

Review Article

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Soil Aggregation and Organic Carbon Fractions and Indices in Conventional and Conservation Agriculture under Vertisol soils of Sub-tropical Ecosystems: A Review

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ABSTRACT

Tillage systems can changes in soil organic carbon dynamics and soil microbial biomass by changing aggregate formation and C distribution within the aggregate. However, the effects of tillage method or straw return on soil organic C (SOC) have showed inconsistent results in different soil/climate/ cropping systems. 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. The soil organic carbon (SOC) stock in bulk soil was 40.2-51.1% higher in the 0.00-0.05 m layer and 11.3-17.0% lower in the 0.05-0.20 m layer in NT system no-tillage without straw (NT-S) and with straw (NT+S), compared to the MP system moldboard plow without straw (MP-S) and with straw (MP+S), respectively. 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. 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. A considerable proportion of the total SOC was found to be captured by the macro-aggregates (>2–0.25 mm) under both surface (67.1%) and sub-surface layers (66.7%) leaving rest amount in micro-aggregates and ‘silt + clay’ sized particles. Application of inorganic fertilizer could sustain soil organic carbon (SOC) concentrations, whereas long-term application of manure alone or combined with NPK (M and NPK + M) significantly increased SOC contents compared with the unfertilized control. Manure application significantly increased the proportion of large macro-aggregates (> 2000 μm) compared with the control, while leading to a corresponding decline in the percentage of micro-aggregates (53–250 μm). Carbon storage in the intra-aggregate particulate organic matter within micro-aggregates was enhanced from 9.8% of the total SOC stock in the control to 19.7% and 18.6% in the M and NPK + M treatments, respectively. The shift in SOC stocks towards micro-aggregates is beneficial for long-term soil C sequestration. Moreover, the differences in the micro-aggregate protected C accounted, on average, for 39.8% of the differences in total SOC stocks between the control and the manure-applied treatments. Thus, we suggest that the micro-aggregate protected C is promising for assessing the impact of conventional and conservation agriculture on SOC storage in the vertisol. 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. The present study found that SOC change was significantly influenced by the crop residue retention rate and the edaphic variable of initial SOC content.

Keywords

Microbial biomass, Conservation tillage, Organic matter dynamics, Biological activity

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Introduction

More than two-thirds of terrestrial carbon is stored in the soil. There is approximately 1500 Pg C (1 Pg=10⁹ Mg=10¹⁵ g) stored as SOC in the top 1m (Stockmann *et al.*, 2013). The rest of the terrestrial carbon (560 Pg) is stored in plant biomass (Paustian *et al.*, 1997). Oceans store the largest amount of carbon (38,000 Pg) (Stockmann *et al.*, 2013), whereas the atmosphere stores less carbon than there is in the soil (750 Pg) (Paustian *et al.*, 1997). Anthropogenic carbon emissions (e.g. fossil fuel combustion, cement manufacturing), in the form of carbon dioxide (CO₂), have increased in the past 35 years. In the 1980s, anthropogenic carbon emissions was 6 Pg yr⁻¹ (Lal and Follett, 2009), and by 2014, the anthropogenic carbon emissions had increased to 10 Pg yr⁻¹ (Zeebe *et al.*, 2016). Soils are considered a carbon sink, which can help decrease the atmospheric CO₂ concentration and reduce the greenhouse effect (Jaffe, 1970). Storage of SOC is affected by climate, land cover, soil order, and soil texture (Batjes, 2016). It has been reported that soils under deserts store the lowest amount of SOC, and the soils under tropical forests store the highest amount of SOC (Batjes, 2016). Much of the carbon in deserts may be stored in inorganic form (Eswaran *et al.*, 2000). About 8% of SOC is stored in soils under agriculture (Jobbagy and Jackson, 2000). Carbon storage is affected by soil texture and aggregation, and the silt and clay size fractions have the ability to protect SOC from decomposition (Hassink, 2016). When organic matter decomposes, the organic matter binds with silt and clay forming aggregates, which protects the organic matter from decomposition (Churchman, 2018). Hassink (2016) found no relationship between total carbon and and clay + silt content, but there was an increase in the soil carbon stored in <20 µm size fraction with an increase in clay+ silt content. Gabarron Galeote *et al.*, (2015) and Tiessen and Stewart

(1983) found that the highest amount of soil carbon is found in the silt and clay size fractions, and the sand sized fraction is low in soil carbon.

Soil organic matter/carbon (SOM/SOC) has profound effects on soil physical, chemical and biological properties (Haynes, 2005). Maintenance of SOM/SOC in cropland is important, not only for improvement of agricultural productivity but also for reduction in C emission (Rajan *et al.*, 2012). However, short- and medium-term changes of SOC are difficult to detect because of its high temporal and spatial variability (Blair *et al.*, 1995). On the contrary, soil labile organic C (LOC) fractions i.e. microbial biomass C (MBC), dissolved organic C (DOC), and easily oxidizable C (EOC) that turn over quickly can respond to soil management intervention more rapidly than total organic carbon (TOC) [Haynes, 2005; Yadvinder-Singh *et al.*, 2005]. Therefore, LOC fractions have been considered as early sensitive indicators of the effects of land use change on soil quality and soil health [Rudrappa *et al.*, 2006; Yang *et al.*, 2005; Yadvinder-Singh *et al.*, 2005]. Agricultural practices such as tillage methods are conventionally used for loosening soils to grow crops.

