Review Article

Effect of Conservation Tillage on Changes in Soil Aggregate-Associated Organic Carbon and Biological Pools to Nitrogen and Straw Alters in RWCS in North-Western India: A Review

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%overcontrol, 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 in macro-aggregates and the silt + clay fraction, and this effect was more pronounced than the addition of fertilizer NPK. Soil organic carbon build up was affected significantly by tillage and residue level in upper depth of 0-15 cm but not in lower depth of 15- 30 cm. Higher SOC content of 19.44 g kg^{-1} of soil was found in zero tilled residue retained plots followed by 18.53 g kg^{-1} in permanently raised bed with residue retained plots. Whereas, the lowest level of SOC content of 15.86 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots. Zero tilled residue retained plots sequestrated 0.91gkg^{-1}yr^{-1} SOC which was 22.63% higher over the conventionally tilled residue removed plots. NT treatments increased MBC by 11.2%, 11.5%, and 20%, and dissolved organic carbon (DOC) concentration by 15.5%, 29.5%, and 14.1% of bulk soil, >0.25 mm aggregate, and 0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively. The stocks of SOC in the 0–50 cm depth increased from 49.89 Mg ha$^{–1}$ with residue removal to 53.03 Mg ha$^{–1}$ with residue retention. However, no-tillage did not increase SOC stock to a depth of 50 cm relative to conventional tillage, and increased only by 5.35% as compared with rotary tillage. Previous crop residue (S) treatments had higher SOC concentration of bulk soil (12.9%), >0.25 mm aggregate (11.3%), and <0.25 mm aggregate (14.1%) than residue removal (NS) treatments. Compared with conventional intensive tillage (CT) treatments, no tillage (NT) treatments increased MBC by 11.2%, 11.5%, and 20%, and dissolved organic carbon (DOC) concentration by 15.5%, 29.5%, and 14.1% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively. Compared with NS treatments, S treatments significantly increased MBC by 29.8%, 30.2%, and 24.1%, and DOC concentration by 23.2%, 25.0%, and 37.5% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively.

Keywords: Carbon fractions, soil aggregation, aggregate-associated C, microbial biomass carbon

INTRODUCTION

Soil is considered the ‘skin’ of the earth with soil organic carbon (SOC) as the protein that protects the ‘skin’ (Dou and Guan, 2011). SOC is a key indicator of soil quality (Bronick and Lal, 2005) is the basis of soil fertility and function (Huang et al., 2012) and is important for cementing substances as part of the formation of soil aggregates. SOC affects the number and distribution of differently sized soil aggregates (Zheng et al., 2011). Soil aggregates are the basic ‘cells’ of the soil structure and play an important role in improving soil carbon sequestration and fertility (Zhou et al., 2009). Stable soil aggregates not only reduce soil erosion induced SOC loss, but also inhibit microbial and enzymatic decomposition of SOC through coating and isolation effects (Humberto and Lal, 2004). Physical fraction is widely used to study the storage and turnover of soil organic matter (SOC), because it incorporates three levels of analysis by examining three sizes of aggregate. Previous studies have demonstrated that the interaction between soil structure and aggregates determines the quality of the SOC pool. SOC is primarily distributed in water-stable aggregates of larger sizes (> 1mm) and SOC content increases with aggregate diameter (Liu et al., 2009). The combined application of chemical fertilizer and straw greatly improves SOC accumulation in water-stable aggregates of this size (Zhou and Pan, 2007).

Tillage and residue management practices resulted in improves soil structure, associated protection of SOM and biological activities (Sharma et al., 2019; Saikia et al., 2019) which eventually improves organic matter, soil aggregation, and nutrient cycling in agricultural systems. Conventional tillage destroyed large macro-aggregates (LMAs) in the soil (Abid and Lal, 2008). In contrast, long-term no-tillage drastically reduced the rate of macro-aggregate (MA) turnover and resulted in the formation of stable micro-aggregates (MIs), favoring C stabilization and sequestration (Jiang et al., 2010). This effect frequently exposes aggregates to physical disruption (Al-Kaisi et al., 2014). The resulting breaking of aggregates enhances the accessibility of organic matter (OM) to microorganisms, stimulating oxidation and loss of organic matter. Declines in organic matter are thus usually accompanied by a decrease in the number of water-stable aggregates (Six et al., 1999). Intensive tillage that accelerates the conversion of soil macro-aggregates is the main cause of SOC loss (Lal, 2007).The LMAs formed under no-tillage management had higher SOC contents and increased numbers of macro-pores, resulting in higher water infiltration and better aeration when compared with soils that were richer in MIs (Jiang et al., 2011). LMAs also physically protect the labile soil OC from enzymatic and microbial attack (Nakajima et al., 2016). Therefore, the accumulation of soil OC could be achieved by establishing management practices that increase the proportion of soil MAs (Blanco-Canqui et al., 2007). Under no tillage, crop residue decomposes at a slower rate, leading to a gradual build-up and increase in soil organic carbon (SOC). The resulting substrate from residue decomposition contributes to stabilizing soil aggregates (Caesar-TonThat et al., 2011). Although several studies have revealed that no-tillage management affects soil aggregation. We hypothesized that the transition from conventional tillage to the no-tillage and straw-returning pattern would promote MI fraction retention within the LMA, resulting in higher soil OC content in the LMA.

The present carbon status in soil is alarming and, therefore, proper and deliberate management of soil organic carbon is essential for the sustainability of agricultural production systems. SOM is not sensitive to short-term changes of soil quality with different soil or crop management practices due to high background levels and natural soil variability (Haynes, 2005). Labile soil 0rganic carbon pools like dissolved organic C (DOC), microbial biomass C (MBC), and particulate organic matter C (POC) are the fine indicators of soil quality which influence soil function in specific ways (e.g., immobilization–mineralization) and are much more sensitive to change in soil management practices (Xu et al., 2011). Because these components can respond rapidly to changes in Supply, they have been suggested as early indicators of the effects of land use on SOM quality (Naresh et al., 2017).

