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Soil Organic Carbon Dynamics and Carbon Sequestration Under Conservation Tillage in Tropical Vertisols

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Abstract

Soils, especially managed agricultural soils, have the potential to sequester carbon (C) and contribute to the mitigation of GHGs emissions. Increasing the amount of organic matter addition to soils may not only mitigate GHG emissions, but also benefit agricultural productivity through improvements in soil health and environmental quality. One potential method for increasing the amount of C held in agricultural soil is through conversion of conventional tillage practices to conservation tillage practices that reduce tillage and retain crop residues. Vertisols in India occupy 8.1% of the total geographical area of the country and are generally low in organic carbon content, but these soils have great potential to increase the soil organic carbon (SOC) level. Improvement in SOC content in these soils through traditional/conventional soil management practices is very difficult, as it has already attained the equilibrium level. One of the most attainable pathways to improve and sequester SOC content in this soil is through either regular addition of organic manures such as farmyard manure, compost or crop residues or by switching traditional tillage practices to no-tillage or other forms of conservation tillage. Several long- and short-term field studies on Vertisols reported that management strategies, such as no-tillage (NT) and reduced tillage (RT) with residue retention, played a significant role in increasing SOC concentration and favouring aggregate stability. Adoption of conservation tillage practices resulted in an improvement of surface soil aggregation and an increase in the proportion of macroaggregates compared to conventional tillage. Conservation tillage increases the percentage of carbon-rich macroaggregates in the soil particularly in the surface layers, resulting in sequestration of more car-

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bon into soil stabilized through physical protection. More aggregate-C in large and small macroaggregates favoured better aggregation under conservation tillage than that under conventional tillage, which suggested that macroaggregates are sensitive to changes in the soil microbial community associated with short-term conservation management practices. Conservation tillage also resulted in stratification of SOC and available nutrient levels in soil. Conservation tillage in tropical Vertisols could be a useful technology to partially mitigate the deleterious effect of climate change through sequestration of carbon into the soil and reduction of greenhouse gas emission from agricultural activities to atmosphere. It also improves soil health, its resilience to extraneous stresses and the sustainability of agricultural production system.

Keywords
Carbon sequestration · Conservation tillage · Soil aggregate · Tropical Vertisols

12.1 Introduction

The quantity of carbon stored in the soil on a global context is second only to that in the ocean and represents the largest store of terrestrial organic carbon, at more than four times the biotic carbon pool. Approximately 2500 Gt of organic carbon is stored in the top 3 m of soil, with 60% or 1500 Gt of organic carbon stored in the first meter of soil and about 615 Gt stored in the top 20 cm (Guo and Gifford 2002; Jobbagy and Jackson 2000). Any significant change in the soil organic carbon storage present mainly in the form of soil organic matter in the future will have profound consequences on the terrestrial ecosystem. Management of soil organic matter (SOM) in arable lands thus has become increasingly important in many areas of the world in order to combat land degradation (Lal 2006), increase food security (Swaminathan 2000), reduce C emissions and/or mitigate climate change (Lal 2004; Barbara et al. 2012). SOM is considered as the key in developing drought-resistant soils, through water conservation, evaporation and erosion control, and better rainwater infiltration into soil and in ensuring sustainable food production through improved crop productivity, fertilizer-use efficiency, reduced pesticide use and crop ecological intensification (Bot and Benites 2005). The dynamics of SOM are influenced by agricultural management practices such as tillage, mulching, removal of crop residues and application of organic and mineral fertilizers. SOM is a continuum of substances in all stages of decay. Among them, humus is a relatively stable component formed by humic substances, consisting of humic acids, fulvic acids, hymatomelanic acids and humins. Humic and fulvic substances enhance plant growth directly through physiological and nutritional effects but also improve soil health and quality through amelioration of soil's physical, biological and chemical properties.

