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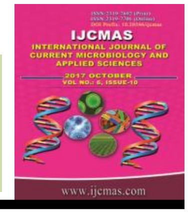

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Effect of Organic Inputs on Strength and Stability of Soil Aggregates Associated Organic Carbon Concentration under Rice-Wheat Rotation in Indo-Gangetic Plain Zone of India

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A B S T R A C T

The study aims to elucidate the impact of organic inputs on strength and structural stability of aggregates in a sandy loam soil of Indo-Gangetic Plain Zone of India. Tensile strength, friability and water stability of aggregates, and the carbon contents in bulk soil and in large macro (>2mm), small macro (0.25-2 mm), micro (0.053-0.25 mm) and silt+ clay size (<0.053) The aggregate were evaluated in soils with different sources and amounts of organic C inputs as partial substitution of N fertilizer. Addition of organic substrates significantly improved soil organic C contents, but the type and source of input had different impacts. Tensile strength of aggregates decreased and friability increased through organic inputs, with a maximum effect under rice residue-farmyard manure and wheat residue substitution.The aggregate strength and density were lower with organic substitution ($p < 0.05$) while water retention by aggregates at field capacity was 2–4% higher with organic inputs. Macro-aggregates (>0.25 mm) constituted 58–92% of water stable aggregates and varied significantly among treatments and soil depths. Organic material incorporation improved soil aggregation and structural stability and resulted in higher C content in macro-aggregates. Higher macro-aggregates in the crop residue- and farmyard manure-treated soils resulted in a higher aggregate mean weight diameter, which also had higher soil organic C contents. The bulk soil organic C had a strong relation with the mean weight diameter of aggregates, but the soil organic c content in all aggregate fractions was not necessarily effective for aggregate stability. The soil organic C content in large macro-aggregates (2-8mm) had a significant positive effect on aggregate stability, although a reverse effect was observed for aggregates<0.25 mm. Partial substitution of nitrogen by organic substrates improved aggregate properties and the soil organic C content in bulk soil and aggregate fractions, although the relative effect varied with the source and amount of the organic inputs.

Introduction

Crop residues, usually considered a problem, when managed correctly can improve soil organic matter dynamics and nutrient cycling, thereby creating a rather favorable environment for plant growth. The intelligent management and utilization of crop residues is essential for the improvement of soil quality and crop productivity under rice-based cropping systems of the tropics. Viable option is to retain residue in the field; burning should be avoided. The major issue is adapting drills to sow into loose residues. Strategies include chopping and spreading of straw during or after combining or the use of disc-type trash drills. Residues rich in lignin and polyphenol contents experience the lowest decay. Decomposition of crop residues occurs at a rapid rate—about 80% of crop residue C is lost in the first year—under the warm and humid conditions of the tropics. Factors that control C decomposition also affect the N mineralization from the crop residues. Decomposition of poor-quality residues with low N contents, high C: N ratios, and high lignin and polyphenol contents generally results in microbial immobilization of soil and fertilizer N. Nutrient cycling in the soil–plant ecosystem is an essential component of sustainable productive agricultural enterprise. Although during the last three decades, fertilization practices have played a dominant role in the rice-based cropping systems, crop residues—the harvest remnants of the previous crop still play an essential role in the cycling of nutrients. Incorporation of crop residues alters the soil environment that in turn influences the microbial population and activity in the soil and subsequent nutrient transformations.

Tensile strength (*TS*), a fundamental property of aggregates, is a measure of the resistance of the aggregate against breaking forces (Watts and Dexter, 1998), and thus, is highly sensitive to soil management (Blanco-Canqui *et al.,* 2005). High *TS* of aggregates helps in proper maintenance of soil tilth and pro-vides a stable traction for farm implements, but limits intra-aggregate root growth (Król *et al.*, 2013; Turski, 2002). The friability of the soil, on the other hand, is the tendency of a body of soil to break into smaller pieces under an applied stress or load (Watts and Dexter, 1998). This might be another important physical property of agricultural soils, since the condition of friability is desirable for better tillage and sowing of plants (Dexter and Watts, 2001; Watts and Dexter, 1998). However, data on *TS* and friability under various combinations of organic and inorganic inputs and their interrelationships with management-induced changes in SOC are scanty (Blanco-Canqui *et al.,* 2005) and none under the intensive rice-wheat system. Water stability of aggregates is the indicator of soil resistance against disintegration (Mohanty *et al.,* 2012), while the size of aggregates indicates the influence of management on soil structural stability. Organic binding agents are mostly responsible for development and stability of macro-aggregates (>0.25 mm), implying the role of organic matter in aggregate stability. The SOC content decreases with intensive cultivation, which corresponds to a decrease in aggregate stability by changing its structure (Król *et al.,* 2013).

Bulk Density (BD)

Straw management had a large impact on bulk density in the surface layer (0-10 cm) but not significant in the 10-20 cm depth. The bulk density under the high-mulch treatment was 58% lower and that under the low-mulch treatment was 19% lower than the bulk density under the un-mulched treatment for the 0-3 cm depth. In the 3-10 cm depth, bulk density under the high-mulch treatment was only 36% lower and that under the low-mulch treatment was 9% lower than under the control. Annual application of 16 t ha^{-1} of rice straw for 3 years decreased bulk density from 1.20 to 0.98 g cm^{-3} in the 0-5 cm layer on a sandy loam (Lal, 2000). Jill *et al.,* (2011) found that NT than CT in the top 10 cm, but was similar between NT and CT in the 10- to 20-cm depth. Soil BD differed among common rice- based cropping systems with corn, soybean, and winter wheat, but few consistent trends were evident. It appears that, even after 10 years of continuous CT or NT rice production on a silt- loam soil, substantially increased near-surface soil BD has not occurred to the point where soil compaction would be a likely culprit responsible for a reduced early season stand establishment or crop yield differences among rice- based copping systems.

Soil BD is generally greater under reduced tillage, specifically no-tillage (NT), due to machinery traffic and the lack of surface soil disruption and mixing accomplished by annual plowing (Lampurlanés and Cantero-Martínez, 2003; Karamanos *et al.,* 2004). Since soil BD has been shown to be inversely related to SOM (Son *et al.,* 2003; Diana *et al.,* 2008), where increasing SOM generally decreases soil BD by adding additional pore space without adding much additional mass, crop rotations with a large frequency of high-residue-producing crops that are managed using cultural practices that return crop residues to the soil could consequently at least maintain a near-surface soil BD that is favorable for gas exchange, water infiltration, and plant growth.

Blanco-Canqui and Lal (2007a) measured bulk density in no till plots that had receiving three levels of wheat straw mulch (0, 8, and 16 t ha^{-1} yr^{-1}) for 10 consecutive years on a silt loam in central Ohio. Straw management had a large impact on bulk density in the surface layer (0-10 cm) but not significant in the 10-20 cm depth. The bulk density under the high-mulch treatment was 58% lower and that under the low-mulch treatment was 19% lower than the bulk density under the un-mulched treatment for the 0-3 cm depth. In the 3-10 cm depth, bulk density under the high-mulch treatment was only 36% lower and that under the low-mulch treatment was 9% lower than under the control. Annual application of 16 t ha^{-1} of rice straw for 3 years decreased bulk density from 1.20 to 0.98 g cm^{-3} in the 0-5 cm layer on a sandy loam (Lal, 2000). Dalal *et al.,* (2011) also reported the residues management practices had not significant influence on the bulk density of vertisol soil of Australia. Naresh *et al.,* 2016 also reported that mean soil bulk density in the 0- to 20-cm soil layer of the FIRB with residue retention and ZT with residue retention plots was 12.4 and 6.8% lower, respectively ($P < 0.05$), than the CT plots. In addition, the FIRB treatment had significantly ($P < 0.05$) lower soil bulk density in the 0- to 10- and 10- to 20-cm soil layers than CT by 14.3 and 12.8%, respectively. The changes in bulk density were mainly confined to top 10-15 cm layer.

Aerobic soil conditions also exist during the dry periods between flooding and heavy precipitation, which stimulates the rapid breakdown of accumulated SOM.

This decline in SOM can, in turn, adversely affect soil productivity, soil quality, and the overall sustainability of rice production (Salinas-Garcia *et al.,* 1997; Amuri and Brye, 2008). The frequent cycling between anaerobic and aerobic conditions can potentially lead to a greater rate of SOM decomposition (Xu *et al.,* 2007), which could essentially increase the BD of the soil. Increasing soil BD over time is a reasonable concern because compacted soil may hinder short-term plant growth and long-term crop yield.

Water Stable Aggregates (WSA)

Aggregation is a dynamic process that depends on various agents such as soil fauna, roots, inorganic binding agents and environmental variables. Macro aggregates are gradually bound together by temporary (i.e., fungal hyphae and roots) and transient binding agents (i.e., microbial and plant-derived polysaccharides) as the decomposition of soil organic matter takes place (Six *et al.,* 2004). Zero tillage with residue retention improves soil structure compared to conventional tillage (Govaerts *et al.,* 2007). Research on conservation agriculture showed that no-till with stubble retained treatment had more water stable aggregation (Zhang *et al.,* 2009).Retaining crop residues on the soil surface lead to an increase of soil organic carbon, which gives rise to improved soil aggregate stability (Limon-Ortega *et al.,* 2002) and the return of biological diversity to the soil, particularly earthworms (Chan 2001). Mehuys (1988) observed a decrease in MWD of WSA after four years plough till compared with no-till. No tillage increased the proportion of the macro aggregates (>2 mm) at 0-5 cm but not at 5-15 cm depth. The majority of SOC and SON storage under both CT and NT was observed in the largest aggregate size fractions (>2 mm, 250 mm to 2 m.