The objectives of the present review were to (i) analyze the effects of changes in tillage and straw returning management on the sequestration of OC in different size aggregates and maintain soil structure and quality in the intensive agro-ecosystem in the Western Uttar Pradesh. (ii) (2) microbial metabolic activity is improved by conservation tillage at the small-scale in soil in the plow layer, and the microbial metabolic activity is correlated to SOC within aggregates under conservation tillage and (iii) among tillage systems (straw systems), microbial metabolic activities, organic C fractions, and SOC to elucidate the relationship better between soil microbial metabolic diversity and SOC within aggregates in the Rice-Wheat Cropping System.

Soil and Water-Stable, Aggregate-Associated Organic Carbon Content

Simansky et al. (2017) reported that the soil-management practices significantly influenced the soil organic carbon in water-stable aggregates (SOC in WSA). The content of SOC in WSA ma increased on average in the following order: T < G < G+NPK1 < G+NPK3 < T+FYM. Intensive soil cultivation in the T treatment resulted in a statistically significant buildup of SOC in WSA ma at an average rate of 1.33, 1.18, 0.97, 1.22 and 0.76 $gkg^{-1}yr^{-1}$ across the size fractions > 5 mm, 5–3 mm, 2–1 mm, 1–0.5 mm and 0.5–0.25 mm, respectively [Fig.1].

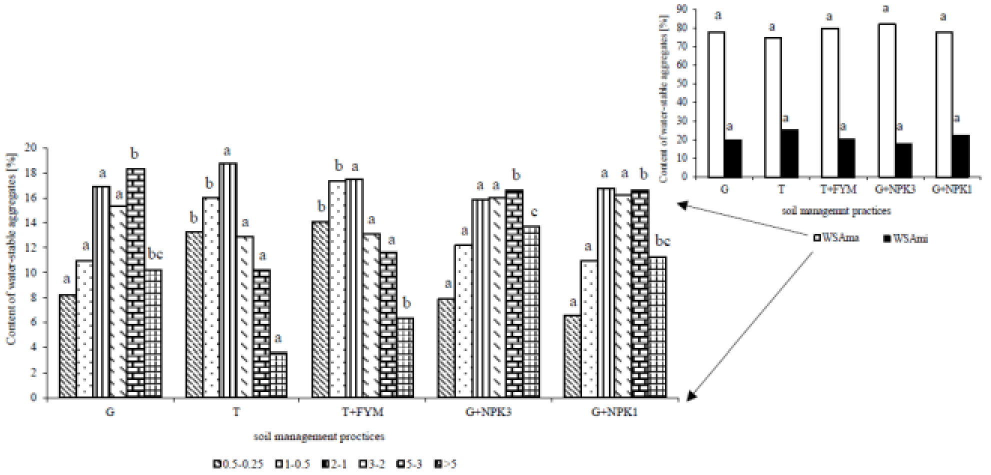
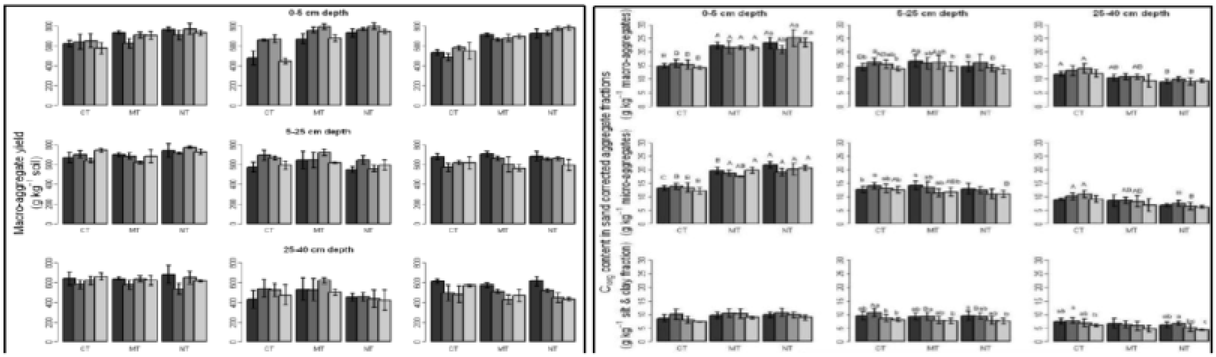


Fig. 1: Water-stable aggregates contents under different soil-management practices where: G – control; T – tillage; T+FYM – tillage+ farmyard manure; G+NPK3 – doses of NPK fertilizers in 3-rd intensity for

vineyards; G+NPK1 – doses of NPK fertilizers in 1st intensity for vineyards; WSA_{ma} – water-stable macro-aggregates; WSA_{mi} – water-stable micro-aggregates.