Soil can function as either a source of, or a sink for, atmospheric C, and may have an important role in sequestering C from the atmosphere; thus, it can help to restrain build-up of greenhouse gases and aid in mitigating global climate change. Conservation and enhancement of soil organic matter is important for plant nutrition, soil structure, soil compactibility and water-holding capacity. One potential method for increasing the amount of C held in agricultural soil is through conversion of conventional tillage practices to conservation tillage practices that reduce tillage and retain crop residues. Conservation tillage practices reduces the tillage-induced breakdown of soil aggregates resulting in slowdown of the organic matter decomposition relative to the conventional cultivation system and also adds organic matter as residues to the surface soil. Besides this, through reduction of surface soil losses through runoff, conservation tillage decreases loss of soil carbon and plant nutrients with the sediments particularly in sloping terrain.

12.2 Importance of Conservation Tillage

Improvement and sustenance of the SOM status of the arable soil is one of the most crucial challenges facing today's intensive agricultural production system. Thus, conservation tillage (CT) has been recommended as an alternative strategy to invert the soil degradation spiral in many parts of the world partly due to loss of soil organic carbon from the top soil (Derpsch and Friedrich 2009). The conservation tillage systems affect not only the amount of SOM but also its characteristics (Ding et al. 2002). SOM quality is affected by no-tillage either in terms of particulate organic matter or in terms of its composition of humic acids, fulvic acids and humin (McCallister and Chien 2000). These humic substances are specifically involved in improving soil structural stability and plant growth.

The bare and pulverized topsoil under conventional cultivation made them vulnerable to accelerated soil loss through runoff and also to soil loss by wind in arid and semiarid regions. Besides soil and accompanied nutrient losses, conventional tillage operation breaks soil aggregates and exposes soil organic carbon locked inside the aggregates to accelerated microbial degradation resulting in net loss of organic carbon from the arable ecosystem. Burning of surface residue commonly practised in a large geographical location of the country, repeated tillage operations particularly inversion tillage operations with disc harrows, sowing of crop along the slopes, keeping the soil bare in the rainy season as commonly followed under traditional agricultural causes substantial loss of plant nutrients and organic carbon from the topsoil. Resource conservation technologies and conservation tillage promote less disturbances of the surface soil through tillage operations and keep the soil surface covered with anchored crop residues or cover crop during the heavy rainfall period to reduce the negative impact of agriculture on the natural ecosystem. Conservation tillage also offers a sustainable residue management options for a large part of the country where residues are burnt, which causes air pollution through shoot particles and releases considerable amount of carbon dioxide to the atmosphere.

12.3 Need for Conservation Tillage in Vertisols of Central India

Poor SOM content due to lack of crop residues and excessive tillage degrades soil health. This effect is pronounced further under uncertain rainfall, limited water resources, poor nutrient inputs, soil specific constraints like low water infiltration, high incidence of inundation, accelerated runoff and soil erosion in Vertisols of central India (Hati et al. 2006). Vertisols in India occupy a total area of 26.8 m ha, constituting 8.1% of the total geographical area of the country, of which about 60% of the area comes under central India (Bhattacharyya et al. 2009). Improvement in SOC content in these soils through traditional/conventional soil management practices is very difficult, as it has already attained the equilibrium level due to high temperature and decomposition rate of SOC (Jha et al. 2012). The only way to improve and sequester SOC content is either through regular addition of organic manures such as farmyard manure, compost or crop residues (Manna et al. 2005; Hati et al. 2007) or switching traditional tillage practices to no-tillage or other forms of conservation tillage (Lal and Kimble 1997). Stewart et al. (2008) reported that the C sequestration capacity of a soil is determined mainly by the protection of C in the aggregates.

A long-term experiment was conducted with the soybean–wheat cropping system at an experimental farm of the Indian Institute of Soil Science, Bhopal, to assess the effect of different tillage management practices at different nitrogen application levels on soil properties, crop productivity and soil health. In the experiment, three wheat residue management treatments (Fig. 12.1), namely, mould board tillage system (MB), reduced tillage (RT) and no-tillage (NT), were compared against the conventional tillage (CT) system. In the mould board tillage system, wheat residues were incorporated into the soil by mould-board plough during the summer season and allowed to decompose during the summer and before sowing of soybean after the onset of monsoon, the field was ploughed twice by a sweep cultivator for the preparation of a clean seed bed, while in winter season wheat was sown after one pass of rotavator tillage operation. In the reduced tillage system, wheat residues were kept on the surface and soybean was sown after one pass of sweep cultivator. One pass by sweep tillage was included to partially incorporate the wheat residue, for mixing of surface broadcasted fertilizer and controlling weeds and to ease the sowing operation. In conventional tillage treatment, wheat residues were removed