At the same time, long-term soil disturbance by tillage is believed to be one of the major factors reducing SOC in agriculture (Baker *et al.*, 2005). Nevertheless, SOC pool plays a significant role in the global carbon cycle and is a key determinant of the physical, chemical and biological properties and is required for the proper functioning of the soil system. Soil aggregation (macro- and micro-) and stability can have a large effect on SOC dynamics and sequestration, and C availability. Soil macro-aggregates affect C storage by occluding organic residues, making them less accessible to degrading organisms and their enzymes (Six *et al.*, 2000).

Soil organic carbon (SOC) plays an important role in the formation and stabilization of soil aggregates (Spohn and Giani, 2011). There exists a close relationship between soil aggregation and SOC accumulation; generally SOC promotes soil aggregation, whereas aggregates, in turn, store SOC and reduce the rate of its decomposition. The stable soil aggregates act as the nuclei for long-term stabilization of SOC. These protect the SOC by forming physical barriers between microbes and enzymes and thus reduce SOC turnover rate (Pulleman and Marinissen, 2004). The size and stability of aggregates is determined by the quality and quantity of humic compounds and the degree of their interaction with the soil particles (Jastrow and Miller, 1998). The extent of carbon retention in soil depends on the nature of aggregation (Carter, 1996), degree of physico-chemical characteristics and stabilization of organic carbon inside the aggregates (Debasish *et al.*, 2011). Dynamics of soil aggregation and SOC are strongly influenced by land use changes and their management practices (Kumar *et al.*, 2013). Land use change may alter the soil physico-chemical properties, soil microbial composition and functioning of rhizosphere (Maharning *et al.*, 2009). These changes may affect soil structural stability, soil aggregation and on some occasions, favours one microbial sub-group on the expense of other groups, thereby affecting the SOC storage and nutrient turnover in soils (Belay-Tedla *et al.*, 2009).

Microorganisms through their enzymatic activities help in maintaining the soil ecosystem function by degrading soil organic matter, catalyzing the biochemical reactions involved in nutrient cycling and energy transfer (Sinsabaugh *et al.*, 1991). Microbial activities are therefore, recognized as possible indicators of the changes in soil management and are believed to indicate early responses to changes in management practices (Bandick and Dick, 1999). The SOC is recognized to

consist of various fractions varying in degree of decomposition, recalcitrance and turnover rate (Huang *et al.*, 2008). These fractions can be classified as labile, semi-labile and recalcitrant (Stevenson, 1994). These fractions exhibit different rates of biochemical and microbial degradation (Stevenson, 1994). Generally, presence of different SOC fractions in soil reflect key processes of nutrient cycling and availability, soil aggregation and stability and soil carbon accrual (Wander, 2004). Due to spatial variability of soils, the SOC losses or gains in a short time are difficult to directly measure. Therefore, it is now becoming more evidential that the labile fractions of SOC such as cold water extractable organic carbon, hot water extractable organic carbon, microbial biomass carbon, carbohydrate carbon, particulate organic matter are mainly used to detect changes associated with land use. The SOC fractions have comparatively rapid turnover rate (Von-Lutzow *et al.*, 2002), respond rapidly to changes in management practices and are more sensitive indicators of the effects of land use as compared to total soil organic carbon (He *et al.*, 2008).

Aggregate distribution and stability

Aggregate stability refers to the ability of soil aggregates to resist disintegration when disruptive forces associated with tillage and water or wind erosion are applied. Aggregate stability is an indicator of organic matter content, biological activity, and nutrient cycling in soil. Generally, the particles in small aggregates (< 0.25 mm) are bound by older and more stable forms of organic matter. Microbial decomposition of fresh organic matter releases products (that are less stable) that bind small aggregates into large aggregates (> 2-5 mm). These large aggregates are more sensitive to management effects on organic matter, serving as a better indicator of changes in soil quality. Greater amounts of stable aggregates suggest better

soil quality. When the proportion of large to small aggregates increases, soil quality generally increases.

Wright *et al.*, (2007) reported that in the 0-5 cm soil depth, no-tillage increased macro-aggregate associated OC as compared to conventional tillage. Macro-aggregates accounted for 38- 64, 48-66, and 54-71% of the total soil mass in the 0-5, 5-10, and 10-20 cm soil depths, respectively. The corresponding proportions of the silt + clay fraction were 3-7, 2-6, and 1- 5%, respectively. Proportions of macro-aggregates were increased with reduction of soil tillage frequency. For the 0-5 cm soil depth, treatments NT and 4T had significantly higher mass proportions of macro-aggregates (36 and 23%, respectively) than that of treatment. With additions of crop residues, the amount of macro-aggregates increased in all tillage treatments. Naresh *et al.*, (2015) also observed that macro-aggregates are less stable than micro-aggregates and more susceptible to the disruptive forces of tillage, and > 2 mm size macro-aggregates showed the lowest percentage distribution across depths. This might be attributed to the mechanical disruption of macro-aggregates with frequent tillage operations and reduced aggregate stability. The proportion of the micro-aggregates in all treatments was small and they had the lowest OC content. However, micro-aggregates formation and the micro-aggregates within the macro-aggregates can play an important role in C storage and stabilization in the long term (Kumari *et al.*, 2011). Xue *et al.*, (2015) also found that over time, CT generally exhibits 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. Zhou *et al.*, (2013) also found that, compared to CT, macro-aggregates

in RT in wheat coupled with unpuddled transplanted rice (RT-TPR) was increased by 50.1% and micro-aggregates in RT-TPR decreased by 10.1% in surface soil. Surface residue retention (50%) caused a significant increment of 15.7% in total aggregates in surface soil (0 - 5 cm) and 7.5% in subsurface soil (5 - 10 cm). In surface soil, 19.2% of total aggregate C was retained by > 2 mm and 8.9% by 0.1 - 0.05 mm size fractions. RT-TPR combined with ZT on permanent wide raised beds in wheat (with residue) had the highest capability to hold the OC in surface (11.6 g kg⁻¹ soil aggregates).