Wagner *et al*. (2007) also found that in the surface soil, the mean yields of water-stable macro-aggregates were significantly higher under MT and NT than under CT treatment. Statistically significant differences below 5 cm were only found in 25-40 cm soil depth under NT [Fig.2a]. The carbon content of the micro-aggregates within macro-aggregates was higher under reduced tillage treatments, indicating increased macro-aggregate turnover under CT. However, in contrast, in 5-25 and 25-40 cm soil depth no negative effect by CT was found on yields of macro-aggregates and carbon contents within macro-aggregates assume that the soil mixing and litter incorporation in higher soil depths by CT might lead to a flush of microbial activity, producing binding agents as nucleation sites for macro-aggregates, probably counteracting the physical impact of tillage. In comparison to the CT treatment; both treatments under reduced tillage had in general significantly higher C_{org} contents within macro-aggregates in 0-5 cm soil depth [Fig. 2b]. Due to decreasing C_{org} contents within macro-aggregates with depth under MT and NT, the differences in comparison to the CT treatment were less pronounced in 5-25 cm soil depth. In 25-40 cm soil depth the C_{org} content within macro-aggregates was in general higher under CT than under MT and NT, with significant differences between CT and NT. Over time the C_{org} content within macro-aggregates showed only significant variations under NT in 0-5 and 25-40 cm soil depth [Fig. 2b].



(a) (b)

Fig. 2(a): Average dry matter yields of the macro-aggregate (>250μm) fractions of the different tillage treatments. CT with annual mould-board plowing to 25-30 cm; MT with a cultivator or disc harrow 10-15 cm deep, and NT with direct drilling

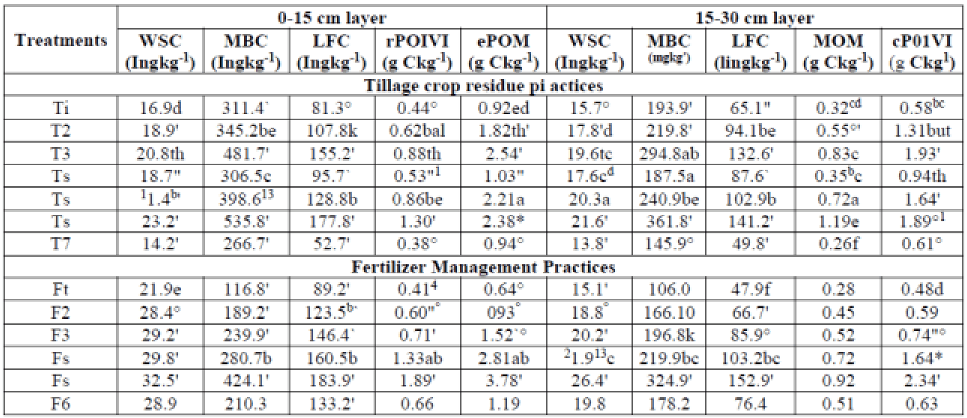
Fig. 2(b): Average C_{org} content in sand corrected macro-aggregate (>250μm) and micro-aggregate (250-53 µm) fractions and of the silt and clay sized (<53 µm) fractions of the different tillage treatments

Naresh et al. (2018) reported that the distribution of soil mass among the size classes of WSC was strongly influenced by tillage crop residue practices in both the soil depths (0–15 cm and 15-30 cm). WSC was found to be 5.48% higher in surface soil than in sub-surface soil [Table 1]. In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to CT, FIRB and ZT coupled with 6tha^{-1} CR increased 35.6% WSC in surface soil and 33.1% in sub surface soil. Among all the treatments, T_6 had significantly higher (19.73%) proportion of WSC than the other treatments compared. Irrespective of tillage practices, residue retention resulted in 22.56% and 25.61% higher WSC as compared to the non-residue treatments in surface and subsurface soil, respectively. The WSC content in surface soil (0–15 cm) was significantly higher in 100% RDN as CF+ VC@ 5tha^{-1} (F$_5$) treatment (32.5 mg kg^{-1}) followed by 75% RDN as CF+ VC@ 5tha-1 (F4) (29.8 mgkg^{-1}) and least in unfertilized control plot [(F$_1$) (21.9 mgkg^{-1}) [Table 1]. However, similar significant effect was observed in subsurface soil (15-30 cm) and the magnitude was relatively lower. The increase in WSC in 0–15 cm soil depth was 37.2 and 28.4% in 100% RDN as CF+ VC@ 5tha^{-1} (F5) and 75% RDN as CF+ VC@ 5tha^{-1} (F$_4$) treated plots over control. WSC, an active pool of organic C, serves as both source and sink for mineral nutrients and organic substrates in a short term, and as a catalyst for conversion of plant nutrients from stable organic form over a longer period there by influencing crop productivity and nutrient cycling.

Changes in MBC can indicate the effects of management practices on soil biological and biochemical properties. The higher MBC was observed in the ZT and FIRB with residue retention plots than the CT plot under the RWCS suggests that abandonment of the cropland had substantial beneficial effects on the activity of microbial organisms probably caused by the accumulation of organic C compounds at the soil surface. A possible reason for this difference is that in the absence of growing plants other labile C fractions may provide food for microbes, and thus maintain MBC. Another possible reason could be related to the soil moisture status. Under the CT treatment, in which biomass production would inevitably deplete much more soil moisture, the microbes in the plot would be stressed at the time of sampling (wheat maturity). The microbial biomass carbon (MBC) is an important component of the SOM that regulates the transformation and storage of nutrients. The soil MBC regulates all SOM transformations and is considered to be the chief component of the active SOM pool. It is evident that the MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 100% RDN as CF+ VC@ 5tha^{-1} (F$_5$) and 75% RDN as CF+ VC@ 5tha^{-1} (F$_4$) treated plots compared to 100% RDN as CF (F$_2$) fertilizer and unfertilized control plots [Table 1]. 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 100% RDN as CF+ VC@ 5tha^{-1} plots, respectively; while it varied from 106.6 mgkg^{-1} (control) to 324.9 mgkg^{-1} (100% RDN as CF+ VC@ 5tha^{-1} (F$_5$) in subsurface (15-30 cm) soil layer. The values of MBC increased by 72.5 and 58.4% fewer than 100% RDN as CF+ VC@ 5tha1 (F5) and 75% RDN as CF+ VC@ 5tha^{-1} (F$_4$) treatment in surface soil over control. While, there were 34.4% increase of MBC over 100% RDF as CF (F$_2$) 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 fewer than100% RDN as CF+ VC@ 5tha^{-1} treatment. Application of 100% RDN as CF fertilizer is not only required for better growth of the crop but also required for synthesis of cellular components of microorganisms. Therefore, higher root biomass under 100% RDN as CF+ VC@ 5tha^{-1} fertilizer treatment helped in increasing MBC over other treatments. Moreover, LFC is considered as a useful approach for the characterization of SOC resulting from different soil management practices including cropping systems and application of organic and inorganic sources of nutrients. The values of LFC in surface soil (0-15 cm) were 81.3, 95.7, 107.8, 128.8, 155.2, 177.8 and 52.7 mgkg^{-1} in ZT and FIRB without residue retention, ZT and FIRB with 4 & 6 tha^{-1} residue retention and