Aulakh *et al.,* 2013 showed total WSA after 2 years of the experiment in 0 - 5 cm soil layer of CT system, T_2 and T_4 treatments increased total WSA from 71% in control (T_1) to79 and 81% without CR, and to 82 (T_6) and 83% (T_8) with CR. The corresponding increase of total WSA under CA system was 75% in control (T_9) to 81 (T_{10}) and 82% (T_{12}) without CR and 83 (T_{14}) and 85% (T_{16}) in with CR. Naresh *et al.,* (2012) showed significant effects of NT and residue retention on soil aggregate stability in western Uttar Pradesh under an alternative wheat production system. The capillary-wetted soil aggregates did not show any clear trends across the treatments. Das *et al.*, (2014) observed that a large reduction (50–75%) in MWD was observed upon slaking, more in case of inorganic N treatments. Variation in MWD of capillary-wetted aggregates was also less (3.5–4.5 mm). Treatment T_7 had significantly higher MWD in all the layers (3.9–4.6 mm), while rest of the treatments was similar and not different from T_1. However, the MWD of slaked aggregates showed larger variations, and the treatments differences were large. In the layer 0–7.5 cm, treatments T_4, T_6, T_7 and T_8 had significantly higher MWDs of slaked aggregates. At 7.5–15 and 15–30 cm, the values were significantly higher in T_7 and T_8. Rests of the treatments were comparable, although significantly higher than (7.5–15 cm) or similar to (15–30 cm) T_1.

Mazumdar *et al.*, (2015) found that he 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. Naresh *et al.*, (2016) revealed that the small macro-aggregates accounted for >30% of the total aggregates (mean of both main plots) in the surface soil layer. Silt- plus clay-sized aggregates comprised the greatest proportion of the whole soil, followed by the small macro-aggregates. The amount of water-stable large and small macro-aggregates in the FIRB and ZT plots were significantly higher than in the CT plots in the 0- to 5-cm soil layer. These differences may be attributed to the different planting systems. A reduced presence of macro aggregates (>0.25 mm) under TT was partly due to excessive tillage and heavy traffic, which hindered the soil biological activity (Tisdall and Oades, 1979). Bappa Das *et al.*, (2014) revealed that the increased amounts of large (>2 mm) macro-aggregate fractions in NPK + GR (rice) + FYM (wheat) and NPK + CR (rice and wheat) are associated with the very large MWD in these treatments. Similar trends are observed in other organic treatments, with a large amount of small macro-aggregate fractions, along with large macro-aggregates. A higher amount of silt- and clay-sized fractions was observed in the control (43.84%). Song *et al.,* (2016) observed that zero tillage and straw incorporation also increased the mean weight diameter and stability of the soil aggregates.

Tensile strength of aggregates

Aggregate strength decreases with increase in SOC, initially at a faster rate and then gradually. The tensile strength was the highest in the unfertilized plots. Due to the low amount of SOC, the air-dry aggregates from the unfertilized plots had increased internal friction between the particles upon drying (Schjonning *et al*., 1994), and a large amount of readily dispersible clay was available for internal crust formation, cementation of particles and aggregates (Elmholt *et al.*, 2008). The tensile strength of aggregates was the lowest in the plots with the addition of either rice-wheat or green gram crop residue. The decrease in the strength of air-dry aggregates with the increase in organic inputs agrees with other studies (Arthur *et al.,* 2012; Schjonning *et al.,* 2007), but differs from a few (Bartoli *et al.*, 1992). Organic matter helps in particle orientation to form aggregates and also reduces the amount of non-complexed clay for cementation upon drying of the aggregates (Schjonning *et al.*, 2012). Cambardella and Elliott, (1993) reported that soil inversion and disruption by tillage in control and NPK treatments, exposed the protected organic matter to soil organisms, accelerate decomposition and thus affect the average size and stability of soil aggregates. Six *et al.,* (2000) 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. In addition, the concentration of intra-micro-aggregate POM-C was three-fold greater in NT compared with CT while the concentration of inter-micro-aggregate POM-C (i.e., POM-C held within macro-aggregates but not within micro-aggregates) was twofold greater in CT compared with NT. Singh *et al.*, (2007) revealed that the added organics could supply additional fresh organic residues (water soluble and hydrolysable substrates) and C to the soil resulting in production of microbial polysaccharides that increase aggregate cohesion which could explain the observed progressive increase in aggregate stability to mechanical breakdown.

Six *et al.*, (2000) found that the increase in total fine iPOM (i.e., inter– plus intra-micro-aggregate iPOM) alone accounted, on average, for 21% of the total C difference between NT and CT for temperate climatic condition. Kong *et al.*, (2005) revealed that the addition of organic inputs substantially increased both the fractions, although no preferential accumulation of C could be identified. However, larger $_{m}$M-C in organic treatments, especially with GR (rice)–FYM (wheat) is indicative of scope of long-term C protection within aggregates, which may be a possible indicator of C sequestration. 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.

Aggregation and structural indices

The role of soil organic matter in aggregate stability is summarized in Figure 2. Straw incorporation helps the formation and stability of aggregates through increase in microbial cells, and excretes microbial products and decomposition products released during the death of the microorganisms (Lynch and Elliott, 1983). The soil organic matter in turn is protected within aggregates for decomposition (Dalal and Bridge, 1996).

The amount and chemical composition of organic residues, temperature, and moisture conditions are the major factors determining aggregation in soil (Prasad and Power, 1991). Thus, easily decomposable plant residues such as green manure and grain legume residues provide transient and temporary aggregate stabilizing agents, while cereal crop residues provide persistent aggregate stabilizing agents (Elliott and Lynch, 1984). Chaudhary and Ghildhyal (1969) obtained a close relation (r = 0.76) between organic C increased by organic materials addition and aggregate stability of soil under wetland rice. Likewise, Elliott and Lynch (1984) found that the effect of straw on aggregation in a silt loam soil decreased with increasing straw N content in the range of 0.25 to 1.09%.

In a rice–wheat cropping system on a loamy sand soil, incorporation of wheat straw over a 5-year period in rice promoted formation of soil aggregates, particularly 1–2 mm size, and mean weight diameter. A mixed application of green manure and crop residues was more effective compared to their separate applications. Similarly, in a long-term experiment (1981–1990) on rice–rice rotation in China, Liu and Shen (1992) noted that application of crop residues promoted aggregation. The contents of micro-aggregates (0.25–1.0 mm) were increased from 10.9% in inorganic fertilizer treatment to 12.1% in milk vetch green manure and to 13.6% in green manure plus rice straw treatment. The effect of crop residues on aggregation also depends on the aggregation potential of the soil.

Datta *et al.,* (1989) have shown that when clay clayey soil significantly increased water stable aggregates >0.25 mm. Total organic C also increased, which resulted in a marked increase of macro-pores as well as the aggregate size in the 2.0–0.84 mm size fractions (El Samanoudy *et al.,* 1993). In friable self-mulching clay of the vertisol group, 34 years of either stubble burning or incorporation had, however, little effect on soil structure (Dexter *et al.,* 1982).

The nature of plant material also plays an important role in the development of soil structure. For example, Dhoot *et al.,* (1974) recorded the highest percentage of water-stable aggregates in pearl millet-amended soil followed by rice straw or wheat straw and sesbania green manure.

Singh *et al.,* (2007) have shown that addition of various organic manures along with inorganic fertilizers in rice-wheat system improved the aggregation status of the soil. Aggregate ratio varied significantly with treatments. Compared with the control, treatments where more organic matter was added either through FYM, CR and GM maintained a greater fraction of macro-aggregate. Yang *et al.,* (2014) noticed that long-term winter planted green manure (Chinese milk vetch) substantially improved the SOC content and the C: N ratio coupled with redistribution of the macro-aggregates into micro-forms.

Size composition of the soil aggregates

Li *et al.,* (2007) have shown that the aggregated C concentration of coarse macro-aggregates were higher (both under CT, RT and ZT) to those of the meso-aggregates and micro-aggregates. The macro-aggregates were generally formed by soil particles held together by organic residues. Moharana *et al.,* (2012) observed that the highest values of TOC (11.48 g kg^{-1}) and WBC (7.86 g kg^{-1}) were maintained in FYM treated plot, while the highest values of LBC (1.36 g kg^{-1}) and MBC (273 mg kg^{-1}) were found in FYM + NPK. The magnitude of change in pools of SOC in sub-surface (15–30 cm) soil was low as compared to the surface soil (0–15 cm). Das *et al.,* 2014 found that the aggregate strength and density were lower with organic substitution ($p<0.05$) while water retention by aggregates at field capacity was 2–4% higher with organic inputs. Macro-aggregates (>0.25mm) constituted 58–92% of water stable aggregates and varied significantly among treatments and soil depths. Organic material incorporation improved soil aggregation and structural stability and resulted in higher C content in macro-aggregates. Chaudhary *et al.,* 2014 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 >2 mm and 0.1–0.05 mm size fractions, respectively. According to Edwards and Bremner (1967), the only highly stable aggregates are fine sand- and silt-sized micro-aggregates (<250μm) consisting of clay–polyvalent metal–organic matter complexes (Figure 2a). Micro-aggregates are formed by bonding of C–P–OM clay sized units, where C: clay particle, P: polyvalent metal (Fe, Al, Ca) and OM: organo-metal complex, and are represented as $[(C\text{–}P\text{–}OM)_x]_y$.

Tisdall and Oades (1982) reported that implicitly understood that aggregates are sequentially formed, i.e. micro-aggregates are first formed free and then serve as the building blocks for the formation of macro-aggregates. Oades (1984) postulated that the roots and hyphae holding together the macro-aggregate form the nucleus for micro-aggregate formation in the center of the macro-aggregate. Since roots and hyphae are temporary binding agents, they do not persist and decompose into fragments (Figure 2b). These fragments coated with mucilage are produced during decomposition become en crusted with clays resulting in the inception of a micro-aggregate within a macro-aggregate.