Fig. 12.1 (**a**) Residue removed. (**b**) Residue incorporation. (**c**) Residue retention

during harvest, soil was ploughed once during the summer season as practised in traditional cultivation system and then two passes of sweep cultivator were allowed before sowing of soybean in the rainy season. Both soybean and wheat were grown with three nitrogen levels, namely 50%, 100% and 150% of the recommended dose of nitrogen under each of the four tillage treatments. The experiment was conducted for ten cropping cycles. The results from the experiment showed that the crop growth and productivity of soybean and wheat under no- and reduced-tillage treatments were on par with the conventional tillage system.

12.4 Impact of Conservation Tillage and Soil Organic Carbon Dynamics

Tillage plays a key role in the manipulation of nutrient storage and release from SOM. A global analysis of 67 long-term experiments indicated that, on average, a change from conventional tillage to no-till (NT) can sequester 57–14 g C m^{-2} $year^{-1}$ (excluding NT in wheat fallow systems), with peak sequestration rates being reached within 5–10 years after conversion (West and Post 2002). By contrast, Six et al. (2002b, c) found a general increase in soil C contents of 325–113 kg C m^{-2} $year^{-1}$ under NT compared with CT for both tropical and temperate systems. They also reported that, on an average, C turnover was 1.5 times slower in NT than in CT. The amount of SOM loss due to tillage is dependent on the clay content of the soil. In general, greater SOM loss is observed in coarse-textured than fine-textured soils, primarily due to lack of physical protection of organic matter in sandy soils (Hassink 1995). In fine-textured soils, clay- and silt-sized particles with high surface activity may chemically stabilize SOM and form the building blocks for aggregates, thereby inducing physical protection of SOM by occlusion in aggregates, especially microaggregates (Six et al. 2000). Soil disturbance through tillage is a major cause of reduction in the number and stability of soil aggregates and subsequently organic matter depletion (Six et al. 2000).

The experimental result in Vertisols of central India showed that, after ten crop cycles, the organic carbon content of the soil up to 30 cm depth was higher in conservation tillage treatments compared to the conventional tillage treatment. At 0–5 cm depth, the SOC content recorded was the highest in NT, followed by RT, MB and CT, whereas at 5–15 cm depth, SOC content in NT, RT and MB showed no significant difference, but it was significantly more than that in CT (Fig. 12.2). At 15–30 cm depth, the difference in SOC content was not conspicuous. Conservation tillage, particularly no-tillage, leads to a concentration of SOC in the top layer of the soil (0–5 cm) and alters its distribution within the soil profile because plant residues tend to accumulate on the surface soil (McCarty et al. 1998). Increase in SOC in the surface soil is attributed to a combination of reduced litter decomposition and less soil disturbance under NT. Besides this, organic matter below the surface, including the previous crop's roots, is left undisturbed and thus is not subject to accelerated decay in conservation tillage treatments. This combination of adding organic residues to the soil surface, while not disturbing the existing organic matter stocks

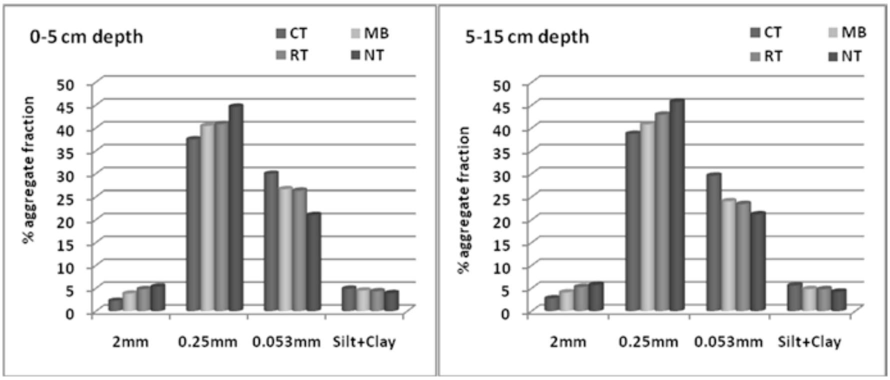

Fig. 12.2 Percent distribution of aggregate size fractions as influenced by conservation tillage