C T treatments, respectively [Table 1]. The LFC content of the soil increased with the application of fertilizers and/or VC [Table 1]. In the surface layer, the organic treatment accumulated 51.5% greater LFC (183.9 mg kg^{-1}) followed by 44.4% greater in integrated (160.5 mgkg^{-1}) and 27.7% greater in RDN (123.5 mg kg^{-1}) as compared to the control treatment.

Table 1: Concentrations of different soil organic matter carbon fractions fPOM and cPOM at different soil depths as affected by tillage and nutrient management to the continuous RW cropping system [Source: Naresh *et al*., 2018]



Treatments	0-15 cm layer					15-30 cm layer				
	WSC (Ingkg^{-1})	MBC (Ingkg^{-1})	LFC (Ingkg^{-1})	rPOIVI (g Ckg^{-1})	ePOM (g Ckg^{-1})	WSC (Ingkg^{-1})	MBC (mgkg')	LFC (lingkg^{-1})	MOM (g Ckg^{-1})	cP01VI (g Ckg^{1})
Tillage crop residue pi actices										
Ti	16.9d	311.4`	81.3°	0.44°	0.92ed	15.7°	193.9'	65.1"	0.32^{cd}	0.58^{bc}
T2	18.9'	345.2be	107.8k	0.62bal	1.82th'	17.8'd	219.8'	94.1be	0.55°'	1.31but
T3	20.8th	481.7'	155.2'	0.88th	2.54'	19.6tc	294.8ab	132.6'	0.83c	1.93'
Ts	18.7"	306.5c	95.7`	0.53"^{1}	1.03"	17.6c^{d}	187.5a	87.6`	0.35^{b}c	0.94th
Ts	^{1}1.4$^{b\cdot}$	398.6^{13}	128.8b	0.86be	2.21a	20.3a	240.9be	102.9b	0.72a	1.64'
Ts	23.2'	535.8'	177.8'	1.30'	2.38*	21.6'	361.8'	141.2'	1.19e	1.89°^{1}
T7	14.2'	266.7'	52.7'	0.38°	0.94°	13.8'	145.9°	49.8'	0.26f	0.61°
Fertilizer Management Practices										
Ft	21.9e	116.8'	89.2'	0.41^{4}	0.64°	15.1'	106.0	47.9f	0.28	0.48d
F2	28.4°	189.2'	123.5$^{b\cdot}$	0.60"$^{\circ}$	093°	18.8°	166.10	66.7'	0.45	0.59
F3	29.2'	239.9'	146.4`	0.71'	1.52`°	20.2'	196.8k	85.9°	0.52	0.74"°
Fs	29.8'	280.7b	160.5b	1.33ab	2.81ab	^{2}1.9^{13}c	219.9bc	103.2bc	0.72	1.64*
Fs	32.5'	424.1'	183.9'	1.89'	3.78'	26.4'	324.9'	152.9'	0.92	2.34'
F6	28.9	210.3	133.2'	0.66	1.19	19.8	178.2	76.4	0.51	0.63

Zotarelli *et al*. (2007) revealed that the amount of C within the macro-aggregates was still markedly higher after 7 and 28 days of incubation [Fig. 3a] than in the original soil prior to macro-aggregate disruption. At early stages of formation the macro-aggregates are not yet resistant and can easily break up into micro-aggregates. The fast aggregate formation rate within the first few days of incubation, the increased amount of microbial biomass and therefore the decreasing substrate availability might have led to a shortage of free organic material in the soils receiving organic C and the microbial biomass used organic C within the newly built macro-aggregates, resulting in decreased organic C contents within macro-aggregates [Fig.3b]. Moreover, the macro-aggregates after formation are oversaturated with SOC and only a smaller amount is stabilized for longer periods within macro-aggregates in the soil.

