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Soil carbon and nitrogen mineralization dynamics following incorporation and surface application of rice and wheat residues in a semi-arid area of North West India: A review

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Abstract

Understanding of crop residue mineralization is imperative for crop residue management in crop production. Carbon (C) and Nitrogen (N) mineralization dynamics of rice and wheat residues under surface applied and soil incorporated conditions were evaluated in the review paper. Both rice and wheat residues either incorporated or surface applied immobilized soil mineral N. Incorporated residues increased soil organic carbon and soil aggregate stability significantly by 18% and 55% over control, respectively. This review study indicated that crop residues incorporated into the soil have higher decomposition rate with a quicker mineral N release, more organic matter build up and soil structure improvement than retaining crop residues at the soil surface. Compost amendment also significantly lowered the specific activities of invertase in macro-aggregates and the silt + clay fraction, and this effect was more pronounced than the addition of fertilizer NPK. In contrast, inorganic fertilizer and compost application significantly increased the specific activities of cellobiohydrolase in soil, macro-aggregates and micro-aggregates (but not in the silt + clay fraction), and xylosidase in micro-aggregates. We considered that the increase in organic C in compost-amended soil was therefore probably associated with the accumulation of lignocellulose and sucrose in macro-aggregates, lignocellulose and hemi-cellulose in micro-aggregates and lignin (its derivative) and nonstructural carbohydrates in the silt + clay fraction.

Average soil organic carbon (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. Compared to F_1 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 zero tillage (ZT) and permanent raised beds (PRB) since under conventional tillage (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}. In long term trial, 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.

Keywords: aggregate, enzyme activity, organic carbon accumulation, rice-wheat cropping system

Introduction

Soil is an essential natural resource that provides several important ecosystem functions for plant growth and regulation of water flow in the environment. Soil organic carbon (SOC) and soil organic matter (SOM), which includes all soil macro biota, plant residues and microorganisms and their organic products, play an important role in soil fertility, structure and the supply of ecosystem services (Dikgwatlhe *et al*., 2014) [30]. According to Ito *et al*. (2015) [46] tillage and cropping impacted a range of soil physical and chemical properties. Bai *et al*. (2009) [9] showed that no-tillage (NT) and straw cover decreased mean bulk density (ρd) by 0.08 on silt loam soils. Wang *et al*., (2014) [103] claimed that NT with sub-soiling and straw cover reduced rd in the 0–30 cm soil layer, and increased total porosity, water stable aggregates and pore size class distribution, and improved infiltration. However, soil disturbance associated with tillage and changed organic matter cycling, caused organic matter levels in the soil to decline and aggravated off-site transport of N (Lal, 2007) [55].

Numerous authors have confirmed that soil fertility declines as organic matter runs down. Less organic matter, combined with tillage disturbance, has led to reduced aggregate stability and

and increased surface crusting, causing restricted infiltration, poor quality of seedbed preparation and inefficient use of rainfall. The retention of standing stubble and mulch also alleviates soil compaction and there is typically an increase in infiltration rates that results in decreased off site movement of fertilizers, herbicides and pesticides (Brendan *et al*., 2010) [20]. Riley (2014) [82] found that reduced tillage increased porosity at 4–8 cm depth and decreased it slightly at 24–28 cm, altered soil moisture-holding capacity and increased aggregate stability, and thought that changes in bulk density and total porosity were mostly attributable to changes in the stratification of SOM. Soil aggregates are important for SOM retention and they protect against C oxidization (Haile *et al*., 2008). Ochoa *et al*., (2009) [79] concluded that the increase in surface soil water-stable macro-aggregates was related to the hydrolysable organic carbon with longer years under no-tillage which contributed to the buildup of SOM in soil macro-aggregates. Huang *et al*. (2010) [45] concluded that NT facilitated soil particle aggregation by stimulating C accumulation within micro-aggregates, which acted upon the soil to form macro-aggregates. This shift of SOC to within micro-aggregates is essential for long-term C sequestration in soil.

Soil aggregates physically protect the organic matter. Organic inputs like crop residues, organic manures etc. improve soil aggregation and aggregate stability (Bandopadhyay *et al*., 2010; Karami *et al*., 2012; Naresh *et al*., 2017) [53, 77] and could be a possible way to counteract organic matter depletion. Organic amendments help in improving the formation of macro-aggregates (Bandyopadhyay *et al*., 2010) with a proportionate decrease in micro-aggregates and this imply that addition of organics support formation of macro-aggregates through binding of micro-aggregates (Huang *et al*., 2010) [45]. Wang *et al*. (2014) [103] and Naresh *et al*. (2016) [75] indicated that soil organic matter was significantly greater to 30 cm in no-tillage with straw cover (NTSC), while total soil nitrogen was lower than traditional tillage with straw removal (TTSR) treatments. However numerous studies have been conducted on the influence of tillage and cropping systems on SOM and the relationship between SOM and soil chemical and physical properties at singular sites largely over the shorter term with limited positive results (Dikgwatlhe *et al*., 2014a; Zhang *et al*., 2014; Naresh *et al*., 2017) [31, 77].

It is known that soil aggregate formation and stabilization are linked to SOC dynamics. Organic inputs have significant impacts on both the bulk soil and aggregate C contents and manures significantly increase C in aggregates (Sui *et al*., 2012) [98]. Comparison of SOC content in different WSA sizes shows macro-aggregates are the main source of enriched SOC fractions (Das *et al*., 2014) [26]. The C sequestration in soil through enhanced aggregation is an important approach of judicious soil management to mitigate the increasing concentration of atmospheric CO_2. Aggregate associated C is an important reservoir of soil C, protected from mineralization because it is less subjected to physical, microbial and enzymatic degradation. Carbon inputs from different organics may affect SOC distribution and stabilization in soil aggregate size fractions and for maintaining productivity of rice-wheat cropping system. The present review, therefore, investigated the effect of soil carbon and nitrogen mineralization dynamics following incorporation and surface application of rice and wheat residues on the activities of C-cycle enzymes in soil and separated aggregates under long-term compost and inorganic fertilizer treatments to understand the relationship between organic C content and enzyme activities and to explore the processes of organic C accumulation at the aggregate scale on a *Inceptisol* of North Western Gangetic plains of rice-wheat rotation.