below the surface, could be the probable reason for the increase in organic carbon in the top layers of the soil. Similarly, Paustian et al. (1997) compiled data on NT and CT systems from several long-term field studies and found in most cases an increase in carbon content under NT. The increase in organic matter was largest near the surface but increased slightly below 15 cm soil depth in the conservation tillage system. This attribute is referred as stratification of soil organic carbon in the profile (Franzluebbers 2002).

In this study, a higher stratification ratio was registered under NT (2.11) and RT (1.77) compared to CT (1.53). This indicates better soil quality and soil ecosystem functioning under no-tillage and reduced tillage than that in conventional tillage and MB tillage, as surface organic matter is essential to erosion control, water infiltration and conservation of nutrients. Similar findings were also reported by Franzluebbers (2002). The total carbon stock up to 30 cm depth was also higher in three residue retention treatments than in conventional tillage treatment (Table 12.1). This reasserts that, in Vertisols, the organic carbon stock can be improved through adoption of the conservation tillage system (Hati et al. 2015a).

Another study conducted to evaluate the long-term effect of three wheat residue management practices (residue burning, incorporation and surface retention) in combination with three supplementary nutrient inputs (SNI) – control, fertilizer and farmyard manure (FYM) – on stratification of SOC and phosphorus in the soybean–wheat system in Vertisol showed that wheat residue either incorporated or retained on the soil surface increased the availability of P and SOC content as compared to the common practice of residue burning. Residue retention or incorporation increased stratification of P and soil organic carbon over the residue burning. Irrespective of the nutrient treatments, the stratification ratio of SOC and P was greater under wheat residue incorporation or retention than under residue burning (Kushwah et al. 2016).

Besides this, the results of a short-term experiment conducted on a Vertisol with two tillage treatments, namely no-tillage (NT) and conventional tillage (CT), and five nutrient management practices indicated that soil organic carbon (SOC)

Table 12.1 Effect of tillage systems on soil organic carbon (SOC) content, stratification ratio (0–5 cm)/(15–30 cm) and SOC stock of the top 30 cm soil (Hati et al. 2015a)

Treatment	SOC content (g kg^{-1})				
Tillage system	0–5 cm	5–15 cm	15–30 cm	Stratification ratio	SOC stock (0–30 cm) (mg ha^{-1})
NT	10.4a	6.3b	5.0a	2.11a	24.96
RT	9.1b	6.6b	5.1a	1.77b	24.85
MB	8.3c	7.4a	5.4a	1.54b	26.08
CT	7.8d	5.9c	5.1a	1.53b	23.26

Different letters within a column indicate significant difference between values at $P < 0.05$

Table 12.2 Effect of short-term tillage treatment on soil organic carbon (SOC) concentration and SOC stock of the top 30 cm soil in a Vertisol (Hati et al. 2015b)

	SOC concentration (g kg^{-1})			Total SOC stock (0–30 cm depth) on soil equivalent mass (mg ha^{-1})
Treatment	0–5 cm	5–15 cm	15–30 cm	
Tillage system				
CT	9.8	7.6	5.7	28.18
NT	11.9	8.9	5.5	30.79
LSD (P = 0.05)	1.6	1.1	NS	1.82

concentration of the top 15 cm soil depth and SOC stock of the top 30 cm soil increased significantly under NT compared to that under CT (Table 12.2). Soil organic C stock of the top 30 cm soil was 9.2% higher under NT compared to that under CT practice. The proportion of macroaggregates (>250 μm) was also increased by 6.1% and 2.7%, respectively under NT compared to CT system in 0–5 and 5–15 cm soil layers. The study showed that the short-term no-tillage system could improve soil aggregation and SOC concentration of Vertisols in 0–15 cm soil layer while maintaining the yield level similar to that in the conventional tillage system in the soybean–wheat cropping system. Another experiment of conservation agriculture conducted in Vertisols reported that the SOC was higher in surface layer (0–15 cm) than in the subsurface (15–30 cm) under both tillage systems (Fig. 12.3). Conservation agricultural practices significantly improved SOC (5–6%) compared to conventional cultivation at 0–15 cm depth after completion of three crop cycles. Similarly, soil microbial biomass carbon (SMBC) significantly increased (6–12%) under reduced tillage (RT) compared to that in conventional tillage (CT) system after completion three crop cycles (Fig. 12.4).