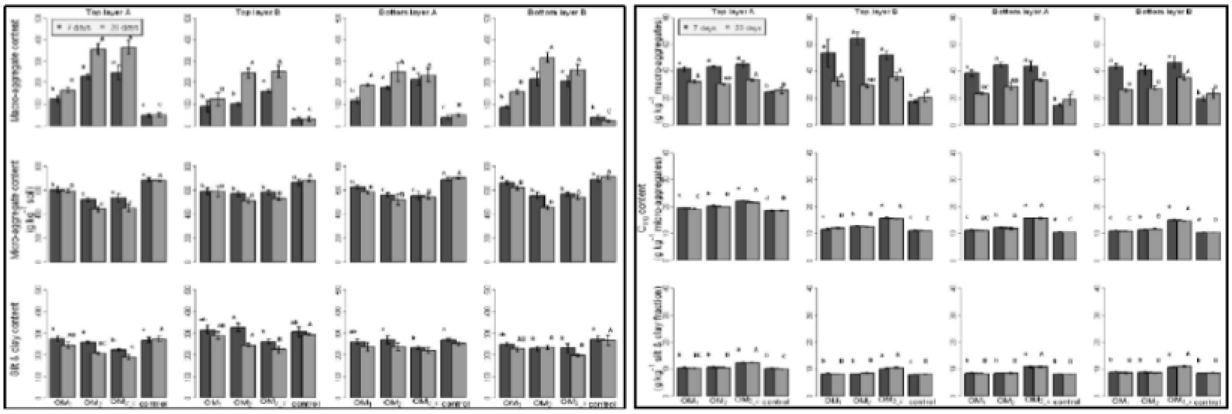


Fig. 3 (a): Mean dry matter yields of macro-aggregate (>250 µm), micro-aggregate (250-53 µm) and silt & clay sized (<53 µm) fractions of different soils at 0-5 and 5-25 cm soil depth and treatments (OM1: addition of OM: pre-incubated wheat straw at a rate of 4.1 g C kg^{-1} soil, OM2: addition of pre-incubated wheat straw at a rate of 8.2 g C kg^{-1} soil, OM2_c: addition of pre-incubated wheat straw at a rate of 8.2 g

C kg^{-1} soil, whereat the clay content was increased to 25%, control: without any addition) after 7 and 28 days of incubation

Fig. 3 (b): Mean C_{org} content within macro-aggregate (>250 µm), micro-aggregate (250-53 µm) and silt & clay sized (<53 µm) fractions of the different soils at 0-5 and 5-25 cm soil depth and treatments

Hui-Ping Ou et al. (2016) reported that the proportion of the >2 mm aggregate fraction in NT+S was 7.1 % higher than that in NTS in the 0.00-0.05 m layer. There was no significant difference in the total amount of all the aggregate fractions between NT+S and NT-S in both the 0.05-0.20 and 0.20-0.30 m layers. NT+S and NT-S showed higher proportions of >2 mm aggregate and lower proportions of 0.25 mm macro-aggregate was significantly higher in MP+S than in MP-S in most cases, but the proportion of <0.053 mm aggregate was 11.5-20.5 % lower in MP+S than in MP-S for all the soil layers [Fig.4].

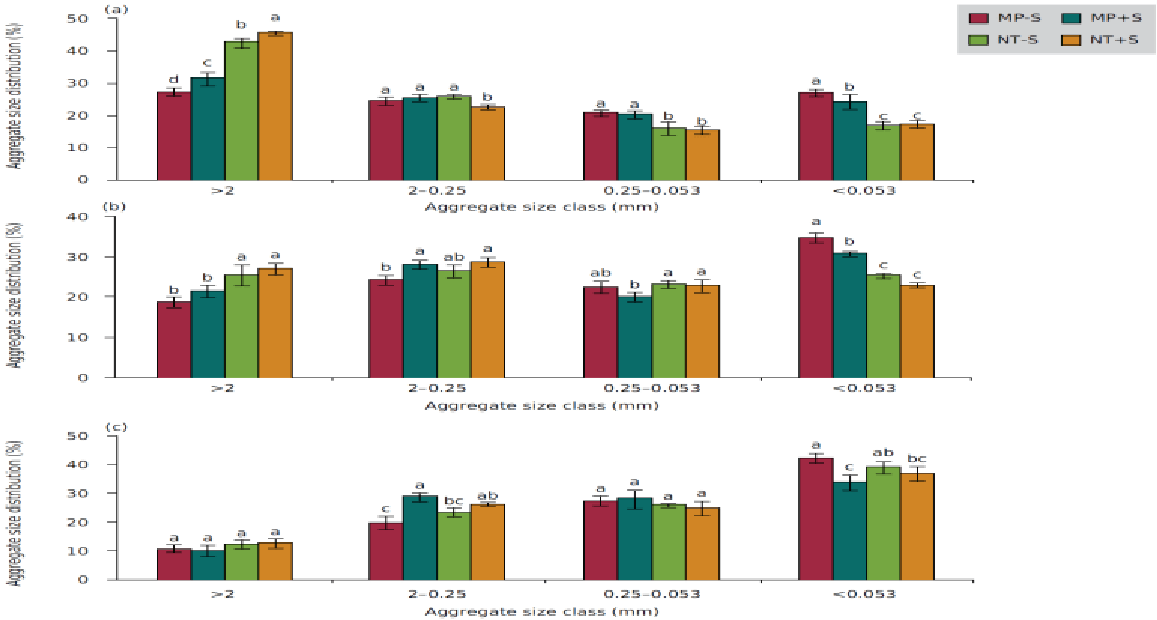
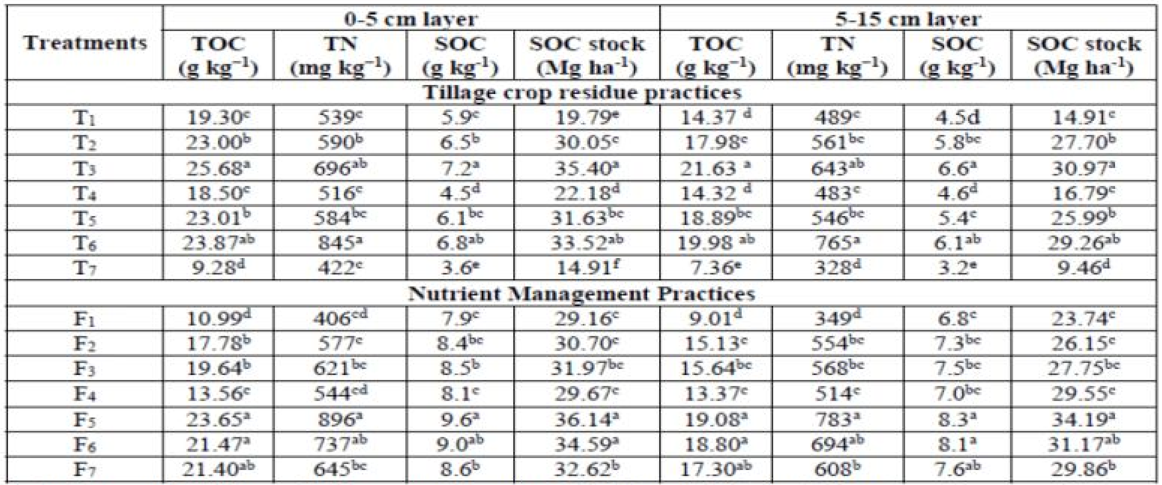