Aggregation Indices

Lorenz *et al*. (2005) also observed that the mean weight diameter (MWD) and aggregate stability (AS) of the soil aggregates were higher for the RWzt + RWsi treatment than for the RWzt + Nsi treatment. From the perspective of a farmland ecosystem, zero tillage and straw incorporation enable the topsoil to form a complex decomposition sub-system that simulates the natural ecosystem. This sub-system can buffer the impact of external force on the soil mass and gather matter and energy in the topsoil under zero tillage, where the crop roots are growing. This phenomenon of identical distributions can improve the nutrient recycling capacity and energy utilization efficiency. Singh *et al.* (2007) found that the MWD was significantly higher in organic-amended plots as compared to control and NPK treatments. The plots receiving NPK+FYM showed the largest MWD (1.36 mm) compared to the control plots (0.89 mm).

Ferreira *et al*. (2007) found that soil management without tillage and with the use of cover crops favored an increase in the number of macro-aggregates, which may be due to the growth of these plants as they release their root exudates in the soil medium, developing links among soil mineral particles, favoring the formation and stabilization of aggregates in the A horizon. Abid and Lal (2008) [55] observed trends indicate that CT disrupted soil macro-aggregates into micro-aggregates or individual particles. The MWD was significantly affected by tillage treatments, showing a higher value under NT than CT. The degree of macro-aggregation in this soil was much lower than in most other agricultural systems, due primarily to the puddling of soil which tends to destroy aggregates. Souza *et al*. (2009) [94] reported that the vigorous root system of perennial forages contributed to the formation of aggregates and to improving soil physical properties, which could be observed in the aggregates larger than 8 mm under the fallow, *P. maximum*, *B. ruziziensis*, and *B. brizantha* treatments, especially at the soil depth of 0.00-0.05 m. Jiang *et al*. (2011) [49] also observed that the proportion of silt + clay sized aggregates (<0.053 mm) comprised the greatest fraction of whole soil for CT while the aggregates size (<0.25 mm) and silt + clay fraction constituted the greatest fraction for RNT.

Choudhury *et al*. (2014) [23] reported that compared to conventional tillage, water stable macro-aggregates in conservation tillage (reduced and zero-tillage) in wheat coupled with direct seeded rice (DSR) was increased by 50.13% and water stable micro-aggregates of the later decreased by 10.1% in surface soil. Residue incorporation caused a significant increment of 15.65% in total water stable aggregates in surface soil (0–15 cm) and 7.53% in sub-surface soil (15–30 cm). In surface soil, the maximum (19.2%) and minimum (8.9%) proportion of total aggregated carbon was retained with >2mm and 0.1–0.05mm size fractions, respectively. Mazumdar *et al*. (2015) reported that the MWD was significantly higher in plots receiving 50%NPK+ 50% N through FYM in rice (1.36 mm), 100% NPK in wheat or 50%NPK+ 50% N through CR in rice (1.28 mm), 100% NPK in wheat or 50%NPK+ 50% N through GM in rice (1.29), 100% NPK in wheat (1.18mm) as compared to control (0.89 mm). Nascente *et al*., (2015) [78] also found that mean weight diameter (MWD) values under fallow (7.591 mm), *B.*

brizantha (8.619 mm), *B. ruziziensis* (7.372 mm), and *P. maximum* (7.617 mm) were higher than under the fallow plus CTS treatment (3.371 mm). The lowest mean geometric diameter (MGD) value was under *B. ruziziensis* (1.112 mm). The lowest value of the aggregate stability index (ASI) was obtained under fallow plus CTS (74.62 %), which differed from all other treatments.

Kumar *et al*. (2016) [54] further argued 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- and 5–15-cm soil layers under both CT and CA practices. Song *et al*. (2016) [93] reported that zero tillage and straw incorporation also increased the mean weight diameter and stability of the soil aggregates. In surface soil (0–15 cm), the maximum proportion of total aggregated carbon was retained with 0.25–0.106 mm aggregates, and rice-wheat double-conservation tillage had the greatest ability to hold the organic carbon (33.64 g kg^{-1}). However, different forms occurred at higher levels in the 15–30 cm soil layer under the conventional tillage.

Aggregate Associated Carbon

Fonte *et al*. (2012) [37] propose that a massive input of plant residues and the avoidance of disturbance under zero tillage are the main factors underlying the improved content and stability of macro-aggregates in the surface soil layer. Coppens *et al*. (2007) [25] revealed that incorporated rice and wheat residues increased soil organic carbon by 18% while soil stable macro-aggregates by 50% over un-amended soil. Therefore, crop residue incorporation will enhance soil organic matter and will improve soil structure.

Sodhi *et al*. (2009) [91] observed that long term application of organics increased aggregate associated C as compared in all aggregate size fractions; the highest increase was observed in plots receiving NPK and FYM in combination. Das *et al*. (2014) [26] revealed that 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. This type of C is physically protected within macro-aggregates.

Wright and Hons, (2005) [100] also report that SOC concentrations are similar among aggregate-size fractions between NT and CT at 5–15 cm for a sandy loam soil. Madari *et al*. (2005) [61] found that the difference in SOC distribution between aggregate-size fractions is greater under cultivation than forest, regardless of the tillage system. Impacts of tillage on SOC in different size fractions vary greatly because of many factors, including climate, soil type, texture, pH and dominant mineralogy. Yu *et al*. (2012) [114] revealed that fertilization also significantly increased organic C contents in soil, macro-aggregates and the silt + clay fraction, but not in micro-aggregates. Compost application significantly reduced the specific activities of polyphenol oxidase (activity per unit organic C) in soil and three aggregate sizes compared with control, whereas fertilization had a much weaker effect. Compost amendment also significantly lowered the specific activities of invertase in macro-aggregates and the silt + clay fraction, and this effect was more pronounced than the addition of fertilizer NPK.