Zhou *et al.*, (2013) concluded that the application of NPK plus OM increased the size of sub-aggregates that comprised the macro-aggregates. Also, they observed that long-term application of NPK plus OM improves soil aggregation and alters the three-dimensional microstructure of macro-aggregates, while NPK alone does not. Zhang *et al.*, (2013) showed that NT and RT significantly increased the proportion of macro-aggregate fractions (> 2000 and 250 - 2000 μ m) compared with the moldboard plow without residue (MP-R) and moldboard plow with residue (MP + R) treatments. Averaged across depths, MWD of aggregates in NT and RT were 47 and 20% higher than that in MP+R. Hati *et al.*, (2014) revealed that the MWD of the top 15 cm soil under NT (1.05 mm) was significantly higher than that under RT and MB (moldboard tillage) and the MWD was least under CT (0.71 mm). Similarly, %WS_{ma} was maximum under NT (63.5%) and minimum under CT (50.2%). Mamta Kumari *et al.*, (2014) showed that the tillage induced changes in the intra-aggregate POM-C content was distinguishable at 0- to 5-cm depth. On average, the iPOM C content in soil was higher at wheat than at rice harvest, and accumulated in greater portion as fine (0.053–0.25 mm) than the coarse (0.25–2 mm) fraction. A significantly higher particulate-C fraction was recorded in the zero-till systems

(T₅ and T₆), and was associated more with the fine fractions (20–30% higher than under conventional-tillage T₁ and T₂).

Ou *et al.*, (2016) reported that 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 <0.053mm fraction between NT-S and MP-S, as well as between NT+S and MP+S, indicating that the SOC concentration in Silt + Clay fraction. In average across the soil layers, the soil organic carbon concentration in the macro aggregates was increased by 13.5% in MP+S, 4.4% in ST-S and 19.3% in NT+S, and those the micro aggregates (<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 NT system.

Song *et al.*, (2016) showed that the mean percentages of > 2 mm macro-aggregates and water-stable macro-aggregates were increased by 12.77% and 43.21%, respectively, for the treatment group of rice-wheat under zero tillage compared to rice-wheat conventional tillage. In the 0–15 cm and 15–30 cm soil layers, the percentage of 2–0.25 mm water-stable macro-aggregates was increased by 25% and 40%, respectively, for the Rice Wheat zero tillage treatment compared to the Rice Wheat conventional tillage treatment. Thus, compared to conventional tillage, zero tillage can reduce the turnover of macro-aggregates in farmland and facilitate the enclosure of organic carbon in micro-

aggregates, which enables micro-aggregates to preserve more physically protected organic carbon and form more macro-aggregates. Moreover, results showed that zero tillage resulted in higher organic carbon storage in soil aggregates in the 0–15 cm soil layer than conventional tillage primarily because conservation tillage reduces the damage to soil aggregates and increase the content and stability of associated organic carbon accordingly. The highest SOC concentration was found for the 0.25–0.106 mm micro-aggregates in the 0–15 cm and 15–30 cm soil layers. Simansky *et al.*, (2017) reported that the soil-management practices significantly influenced the soil organic carbon in water-stable aggregates (SOC in WSA). The content of SOC in WSA ma increased on average in the following order: T<G<G+NPK₁<G+NPK₃< T+FYM. Intensive soil cultivation in the T treatment resulted in a statistically significant build-up of SOC in WSA ma at an average rate of 1.33, 1.18, 0.97, 1.22 and 0.76 gkg⁻¹yr⁻¹ across the size fractions > 5 mm, 5–3 mm, 2–1 mm, 1–0.5 mm and 0.5–0.25 mm, respectively.

Soil organic carbon fractions

Soil organic carbon (SOC) consists of various fractions varying in degree of decomposition, recalcitrance and turnover rates (Huang *et al.*, 2008). The SOC fractions can be classified as labile, semi labile and recalcitrant. These fractions exhibit different rates of biochemical and microbial degradation (Stevenson, 1994) as well as different sensitivity to changes in different environmental conditions. Presence of different SOC fractions in soil reflect key processes of nutrient cycling and availability, soil aggregation and stability and soil carbon accrual (Wander, 2004). Sheng *et al.*, (2015) observed 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. POC stock in topsoil was more sensitive to land use change than that in subsoil. 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. Significant loss of LFOC occurred not only in topsoil, but also in subsoil below 20 cm following land use change. The decrease in ROC stock through the soil depth profile following land use change was smaller than that of LFOC. ROC stocks did not differ significantly between natural forest and sloping tillage areas, suggesting that ROC stock was relatively insensitive to land use change. 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. The proportion of the different LOC pools in relation to SOC can be used to detect changes in SOC quality. 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.