Fig 4: Distribution (%) of water-stable aggregates with different sizes in different soil layers as influenced by tillage treatments. (a) 0.00-0.05 m; (b) 0.05-0.20 m; (c) 0.20-0.30 m. MP-S: moldboard plow without straw; MP+S: moldboard plow with straw; NT-S: no-tillage without straw; NT+S: no-tillage with straw

Naresh et al. (2017) reported that the highest SOC concentration was obtained for 0–5 cm depth and decreased with sub surface depth for all treatments. The SOC concentration in 0–5 and 5– 15 cm depths increased significantly by farmyard manure or GM/SPM application. At the 0–5 and 5–15 cm soil depths, SOC was highest in 50% RDN as CF+50% RDN as FYM (F_5) followed by 50% RDN as CF+50% RDN as GM/SPM (F_6) treatments and the least in Control (no manure and fertilizer) F_1 treatment. The total SOC stocks in the 0-15 cm layer was 35.17 Mgha^{-1} for 50% RDN as CF+50% RDN as FYM-treated soils compared with 28.43 Mgha^{-1} for 100% RDN as CF-treated plots and 26.45 Mg ha^{-1} for unfertilized control plots [Table 2]. Soil organic C content in the 0–15 cm soil layer in the plots under 50% RDN as CF+50% RDN as FYM treatment was 16% higher than that under 75% RDN as CF+25% RDN as FYM treated plots. The TOC in surface soil were in the order of 50% RDN as CF+50% RDN as FYM (23.65 g kg^{-1}) >

50% RDN as CF+50% RDN as GM/SPM (21.47 g kg^{-1}) >1/3rd N as CF+1/3rd N as FYM+1/3rd N as GM/SPM (21.40 gkg^{-1}) >75% RDN as CF+25% RDN as FYM (19.64 gkg^{-1}) >unfertilized control (10.99 gkg^{-1}).

Table 2: Effect of 15 years of application of treatments on total organic C (TOC), total N (TN), and soil organic carbon (SOC) [Naresh *et al*., 2017]



Treatments	0-5 cm layer				5-15 cm layer			
	TOC ($g\ kg^{-1}$)	TN ($mg\ kg^{-1}$)	SOC ($g\ kg^{-1}$)	SOC stock ($Mg\ ha^{-1}$)	TOC ($g\ kg^{-1}$)	TN ($mg\ kg^{-1}$)	SOC ($g\ kg^{-1}$)	SOC stock ($Mg\ ha^{-1}$)
Tillage crop residue practices								
T_1	19.30^{c}	539^{c}	5.9^{c}	19.79^{e}	14.37^{d}	489^{c}	4.5d	14.91^{c}
T_2	23.00^{b}	590^{b}	6.5^{b}	30.05^{c}	17.98^{c}	561^{bc}	5.8^{bc}	27.70^{b}
T_3	25.68^{a}	696^{ab}	7.2^{a}	35.40^{a}	21.63^{a}	643^{ab}	6.6^{a}	30.97^{a}
T_4	18.50^{c}	516^{c}	4.5^{d}	22.18^{d}	14.32^{d}	483^{c}	4.6^{d}	16.79^{c}
T_5	23.01^{b}	584^{bc}	6.1^{bc}	31.63^{bc}	18.89^{bc}	546^{bc}	5.4^{c}	25.99^{b}
T_6	23.87^{ab}	845^{a}	6.8^{ab}	33.52^{ab}	19.98^{ab}	765^{a}	6.1^{ab}	29.26^{ab}
T_7	9.28^{d}	422^{c}	3.6^{e}	14.91^{f}	7.36^{e}	328^{d}	3.2^{e}	9.46^{d}
Nutrient Management Practices								
F_1	10.99^{d}	406^{cd}	7.9^{c}	29.16^{c}	9.01^{d}	349^{d}	6.8^{c}	23.74^{c}
F_2	17.78^{b}	577^{c}	8.4^{bc}	30.70^{c}	15.13^{c}	554^{bc}	7.3^{bc}	26.15^{c}
F_3	19.64^{b}	621^{bc}	8.5^{b}	31.97^{bc}	15.64^{bc}	568^{bc}	7.5^{bc}	27.75^{bc}
F_4	13.56^{c}	544^{cd}	8.1^{c}	29.67^{c}	13.37^{c}	514^{c}	7.0^{bc}	29.55^{c}
F_5	23.65^{a}	896^{a}	9.6^{a}	36.14^{a}	19.08^{a}	783^{a}	8.3^{a}	34.19^{a}
F_6	21.47^{a}	737^{ab}	9.0^{ab}	34.59^{a}	18.80^{a}	694^{ab}	8.1^{a}	31.17^{ab}
F_7	21.40^{ab}	645^{bc}	8.6^{b}	32.62^{b}	17.30^{ab}	608^{b}	7.6^{ab}	29.86^{b}

Values in a column followed by the same letter are not significantly different ($P < 0.05$).