Kumar *et al.,* (2016) 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. Mazumdar *et al.,* (2015) also found that 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) reported that compared to conventional tillage, the percentages of >2mm 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. In surface soil (0–15cm), the maximum proportion of total aggregated carbon was retained with 0.25–0.106mm aggregates, and rice-wheat double-conservation tillage had the greatest ability to hold the organic carbon (33.64g kg^{-1})

Naresh *et al.,* (2017) it is evident that the MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 50% RDN as CF+50% RDN as FYM (F_5) and 100% RDN as FYM (F_4) treated plots compared to 100% RDN as CF (F_3) fertilizer and unfertilized control plots. The values of MBC in surface soil varied from 116.8 $mgkg^{-1}$ in unfertilized control plot to 424.1 $mgkg^{-1}$ in integrated nutrient use of 50% RDN as CF+50% RDN as FYM (F_5) plots, respectively; while it varied from 106.6 $mgkg^{-1}$ (control) to 324.9 $mgkg^{-1}$ (100% RDN as FYM F_5) in sub-surface (15-30 cm) soil layer. The values of MBC increased by 58.4 and 72.5% under 50% RDN as CF+50% RDN as CF foliar (F_5) treatment in surface soil over control. While, there were 14.5 and 43.4% increase of MBC over 100% RDF as CF (F_3) fertilizer, respectively. The highest value of MBC due to integrated use of FYM and RDN fertilizer might be due to higher turn-over of root biomass produced under 50% RDN as CF+ 50% FYM treatment.

Aggregate-associated organic carbon

Das *et al.,* (2014) revealed that the 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. Arthur *et al.,* (2012) also 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. Addition of organics also reduces strength of air-dry aggregates, and the effect is most significant with crop residue addition. Das *et al.,* 2014 found stability of aggregates is expressed by the mean weight diameter of the size range, which is proportional to the amount of larger water stable aggregates. Increased amounts of large (>2 mm) macro-aggregate fractions in NPK + GR (rice) + FYM (wheat) and NPK + CR (rice and wheat) are associated with the very large MWD in these treatments. The strong linearity between the MWD and SOC indicates that long-term application of organic amendments can impart a significantly higher stability to the aggregates and thus, highly improves the soil structure (Abrishamkesh *et al.,* 2011).

Six *et al.,* (2000) revealed that the rate of macro- and micro-aggregate formation, stabilization and degradation are directly related to the dynamics of POM-C. Following the incorporation of fresh residue in the soil, soil fungi and other soil microorganisms utilize the more easily available C and produce mucilage's resulting in the formation of macro-aggregates around coarse (>250µm) intra-aggregate POM (coarse iPOM). Coarse iPOM is further decomposed and fragmented into fine (53–250 µm) iPOM. The fine iPOM and associated mucilage's become encrusted with minerals to form the stabilized organic core of a newly developed micro-aggregate within macro-aggregate (Figure 3).The latter process is cut short if the macro-aggregate turnover is increased by disturbance, resulting in a reduced sequestration of C (Six *et al.,* 2000a). Schjønning *et al.,* (2012) observed that 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. 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. Mazumdar *et al.,* (2015) reported 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.

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. 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) and through FYM in clay soil of central India (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). Greater amount of water stable aggregates >0.25 was also reported by Karami *et al.,* (2012) under similar kinds of amendment (rice husk and wheat straw, cow manure) and climate (semi-arid) as in the present study. 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). Green gram residue in rice has less impact on aggregate stability (e.g. P.K. Bandyopadhyay *et al.,* 2010), but becomes effective when combined with FYM in wheat. Higher amount of macro-aggregates through organic amendments and a lower proportion of micro-aggregates imply that addition of organics supports formation of macro-aggregates through binding of micro-aggregates (Huang *et al.,* 2010).

Carbon content and aggregate stability

A higher amount of MicAC (<0.25 mm) that was incarcerated by NPK+GM (52.3%) treatment may be attributed to the nature of the lignin present or the polysaccharides originating from GM that might not have the same ability to bind particles together as those from FYM and PS. Again, the efficiency of the polysaccharides as binding aggregates depends on their location within the aggregated particle (Abiven *et al.,* 2007).

Shrestha *et al.,* (2007) found similar variations under different land uses in Nepal. Upon sieving, C in different size fractions were exposed more and oxidized extra C during chemical reaction for C estimation, than that resulted in bulk soil, which could make differences between them. This possibility cannot be ruled out as the 'silt+ clay' C fraction recovered N50% of soil C under different treatments.

Dou *et al.,* (2008) revealed that reduced tillage practices allow C to build-up in the plow layer by enhancing soil aggregation and reducing oxidation. According to Lewis *et al.,* (2011), increasing tillage intensity could reduce $KMnO_4$-C levels in soils as a result of destruction of soil macro-aggregates and elevated respiration. Lower amount of $KMnO_4$-C, hence is likely under CT due to increased soil disturbances subjecting aggregated protected SOC fraction to rapid decomposition via oxidation.

Particulate organic matter (POM, >53μm) represents a significant proportion of the slow pool of SOM and is important in maintaining the stability of macro-aggregates (>250μm). POM contains about 20-45% of total organic carbon and 13-40% of total soil N (Cambardella and Elliott, 1992).

POM and microbial biomass are considered as biologically active fractions of SOM and are sensitive indicators of management-induced changes in the fate of crop residues and the turnover of SOM constituents. Melero *et al.,* (2011) reported that the magnitude of changes in SOC fractions between conservation tillage practices (ST and NT) and CT ranged in the decreasing order of CPOM-C (17.2–41.8%) > cumulative C_{min} (6.6–22.5%) > $KMnO_4$-C (2.6–4.8%).

These suggest that tillage induced changes were sensitively reflected by the changes in physical (CPOM-C), chemical ($KMnO_4$-C), and biological (cumulative C_{min}) SOC fractions and therefore, can be used to estimate early changes in SOC dynamics.

Bhattacharyya *et al.,* 2013 found that small macro-aggregates accounted for >30% of the total aggregates (mean of both main plots) in the surface soil layer. Silt- plus clay-sized aggregates comprised the greatest proportion of the whole soil, followed by the small macro-aggregates.

Soil organic matter pattern

Soil organisms use residues as a source of energy and nutrients, thereby releasing CO_2, inorganic compounds, and recalcitrant molecules, which contribute to the formation of soil humus. Decomposition of crop residues releases about 55–70% of the C to the atmosphere as CO_2, 5–15% is incorporated into microbial biomass, and the remaining C (15–40%) is partially stabilized in soil as new humus (Stott and Martin, 1989). Because the amount of carbon in soils is large and changes rather slowly, the implications of a particular management system on the soil carbon may be apparent only after several years to decades. Numerous calculations have been made of the amount of residues needed to maintain organic matter at a particular level (Paustian *et al.,* 1997).

Incorporation of both residues increased organic C and total N compared to removal or burning of straw (Dhiman *et al.,* 2000). When only rice or wheat straw was incorporated, organic C content did not differ significantly from removal or burning of straw. Rice straw was more effective in increasing total N content of soil than wheat straw. 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.

Burning and removal of crop residues were at par for their effect on organic C content. In another long-term study, Yadvinder-Singh *et al.,* (2004a) reported that wheat straw incorporation in rice increased organic C content from 0.40% in straw removal treatment to 0.53% in straw incorporation treatment after 12 years of experimentation on a loamy sand soil. The values after 6 years were 0.38 and 0.49%, respectively, suggesting smaller increases in organic C between 6 and 12 years than during 0–6 years.

Naklang *et al.,* (1999) observed no significant effect of rice straw incorporation for 3 years on total and labile C content of a sandy soil. In a rice-barley rotation under dryland conditions in northern India, Kushwaha *et al.,* (2000) observed a significant increase (28%) in soil organic carbon and 33% increase in total N with the incorporation of crop residues compared to their removal after one annual cycle. It was suggested that for soil fertility enhancement in dryland agro-ecosystems, postharvest retention of crop residues (20–40% aboveground biomass) of previous crop and its incorporation in soil through minimum tillage in the succeeding crop should be followed.

Application of rice straw at 10 t ha^{-1} to an upland sandy soil caused a net increase in soil C by 0.31 t ha^{-1} over no rice straw treatment (Ono, 1989). The increase in C represented 8% of the C applied in rice straw. At higher rates of straw addition, the net increase in soil C was increased but the percent C increase did not change significantly. The soil C buildup in the soil was significantly positively correlated with %N and negatively correlated with C: N ratio. Adiningsih (1984) reported that incorporation of rice straw into the soil for 4 years increased the soil organic matter content from 2.4 to 3.9% and total N content from 0.25 to 0.33% over straw removal in Indonesia. In China, Liu and Weng (1991) found that returning rice straw to rice fields for 2 years usually increased soil organic matter content by 0.03 to 0.05%. From a long-term field experiment in Japan, Gotoh *et al.,* (1984) estimated that 13 to 25% of the organic matter returned to soil through rice straw was incorporated into the soil organic matter in a slowly permeable grey lowland soil. In a long-term study on a rice–wheat cropping system in northwestern India, the incorporation of crop residues along with green manure in rice increased soil organic carbon and total N contents as compared to straw removal, but the increase was almost similar to that when crop residues were applied alone. These data suggested little effect of green manure on soil organic matter content in semi-arid climates, particularly in coarse-textured soils Ponnamperuma (1984).