Zhu *et al.*, (2015) revealed that the soil total organic C (TOC) and labile organic C fraction contents were higher under the straw return treatments compared to the no straw return treatment (0% S) at a 0–21 soil depth. The 50% annual straw return rate (50% S) had significantly higher soil TOC, dissolved

organic C (DOC), and easily oxidizable C (EOC) contents than the 0% S treatment at a 0–21 cm depth. All of the straw return treatments had a significantly higher DOC content than the 0% S treatment at a 0–21 cm depth, except for the 100% only rice straw return treatment (100% RS). Wang *et al.*, (2015) also found that in the early paddy field, the average values of the total SOC, LFOC, and DOC concentration in the top 40cm soil were significantly higher in the straw application plots than in the controls, by 7.2% 8.8% and 15.6%, respectively. Naresh *et al.*, (2017) reported that the T₃ treatment resulted in significantly increased 66.1%, 50.9%, 38.3% and 32% LFOC, PON, LFON and POC, over T₇ treatment and WSC 39.6% in surface soil and 37.4% in subsurface soil. 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 compared with unfertilized control plots. Nevertheless, application of F₅ or F₆ significantly increased contents of POC relative to F₁ (by 49.6% and 63.4%, respectively).

Kumar *et al.*, (2018) also found that the ZTR (zero till with residue retention) (T₁) and RTR (Reduced till with residue retention) (T₃) showed significantly higher BC, WSOC, SOC and OC content of 24.5%, 21.9%, 19.37 and 18.34 gkg⁻¹, respectively as compared to the other treatments. Irrespective of residue retention, wheat sown in zero till plots enhanced 22.7%, 15.7%, 36.9% and 28.8% of BC, WSOC, SOC and OC, respectively, in surface soil as compared to conventional tillage. Simultaneously, residue retention in zero tillage caused an increment of 22.3%, 14.0%, 24.1% and 19.4% in BC, WSOC, SOC and OC, respectively over the treatments with

no residue management. Similar increasing trends of conservation practices on different forms of carbon under sub-surface (15– 30cm) soil were observed however, the magnitude was relatively lower. However, the 0–15 and 15-30 cm, POC, PON, LFOC and LFON content under ZT and RT with residue retention was greater than under without residue and conventional sown plots, respectively. The decrease in the disruption of soil macro-aggregates under ZT plots permitted a greater accumulation of SOC between and within the aggregates. Thus less soil disturbance is the major cause of higher POC in the ZT and RT plots compared with the CT plots in the 0-15cm and 15-30cm soil layers. This phenomenon might lead to micro-aggregate formation within macro-aggregates formed around fine intra-aggregate POC and to a long-term stabilization of SOC occluded within these micro-aggregates. The sequestration rate of POC, PON, LFOC and LFON in all the treatments followed the order 200 kg Nha⁻¹ (F₄) 160 kg Nha⁻¹ (F₃) >120 kg Nha⁻¹ (F₂) >800 kg Nha₁ (F₁) >control (unfertilized) (F₀). Kashif *et al.*, (2019) also found that the particulate organic carbon (POC), easily oxidizable carbon (EOC), dissolved organic carbon (DOC) contents of 0–20 cm depth were 80, 22 and 13%, respectively, higher under no-tillage with straw returning (NTS) treatment.

Soil organic carbon, soil aggregation vis-à-vis soil organic fractions

Soil aggregation results from the rearrangement of particles, flocculation and cementation. In binding soil particles together, the SOC and its fractions play a great role as the gluing agent. There exists a closer interaction between SOC concentration and soil aggregation due to the binding action of humic substances and other microbial by-products on soil particles (Shepherd *et al.*, 2001). The SOC promotes soil aggregation,

whereas aggregates in return store SOC, reducing the rate of SOM decomposition.

Since soil aggregation and stability of aggregates is a function of SOC and its fractions, their concentration and stock are of paramount importance in determining the formation and stabilization of soil aggregates (Debasish *et al.*, 2011). Keeping in view the role played by SOC and its fraction as a binding agent, variation of its content as a result of land use change may strongly affect the process of soil aggregation.

Mangalassery *et al.*, (2014) revealed that zero tilled soils contained significantly more soil organic matter (SOM) than tilled soils. Soil from the 0–10 cm layer contained more SOM than soils from the 10–20 cm layers in both zero tilled (7.8 and 7.4% at 0–10 cm and 10–20 cm respectively) and tilled soils (6.6% at 0–10 cm and 6.2% at 10–20 cm). Wang *et al.*, (2018) reported that tillage system change influenced SOC content, NT, ST, and BT showed higher values of SOC content and increased 8.34, 7.83, and 1.64 Mg·C·ha⁻¹, respectively, compared with CT. Among the 3 changed tillage systems, NT and ST showed a 12.5% and 11.6% increase in SOC content then BT, respectively. Tillage system change influenced SOC stratification ratio values, with higher value observed in BT and NT compared CT but ST. Therefore, in loess soil, changing tillage system can significantly improve SOC storage and change profile distribution. Moussadek *et al.*, (2014) observed that the SOC_s was significantly higher in NT compared to CT (10% more in Vertisol), but no significant difference was observed in the Luvisol. Average SOC_s within the 0–30 cm depth was 29.35 and 27.36 Mg ha⁻¹ under NT and CT, respectively. The highest SOC_s (31.89 Mg ha⁻¹) were found in Vertisols under NT.

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 OC m⁻² yr⁻¹ and 2.4 g N 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⁻² yr⁻¹) at the 20–40 cm depth. Das *et al.*, (2017) 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. Dhaliwal *et al.*, (2018) revealed that the mean SOC concentration decreased with 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%).