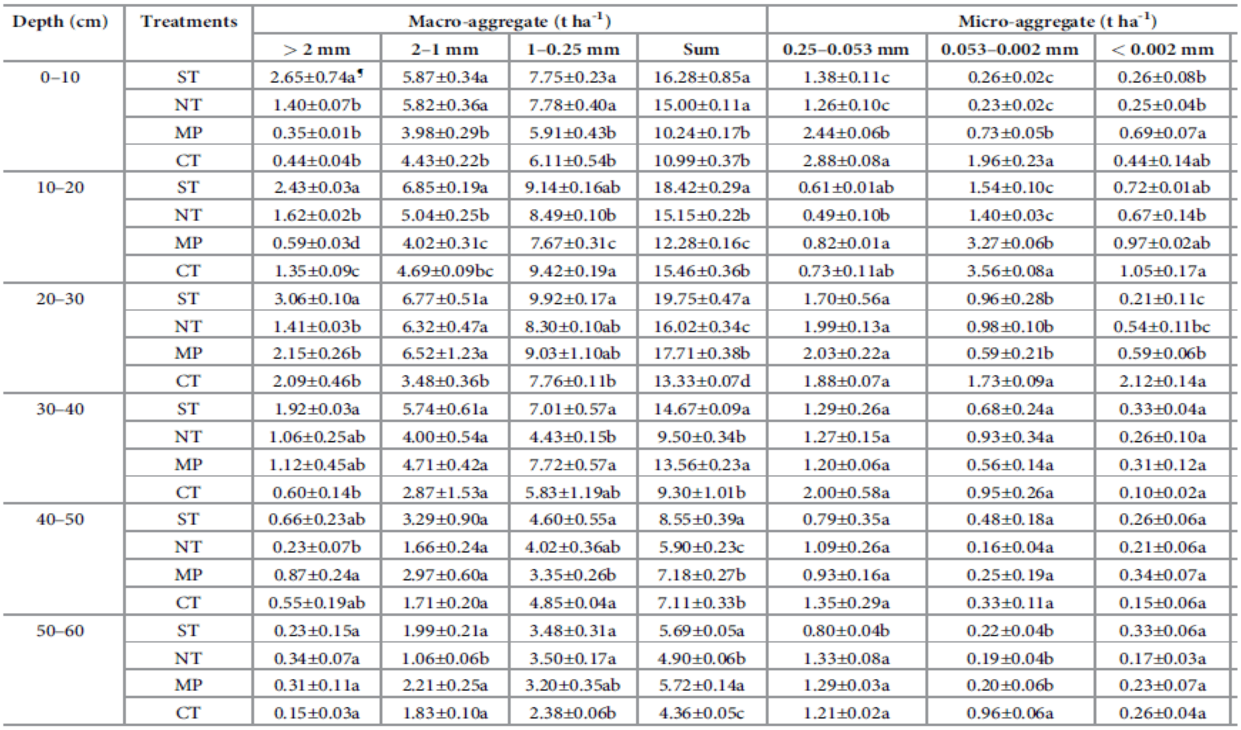
Soil organic carbon fractions and SOC storage in water-stable aggregates

SOC is an important index of soil quality and health and is an important component of the soil fertility of farmlands, as well as being the core of soil quality and function. SOC content can directly affect soil fertility and crop yield, and greatly affects the formation and stability of the water-stable soil aggregate structure.

Zheng et al. (2018) reported that the SOC storage in macro-aggregates under different treatments significantly decreased with soil depth (Table 3). However, no significant variation was observed in the micro-aggregate associated C storage with depth. SOC storage increased with aggregate size from 1-2 to > 2mm and decreased with a decrease in aggregate size. The SOC storage in macro-aggregates of all sizes from 0-30cm depth was higher in the ST treatment than in other treatments. SOC storage in micro-aggregates showed the opposite trend, with significantly higher levels in the CT treatment from 0-30cm, and no significant differences between treatments below this depth. The 0.25-1.00mm diameter aggregates contributed the most to SOC at the 0-10cm depth for each of the tillage treatments. The contributing rate was 34.7%-45.7%, with that of the ST and NT treatments significantly higher than that of MP and CT. The < 0.002mm aggregates contributed the least to SOC, with a contributing rate of 1.5%-13.4%; and those of the ST and NT treatments were significantly lower than those of MP and CT. The total contributing rate of SOC at all depths in macro-aggregates was in the order NT>ST>CT>MP, while that for micro-aggregates was MP>ST>CT>NT.

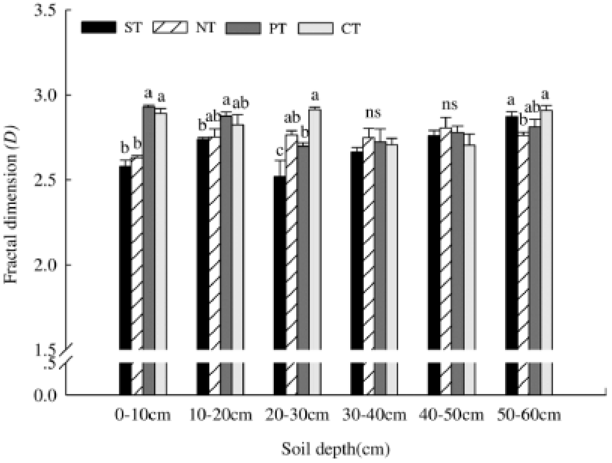
The mechanism and reason for this phenomenon were the higher straw cover in the NT and ST treatments, which can reduce soil erosion, land surface evaporation, and loss of soil organic matter, and can improve the soil structure. Another reason is that straw mulching has a moisture preservation effect and benefits the activities of microorganisms, which can accelerate the SOC turnover. Furthermore, the sub-soiling effect can promote root system growth, and a large amount of the root system and stubble can be converted into SOC through decomposition and humification effects, thereby increasing the SOC content in deep soil and enhancing the soil ability to accumulate C under the ST treatment. The advantage was dependent on tillage depth and healthy soil structure throughout the soil profile. The aggregate-associated C in the NT and ST treatments were higher than for the MP and CT treatment sat the 0-10cm depth due to the amounts of organic matter and favorable soil structure. However, the aggregate-associated C of the NT treatment decreased with soil depth but remained high under the ST treatment. The aggregate-associated C in the NT and ST treatments were higher than for the MP and CT treatment sat the 0-10cm depth due to the amounts of organic matter and favorable soil structure. However, the aggregate-associated C of the NT treatment decreased with soil depth but remained high under the ST treatment.