Naresh *et al.,* (2015) reported that average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+ FYM treatment. Compared to F_1 control treatment the RDF+FYM treatment sequestered 0.33 Mg C ha^{-1} yr^{-1} whereas the NPK treatment sequestered 0.16 Mg C ha^{-1} yr^{-1}. Naresh *et al.,* (2017) found that the quantities of SOC at the 0-400 kg of soil m^{-2} interval decreased under ZT without residue (T_1), PRB without residue (T_4) and Conventional tillage (T_7) treatments evaluated. Stocks of SOC in the top 400 kg of soil m^{-2} decreased from 7.46 to 7.15 kg of C m^{-2} represented a change of -0.31 ±0.03 kg of C m^{-2} in T_1, 8.81 to 8.75 kg of C m^{-2} represented a change of -0.06 ±0.05 kg of C m^{-2} in T_4, and 5.92 to 5.22 of C m^{-2} represented a change of -0.70 ±0.09 kg of C m^{-2} in T_7 between 2000 and 2016 (Table 1).

Soil Organic Carbon Distribution

Majumder *et al.,* (2008) reported 67.9% of C stabilization from FYM applied in a rice–wheat sys-tem 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). Soil C: N ratio was significantly influenced by tillage system, residues and N rates, being decreased with chisel treatment and increased residues and N rates (75–150 kg ha^{-1}) in both years. The C: N ratio is related to the changes in soil C and N contents. The C: N ratio of soil is related to the patterns of N immobilization and mineralization during organic matter decomposition by microorganisms and is negatively correlated with net N mineralization (Van Den Bossche *et al.,* 2009). Alijani *et al.,* 2012 revealed that the soil with chisel treatment had about 8 and 15% more soil organic carbon (SOC) and total N than moldboard plow treatment, respectively. Incorporation of increased amounts of corn residues and a higher N rate reduced C: N ratios in the chisel treatment in both years.

According to Chatterjee and Lal (2009), crop residues are left on the soil surface under NT and ST practices whereas residues are incorporated in the soil during tillage under CT, thereby favoring increased mineralization of CPOM-C by soil microbes under the latter. Similarly, tillage induces the disruption of soil aggregates, and, increased exposure of soil aggregate protected CPOM-C to microbial decomposition following the collapse of aggregates by increased tillage intensity (CT) as compared with reduced tillage (ST and NT) may have contributed to the low levels of CPOM-C under CT treatment (Mikha and Rice, 2004).

Chaudhary *et al.,* 2014 also found 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 g kg^{-1} soil aggregates) with the highest stratification ratio of SOC (1.5). Plante and McGill (2002a) suggested that the relationship between physical protection of SOM and the turnover of macro-aggregates differs for fresh residue versus stabilized SOM. For stabilized SOM, the slower the macro-aggregate turnover the higher the protection level. An intermediate aggregate turnover would be optimal for newly incoming fresh residue because a certain aggregate turnover is needed to have aggregate formation and occlusion and subsequent protection of C within the aggregates. However, we suggest that macro-aggregate turnover in most ecosystems is never so slow that it hinders the stabilization of C (Figure 4).

Paudel *et al.,* (2014) showed that, soil organic carbon buildup was affected significantly by tillage and residue level in upper depth of 0-20 cm but not in lower depth of 20-40 cm. Higher SOC content of 19.44 g kg^{-1} of soil was found in zero tilled residue retained plots followed by 18.53 g kg^{-1} in permanently raised bed with residue retained plots. Whereas, the lowest level of SOC content of 15.86 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots. Naresh *et al.,* (2015) revealed that the highest SOC stock of 72.2Mg C ha^{-1} was observed in F_4 with T_6 followed by that of 64Mg C ha^{-1} in F_6 with T_2> that in F_3 with T_4 (57.9Mg C ha^{-1})> F_5 with T_1 (38.4Mg Cha^{-1}) = F_7 with T_5 (35.8Mg C ha$^{-1)}$, and the lowest (19.9Mg C ha^{-1}) in F_1 with T_7. Relatively higher percentage increase of SOC stock was observed in F_4 with T_6 treatment (56.3Mg Cha^{-1}) followed by F_6 with T_2 (51.4Mg Cha^{-1}) and F_3 with T_1 (48.4Mg Cha^{-1}). Xue *et al.,* (2015) found that over time, CT system generally exhibit a significant decline in SOC concentration due to destruction of the soil structure, exposing SOM protected within soil aggregates to microbial organisms. 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. Pandey *et al., (*2014) revealed that no-tillage before sowing of rice and wheat could increase SOC by 0.59 Mg C $ha^{-1}yr^{-1}$. The rate of SOC sequestration due to reduced- or no-tillage management in rice-based systems in South Asia varied from 0- to 2114 kg ha^{-1} yr^{-1} (Bhattacharyya *et al.*, 2012a).

Carbon dynamics

The combined effects of land use patterns and their changes can influence SOM content considerably, as they exert control on common factors determining the soil system (e.g., quality of biomass input, biomass decomposition rates, and pace of organic matter stabilization) (Gelaw *et al.,* 2014) (Figure 6). It was reported that the SOC pool can be cumulatively affected due to fertilization, tillage, crop rotation, and soil water conservation farming (Hao *et al.*, 2002). Hence, SOC content was found to increase substantially with the application of adequate fertilizer (N and P) in semiarid southwestern Saskatchewan (Campbell *et al.,* 2000). Many studies have advocated the usage of organic inputs toward achieving better soil quality with elevated SOC content, enhanced agronomic stability, and improved soil structure (Bhattacharyya *et al.*, 2008).

Different types of amendments (compost, green manure, bio-fertilizer, and raw wastes) on planet soil systems not only showed very similar patterns, but were also identified as very dependent on considerable variability (e.g., agricultural techniques, climate, soil type and texture, and material characteristics). Among the numerous changes associated with soil properties, biochemical and microbiological properties have been identified as very sensitive to additional organic inputs by soil modification (Abd El-Fattah *et al.,* 2013).

Artificial organic inputs in the form of organic modifications continuously provided various indispensible nutrients to microbial communities due to the slow decomposition kinetics of organic matter (Murphy *et al.*, 2007); such inputs were superior to mineral fertilizer with many known versatile advantages. Application of organic inputs via soil amendment significantly enhanced the cation exchange capabilities due to the negative charge induced by organic carbon (Weber *et al.*, 2007; Kaur *et al.*, 2008): these capabilities are a very important contributor to detainment of various nutrients from organic inputs and for nourishing agricultural plants. Lastly, 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 (Carter, 2002).

Continuous application of chemical fertilizers coupled with farmyard manure led to a significant increase in SOC and total N compared to adjacent fallow land in a eutrochrept soil (Reddy *et al.,* 2003). However, long-term use of inorganic fertilizers (N, P, and K) without organic nutrient sources may lead to significant degradation of soil quality and subsequent loss of SOC (Fan *et al.*, 2005). Mozumder and Barrens (2007) opined that excessive use of chemical fertilizers should impose adverse effects on the soil biodiversity which can invariably harm its functioning. Consequently, optimization of chemical fertilization with organic substitution is a better and safer proposition to sustain soil health (Saikia *et al.*, 2015).

Lima *et al.,* (2009) advocated that long-term application of farmyard manure enriches SOM with carbohydrates as well as lignin and lignin-like products. A positive correlation between the soil quality index (SQI), SOM, and crop yield was observed from farm compost (D'Hose *et al.,* 2014). Incorporation of municipal solid waste compost (MSWC) and farmyard manure to soil enhanced the SOM by 2.2 and 2 times, respectively (Hemmat *et al.,* 2010).Bhattacharya *et al.,* (2012) reported a significant increase in SOC after enriching typical red and lateritic soil with coal fly ash vermin-compost. Lin *et al.,* (2008) observed a very large 59-63% increase in SOC after incorporation of green manure in conjunction with industrial waste water. An overall relative increase in the SOC content was achieved under green manuring with *Sesbania rostrata*, *Sesbania aculeate*, and green gram residue over fallow in a rice field (Mandal *et al.,* 2003).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.

Crop residue and carbon sequestration

Duxbury and Lauren (2004) revealed that an average, soil C stock increased by 1.48 tha^{-1} when residues were added. The total amount of residues added over the period of 7 years was 29.5 t/ha or 14.75tC ha^{-1}. Thus, C retention was 10% of that added or 0.21 t C $ha^{-1}yr^{-1}$. Puget and Drinkwater (2001) in their study with leguminous green manure observed that nearly half of the root derived C was still present in the soil after one growing season in comparison to only 13% of shoot-derived Singh and Sidhu (2014) found that zero-till sowing of wheat with rice residue as surface mulch, while maintaining yield, reduces tillage costs and time saving, avoids the need for burning. Dikgwatlhe *et al.,* (2014) further argued that the amount of SOC storage depends on the balance between the quantity and quality of SOM inputs outputs which is largely determined by the combined interaction of climate, soil properties and land use management. Verma and Bhagat (1992) have also recorded the maximum soil build-up of organic carbon under the rice straw chopped and incorporated with animal manure, followed by animal manure and straw mulch, while minimum organic carbon under rice straw burnt and rice straw removed. Less carbon sequestration in bed planting than zero tillage in same level of residue retention in this cropping system might be due to earlier dryness, less microbial population and less decomposition in bed during wheat season. The variation of soil organic carbon sequestration also depends on difference in microbial populace, moisture and temperature fluctuation (Govaerts *et al.,* 2009).