Yu *et al*. (2012c) [114] suggest that the studied soil would be saturated at a quite low level with long-term inorganic fertilizer application compared with long-term compost application. This was attributed mainly to the fact that compost application could improve soil aggregation and aggregate-associated organic C whereas inorganic fertilizer had no obvious effect. Naresh *et al*. (2017) revealed that averaged over tillage crop residue practices, stocks of SOC in 1200 kg of soil m^{-2} (approx. 0-90 cm) decreased by -0.83 ±0.2 kg m^{-2} from 14.96 to 14.13 kg m^{-2} between 2000 and 2016 in CT treatments but treatments ZT and PRB with residue retention stocks of SOC in 1200 kg of soil $m^{- -2}$ increased by +1.36 kg m^{-2} from in ZT and +0.87± 0.3 kg m^{-2} in PRB treatments from 22.02 to 23.38 and 20.84 to 21.71.

Soil Aggregate Stability

Aggarwal *et al.* (1995) [3] found that organic residues applied to soil improve structure by increasing soil aggregate stability. High aggregate stability due to incorporated crop residue may be due to the high soil organic carbon content in those treatments which act as a cementing agent for aggregate formation and stabilization. Blanco-Canqui and Lal (2007) [55] indicate that post-tillage consolidation of soils developing into compact and denser aggregates is significantly reduced through addition of organic inputs. However, variation among the treatments reveals different degrees of organic matter decomposition to influence aggregate densities. Arthur *et al.* (2012) [8] found a strong and positive relation between aggregate density and strength implies that the decrease in tensile strength is a result of increase in aggregate porosity through organic matter incorporation. Low organic matter in the zero-N plots increases the strength of air-dry aggregates due to increased internal friction between the particles upon drying.

Six *et al.* (2000) [89] found that micro-aggregates within macro-aggregates accounted for only 27% of the macro-aggregate weight in CT, compared with 47% of the macro-aggregate weight in NT. Hence, the formation of new micro-aggregates within macro-aggregates was reduced by a factor of about 2 (27% vs. 47%) in CT compared with NT. Organic matter plays the pivotal role in orienting soil particles to form aggregates and also by reducing the amount of non-complexed clay available for cementation upon drying of aggregates (Schjønning *et al*., 2012). Greater proportion of macro-aggregates with fertilizer + manure application than chemical fertilizers alone is in agreement with Schjønning *et al*. (2007), P.K. Bandyopadhyay *et al*. (2010) and Sui *et al*. (2012) [98]. However, inorganic fertilizer-N improves soil aggregation in the plough layer compared to no-N application. Organic material incorporation improves the relative abundance of macro-aggregates at the expense of other fractions and also results in higher C in macro-aggregate fractions Yu *et al*. (2012) [114].

Ali and Nabi, (2016) [14] observed that crop residue incorporation treatments increased soil aggregate stability by 46% and 55% over surface application treatments and control soil respectively. Similar results were also reported by Martens (2000) [69] who observed that addition of the seven plant residues increased soil aggregate stability for the soil at all incubation times when compared to the control (no residue added). Allison (1968) [5] also reported that stabilization of soil aggregates is a function of the physical forming forces present in soils to form aggregates and the release of aggregating agents by soil microorganisms upon organic residue decomposition. Continuous incorporation of crop residues could replenish the fast depletion of soil organic matter through continuous turnover of soil under intensive agriculture, thereby improving stability of aggregates. Results are in agreement with increase in macro-aggregates by addition of rice straw and FYM in sandy loam soil in northwest India (Benbi and Senapati, 2010) [91] and through FYM in clay soil of central India (K.K. Bandyopadhyay *et al*., 2010); increase in slaking-resistant macro-aggregates through manure in silt loam soil in Canada (Aoyama *et al*., 1999); and wheat straw in central Ohio (Blanco-Canqui and Lal, 2007) [55].

Greater amount of water stable aggregates >0.25 was also reported by Karami *et al*., (2012) [53] under similar kinds of amendment and climate. The LM (>2 mm) fractions are also significantly in higher proportion at 0–7.5 cm layer with crop residue incorporation indicating greater soil microbial activities through freshly available C (Mikha and Rice, 2004) [70]. Das *et al*. (2014) found that the density, tensile strength and friability of aggregates increased with soil depth but decreased with additional organic inputs. Treatment T_1 had the highest aggregate densities (1.82– 1.91 Mg m^{-3}) and strengths (127.2–171.6 kPa), but the lowest friability (0.10–0.15). The lowest density was recorded in T_7 and T_8, which was significantly higher than T_1, in all the layers. Treatment T_4 had similar effect as in T_7 and T_8 in 0–7.5 and 7.5– 15.0 cm layers. Effect of inorganic fertilizers was not significant except in T_3 at 0–7.5 cm. The TS was minimum in T_4 (85.6–124.0 kPa), T6 (84.2–123.3 kPa), T_7 (80.3–117.6 kPa) and T_8 (79.6– 117.2 kPa), while effect of inorganic N was significant in 0–7.5 cm layer only. Similarly, the effect of SPM in reducing the density and strength of aggregates was restricted to 0–7.5 cm layer. Friability of aggregates improved significantly with addition of organic inputs and was most evident in T_7 (0.44, 0.36 and 0.30 at 0–7.5, 7.5–15.0 and 15–30 cm, respectively). Treatments with inorganic N only (T_1 and T_2) had no apparent effect on the friability. Substitution of inorganic N by organic sources improved water retention by aggregates although it varied among soil layers and size of aggregates. Naresh *et al*. (2017) revealed that compared to conventional tillage, macro-aggregates in conservation tillage in wheat coupled with unpuddled transplanted rice (RT-TPR) was increased by 50.13% and micro-aggregates of the later decreased by 10.1% in surface soil.50% surface residue retention caused a significant increment of 15.65% in total aggregates in surface soil (0–5cm) and 7.53% in sub-surface soil (5–10 cm). In surface soil, the maximum (19.2%) and minimum (8.9%) proportion of total aggregated carbon was retained with >2mm and 0.1–0.05mm size fractions, respectively.