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. Naresh *et al.*, (2018) reported that conservation tillage

practices significantly influenced the total soil carbon (TC), Total inorganic carbon (TIC), total soil organic carbon (SOC) and oxidizable organic carbon (OC) content of the surface (0–15 cm) soil. Wide raised beds transplanted rice and zero till wheat with 100% (T₉) or with 50% residue management (T₈) showed significantly higher TC, SOC content of 11.93 and 10.73 g kg⁻¹, respectively in T₉ and 10.98 and 9.38 g kg⁻¹, respectively in T₈ as compared to the other treatments. Irrespective of residue incorporation/ retention, wide raised beds with zero till wheat enhanced 53.6%, 33.3%, 38.7% and 41.9% of TC, TIC, SOC and OC, respectively, in surface soil as compared to conventional tillage with transplanted rice cultivation. Simultaneously, residue retention caused an increment of 6.4%, 7.4%, 8.7% and 10.6% in TC, TIC, SOC and OC, respectively over the treatments without residue management. Concerning the organic carbon storage, SOC_s varied between 31.9 Mg·ha⁻¹ and 25.8 Mg·ha⁻¹ under NT, while, in tilled treatments, SOC_s ranged between 28.8 Mg·ha⁻¹ and 24.8 Mg·ha⁻¹. These values were lower than those observed by Fernández-Ugalde *et al.*, (2009) who found, in silty clay soil, a SOC_s at 0–30 cm of 50.9 Mg·ha⁻¹ after 7 years of no tillage, which was significantly higher than the 44.1 Mg·ha⁻¹ under CT under wheat-barley cropping system in semiarid area.

Xu *et al.*, (2013) observed that the SOC stocks in the 0–80 cm layer under NT was as high as 129.32 Mg C ha⁻¹, significantly higher than those under PT and RT. The order of SOC stocks in the 0–80 cm soil layer was NT > PT > RT, and the same order was observed for SCB; however, in the 0–20 cm soil layer, the RT treatment had a higher SOC stock than the PT treatment. Alemayehu *et al.*, (2016) also found that the carbon storage per hectare for the four soil textures at 0 to 15 cm depth were 68.4, 63.7, 38.1 and 31.3 t ha⁻¹ for sandy loam, silt loam, loam and clay loam; respectively. Sand and silt loams had nearly twice the

organic carbon content than loam and clay loam soil. The soil organic carbon content for tillage type at 0 to 15 cm was 8.6, 10.6, 11.8 and 19.8 g kg⁻¹ for deep significant accumulation at 0-20cm depth.

Zheng *et al.*, (2018) reported that across treatments, aggregate-associated C at a depth of 0–10cm was higher in the NT and ST treatments than in the MP and CT treatments. The advantage of the NT treatment weakened with soil depth, while the amount of aggregate-associated C remained higher for the ST treatment. There were more macro-aggregates in the ST and NT treatments than in the MP and CT treatments, while the MP and CT treatments had more micro-aggregates. The sum of macro-aggregate contributing rates for soil organic C (SOC) was significantly superior to that of the micro-aggregates. Mahajan *et al.*, (2019) reported that the increased SOC stock in the surface 50 kg m⁻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. Soil organic carbon fractions (SOC), microbial biomasses and enzyme activities in the macro-aggregates are more sensitive to conservation tillage (CT) than in the micro-aggregates. Responses of macro-aggregates to straw return showed positively linear with increasing SOC concentration. Straw-C input rate and clay content significantly affected the response of SOC.

Particulate organic matter

Particulate organic matter (POM) is readily decomposable, serving many soil functions and providing terrestrial material to water bodies. It is a source of food for both soil organisms and aquatic organisms (see below), and provides nutrients for plants. In water bodies, POM can contribute

substantially to turbidity, limiting photic depth which can suppress primary productivity. POM also enhances soil structure leading to increased water infiltration, aeration and resistance to erosion. Soil management practices, such as tillage and compost/manure application, alter the POM content of soil and water. Coarse particulate organic matter, or CPOM, in streams is functionally defined as any organic particle larger than 1 mm in size (Cummins, 1974). Regardless of source, this CPOM is broken down by stream biota during an activity known as organic matter processing. Organic particles in the size range of >0.45 to <1000 µm that are either suspended in the water column or deposited within lotic habitats are considered as fine particulate organic matter or FPOM. FPOM also varies in quality, often as a product of its source.

Liu *et al.*, (2013) revealed that the particulate organic C was found stratified along the soil depth. A higher POC was found in surface soil decreasing with depth. At the 0–20 cm, POC content under NP+FYM, NP+S and FYM were 103, 89 and 90% greater than under CK, respectively. In 20–40 cm and 40–60 cm soil layers, NP+FYM had maximum POC which was significantly higher than NP+S and FYM treatments. Even though POC below 60cm depth was statistically similar among fertilization treatments, the general trend was for increased POC with farmyard manure or straw application down to 100 cm soil depth. Irrespective of soil depths, NP+FYM invariably showed higher content of DOC over all other treatments. The CK and N treatments showed lower content of DOC. The DOC concentrations in 0–20 cm, 20–40cm and 40–60 cm depths were observed highest for NP+FYM followed by NP+S and FYM, and both of them were significant higher than NP. However, in the deeper layers (60–80 cm and 80–100 cm), the difference in DOC among the treatments was not significant.