Verma and Pandey, (2013) found that significantly higher organic carbon content was recorded with rice residue incorporation with application of 30% additional N+P+K + recommended NPK and rice residue incorporation with application of 15% additional N+P+K + recommended NPK against sowing of wheat without incorporation of rice residue + recommended NPK. It is probably due to the fact that addition of carbonaceous substances in soil which on decomposition added organic matter. Moreover, residue retention on soil surface has also been shown to increase the amount of SOC concentration (Wilhelm *et al.,* 2004). In a long term study (11 years) conducted by Dikgwatlhe *et al.,* (2014) it was found that zero-tillage with residue retention resulted in an increase of SOC in the 0–10 cm soil layer compared to rotary tillage with residues incorporated and PT with residue retention and removed. Similar results were observed by Blanco- Canqui and Lal, (2008) in a CA study conducted over a period of 10 years. The rate of residue decomposition depends not only on the amount retained but also on the characteristics of the soil and the composition of the residues (Verhulst *et al.,* 2010). In previous studies, higher soil organic

C contents under zero till with residue return than under conventional tillage (Razafimbelo *et al.*,2008), under reduced tillage than under conventional tillage (Šimanský *et al.*,2008), have been reported. Lin *et al.,* (2008) observed a very large 59-63% increase in SOC after incorporation of green manure in conjunction with industrial waste water. An overall relative increase in the SOC content was achieved under green manuring with *Sesbania rostrata*, *Sesbania aculeate*, and green gram residue over fallow in a rice field.

Chen *et al.,* (2009) observed that shallow tillage (with residue retention) and ZT (with residue retention) treatments had 14.2 and 13.7% higher total SOC than CT (without residue retention) in the upper 15-cm soil layer after 11 yr of maize (*Zea mays* L.) mono-cropping in the Loess Plateau of China. Gershenson *et al.,* (2009) reported that T_3 (FYM treatment) and T_5 (crop residue treatment) had lower activation energies of SOC decomposition among the organic treated plots indicating a lesser thermal sensitivity for macro-aggregate carbon. However a perusal of the Q_{10} values shows that SOC in macro-aggregates of T_5 (Q_{10}> 2) is highly temperature responsive and the higher activation energy is due to chemical recalcitrance of the residues which is overcome with rises in temperature. Song *et al.,* (2016) indicates that it is necessary to consider deeper soil when assessing the influence of tillage practices on soil organic carbon. Particularly in farmland under rice-wheat rotation, different tillage practices combined with the alternating wet and dry soil environment cause quantitative changes in the soil organic carbon of deep soil. However, compared to zero tillage, conventional tillage, such as ploughing, incorporates organic materials, including straw mulch at the soil surface and residual roots in shallow soil, into deeper soil. 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 Pinheiro *et al.,* (2004).

Fig.1 A generalized summary of soil aggregates stabilization by various sources of organic matter *Source*: (Dalal and Bridge, 1996)

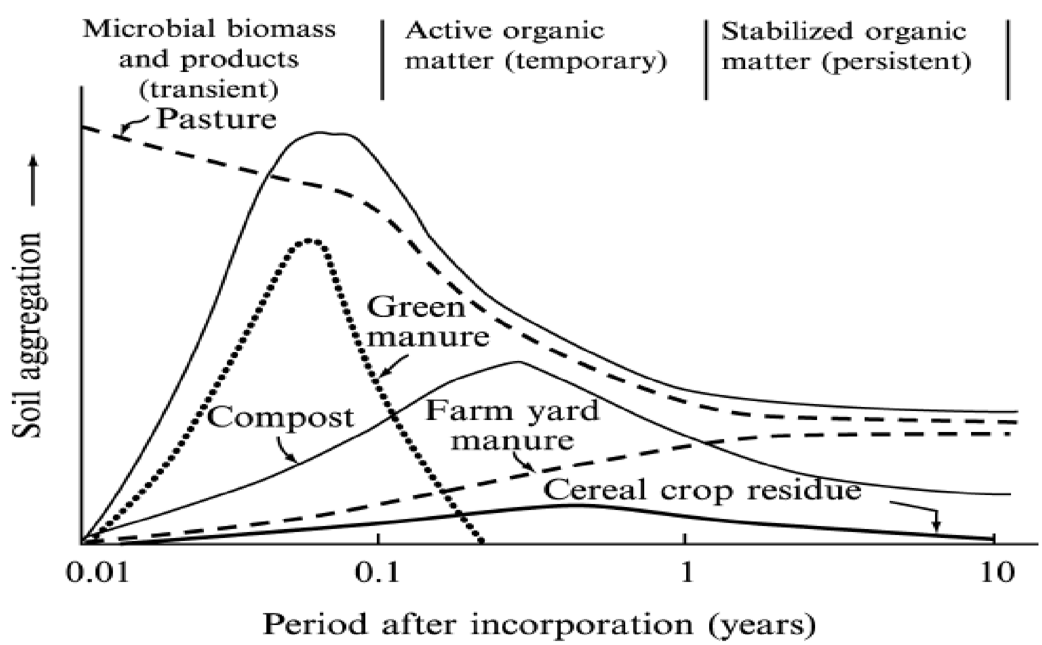

Fig.2a The multiplicity of interactions and feedbacks formation and stabilization described by Tisdall and Oades (1982) vs. postulated by Oades (1984). **Fig.2b** The opposing chronology of the formation between the five major factors influencing aggregate of the hierarchical aggregate orders implicitly

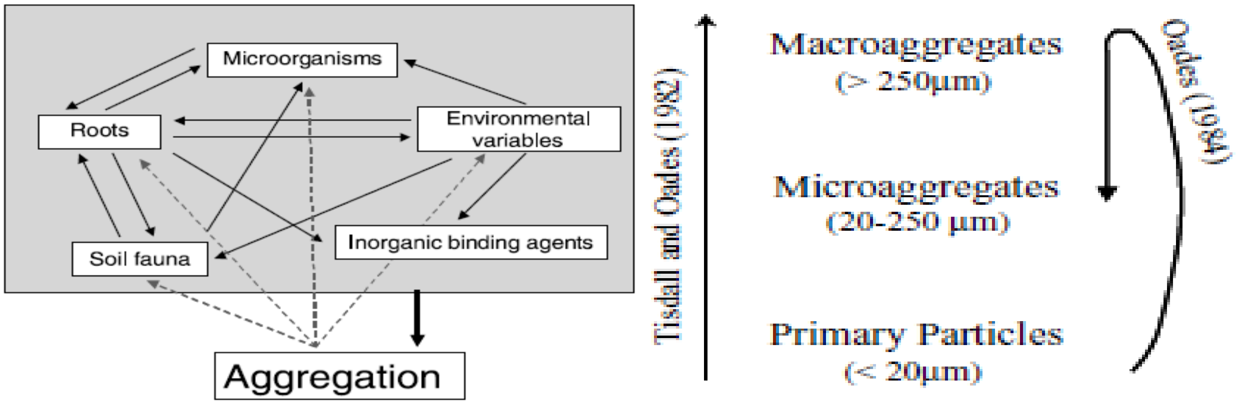

Fig.3 This conceptual model of the 'life cycle 'of a macro-aggregate shows the formation of new micro-aggregates within-macro-aggregates and the accumulation and mineralization of aggregate-associated organic C (Adapted from Six *et al.*, 2000)

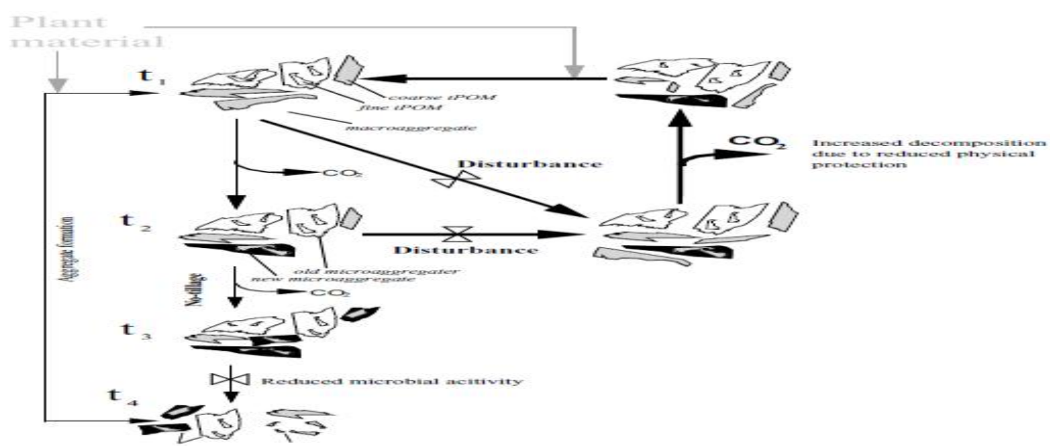

Fig.4 Change in aggregate turnover and mineralization of newly added C input across ecosystems representing a range of disturbance regimes. Figure based on Plante and McGill (2002a)

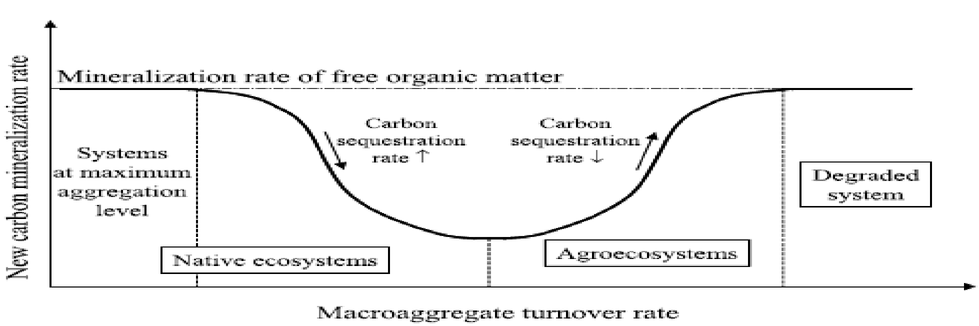

Fig.5 Relationship between the Henin instability index (Is) and infiltration rate (k). Adapted from Maymard and Combeau, 1960