Soil Organic Carbon

Raju and Reddy (2000) reported that in rice–rice rotation, incorporation of rice straw to supply 25% of the recommended N fertilizer dose for rainy season crop for 6 years significantly increased organic C content from0.98% in straw removal treatment to 1.29%. Sharma (2001) reported that organic C content increased from 0.56% in straw removal to 0.66% when both the residues were incorporated for 2 years in rice–wheat rotation. Liebig *et al.* (2002) observed that high N rate treatments increased C sequestration rate by 1.0–1.4 Mg ha^{-1} yr^{-1}. The application of FYM at 10–15 Mg ha^{-1} yr^{-1} along with NPK increased SOC sequestration at the rate of 50.7–900 kg ha^{-1} yr^{-1} over 28–33 years. Majumder *et al.* (2008) reported 67.9% of C stabilization from FYM applied in a rice–wheat system in the lower Indo-Gangetic plains. It is well recognized that improved management practices promote soil carbon sequestration, and thus increase soil carbon storage (Lu *et al.,* 2009). Ma *et al.* (2011) observed that the incorporation of green manure with FYM sequestered relatively low organic C as compared to green manure with FYM and crop residue. Ghimire *et al. (*2012) revealed that 9.89% greater SOC in 0–50 cm soil profile under no-tillage than under conventional tillage in a rice-wheat system. The significant fraction of SOC under no-tillage was accumulated in surface soil with 28.3% greater SOC content in 0–5 cm depth of no-tillage system than that in the conventional tillage system.

Manna *et al*. (2013) found that long term application of NPK or farm yard manure (FYM) significantly increased the C sequestration rate in rice–wheat system (55% higher SOC in FYM plots and 70% higher in NPK plots) than in maize–wheat cropping system. Esther *et al.* (2013) observed that wheat straw amendment significantly increased total soil organic matter above the un-amended soil by 26 % for wheat straw incorporation treatments. High decomposition of incorporated residues also causes faster transformation of residues carbon into microbial components which may impact SOC by cycling C sooner into stable carbon pools that are protected (Moran *et al*., 2005).

Mandal *et al.* (2007) reported that long term (7–36 years) application of organic amendments (5–10 Mg ha^{-1} yr^{-1}) through farmyard manure or compost in subtropical India could increase SOC by 10.7%, constituting 18% of the applied C. In our research, relative to the NPK treatment, SOC increased by 10.8% in the CM1 treatment, similar to what Mandal *et al.* (2007) reported. However, the SOC increased 6.3 times more in CM3 (67.3%) than in CM1 (10.8%), though the application rate of rice straw compost was only 3 times higher in CM3 than in CM1. This indicates that application of 30 Mg ha^{-1} rice straw compost every year accelerated SOC sequestration compared to the local conventional application at 10 Mg ha^{-1} in the cold temperate region of Yamagata, Japan.

Bhattacharyya *et al.* (2013) also observed a higher total N accumulation under residue retained plots as compared to residue incorporated plots. Further, a positive and strong correlation between SOC and Kjeldahl N, Olsen's P and extractable K signifies availability of nutrients from enhanced SOC. It is reported that application of crop residues leads to reduced soil compaction, which facilitates deeper growth of pigeonpea roots, thus recycling of nutrients occur from deeper soil surface. Brar *et al*. (2015) reported that the SOC pool was the lowest in control at 7.3 Mg ha^{-1} and increased to 11.6 Mg ha^{-1} with 100% NPK+FYM. Organic manures contains most of carbon in recalcitrant forms resulting in more carbon sequestration as it had already gone under some decomposition before application in agricultural fields Benbi and Senapati (2010) [91].

Du *et al*.(2010); Mishra *et al.* (2010) revealed that higher SOC and N concentrations in the surface layer under NT than those under RT and PT systems can be attributed to a combination of less soil disturbance and reduced litter decomposition due to less soil/residue interaction. Furthermore, the presence of mulch may have improved soil structure by stabilizing aggregates and protecting SOM against microbial degradation and reduced the rate of SOC decomposition. (Luo *et al*., (2010) and Verhulst *et al*. (2011) also reported that the retention and management of preceding crop residue had a significant influence on SOM content under long-term of conservation agriculture. N was lost in TTSR through soil disturbance, rapid consumption and volatilization. Sun *et al*., (2013) reported that under TTSR treatment, plant material was incorporated in the soil profile by tillage, which increased distribution of SOM and exposure to a larger surface area of soil and rapid decomposition and release of nutrients and increasing the potential for loss.

Wang *et al*. (2014) [103] indicated that soil organic matter was significantly greater to 30 cm in no-tillage with straw cover (NTSC), while total soil nitrogen was lower than traditional tillage with straw removal (TTSR) treatments. Han *et al*. (2016) also observed that topsoil organic carbon (C) increased by 0.9 (0.7–1.0, 95% confidence interval (CI)) g kg^{-1} (10.0%, relative change, hereafter the same), 1.7 (1.2–2.3) g kg^{-1} (15.4%), 2.0 (1.9–2.2) g kg^{-1} (19.5%) and 3.5 (3.2–3.8) g kg^{-1} (36.2%) under UCF, CF, CFS and CFM, respectively. Naresh *et al*., (2017) found that RT-TPR combined with zero tillage on permanent wide raised beds in wheat (with residue) (T_9) had the highest capability to hold the organic carbon in surface (11.57g kg^{-1}soil aggregates).

