovery rates of 3.0 OC m⁻² yr⁻¹ and 0.03 g N m⁻²yr⁻¹) at the 20–40 cm depth. Maharjan *et al.*, (2017) also found that the total soil organic C was highest in organic farming (24 mg C g⁻¹ soil) followed by conventional farming (15 mg C g⁻¹ soil) and forest (9 mg C g⁻¹ soil) in the topsoil layer (0–10 cm depth).

Total C content declined with increasing soil depth, remaining highest in the organic farming soil at all depths tested. Zhao *et al.*, (2018) reported that the SOC content of each aggregate class in the 0–20 cm layer was significantly higher than that in the 20–40 cm layer.

Increases in the SOC content of aggregate fractions were highest in MRWR, followed by MR, and finally WR. Crop derived organic particles or colloids can combine with mineral matter, binding micro-aggregates into macro-aggregates. Fresh straw incorporation provides substrate for microorganisms (An *et*

al., 2015) , and straw input can alter the distribution of SOC and increase the SOC content of aggregates, especially in macro-aggregates (Guan *et al.*, 2015). Sapkota *et al.*, (2019) also found that the treatment effects on SOC stock were significant at 0–0.05 and 0.05–0.15 m soil depths only.

At 0–0.05 m, ZTDSR-ZTW+R and PBDSR-PBW+R, on an average, had significantly higher SOC stocks, that is 2.4 t/ha more than CTR-CTW. ZTDSR-ZTW, ZTDSR-ZTW+R and PBDSR-PBW+R had a similar improvement in total SOC at 0.05–0.15 m, which was significantly higher (by about 2.0 t/ha) than for CTR-CTW.

All the treatments had similar SOC stock at 0.15–0.3 m and 0.3–0.6 m soil depths. Calculations for the whole 0–0.6 m depth showed that ZTDSR-ZTW+R and PBDSR-PBW+R contained 5.6 t and 3.9 t/ha more SOC than CTR-CTW, respectively.

Carbon in soil aggregates

Aulakh *et al.*, (2013) also found that an application of fertilizer N, P, FYM and crop residue (CR) significantly increased water stable aggregates and had profound effects in increasing the mean weight diameter as well as the formation of macro-aggregates, which were the highest in both surface (85%) and subsurface (81%) soil layers with application of 20 kg N + 60 kg P₂O₅ + 10 t FYM + 6 t WR ha⁻¹ applied to soybean and 120 kg N + 60 kg P₂O₅ + 3 t SR ha⁻¹ applied to wheat crop in CA, respectively, and were 83% and 77% in CT treatments after 2 years.

Hence, better aggregation was found with 100% NP + FYM + CR, where macro-aggregates were greater than 50% of total soil mass. Das *et al.*, (2014) observed that a large reduction (50–75%) in MWD was observed upon slaking, more in case of inorganic N

treatments. Variation in MWD of capillary-wetted aggregates was also less (3.5–4.5 mm). Treatment T₇ had significantly higher MWD in all the layers (3.9–4.6 mm), while rest of the treatments was similar and not different from T₁.

However, the MWD of slaked aggregates showed larger variations, and the treatment differences were large. In the layer 0–7.5 cm, treatments T₄, T₆, T₇ and T₈ had significantly higher MWDs of slaked aggregates. At 7.5–15 and 15–30 cm, the values were significantly higher in T₇ and T₈.

Rests of the treatments were comparable, although significantly higher than (7.5–15 cm) or similar to (15–30 cm) T₁. Its due to the improvement in water stable indices under balanced application of inorganic–organic N sources is in close agreement with results from similar field trials (Karami *et al.*, 2012). This improvement is due to proportional increase in soil organic matter content, which imparts better resistance of aggregates to slaking.

Mikha *et al.*, (2015) revealed that Aggregate-associated C at 0- to 5-, 5- to 10-, and 10- to 15-cm depths was significantly influenced by N treatment and depth. At the surface 0- to 5-cm depth, substantial amounts of C were associated with macro-aggregates (>1000, 250–500, and 53–250 μm) when different rates of F were combined with M (0 + M, 90 + M, and 180 + M) compared with F or control treatments. Yu *et al.*, (2012) reported an increase in micro-aggregate-associated C with combination of F and organic amendment compared with F alone and control treatments.

Averaged across N treatments, aggregate-associated C was greater at the 0- to 15-cm depth than the 15- to 30-cm depth except for 250- to 500-μm aggregates. Across aggregate-

size classes, aggregate-associated C was 64% greater at the 0- to 15-cm depth compared with the 15- to 30-cm depth. A similar pattern was observed with aggregate-associated N. This study indicates that M addition influenced soil C and N distributions and C and N conservation associated with different aggregate-size classes and that the effects are depth dependent.

Nandan *et al.*, (2019) reported that tillage based crop establishment practices and residue management treatments strongly influenced TOC and soil C-fractions, C-pools, and C-management indices. Residue retention treatment increased C_{frac1} , C_{rac2} , C_{rac3} , C_{rac4} , and TOC by 18, 24, 5, 10, and 12%, respectively, over residue removal treatment. Conservation tillage treatments (NPTPR-ZT, ZTTPR-ZT and ZTDSR-ZT) had 13–21%, 12–16%, 5–7%, 9–13%, and 9–14% higher C_{rac1} , C_{rac2} , C_{rac3} , C_{rac4} , and TOC, respectively, over CTPR-CT. ZTDSR-ZT and ZTTPR-ZT treatments increased ($p < 0.05$), active C-pool, LI and CMI over CTPR-CT.