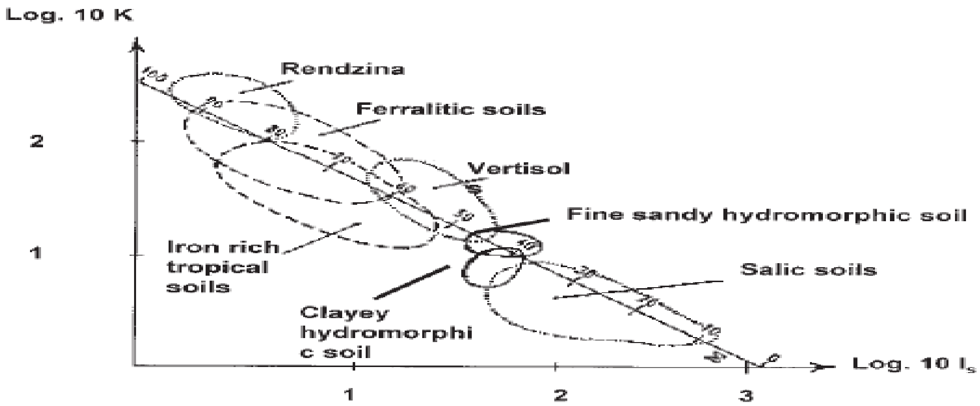

Fig.6 The C dynamics within different spheres of the earth as of 2013 (IPCC Climate report, 2013)

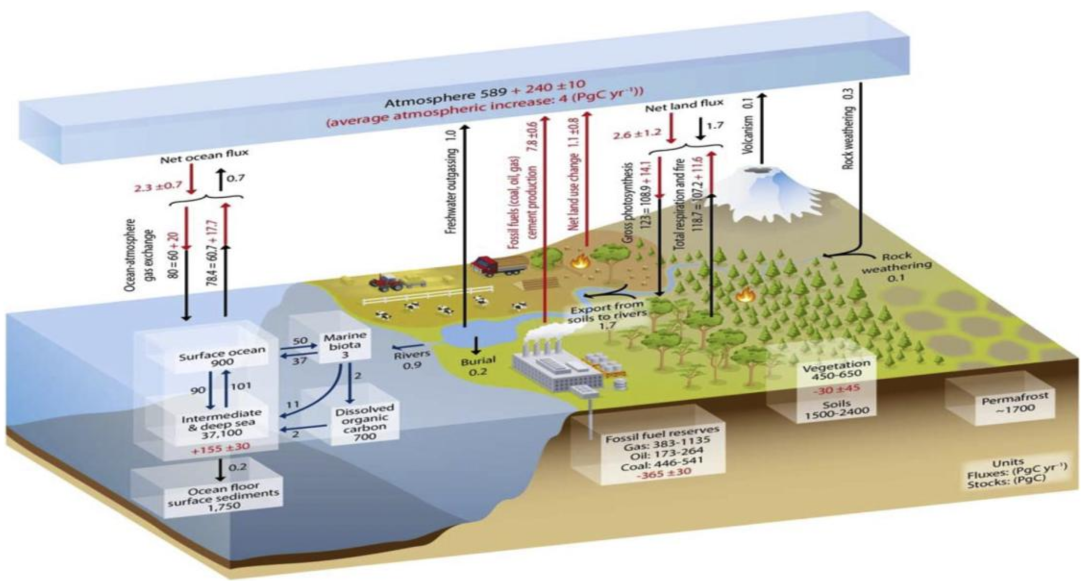

Fig.7 Scientist and farmers evaluate chopped and retained stubbles for their efficacy in soil carbon

Fig.8 Aggregate formation and degradation mechanisms in temperate and tropical soils. Fungal and bacterial activity, active root growth and earthworm activity are the biological aggregate formation agents in both temperate and tropical soils, whereas the mineral-mineral interactions in tropical soils are the physicochemical aggregate formation agents

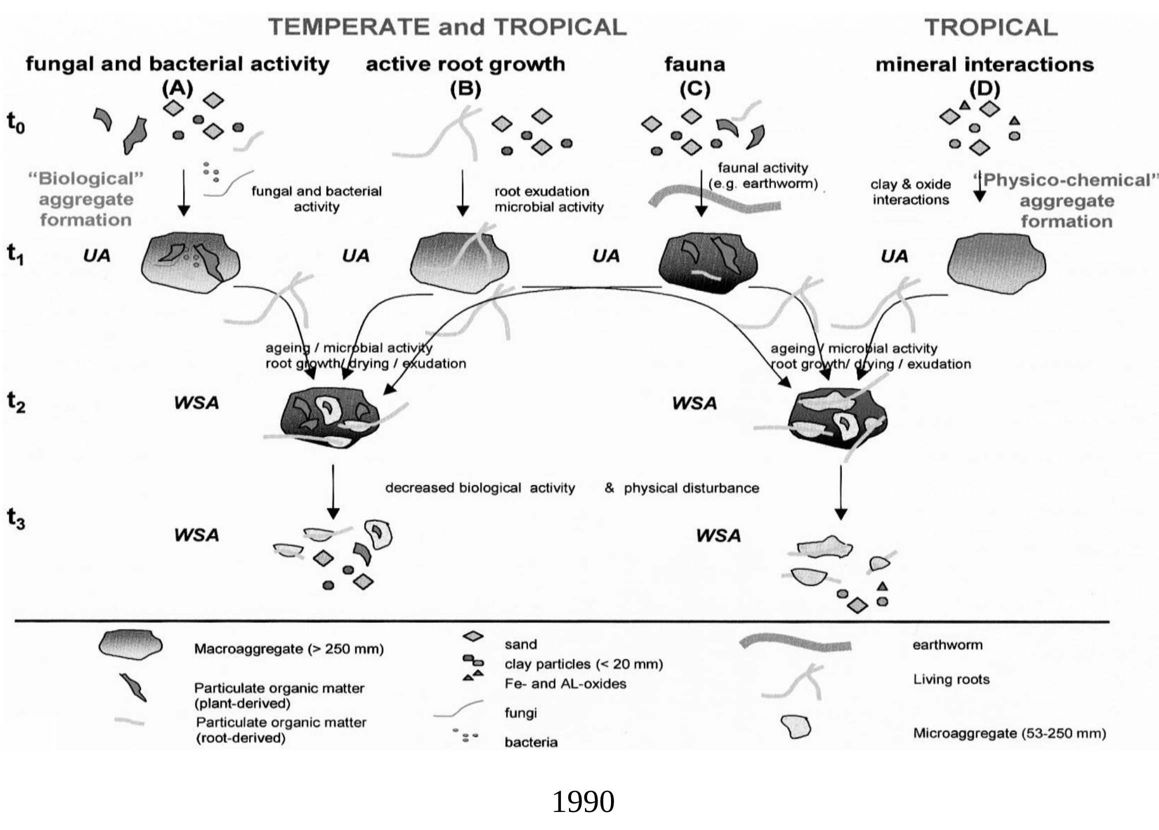

Table.1 Changes in soil physical and biological health indices in 100 year permanent trial in an Alfisol at Coimbatore

Treatment	Soil Depth (cm)	1983 (Rainfed)			2009 (Irrigated)		
		Bacteria	Fungi	Actinomycetes	Bacteria	Fungi	Actinomycetes
		10^6 /g	10^4 /g	10^4/g	10^6 /g	10^4 /g	10^4/g
Control	**0-5**	19.2	7.2	2.3	34.9	8.1	8.9
	5-15	10.8	1.8	1.2	26.6	2.6	6.5
	15-30	8.7	0.5	1.1	20.0	1.9	4.3
NPK	**0-5**	22.3	14.2	7.7	83.5	31.8	16.5
	5-15	14.4	3.7	4.7	43.6	8.6	14.4
	15-30	9.4	1.3	1.9	15.9	3.9	9.5
Cattle manure	**0-5**	26.8	10.3	9.5	103.0	39.6	20.4
	5-15	16.2	6.0	6.8	90.6	17.5	11.2
	15-30	13.7	2.9	4.0	68.9	4.6	8.1

** Source: Boopathi et al., (2011)*

Table.2 Changes in bacterial and fungal numbers and soil microbial biomass 21 weeks after the growth of inoculated BGA in surface one cm of a brown earth soil in UK

Property	Dark Control	Inoculated Cyanobacteria
Bacteria (x 10^7)	17.5	48.4
Fungi (x 10^4)	1.7	2.7
SMBC[a] (mg C 100 g^{-1})	59.2	118.6
Dehydrogenase[b]	50.9	107.5
Urease[c]	1.31	3.61
Phosphatase[d]	0.44	1.40
Polysaccharides[e]	3.94	6.67
Stability index[f]	0.787	0.818

[a] mg C 100g^{-1} soil; [b]µg TPF g^{-1} soil in 24 h; [c]µ mol NH_3 g^{-1} soil h^{-1}; [d]µg PNP g^{-1} h^{-1}, [e]mg glucose g^{-1}, [f]indirect measure of POM.
Source: Rao and Burns (1990).

Table.3 Organic carbon and biological activity under different tillage practices at the end of four cropping cycles in North-east India

Treatment	Organic carbon (%)	SMBC (µg/g soil)	Earthworm population	Dehydrogenase activity (µg TPF/g/24 h)
Conventional tillage	1.47	91.3	60,000	29.5
Zero tillage	2.23	128.5	1,60,000	131.5
Double no-till	2.51	134.1	3,80,000	166.6
Minimum tillage	2.17	121.3	1,00,000	127.5
CD(P=0.05)	0.78	12.1	-	27.5

OC, organic carbon; SMBC, Soil microbial biomass carbon
Source: Ghosh et al., (2010).

Table.4 Effect of fertilizers on soil biological properties in a pearl millet-wheat rotation in a sandy loam at Hisar.