Manna *et al*. (2017) revealed that in tropical agriculture, the application of manures at 10–15 Mg ha^{-1}yr^{-1} along with nitrogen, phosphorus, and potassium (NPK) increased soil organic C sequestration at the rate of 50.7–900 kg ha^{-1}yr^{-1} over 28–33 years of management. Globally, agricultural soils are estimated to potentially sequester 0.4–0.8Pg C yr^{-1} by the adoption of recommended management practices on croplands, 0.01–0.03 Pg C yr^{-1} on irrigated soils, and 0.01–0.3 Pg C yr^{-1} on grasslands. Naresh *et al*. (2017a) reported that the profile SOC stock differed significantly ($P < 0.05$) among treatments The highest SOC stock of 72.2Mg C ha^{-1} was observed in F_6 with T_6 followed by that of 64Mg C ha^{-1} in F_4 with T_2> that in F_3 with T_4 (57.9Mg C ha^{-1})> F_5 with T_1 (38.4Mg C ha^{-1})= F_7 with T_5 (35.8 Mg C ha^{-1}),and the lowest (19.9Mg C ha^{-1}) in F_1 with T_7. Relatively higher percentage increase of SOC stock was observed in F_6 with T_6 treatment (56.3Mg C ha^{-1}) followed by F_4 with T_2 (51.4Mg C ha^{-1}) and F_3 with T_1 (48.4Mg C ha^{-1}).

Water Dispersible Silt + Clay

Yu *et al*. (2012) [114] observed that micro-aggregates had the lowest carbohydrate content. The carbohydrate content in macro-aggregates was significantly higher than in the silt + clay fraction in the PK, NK and CK treatments, but not in the CM, HCM, NPK and NP treatments. Compared with CK, compost and NPK application increased the carbohydrate contents in soils and micro-aggregates. An increase in carbohydrate content was also observed in macro-aggregates and the silt + clay fraction in the compost and fertilizer treatments except NK. Long term application of compost rather than inorganic fertilizer more obviously increased the carbohydrate contents in soils and aggregates. The carbohydrate-to-organic C ratio was highest in the silt + clay fraction, with an average value of 16% in all treatments, and smallest in micro-aggregates (7%). The application of fertilizers, especially compost, slightly reduced the carbohydrate-to-organic C ratio in the silt + clay fraction, but no obvious effect was observed in macro-aggregates, micro-aggregates and soils.

Causarano *et al*. (2008) reported that 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. Vasconcelos *et al*. (2010) adds that stabilization of aggregates is directly related to organic matter content, mainly in the surface layer, and that as the amount of organic matter decreases due to conventional tillage or low input of plant biomass, a reduction in the stability of soil aggregates usually occurs. Jiang *et al*., (2011) [49] found that surface soil (0–15 cm) was fractionated into aggregate sizes (>4.76 mm, 4.76–2.00 mm, 2.00–1.00 mm, 1.00–0.25 mm, 0.25–0.053 mm, <0.053 mm) under two tillage regimes. Tillage significantly reduced the proportion of macro-aggregate fractions (>2.00 mm) and thus aggregate stability was reduced by 35% compared with RNT, indicating that tillage practices led to soil structural change for this subtropical soil.

Choudhury *et al*. (2014) [23] also observed that DSR combined with zero tillage in wheat along with residue retention (T_6) had the highest capability to hold the organic carbon in surface (11.57 gkg^{-1} soil aggregates) with the highest stratification ratio of SOC (1.5). Moreover, it could show the highest carbon preservation capacity (CPC) of coarse macro and meso-aggregates. A considerable proportion of the total SOC was found to be captured by the macro-aggregates (>2–0.25mm) under both surface (67.1%) and sub-surface layers (66.7%) leaving rest amount in micro-aggregates and ‘silt + clay’ sized particles.

Majumder *et al*. (2015) revealed that the macro-aggregates constituted 37-60% of total WSA and the proportion of micro-aggregates ranged from 19 to 30%. Addition of FYM, wheat straw and green manure increased macro-aggregate fractions, with a concomitant decrease in micro-aggregate fractions. Among the macro-aggregates, 0.25-0.50 mm fraction constituted the largest proportion and had higher C density compared to micro-aggregates. Song *et al*., (2016) [93] reported that as compared to conventional tillage, the percentages of >2 mm macro-aggregates and water-stable macro-aggregates in rice-wheat double conservation tillage (zero-tillage and straw incorporation) were increased 17.22% and 36.38% in the 0–15 cm soil layer and 28.93% and 66.34% in the 15–30 cm soil layer, respectively.

Aggregate-Associated SOC Concentration

Six *et al*. (2002) [89] showed that regardless of tillage practice, 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, which is inconsistent with the result of Six *et al*., (2000) [89] who found that >2 mm aggregates had the highest SOC level compared to the other size classes of aggregates. Six *et al*. (2000) [89] suggested that macro-aggregates are formed by the aggregation of soil particles through cementation of organic substances and indicated that macro-aggregate particles are the main carrier of organic carbon. Causarano *et al*. (2008) reported that 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.

Razafimbelo *et al*. (2008) suggested that micro-aggregates, which possess a larger specific surface area with more abundant active points, can absorb organic substances and preserve organic carbon through strong ligand exchange and multivalent cation bridging. Consequently, the SOC levels are even higher in micro-aggregates than in macro-aggregates. Mandal *et al*. (2008) found that continuous cultivation without the addition of N or P fertilizer (CK, NK, and PK treatments) over 20 years caused a significant decrease in the SOC stock in the 0–60 cm soil profile. This decrease was attributed mainly to low inputs of exogenous organic C from crop residues (0.93–1.35 Mg C ha^{-1} yr^{-1}), which were lower than the magnitude of mineralized SOC (1.99–2.19 Mg C ha^{-1} yr^{-1}). Bhattacharyya *et al.* (2011) found that the 15–30 cm soil layer was the most efficient in stabilizing applied organic C and that the proportion of applied manure C stabilized in this layer was 1.37 times the proportion in the 0–15 cm layer and 6.14 times the proportion in the 30–45 cm layer. However, with respect to the low C-retention capacity of the 20–40 cm soil layer (sandy soil) at the study site, organic C may have moved downward from the 0–20 cm layer, passed through the 20–40 cm layer, and been sequestered in the 40–60 cm soil layer.