Naresh *et al.*, (2016) also found significantly higher POC content was probably also due to higher biomass C. Results on PON content after 3-year showed that in 0-5 cm soil layer of CT system, T₁, and T₅ treatments increased PON content from 35.8 mgkg⁻¹ in CT (T₀) to 47.3 and 67.7 mg·kg⁻¹ without CR, and to 78.3, 92.4 and 103.8 mgkg⁻¹ with CR @ 2, 4 and 6tha⁻¹, respectively. The corresponding increase of PON content under CA system was from 35.9 mgkg⁻¹ in CT system to 49 and 69.6 mgkg⁻¹ without CR and 79.3, 93.0 and 104.3mgkg⁻¹ with CR @ 2, 4 and 6tha⁻¹, respectively. Juan *et al.*, (2018) observed that the pure organic manure treatments (DMA and SMA) showed significantly higher concentrations of POC as compared to integrate (1/2SMF +1/2SMA) and mineral-fertilized plots (DMF and SMF). POC constituted 10.20 to 23.65% of total SOC with a mean value of 16.43%. Highest proportion of POC was observed under DMA, followed by SMA, which was not significantly different from DMF; 1/2SMF+1/2SMA and SMF had a lower proportion of POC and the lowest proportion was found in the CK treatment.

Microbial biomass carbon

Kushwaha *et al.*, (2000) observed that the highest levels of soil MBC and MBN (368-503 and 38.2-59.7µg g⁻¹, respectively) were obtained in minimum tillage residue retained (MT+R) treatment and lowest levels (214-264 and 20.3-27.1µg g⁻¹, respectively) in conventional tillage residue removed (CT-R, control) treatment. Along with residue tillage reduction from conventional to zero increased the levels of MBC and MBN (36-82 and 29-104% over control, respectively. This increase (28% in of C and 33% N) was maximum in MT+R and minimum (10% for C and N both) in minimum tillage residue removed (MT-R) treatment. In all treatments concentrations of N in microbial biomass were greater at seedling stage, thereafter these concentrations decreased drastically (21-38%) at grain

forming stage of both crops. In residue removed treatments, N-mineralization rates were maximum during the seedling stage of crops and then decreased through the crop maturity. The increase in the level of MBC from the seedling to grain-forming stage of crops was probably a result of increased C input from the rhizosphere products to the soil before and during flowering. Dou *et al.*, (2008) reported that SMBC was 5 to 8%, mineralized C was 2%, POM C was 14 to 31%, hydrolyzable C was 53 to 71%, and DOC was 1 to 2% of SOC. No-till significantly increased SMBC in the 0- to 30-cm depth, especially in the surface 0 to 5 cm. Under NT, SMBC at 0 to 5 cm was 25, 33, and 22% greater for CW, SWS, and WS, respectively, than under CT, but was 20 and 8% lower for CW and WS, respectively, than under CT at the 5- to 15-cm depth. At the 15- to 30-cm depth, no consistent effect of tillage was observed. Enhanced cropping intensity increased SMBC only under NT, where SMBC was 31 and 36% greater for SWS and WS than CW at 0 to 30 cm.

Jiang *et al.*, (2011) observed that the highest levels of MBC were associated with the 1.0–2.0 mm aggregate size class (1025 and 805 mg C kg⁻¹ for RNT and CT, respectively) which may imply that RNT was the ideal enhancer of soil productivity for this subtropical rice ecosystem. However, the lowest in the <0.053 mm fraction (390 and 251mg Ckg⁻¹ for RNT and CT respectively). It is interesting to note the sudden decrease of MBC values in 1–0.25 mm aggregates (511 and 353 mg C kg⁻¹ for RNT and CT, respectively) [Fig.8b].The highest values corresponded to the largest aggregates, N4.76 mm, (6.8 and 5.4% for RNT and CT, respectively) and the lowest to the aggregate size of 1.0–0.25 mm (1.6 and 1.7 for RNT and CT, respectively). Liang *et al.*, (2011) observed that in the 0–10 cm soil layer, SMBC and SMBN in the three fertilized treatments were higher than in the unfertilized treatment on all sampling dates, while

microbial biomass C and N in the 0–10 cm soil layers were the highest at grain filling. In the same soil layer, soil-soluble organic C generally decreased in the order MNPK > SNPK > NPK > CK, while soluble organic N was the highest in the MNPK followed by the SNPK treatment. There was no significant difference in soluble organic N in the NPK and CK treatments throughout most of the maize growing season. Changes in soluble organic N occurred along the growing season and were more significant than those for soluble organic C. Soluble organic N was the highest at grain filling and the lowest at harvest. Overall, microbial biomass and soluble organic N in the surface soil were generally the highest at grain filling when maize growth was most vigorous.

Aulakh *et al.*, (2013) showed that PMN content after 2 years of the experiment in 0-5 cm soil layer of CT system, T₂, T₃ and T₄ treatments increased PMN content from 2.7 mgkg⁻¹ 7d⁻¹ in control (T₁) to 2.9, 3.9 and 5.1 mgkg⁻¹ 7d⁻¹ without CR, and to 6.9, 8.4 and 9.7 mg kg⁻¹ 7d⁻¹ with CR (T₆, T₇ and T₈), respectively. The corresponding increase of PMN content under CA system was from 3.6 mgkg⁻¹ 7d⁻¹ in control to 3.9, 5.1 and 6.5 mgkg⁻¹ 7d⁻¹ without CR and to 8.9, 10.3 and 12.1 mgkg⁻¹ 7d⁻¹ with CR. PMN, a measure of the soil capacity to supply mineral N, constitutes an important measure of the soil health due to its strong relationship with the capability of soil to supply N for crop growth. Bhattacharya *et al.*, (2013) reported that tillage-induced changes in POM C were distinguishable only in the 0- to 5- cm soil layer; the differences were insignificant in the 5- to 15-cm soil layer. Plots under ZT had about 14% higher POM C than CT plots (3.61 g kg⁻¹ bulk soil) in the surface soil layer.