Treatment	% Org C	% N	SMBC	SMBN	Bacteria, 10^6 /g	DHA
$N_0P_0K_0$	0.42	046	150	18	7	53
$N_{60}P_{30}K_{60}$	0.40	0.059	270	51	48	87
$N_{120}P_{60}K_{60}$	0.49	0.062	368	68	63	75
LSD p=0.05	0.02	0.003	42	13	16	9

**SMBC, SMBN= mg kg^{-1} soil, Dehydrogenase, DHA = µg triphenyl formazon g^{-1} soil 24 h^{-1},*
Source: Goyal et al., (1992).

Naresh *et al.,* (2017) revealed that the average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+FYM treatment and increased enzyme activities, which potentially influence soil nutrients dynamics under field condition. 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 ZT and PRB since under CT, SOC stock decreased even below the plow layer. Increased SOC stock in the surface 50 kg m^{-2} under ZT and PRB was compensated by greater SOC stocks in the 50-200 and 200-400 kg m^{-2} interval under residue retained, but SOC stocks under CT were consistently lower in the surface 400 kg m^{-2}. Over the last 16 years, CT lost 0.83 ±0.2 kg of C m^{-2} while ZT gain 1.98 ±0.3 and PRB gain 0.97 ±0.2 kg of C m^{-2} in the 1200 kg of soil m^{-2} profile. These findings suggest that carbon sequestration can be improved if treatments T_4 or T_6 are used in lieu of T_7, respectively

Organic agriculture and carbon sequestration

Feng and Li (2001) concluded that for the same carbon input, carbon storage in soil was higher by 1.18 t ha^{-1} C with manure application than with plant residues. Whalen and Chang (2002) reported that manure application promoted the formation and stabilization of soil macro aggregates. Liu *et al.,* (2005) found that the profile average SOC content (0- 90 cm) was only 0.9%, 4.1%, and 8.6% higher for manure, chemical fertilizers, and manure plus fertilizers, respectively, than that with no fertilizer application or control in the Chinese Mollisols. However, SOC at the 0- 15 cm soil layer was 6.2%, 7.7%, and 9.3% higher with manure, chemical fertilizers, and manure plus fertilizers, respectively, than with no fertilizer application. These results indicated that the annual rate of decline rate of SOC in the 0 15 cm layer without fertilizer was not very high (< 0.58%/yr) when a well-designed crop rotation was used (Table 3).

Kukal *et al.,* (2009) revealed that application of FYM and inorganic fertilizer in rice-wheat and maize-wheat cropping systems. They reported that the SOC sequestration rate was higher in FYM plots in comparison to NPK plots in both the cropping systems. Also the sequestration rate was three times higher in rice-wheat than in maize-wheat cropping system. Parker *et al.,* (2002) who obtained 7-20% higher organic carbon in top soil layer (5 cm) in cotton-rye cropping system with poultry litter as compared to fertilizer. In organic agriculture, biomass is not burned. It reduces the N_2O emissions by 0.6-0.7Gt CO_2 e yr^{-1} in comparison to conventional agriculture (Smith *et al.,* 2007). Organic systems are highly adaptive to climate change due to: (a) the application of traditional skills and farmers' knowledge, (b) soil fertility-building techniques, and (c) a high degree of diversity. Liu *et al.,* (2013) revealed that the average concentration of particulate organic carbon (POC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in organic manure plus inorganic fertilizer treatments (NP+S and NP+FYM) in 0–60 cm depth were increased by 64.9–91.9%, 42.5–56.9%, and 74.7–99.4%, respectively, over the CK treatment. Niggli *et al.,* (2009) found that an organic approach 40 per cent of the GHG emissions of agriculture could be mitigated by sequestering carbon into soils at rates of 100kg of C ha^{-1} yr^{-1} for pasture land and 200kg of C ha^{-1} yr^{-1} for arable crops. By combining organic farming with reduced tillage, the sequestration rate can be increased to 500kg of C ha^{-1} yr^{-1} in arable crops as compared to ploughed conventional cropping systems, but as the soil C dynamics reach a new equilibrium, these rates will decline in the future. This would reduce GHG emissions by another 20 per cent. Organic farming is an important option in a multifunctional approach to climate change. Application of 50% N through different organics (FYM, green manure or wheat cut straw) plus 50% NPK through chemical fertilizers were better over other treatments in respect of soil organic carbon of soil (Sepehya *et al.,* 2012). Bhattacharyya *et al.,* (2008) have advocated the usage of organic inputs toward achieving better soil quality with elevated SOC content, enhanced agronomic stability, and improved soil structure. Abd El-Fattah *et al.,* (2013) also found that different types of amendments (compost, green manure, bio-fertilizer, and raw wastes) on plant soil systems not only showed very similar patterns, but were also identified as very dependent on considerable variabilities (e.g., agricultural techniques, climate, soil type and texture, and material characteristics). Among the numerous changes associated with soil properties, biochemical and microbiological properties have been identified as very sensitive to additional organic inputs by soil modification (Table 4).

Beesley *et al.,* (2014) opined that incorporation of organic manure to the soil should substitute for lost C which in turn should modulate the dynamics of soil C pools. Apart from the addition of essential nutrients to the soil, organic inputs also eradicate the problems of heavy metal pollution to a considerable degree. Naresh *et al.,* (2017) revealed that the carbon (C) sequestration is a cost-effective strategy to mitigate climate change during the first few decades of the 21st century. There are five global C pools, and the third largest pool exists in soil and is estimated at 2.5 trillion tons (1-m depth). The conversion of natural ecosystems to agricultural ecosystems disturbs the soil ecological balance, soil processes, organic C, and biotic C pools.

Microbial population and activity

Residue incorporation into the soil leads to increased bacterial and fungal activities (Beare *et al.,* 1996; Doran, 1980). For example, protein decomposing microorganisms increased during the early stages of incubation of rice straw under waterlogged conditions (Fujii *et al.,* 1972), which was followed by an increase in the population of cellulose-decomposing microorganisms. Sulphate-reducing microorganisms then increased after a lag phase. Nugroho and Kawatskka (1992a) observed that application of rice straw (C: N = 52:1) increased all the microbial populations.

In that study, simultaneous application of rice straw and NH^{+}_{4} –N to soil under upland conditions increased the number of denitrifiers but significantly depressed the N2 fixation activity. Beri *et al.,* (1992) also observed that soil treated with crop residues inhabited 5–10 times more aerobic bacteria and 1.5–11 times more fungi than the soil for which residues were either burned or removed. Fujii *et al.,* (1970), in contrast, found that with a short-term incubation period (10 or 20 days) in an aerobic soil, the population of nitrifying bacteria was higher in the absence of rice straw, but the reverse was true with longer incubation periods (60 or 90 days). Ladatko and Emtsev (1984) observed marked increase in the growth of Clostridium spp. in a soil amended with rice straw. The increase in the growth of anaerobic microorganisms was due to the formation of artificial anaerobic micro-sites around the straw particles. Last but not least, residue quality may affect the microbial population, as smaller bacterial and fungal populations are greater on cereal residues compared to those on legumes. As compared to bacteria, fungi are more influenced by residue quality (Wardle, 1995).

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. Following the incorporation of fresh plant material, microorganisms utilize the more easily decomposable carbohydrates, yielding intra-aggregate POM (iPOM). Wang and Bakken (1997b) reported that the depressing effect of plant uptake of N on soil microbial biomass was much pronounced in N poor barley straw layer suggesting that microbial growth in soil can be limited by nutrient supply rather than C availability. In our study, half early/half late N treatment had higher C substrate with lower available N concentration than the full N treatments. 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. Wuest *et al.,* (2005) observed that Residue retention can have a varying effect on earthworms, however, depending on their ecological niche, as tillage may benefit endogeic (horizontal-burrowing) earthworms if residue is incorporated into the soil, providing a food source.

The effect of crop residue on earthworms and other soil fauna can thus vary depending on tillage frequency, plow depth, residue incorporation, and crop residue type, amount and quality (Eriksen-Hamel *et al.,* 2009).

Based on Six *et al.,* (200b), Jastrow (1996), Kemper Rosenau (1986), Wander and Yang (2000).

UA = unstable aggregates; WSA = water-stable aggregates.

Ha *et al.,* (2008) reported that different residues resulted in different levels of POM, which cultivate distinct microbial communities. 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. A majority of the microbes in the soil exist under starvation conditions and thus they tend to be in a dormant state, especially in tilled soils. Wang *et al.,* (2012) reported increased microbial biomass carbon with crop residue application in comparison to no crop residue application. Moharana *et al.,* (2012) revealed that the highest values of TOC (11.48 g kg^{-1}) and WBC (7.86 g kg^{-1}) were maintained in FYM treated plot, while the highest values of LBC (1.36 g kg^{-1}) and MBC (273 mg kg^{-1}) were found in FYM + NPK. The magnitude of change in pools of SOC in sub-surface (15–30 cm) soil was low as compared to the surface soil (0–15 cm). Significant increase in all the pools of SOC in FYM treated plots indicates the importance of application of organic manure like FYM in maintaining organic carbon in soil.

Naresh *et al.,* 2016 showed that in 3-year experiment LFON content in 0 - 5 cm soil layer of CT system, T_1, and T_5 treatments increased LFOC content from 5.1 $mg{\cdot}kg^{-1}$ in CT (T_9) to 7.9 and 9.6 $mg{\cdot}kg^{-1}$ without CR, and to 10.3, 11.5 and 13.1 $mg{\cdot}kg^{-1}$ with crop residue @ 2, 4 and 6 tha^{-1}, respectively. Compared to conventional tillage (CT), no-tillage and reduced tillage could significantly improve the SOC content in cropland. The enhanced microbial activity induces the binding of residue and soil particles into macro-aggregates, which could increase aggregates stability thus improving the concentration of SOC and increasing C sequestration (Liqun *et al.,* 2014). Carbon input in the form of crop residue had primary factor for stabilization of soil carbon (Singh, 2011). The microbial activity was found more on residue retained plots (Mandal *et al.,* 2004) so that soil organic carbon level increased with the residue retention (Duiker and Lal, 1999). Berger *et al.,* (2013) enumerated the effectiveness of a mixed biofertilizer (phosphate and potash rocks + earthworm compound + free living diazotrophic bacteria and *Cunninghamella elegans*) on increased nodulation and yield in cowpea.