12.5 Soil Aggregate Size Distribution and Sequestration of Organic Carbon in Aggregate Fractions

Stability of macroaggregates depends on the formation of bonding materials from soil organic matter. These consist of transient bonding agents comprised of microbial and plant-derived polysaccharides and temporary bonding agents derived from

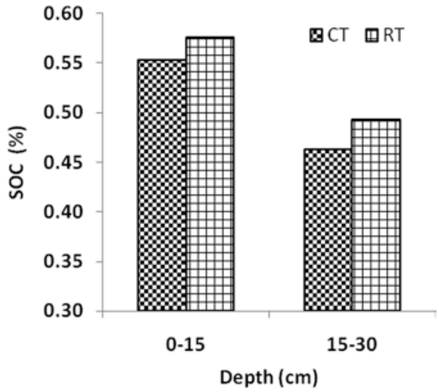

Fig. 12.3 Soil organic carbon after completion of third crop cycle

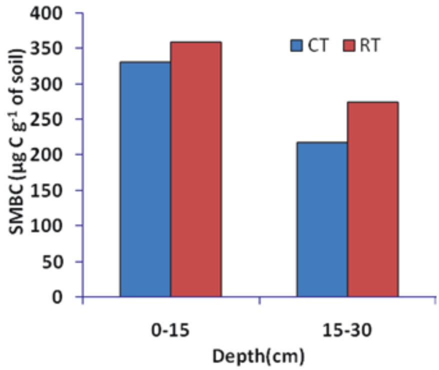

Fig. 12.4 Soil microbial biomass carbon under different tillage systems

roots and fungal hyphae, especially mycorrhizal hyphae (Tisdall and Oades 1982). The retention of crop residues in conservation tillage systems not only protected the soil surface from raindrop impact, but also provided organic materials as a precursor for aggregate formation. A study conducted at Indiana, USA (Griffith et al. 1992), showed that after 5 years of continuous corn cultivation, aggregation in the top 5 cm was increased by 120% for no-till and 35% for ridge-till systems compared to mouldboard ploughing. Removal of residues from the surface and exposing the surface soil through tillage for accelerated decomposition might be responsible for the reduction in aggregate stability under conventional tillage treatment. Physical fractionation of soil for aggregate-size fractions (i.e. wet sieving) has been an effective method for evaluating soil aggregation and degradation induced by management practices, studying the forms and cycling of SOC and providing important information about C sequestration mechanisms (Six et al. 2002a). Data collected from the long-term tillage experiment at IISS, Bhopal, showed that, at 0–5 and 5–15 cm soil depths presence of large macroaggregates (> 2000 µm) in both no-tillage and reduced-tillage systems was significantly higher than that in the conventional tillage system (Fig. 12.2). Similarly, the size fractions of small macroaggregates (2000–250 µm) were also higher in conservation tillage treatments than in conventional tillage treatment. However, the opposite trend was found in microaggregates (250–53 µm) and silt and clay size fractions (<53 µm). This showed that higher percentage of microaggregates were coalesced together in the presence of organic residues and microbial polysaccharides to form macroaggregates under the conservation tillage environment as suggested in the hierarchical model of aggregate formation by Tisdall and Oades (1982). Besides this, macroaggregates are less stable than microaggregates, and therefore, they are more susceptible to the disruption forces of repeated tillage operations in the conventional tillage system (Chen et al. 2009).