Mandal *et al.*, (2013) reported that averaged across fertilization and manure treatments, MBC varied significantly with soil depth, with mean values of 239, 189 and 127 mg kg⁻¹ at 0–

7.5, 7.5–15 and 15–30 cm depths respectively. Surface soil had higher MBC than deeper soil layers, due primarily to the addition of leftover CRs and root biomass to the topsoil. When averaged across soil depths, the MBC content under the different treatments was in the order: NPK+GR +FYM > NPK+FYM=NPK +GR > NPK + SPM > NPK+CR > PKZnS > NPKZn =control. Incorporation of CR slows mineralization processes; hence, microbes take longer to decompose the residue and use the released nutrients. Conversely, incorporation of GR, with a narrow C: N ratio, hastened mineralization by enhancing microbial activity in the soil.

Tripathi *et al.*, (2014) observed that the significant positive correlations were observed between TOC and organic C fractions (POC and SMBC), illustrating a close relationship between TOC and POC and TOC and SMBC and that SOC is a major determinant of POC and SMBC. The microbial biomass carbon includes living microbial bodies (bacteria, fungi, soil fauna and algae) (Divya *et al.*, 2014); it is more sensitive to soil disturbance than TOC. The proportion of SMBC to TOC is evaluation of carbon availability indexes for agriculture soil, which is usually 0.5–4.6%. Liu *et al.*, (2012) showed that SMBC may provide a more sensitive appraisal and an indication of the effects of tillage and residue management practices on TOC concentrations. Ma *et al.*, (2016) reported that the differences in SMBC were limited to the surface layers (0–5 and 5–10 cm) in the PRB treatment. There was a significant reduction in SMBC content with depth in all treatments. SMBC in the PRB treatment increased by 19.8%, 26.2%, 10.3%, 27.7%, 10% and 9% at 0–5, 5–10, 10–20, 20–40, 40–60 and 60–90 cm depths, respectively, when compared with the TT treatment. The mean SMBC of the PRB treatment was 14% higher than that in the TT treatment. Malviya, (2014) also indicated that irrespective of soil depth the SMBC contents were significantly higher under RT over CT.

This was attributed to residue addition increases microbial biomass due to increase in carbon substrate under RT. Spedding *et al.*, (2004) found that residue management had more influence than tillage system on microbial characteristics, and higher SMB-C and N levels were found in plots with residue retention than with residue removal, although the differences were significant only in the 0-10 cm layer.

Mangalassery *et al.*, (2014) observed that zero tilled soils contained significantly more microbial biomass carbon than tilled soils. The mean microbial biomass carbon under zero tilled soil was 517.0 mg kg⁻¹ soil compared with 418.7 mg kg⁻¹ soil in tilled soils. Microbial biomass carbon was significantly higher in the 0–10 cm layer (517 mg kg⁻¹ soil) than the 10–20 cm layer (419 mg kg⁻¹ soil) under zero tillage and conventional tillage. Moreover, tillage and soil depth significantly influenced soil microbial biomass nitrogen. Zero tilled soils contained higher microbial biomass nitrogen (91.1 mg kg⁻¹ soil) than tilled soil (70.0 mg kg⁻¹ soil). Surface layers (0–10 cm) maintained more microbial biomass nitrogen than sub surface layers (10–20 cm) under both zero tilled soils and tilled soils. Gu *et al.*, (2016) reported that as 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, >0.25mm aggregate, and <0.25mm aggregate in the 0–5cm 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 0–5cm soil layer, respectively. Conservation tillage (NT and S) increased microbial metabolic activities and Shannon index in >0.25 and <0.25 mm aggregates in the 0–5 cm soil layer. Ma *et al.*, (2016) reported that the differences in SMBC were limited to the

surface layers (0–5 and 5–10 cm) in the PRB treatment. There was a significant reduction in SMBC content with depth in all treatments. SMBC in the PRB treatment increased by 19.8%, 26.2%, 10.3%, 27.7%, 10% and 9% at 0–5, 5–10, 10–20, 20–40, 40–60 and 60–90 cm depths, respectively, when compared with the TT treatment. The mean SMBC of the PRB treatment was 14% higher than that in the TT treatment.