Notably, in the study, the C_{rac3} (32% of TOC) was the dominant C-fraction, followed by C_{frac1} (31%), C_{rac4} (25%), C_{rac2} (12%). Very-labile C-fraction (C_{rac1}) and labile C-fraction (C_{rac2}) are highly prone to oxidation processes (Nath *et al.*, 2017a).

Therefore, higher concentrations of C_{rac1} and C_{rac2} in zero-till based crop establishment treatments indicate that restricted oxidation of organic carbon in conservation tillage treatments. Results further suggests that elimination of tillage could increase recalcitrant C-pool as the higher content of less-labile C-fraction (C_{rac3}) and non-labile C-fraction (C_{rac4}) was observed in zero-till crop establishment treatments.

The results exclusively demonstrate that even

a single wet tillage (puddling) operation could result in substantial SOC loss and that may be the reason for less impact of NPTPR-ZT than ZTTPR-ZT and ZTDSR-ZT. Increased TOC in residue retention treatment was mainly because of increased addition of C-input.

This way, conservation tillage based crop establishment in combination with residue retention may lead to a strong positive impact on soil health, particularly on SOC level. Song *et al.*, (2019) revealed that the topsoil contents of large macro-aggregates (>2 mm), small macro-aggregates (2–0.25 mm), and micro-aggregates (0.25–0.053 mm) were approximately 10%, 50% and 20%, respectively.

The subsoil contents of the three size aggregates had similar distribution trends but were lower than those of the topsoil. No-tillage and straw return caused a significant increase in the contents of macro-aggregates and micro-aggregates, especially in the topsoil. Furthermore, no-tillage (T_7 , T_8 and T_9) increased the numbers of large macro-aggregates (11.25%) and small macro-aggregates (9.45%) compared to those under conventional tillage (T_1 , T_2 , and T_3).

A similar trend was observed in the subsoil. Under the same tillage, the order of large and small macro-aggregate contents in the topsoil and subsoil was as follows: straw return > organic fertilizer > single application of chemical fertilizer. In particular, more large macro-aggregates were observed under no-tillage than under straw return (T_8), and these values were 6.76% and 28.68% higher than those under the single application of fertilizer (T_7) in the topsoil and subsoil, respectively.

It is concluded that the conservation management systems such as reduced- and no-tillage, crop residue addition, FYM incorporation, and integrated nutrient

management increased SOC accumulation and improved sustainability of agricultural systems. No-tillage increased soil aggregation, improved other soil properties, and favorably influenced SOC accretion.

Effects of crop residue addition are often observed when it was integrated with reduced-tillage systems or with improved nutrient management. This review study also revealed several challenges and research opportunities impacts of alternative tillage, crop residue, and nitrogen management practices to improve SOC concentration and stock and enhance soil carbon pools.

The accumulation of C in soil was related to soil aggregation and the distribution of C in aggregates. By significantly improving soil aggregation and associated C content, the potential of conservation tillage (CT) systems in a rice–wheat rotation for enhancing C storage was noted.

The differences were prominent mostly in the top (0–5-cm) soil layer, which is the most disturbed layer under a conventional-tillage system. In a rice–wheat rotation, being highly tillage-intensive, the losses of C from the surface soil can partially be reversed or organic C pools in the soil conserved through the adoption of ZT or alternate resource-conserving technologies such as transplanted rice on furrow irrigated raised beds followed by wheat on the same beds, which offer less physical disturbance to soils. Conservation tillage systems, especially no-till, increased the proportion of macro-aggregates (>250 μ m), which was attributed to higher soil organic C level and less mechanical disturbance as compared with MP.

The NT and RT treatments also increased aggregate size in the 0-10 cm depth, indicating that conservation tillage improved soil structure quality. Increase in SOC

concentration with conservation tillage was partly responsible for the increased macro-aggregation near the soil surface. The adoption of NT and RT practices increased the aggregate C concentration for all aggregate size fractions in the 0-10 cm depths.

Conventional tillage (CT) significantly reduces macro-aggregates to smaller ones, thus aggregate stability was reduced by 35% compared with conservation system (CS), further indicating that tillage practices led to soil structural damage. The concentrations of SOC and other nutrients are also significantly higher under CS than CT, implying that CS may be an ideal enhancer of soil productivity in this *Inceptisol* ecosystem through improving soil structure which leads to the protection of SOM and nutrients, and the maintenance of higher nutrient content. The average concentration of particulate organic carbon (POC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in organic manure plus inorganic fertilizer treatments (NP+S and NP+FYM) in 0–60 cm depth were increased by 64.9–91.9%, 42.5–56.9%, and 74.7–99.4%, respectively, over the CK treatment.

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 and increased enzyme activities, which potentially influence soil nutrients dynamics under field condition.

A regular input of biomass-C along with chemical fertilizers is essential to improving soil quality in the semi-arid tropics of India, and for minimizing the depletion of SOC stock under continuous cropping. Use of organic amendments is essential to enhancing the SOC sequestration.

The minimum input of 1.1 Mg C ha⁻¹ year⁻¹ is needed to maintain SOC at the initial level

(with no change). In view of the decreasing availability of FYM, however, application of 10.7 Mg ha⁻¹ of FYM (equivalent to 60 kg N) on dry weight basis is difficult. Thus, conjunctive use of FYM or other crop residues along with 50% recommended dose of fertilizers is a viable option for curbing SOC depletion and sustaining crop production.

Hence, balanced use of NPK fertilizer along with FYM or other crop residues, which will take care of critical-C-input addition quantitatively, will be a better option to stop SOC depletion and maintain and sustain crop production.

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