Srinivasan *et al.* (2012) showed that zero tillage resulted in higher organic carbon storage in soil aggregates in the 0–15 cm soil layer than did conventional tillage, primarily because conservation tillage reduces the damage to soil aggregates and increases the content and stability of associated organic carbon accordingly. *De Deyn et al. (*2011) and Arai *et al.,* (2013) reported that the influence of tillage on soil organic carbon have only considered the shallow soil layer (0–15 cm) and ignore the SOC level in the deep soil if it shows little differences or exhibits the same distribution as observed in the shallow soil. However, the organic materials are tightly bound to soil particles, thereby improving the stability of their mineralization and promoting the accumulation of organic carbon in the deep soil. Fan *et al.* (2014) reported that the total quantities of sequestered SOC were linearly related ($P<0.01$) to cumulative C inputs to the soil, and a critical input amount of 2.04 Mg C $ha^{-1}yr^{-1}$ was found to be required to maintain the SOC stock level (zero change due to cropping). However, the organic C sequestration rate in the 0–60 cm depth decreased from 0.41 to 0.29 Mg C $ha^{-1}yr^{-1}$ for HCM and from 0.90 to 0.29 Mg C $ha^{-1}yr^{-1}$ for CM from the period of 1989–1994 to the period of 2004–2009, indicating that the SOC stock was getting to saturation after the long-term application of compost. The estimated SOC saturation level in the 0–60 cm depth for CM was 61.31 Mg C ha^{-1}, which was 1.52 and 1.14 times the levels for NPK and HCM, respectively.

Das *et al.* (2013) observed a significant increase in total SOC under ZT plots over CT plots after 4 years of cotton/ maize–wheat cropping in this region. This could be due to difference in residue quality. The C/N ratio of pigeon-pea residues is lower than that of cotton or maize residues. Higher C/N residues resulted in less mineralization of native and added C (and thus had better potential to be retained in soils under ZT), which was perceived to be the major factor for differences in C retention under these two contrasting cropping systems. Naresh *et al.* (2015) observed that in a 3-year study in a rice-wheat system, SOC content was 0.22% greater under no-tillage raised bed than under conventional tillage. The significant fraction of SOC under no-tillage was accumulated in surface soil with 28.3% greater SOC content in 0–5 cm depth of no-tillage system than that in the conventional tillage system. Yang *et al.* (2014) noticed that long-term winter planted green manure substantially improved the SOC content and the C/N ratio coupled with redistribution of the macro-aggregates into micro-forms. Naresh *et al.* (2017) found that higher SOC content of 8.14 g kg^{-1} of soil was found in reduced tilled residue retained plots followed by 10.34 g kg^{-1} in permanently wide raised bed with residue retained plots. Whereas, the lowest level of SOC content of 5.49 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots.

Soil carbon stock

Hao *et al.* (2004) found that the organic input can also ensure aggregate stability, as the high stability of aggregation provides favorable conditions for mass transfer, retention time of water, root growth, and microbial activity. Abiven and Recous (2007) also reported more C mineralization from paddy and wheat straw when incorporated into soil as compared to their mulching. Jin *et al.* (2008) also observed the highest C mineralization in the incorporated winter wheat and peanut residues as compared to their surface application. Faster decomposition with incorporated residues might be due to its close contact with soil, optimal moisture and temperature gradients and more availability of soil nutrients which in turn provide conducive environment for decompositionYadvinder-Singh *et al.*, (2010). Zhang *et al.* (2008) also observed that rice residues with incorporation (RRI) released 10% more CO_2–C than wheat residue incorporation treatments (WRI) while in surface application treatments rice residues gave 16% higher CO_2–C flux than wheat residues. Higher release of CO_2-C from rice residue (C/N = 69) might be due to its narrower C/N ratio than wheat residues (C/N = 116). Plant residues with higher C/N ratios show slower decomposition rates. Sirinavas *et al.,* (2006) and Corbeels *et al.* (2000) who found the highest immobilization period of 12 days for incorporated residues whereas for Kachroo *et al.* (2006) this period was of 15 days. Rice and wheat residue incorporation treatments (RRI and WRI) immobilized 15.79 and 13.51 mg kg^{-1} mineral nitrogen at day 15.

De Roy *et al.* (2011) found significantly higher mineralization from rice residue as compared to wheat residue. This higher N mineralization of rice residues may be attributed to its lower C/N ratio than wheat residues. Jemai *et al.* (2012); Dimassi *et al.* (2013) also indicate that SOC concentrations in the 30–50 cm depth were in the order RT > NT > PT > PT0, supporting the hypothesis that tillage practices can impact SOC concentration in sub-soil. Such a trend can be attributed to the soil properties (e.g., water infiltration, residue decomposition rate) and root penetration under different treatments. Galka *et al.* (2014) reported that the composition of the forest canopy is also known to be a determining factor in mineral weathering, soil acidity, contaminant accumulation, nutrient reserves, and diversity of soil organisms. Chen *et al.* (2014) found that SOC stocks increased in topsoil of double rice-cropping systems with increases in experimental duration. Additionally the SOC sequestration rate in 0–30 cm soil depth was observed to be higher than in single-rice paddy soils or upland soils. Long-term straw mulching could build soil organic matter level and N reserves, increase the availability of macro- and micro- nutrients, and subsequent nutrient transformations.