McGonigle and Turner (2017) concluded that the MBC in cropland increased from 210 µg g⁻¹ at 15 g kg⁻¹ SOC to only 530 µg g⁻¹ at 45 g kg⁻¹ SOC. In contrast, MBC in grassland increased from 440µg g⁻¹ at 15 g kg⁻¹ SOC to 1190 µg g⁻¹ at 45 g kg⁻¹, thereafter increasing further to 1800µg g⁻¹ at 65 g kg⁻¹ SOC. The slope of increase of MBC in response to increasing SOC was 2.5-fold higher in grassland at 27.2 (µg g⁻¹)/ (g kg⁻¹) compared to 10.7 (µg g⁻¹)/ (g kg⁻¹) for cropland. Maharjan *et al.*, (2017) observed that the activity of β-glucosidase was higher in organic farming (199nmol g⁻¹soil h⁻¹) followed by conventional farming (130 nmol g⁻¹ soil h⁻¹) and forest soil (19 nmol g⁻¹ soil h⁻¹) in the topsoil layer. The activity of cellobiohydrolase was higher in organic farming compared to forest soil, but was similar in organic and conventional farming soil. In contrast, xylanase activity was higher under conventional farming (27nmol g⁻¹soil h⁻¹) followed by organic farming (17nmol g⁻¹ soil h⁻¹) and forest soil (12nmol g⁻¹ soil h⁻¹). The activities of N-cycle enzymes (chitinase, leucine amino-peptidase and tyrosine aminopeptidase) in the topsoil layer were higher under organic farming (138, 276 and 255 nmol g⁻¹ soil h⁻¹, respectively) compared with other land-use systems. The activities of tyrosine aminopeptidase and chitinase were also higher in subsoil under organic farming. Acid phosphatase (P-cycle) activity in topsoil was affected by land use. In contrast to C- (except xylanase) and N-cycle enzymes, the activity of acid phosphatase in the topsoil layer was higher under

conventional farming ($936 \text{ nmol g}^{-1} \text{ soil h}^{-1}$) followed by forest ($672 \text{ nmol g}^{-1} \text{ soil h}^{-1}$) and organic farming soil ($118 \text{ nmol g}^{-1} \text{ soil h}^{-1}$). Li *et al.*, (2018) observed that compared with CK, NPSM and NPS treatments caused greater measures of G+ and G- biomarkers by 107-160% and 106-110%, and greater measures of actinomycetes by 66- 86%. The NPSM and NPS treatments were also greater in abundances of fungal communities, the saprophytic fungi were greater by 123- 135% and AMF was greater by 88-96%. The G+/G-ratio was higher under NPSM treatment compared to other treatments, indicating that NPSM fertilization had changed soil microbial communities.

Naresh *et al.*, (2018) revealed that in the turning jointing stage, compared with CT, the ZT and FIRB treatments significantly increased nitrifying bacteria [Gn] by 77% and 229%, respectively. At the booting stage, the Gn rates in ZT and FIRB soils were 2.16 and 3.37 times greater than that in CT soil, respectively. At the milking stage, the Gn rates in ZT and FIRB soils were 1.96 and 3.08 times greater than that in CT soil, respectively. Similarly, the denitrifying bacteria [D] rates of the different treatments. In the jointing stage, the D rates in ZT and FIRB soils were 2.77 and 2.26 times greater than that in CT soil. At the booting stage, compared with CT, the ZT and FIRB treatments significantly increased D by 3.03% and 2.37%, respectively. At the milking stage, the ZT and FIRB treatments increased D by 3.39% and 2.95%, respectively. The Gn rates of the different treatments were $T_6 > T_3 > T_4 > T_7$. The D rates were $T_3 > T_6 > T_2 \geq T_4$. Moreover, FIRB system with residue retention showed statistically significant differences in the phosphatase enzyme activity in the soil comparing with ZT with residue removal and CT. The activity of phosphatase tended to be higher in the FIRB treatment compared to the ZT and CT treatments.

Across the management practices evaluated in the review paper, tillage had the greatest effect on SOC and its various fractions and in the surface (0–15 cm) soil of tillage implementation, with positive results observed with conservation tillage practices compared with conventional tillage. SOC stocks and those of the labile fractions decreased in topsoil and subsoil below 20 cm following land conversion. The LOC fractions to SOC ratios also decreased, indicating a reduction in C quality as a consequence of land use change. 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 land use change.

In fact, only fPOC, LFOC, and MBC in topsoil, and LFOC and DOC in subsoil were highly sensitive to land use change in subtropical climatic conditions of North West IGP. There was a significant reduction in SMBC content with depth in all treatments. SMBC in the PRB treatment increased by 19.8%, 26.2%, 10.3%, 27.7%, 10% and 9% at 0–5, 5–10, 10–20, 20–40, 40–60 and 60–90 cm depths, respectively, when compared with the TT treatment. The mean SMBC of the PRB treatment was 14% higher than that in the TT treatment.

Conventional tillage in comparison with NT significantly reduced macro-aggregates with a significant redistribution of aggregates - into micro-aggregates. Aggregate protected labile C and N were significantly greater for macro-aggregates, (>2000 and $250\text{--}2000 \mu\text{m}$) than – micro-aggregates ($53\text{--}250$ and $20\text{--}53 \mu\text{m}$) and greater for M than F indicating physical protection of labile C within macro-aggregates. No -tillage and M alone each significantly increased soil aggregation and aggregate-associated C and N; however, NT and M together further improved soil aggregation and aggregate-protected C and N.

The distribution pattern of soil microbial biomass associated with aggregates was likely governed by the size of aggregates, whereas the tillage effect was not significant at the aggregate-size scale. Tillage regimes that contribute to greater soil aggregation also will improve soil microbial activity to aid in crop production. Heterogeneous distribution of OC and microbial biomass may lead to “hot-spots” of aggregation, and suggests that microorganisms associated with 1.0–2.0 mm aggregates are the most biologically active in the ecosystem.

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 sub-tropical ecosystem through improving soil structure which leads to the protection of SOM and nutrients, and the maintenance of higher nutrient content. In conclusion, SOC, microbial biomasses and carbon fractions in the macro-aggregates are more sensitive to manure amendment than in the micro-aggregates. Conservation tillage benefited soil structure, increased microbial activities, and most likely aggregate distribution and stability especially soil fertility.

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