The organic carbon content in different aggregate size fractions decreased at lower size fractions under all types of tillage treatments. Larger aggregates generally store more amount of organic carbon in the form of particulate organic matter (POM), a semi-decomposed organic constituent. Stable macroaggregates physically protect a considerable proportion of organic matter from microbial decomposition within it through compartmentalization, making them inaccessible to microbes for decomposition. The organic carbon content was significantly higher in macroaggregates from no and reduced tillage than in the conventional tillage treatment (Fig. 12.5). At lower size fractions also, organic carbon content in conservation tillage was higher than that in the conventional tillage treatment. Organic carbon content in all the size fractions was lower at lower depths, namely 5–15 and 15–30 cm. Addition of organic residues and less disturbance of soil helped in enriching the organic carbon content of the aggregates from conservation tillage (Hati et al. 2013). No tillage here increased the amount of C-rich macro-aggregates and decreased the amount of C-depleted microaggregates. The highest percentages of organic carbon in Vertisols were found in small macroaggregate size fractions. Conservation tillage practices thus helped in sequestration of more carbon in macroaggregate size fractions in Vertisols. Aggregates help in sequestering carbon through compartmentalization, thus restricting the access of microbes to the organic matter inside the aggregates and also creating a relatively less aerobic environment within the aggregates.

Similarly, from 4-year long conservation tillage on a different cropping system experiment on a Vertisol of central India, Somasundaram et al. (2018) reported that

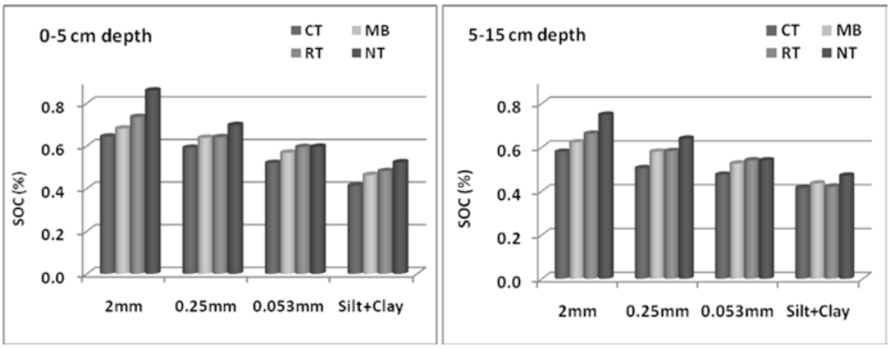

Fig. 12.5 Tillage influence on organic carbon content in different aggregate size fractions

conservation agriculture management had a positive effect on soil aggregation, aggregate stability and soil organic carbon content. Tillage practices also showed a significant positive effect on aggregate-associated C in large macroaggregates at 0–5 and 5–15 cm depths. More aggregate-C in large and small macroaggregates favoured better aggregation under NT and RT than under CT, which suggested that macroaggregates are sensitive to changes in the soil microbial community associated with short-term conservation management practices.

12.6 Conclusion

From the long-term study with the soybean–wheat cropping system on Vertisols, it was observed that management strategies such as NT and N application rate played a significant role in favouring SOC concentration and aggregate stability. Practices of conservation tillage resulted in an improvement of surface soil aggregation and an increase in the proportion of macroaggregates compared to conventional tillage. Conservation tillage increases the percentage of carbon-rich macroaggregates in the soil particularly in the surface layers, resulting in sequestration of more carbon into soil stabilized through physical protection. The effect of reduced tillage was in between NT and CT with respect to SOC concentration and aggregate distribution. The greatest enhancement of SOC in soil could be achieved through higher N dose coupled with NT. Thus, it may be concluded that NT with residue addition coupled with optimal dose of N is the most desirable management strategy for improving soil aggregation, enhancing SOC sequestration in Vertisols. Conservation tillage could also come out as a useful technology to partially mitigate the deleterious effect of climate change on humanity through sequestration of carbon into the soil and reduction of greenhouse gases emission from agricultural activities to atmosphere. It also improves soil health and its resilience to extraneous stresses. In India, through adoption of conservation agriculture, the long-term sustainability of agricultural productivity could be attained, and energy and nutrient use efficiency could be improved. However, for acceptability of this system to larger stakeholders, suitable implements, cropping systems and cover crops are to be assessed and also a crop-specific sustainable weed management package is to be developed for different agro-ecoregions.

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