Microbial Biomass Carbon

Six *et al.* (1999) indicated that in addition to the amount of aggregation, the rate of turnover of soil aggregates influences C stabilization. Microbial growth and the resulting production of extracellular poly- saccharides bind residue and soil particles into macro-aggregates. 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. Tresder *et al.* (2005) revealed that Pigeon-pea, being a legume, have prolific root system, which releases an array of organic compounds viz. psidic acid and oxalic acid. Gloumalin content is perceived to be increased in the rhizosphere. These compounds stimulate and diversify the growth of the microbial biota and enzymatic activity, and thus, increase nutrient cycling and their acquisition, especially N and P to the crop. So, retention of crop residues at 3 t/ha under ZT and an association of pigeonpea leaf litter fall stimulate the growth of microbial population by providing continuous supply of food. Balota *et al.* (2004) showed that residue retention and no tillage increased total C by 45% and soil microbial biomass (SMB) by 83% at 0–50 cm depth as compared to traditional tillage. Similarly, Soon and Arshad (2005) also indicated that SMB was 7-36%higher with no tillage than conventional tillage.

Green *et al*. (2007) found that No-till management practice increase stratification of soil enzyme activities near the soil surface, perhaps due to the similar vertical distribution of SOM in NT than in CT and the activity of microbes. Mina *et al*. (2008) reported that conventional tillage enhances oxidation of organic C and impairment of soil pore networks including mycorrhizal hyphae, which gave low MBC and consequently MBN, while reverse is true for ZT. Higher MBC causes an increase in enzymatic activities viz. dehydrogenase activity (DHA), phosphatase and β-glucosidea activities under ZT. DHA is an oxidoreductase enzyme present in viable cells only.

James *et al*. (2010) revealed that long-term no-tilled soils have significantly greater levels of microbes, more active carbon, more SOM, and more stored carbon than conventional tilled soils. Lu *et al*. (2014) recently concluded that biochar and residue amendment could enhance the readily oxidized C (measured by $KMnO_4$ oxidation). Sepat *et al*. (2016) found that Zero tillage increased the microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) by 15.0 and 18.3 %, respectively, over CT. Plots under zero tillage— raised bed (ZT-B) recorded highest soil MBC, while in the case of MBN, ZT-B remained comparable with zero tillage— flat bed (ZT-F) and conventional tillage— raised bed (CT-B). Plots under conventional tillage— flat bed (CT-F) recorded 17.4 and 19.4 % lower values of MBC and MBN, respectively over ZT-B plots. Crop residue application recorded 41.0 and 39.8 % higher MBC and MBN, respectively than no residue plots.

Soil Enzymatic Activities

Alvarez *et al*. (1995) observed that conventional tillage enhances oxidation of organic C and impairment of soil pore networks including mycorrhizal hyphae, which gave low MBC and consequently MBN, while reverse is true for ZT. Higher MBC causes an increase in enzymatic activities viz. dehydrogenase activity (DHA), phosphatase and β - glucosidea activities under ZT. DHA is an oxidoreductase enzyme present in viable cells only. This enzyme has been considered as a suitable indicator of soil quality and a valid biomarker to indicate changes in total microbial activity due to change in soil management.

Zhang *et al*. (2009) and Lu *et al*. (2014) found that invertase activity generally decreased with soil depth, which can probably be attributed to lower soil organic carbon and microbial biomass in deeper soils. However, the urease enzyme is responsible for the hydrolysis of urea fertilizer applied to the soil into NH_3 and CO_2. Harter *et al*. (2014) [44]; Zhang *et al*. (2013a) and Wu *et al*. (2013) [106] found that biochar application resulted in more nitrate in the upper 1 m of soil profile. Therefore, biochar-induced changes in soil biota (i.e., enzyme, microbial community) regarding soil N transformation (nitrification, denitrification) is needed, because the activity of enzymes involved in the N cycle could potentially be linked to N_2O emissions. Nannipieri *et al*. (2012) also observed that phosphatase, which catalyzes the hydrolysis of ester phosphate bonds, releases inorganic phosphate assimilated by plants and microorganisms.

Yu *et al*. (2012) [114] reported that the invertase activities in micro-aggregates were lower than that in macro-aggregates, the silt + clay fraction and soil in all treatments. Long-term compost amendment led to a significant increase in invertase activities in soil, micro-aggregates and the silt + clay fraction, but not in macro-aggregates, compared with CK. The inorganic fertilizer amendment had a slight effect on invertase activities. The specific invertase activities in macro-aggregates and the silt + clay fraction were reduced by all fertilizer applications in comparison with CK. The activities of cellobiohydrolase and its specific activities were smaller in micro-aggregates than in macro-aggregates, the silt + clay fraction and soil. Compared to CK, the long-term application of compost, NPK and NP significantly increased the activities of cellobiohydrolase and its specific activities in all aggregates and soil. In macro-aggregates and micro-aggregates, the application of NPK had a more pronounced effect on the specific cellobiohydrolase activities than did compost.

In all treatments, the lowest activities of β-glucosidase and its specific activities were in micro-aggregates. The activities of xylosidase in both macro-aggregates and the silt + clay fraction were higher than in micro-aggregates in all treatments. The long-term application of compost and NPK significantly increased xylosidase activities in soil, macro-aggregates and the silt + clay fraction in comparison with CK. The specific xylosidase activities were enhanced by the application of all the fertilizers in the silt + clay fraction. The NPK amendment had a more pronounced effect on the specific xylosidase activities than did compost in micro-aggregates. The activities of polyphenol oxidase and its specific activities in micro-aggregates were slightly higher than in soil, macro-aggregates and the silt + clay fraction in all treatments except CK. The long-term application of compost and inorganic fertilizer significantly reduced polyphenoloxidase activities in soils. The application of compost decreased the specific activities of polyphenol oxidase in soil, macro-aggregates, micro-aggregates and the silt + clay fraction by 73–75, 63–68, 62–67 and 80–82%, respectively, whereas the corresponding values were 58, 57, 45 and 62% in the NPK treatment.