Macroorganisms

Earthworms and micro-arthropods play a dominant role in organic matter decomposition and nutrient cycling associated with different crop residue management systems (Prasad and Power, 1991; Tian *et al.,* 1993). Although enough information is not available from rice-based cropping systems, residue quality greatly influences macroorganism populations in the soil. For example, the earthworm population was negatively correlated with the C: N ratio, lignin: N ratio, and polyphenol concentration of the plant material (Tian *et al.,* 1992), and the population of ants were significantly correlated to N concentration of plant residues (Tian *et al.,* 1993). Nayak *et al.,* (2007) has been shown that although organically farmed soils had greater microbial abundance and activity, as also higher number of bacterial-feeding nematodes than those managed under conventional farming practices, the ability of microbial communities *per se* in the two soils (chemically or organically fertilized) to degrade added organic matter did not differ. Wuest (2014), Lou *et al.,* (2012), Sun *et al.,* (2010) also explained the slight differences in the SOC and TN concentrations in the whole profile between the two years can be attributed to the difference in the activities of soil microorganisms and the rate of residue decomposition due to the seasonal variation in soil temperature and moisture regimes. The results presented herein indicate that soils with retained rice residue had higher SOC and TN concentrations at all soil depths than that with the rice residue removed in both years.

(Boopathi *et al.,* 2011) reported that the results of the permanent manurial trial started in 1909 at Coimbatore show that NPK and cattle manure (CM) applied (12.5 t/ha) were mostly at par. SOC change during 2003-08 was +0.18% in NPK fertilized and +0.19% in manure treated plots (Table 1). The CM treatment did not show much improvement in soil aggregation over NPK. Microbial population under rained conditions (measured in 1983) was similar while in irrigated condition (in 2009) CM-treated plots had higher microbial population over NPK plots. Rao and Burns, (1990) observed that inoculation with BGA in submerged soils improves the general health of soils through building up organic matter, stimulating the bacterial and fungal populations, microbial biomass, soil enzyme activities, polysaccharide production and soil aggregation (Table 2). Wang *et al.,* (2012) also found that the mycorrhizae biomarkers were significantly enriched under no-till treatments, which has also been observed for other cropping systems like rotated maize and wheat. This study was able to establish linkages between shifts in the microbial community structure due to no-tillage that were associated with greater activities of key enzymes of C and N (b-glucosidase), N (b-glucosaminidase) and P cycling (phosphodiesterase) relative to till. The shift in microbial community structure, and increased enzyme activity found under no-till for this soil under cotton production provides evidence that it can take several years of surface residue accumulation for this particular crop. Gunapala *et al.,* (1998) found that the ability of soil microorganisms to decompose added organic matter was the same in organic or conventional systems and that microbial diversity was not compromised by chemical farming with the conclusion that integrated systems are the best. Waring *et al.,* (2013) revealed that reduced tillage is expected to increase the ratio of fungal to bacterial (F: B)-FAME biomarkers. Besides minimal disruption of their hyphal networks, the abundance of fungi has been hypothesized to be greater under reduced tillage mainly because of their cell structural composition comprised of chitin that is more resistant to degradation and has been linked with greater soil C sequestration.

Enzyme activities

Barreto and Westerman (1989) and Gill *et al.,* (1998b) observed a significant increase in urease activity in surface soils after incorporation of wheat straw. Likewise, Guan (1989) reported that application of wheat straw increased the invertase activity of soil by 40–90 times compared to the control treatment in both laboratory and field experiments and that the activities of urease and alkaline phosphatase were also increased by wheat straw additions. Gialhe *et al.,* (1976) observed that dehydrogenase activity increased with rice and wheat straw incorporation and was further increased by N application. Goyal and Chander (1998) also reported an increase in the microbial biomass and dehydrogenase and alkaline phosphates activities with the addition of wheat straw to a sandy loam soil. Rao, (2007) found that the soil microbial biomass was highest under rice-clover, lowest under rice-mustard and intermediate in rice-wheat and sorghum-wheat systems. Metabolic quotient, qCO_2 was higher in rice-clover and rice-mustard as compared to rice-wheat with sorghum-wheat being the lowest. Higher organic carbon, respiration and dehydrogenase activity reflects the influence of more readily available carbonaceous substrates and a greater ‘zymogenous’ microbial population.

Rupela *et al.,* (2005) reported that in an experiment on low-input farming at the ICRISAT Center, near Hyderabad, no- tillage along with addition of rice straw mulch or farm waste mulch (microbial inoculants and bio-pesticides were applied in both) was compared with conventional tillage system with (i) NP fertilizers plus chemical pesticides and (ii) an integrated system involving chemicals and biomass mulch. After 5 years, SOM content, microbial biomass and soil respiration were higher in the two organic plots (with no-till and biomass mulch) as compared to conventional, chemical farming with normal tillage, but highest in the integrated (chemical + plant biomass residue) treatment with normal tillage. In a 2-year field experiment on a sandy loam soil in north India on wheat, conservation tillage significantly increased soil respiration (+81.1%), SBMC (+104%) and soil dehydrogenase activity (+59.2%) compared to conventional tillage (Sharma *et al.,* 2011). Similarly, in a field study on four tillage practices in NE India on ricewheat/mustard/linseed, zero tillage (residue retention and double no-till) recorded higher SMBC, dehydrogenase activity and earthworm population which in turn resulted in good growth and higher yield of all the crops (Ghosh *et al.,* 2010).

Sa *et al.,* (2001) revealed that intensive tillage leads to substantial losses of soil carbon, (30 to 50%). Cultivation depresses activity of soil enzymes. In contrast, conservation tillage causes less soil disturbance and has higher levels of enzymes in the surface soil. Raverkar *et al.,* (2005) studies at a sandy soil site in Rajasthan, we found consistently higher populations of copiotrophic bacteria (that consume high amount of substrate and have higher growth rates) and oligotrophic bacteria ((bacteria that thrive on very low amount of substrate and have slow growth rates) actinomycetes, glomalin, biological activity (dehydrogenase, FDA hydrolysis) and activity of soil enzymes (acid phosphatase, ß-glucosidase) in organic cropping and orchards compared to conventional cropping. on a sandy loam soil in north India on wheat, conservation tillage significantly increased soil respiration (+81.1%), SBMC (+104%) and soil dehydrogenase activity (+59.2%) compared to conventional tillage (Sharma *et al.,* 2011).

Acosta-Martínez *et al.,* (2011) reported that an increase in enzyme activities and soil C and N storage under CA practices, particularly under no-till and vetch cover crop that translated in significantly greater TOC and b-glucosidase quality scores. These results highlight the importance of combining reduced tillage with N-fixing cover crops in improving soil quality as well as yield even under low biomass monoculture production system in the long term.

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. Lu *et al.,* (2014) recently concluded that biochar and residue amendment could enhance the readily oxidized C (measured by $KMnO_4$ oxidation). 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). Srinivasan *et al.,* (2012) observed that SOC protection by soil aggregates, the newly added carbon provides physical protection and is then subjected to chemical conversion and structural stabilization; meanwhile, alternation of the properties and distribution of the carbon pool leads to both the diversification of aggregate-scale microbial habitats and the evolution of microbial biota, along with changes in various fertility service functions such as functional groups and enzyme activity, which promote the development of diverse biota and thereby stabilize ecosystem processes.

Naresh *et al.,* (2017) found that the ZT and PRB with 4 and 6 tha^{-1}residue retention increased the number of nitrifying bacteria at the milky stage by 38.7, 53.7 and 72.4% as compared to CT (conventional tillage), respectively. Compared to the ZT method, the PRB method reduced the number of denitrifying bacteria by 49.6, 14.9, and 13.8% under T_4, T_5, and T_6 at the jointing stage but did not significantly decrease it at the booting stage. However, the ZT method increased the number of denitrifying bacteria at the milky stage by 9.4, 15.7 and 19.7% under T_4, T_5, and T_6 methods.

This long-term assessment was able to provide an overview of the effects of organic inputs on strength and stability of soil aggregates associated organic carbon concentration and the possible resultant effect on nutrient cycling under monoculture rice-wheat system production. The results demonstrate the value of incorporating or retention of residues as a source of substrate for increased microbial activity resulting in greater soil C and N storage. It is apparent that after a continuous period of growing a rice-wheat monoculture crop with residue retention /incorporation, microbial activities that promote both C and N cycling are enhanced. Moreover the organic inputs/residue retention crop improves soil quality without the need of additional inorganic N fertilization. While the zero-till also affected soil pH which was significantly higher without organic input plots than other treatments. However, the trends observed with SOC indicated that conservation tillage managements were creating a more favorable plant growth environment relative to conventional tillage. The SOC concentration and its sequestration were higher with the treatment applied with organics than N–P–K application. Soil carbon sequestration with response to application of fertilizer substituted (50% with organics were higher lying in semiarid climate.

Application of recommended dose of N–P–K or N–P–K partially substituted with organics has increased or maintained the system productivity. It is therefore important that the recommended fertilization either through inorganic fertilizer alone or in combination with manures, crop residue and green manuring has to be promoted in order to maintain long-term rice–wheat system productivity. Nevertheless, there is a need for more quantitative assessment of the carbon sequestration potential of agricultural soils of IGP under different management practices for different climates and agricultural systems by supporting existing long term cropping system and the establishment of new ones where appropriate; quantifying interactions of SOC sequestration and developing soil carbon models that can account for locally relevant agricultural management practices.

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