Wang *et al*. (2007) [103] and Kara & Bolat (2008) demonstrated that the RDA showed that the activities of invertase, β -glucosidase and xylosidase were clearly correlated with the organic C and carbohydrate content in soil, but the activities of cellobiohydrolase and polyphenol oxidase only had a weak correlation with the organic C and carbohydrate content in soil. The activities of invertase and β -glucosidase were linearly correlated with organic C. Lisboa *et al*. (2009), who postulated that for a forest-to-pasture chronosequence, the turnover time of organic C in the slow-cycling C pool of micro-aggregates (53–250 μm, 498 yr) is longer than that of particulate organic matter (>250 μm, 1.29 yr) and silt fraction (2–53 μm, 210 yr). Zhang *et al*. (2011) observed that long-term application of fertilizers, especially compost, significantly increased the population of bacteria and reduced the abundance of actinomycetes, but had no obvious effect on fungi.

Carvalhais *et al*. (2011) [21] observed a higher carbohydrate-to-organic C ratio in the silt + clay fraction than in micro-aggregates and macro-aggregates, and there was a significant or marginal relationship between the carbohydrate content and the activities of invertase, β -glucosidase or xylosidase. These results indicated that the enzymes in the silt + clay fraction were not completely adsorbed onto the mineral surfaces and retain high organic C-decomposing potentials in our tested sandy loam soil. Sepeat *et al*. (2016) revealed that combined application of pigeonpea + wheat residue at 3t/ha resulted in higher dehydrogenase (20.9 µg triphenylformazan/g/h), β- glucosidase (145 µg p-nitrophenol/g/h), and acid phosphatase activities (24.5 µg p-nitrophenol/g/h) than the single application of wheat or pigeonpea residue in either season or no residue control. Jindo *et al*. (2012) [50], who found the urease enzyme, determined from horizons of different soil profiles revealed decreased activities with soil depth. The differences might be attributed to decreases in soil organic matter content and numbers of microorganisms with depth. Zhang *et al*. (2013a) found that RDN+FYM application resulted in more nitrate in the upper 1 m of soil profile. Further study about residue and RDN+FYM-induced changes in soil biota (i.e., enzyme, microbial community) regarding soil N transformation (nitrification, denitrification) is needed, because the activity of enzymes involved in the N cycle could potentially be linked to N_2O emissions (Wu *et al*., 2013; Harter *et al*., 2013) [106, 44].

Conclusions

Long-term compost amendment significantly increased the organic C content in soil by increasing organic C in all aggregates, whereas the increase in organic C in inorganic fertilizer–added soils was mainly because of the enhancement in organic C content in macro-aggregates and the silt + clay fraction. A decrease in specific polyphenol-oxidase activities was also found in inorganic fertilizer–added soils and aggregates. In macro-aggregates and the silt + clay fraction, the specific invertase activities were also decreased by compost or inorganic fertilizer application. In contrast, inorganic fertilizer NPK more obviously increased the specific activities of cellobiohydrolase in soil, macro-aggregates and micro-aggregates (but not in the silt + clay fraction), and xylosidase in micro-aggregates than compost. However, the fertilizer NPK amendment mainly accentuated the accumulation of lignin (its derivatives) and sucrose. The enzymes measured in the silt + clay fraction were found to be not completely absorbed and stabilized on the mineral surfaces and have high organic C –decomposing potentials. The different types of organic C accumulated in different aggregates and were affected by the type of fertilizers applied in our agricultural soils. The application of compost with high lignocellulose is likely to be a good strategy to increase organic C content in the agricultural soils of the North West Gangetic plains, India. Sequestering organic C in soil, creating a nutrient-rich environment for the proliferation of plants, and allowing water to pass through and be filtered are some critical soil functions that can be enhanced with conservation agricultural systems.

The residue incorporation significantly enhanced its decomposition and caused about 30 kg N ha^{-1} (15 mg N kg^{-1}) immobilization within 15 days whereas surface application immobilized about 19 kg N ha^{-1} (9.5 mg N kg^{-1}) in 75 days. In rice-wheat area of North West Gangetic plains, India, the time window between wheat harvesting and rice transplanting is about 60 days which provides enough time for crop residues to decompose and mineralize N. But the time window between rice harvesting and wheat sowing is about 20–25 days thus incorporation must be as early as possible just after rice harvesting and a starter dose of about 10–15 N kg ha^{-1} should also be applied in order to avoid N deficiency during germination and early growth. In the zero drill by happy seeder system crop residues can be left intact or used as mulch in the direct seeded system. In case of surface application of rice and wheat residues, the immobilization process is very slow and long which will not cause N deficiency with the application of recommended dose of N fertilizers. Incorporated rice and wheat residues increased soil organic carbon by 18% while soil stable macro-aggregates by 50% over un-amended soil.

Low organic matter and poor soil structure are one of the key reasons of yield stagnation and even decline in yield of rice-wheat system of India. Therefore, crop residue incorporation will enhance soil organic matter and will improve soil structure. Soil organic C is a key element in the valuation of natural resources and the evaluation of how management affects soil quality and ecosystem services derived from soil. A key to success will be to consider the agronomic, ecological and environmental constraints within a particular farm setting. The magnitude and severity of the depletion of SOC pool are exacerbated through decline in soil quality by accelerated erosion and other degradation processes. Perpetual use of extractive farming practices and mining of soil fertility also deplete the SOC pool. Conversion to a restorative land use and adoption of recommended agricultural management practices, which create positive C and nutrient budgets, can enhance SOC pool while restoring soil quality. Soil carbon sequestration is a win-win-win strategy. The amount of organic carbon stored in various soil pools is the balance between the rate of soil organic carbon input and the rate of mineralization in each of the organic carbon pools. However, the storage of carbon in soil profile is governed by the soil type, climate, management, mineral composition, topography, soil organisms and other unknown factors. More research evaluating impacts of alternative management systems on SOC dynamics is required. Specifically, understanding SOC and nutrient dynamics during transition from conventional to conservation systems are required.

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