Table 3: Distribution of soil organic carbon storage in water-stable aggregates in different soil layers and tillage treatments [Source: Zheng et al., 2018]

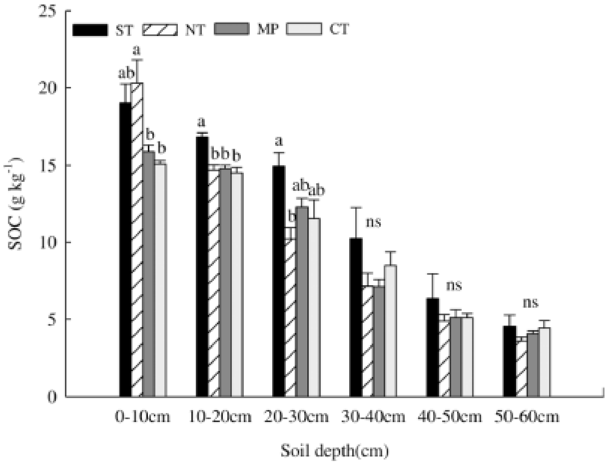


Depth (cm)	Treatments	Macro-aggregate (t ha^{-1})				Micro-aggregate (t ha^{-1})		
		> 2 mm	2–1 mm	1–0.25 mm	Sum	0.25–0.053 mm	0.053–0.002 mm	< 0.002 mm
0–10	ST	2.65±0.74a¶	5.87±0.34a	7.75±0.23a	16.28±0.85a	1.38±0.11c	0.26±0.02c	0.26±0.08b
	NT	1.40±0.07b	5.82±0.36a	7.78±0.40a	15.00±0.11a	1.26±0.10c	0.23±0.02c	0.25±0.04b
	MP	0.35±0.01b	3.98±0.29b	5.91±0.43b	10.24±0.17b	2.44±0.06b	0.73±0.05b	0.69±0.07a
	CT	0.44±0.04b	4.43±0.22b	6.11±0.54b	10.99±0.37b	2.88±0.08a	1.96±0.23a	0.44±0.14ab
10–20	ST	2.43±0.03a	6.85±0.19a	9.14±0.16ab	18.42±0.29a	0.61±0.01ab	1.54±0.10c	0.72±0.01ab
	NT	1.62±0.02b	5.04±0.25b	8.49±0.10b	15.15±0.22b	0.49±0.10b	1.40±0.03c	0.67±0.14b
	MP	0.59±0.03d	4.02±0.31c	7.67±0.31c	12.28±0.16c	0.82±0.01a	3.27±0.06b	0.97±0.02ab
	CT	1.35±0.09c	4.69±0.09bc	9.42±0.19a	15.46±0.36b	0.73±0.11ab	3.56±0.08a	1.05±0.17a
20–30	ST	3.06±0.10a	6.77±0.51a	9.92±0.17a	19.75±0.47a	1.70±0.56a	0.96±0.28b	0.21±0.11c
	NT	1.41±0.03b	6.32±0.47a	8.30±0.10ab	16.02±0.34c	1.99±0.13a	0.98±0.10b	0.54±0.11bc
	MP	2.15±0.26b	6.52±1.23a	9.03±1.10ab	17.71±0.38b	2.03±0.22a	0.59±0.21b	0.59±0.06b
	CT	2.09±0.46b	3.48±0.36b	7.76±0.11b	13.33±0.07d	1.88±0.07a	1.73±0.09a	2.12±0.14a
30–40	ST	1.92±0.03a	5.74±0.61a	7.01±0.57a	14.67±0.09a	1.29±0.26a	0.68±0.24a	0.33±0.04a
	NT	1.06±0.25ab	4.00±0.54a	4.43±0.15b	9.50±0.34b	1.27±0.15a	0.93±0.34a	0.26±0.10a
	MP	1.12±0.45ab	4.71±0.42a	7.72±0.57a	13.56±0.23a	1.20±0.06a	0.56±0.14a	0.31±0.12a
	CT	0.60±0.14b	2.87±1.53a	5.83±1.19ab	9.30±1.01b	2.00±0.58a	0.95±0.26a	0.10±0.02a
40–50	ST	0.66±0.23ab	3.29±0.90a	4.60±0.55a	8.55±0.39a	0.79±0.35a	0.48±0.18a	0.26±0.06a
	NT	0.23±0.07b	1.66±0.24a	4.02±0.36ab	5.90±0.23c	1.09±0.26a	0.16±0.04a	0.21±0.06a
	MP	0.87±0.24a	2.97±0.60a	3.35±0.26b	7.18±0.27b	0.93±0.16a	0.25±0.19a	0.34±0.07a
	CT	0.55±0.19ab	1.71±0.20a	4.85±0.04a	7.11±0.33b	1.35±0.29a	0.33±0.11a	0.15±0.06a
50–60	ST	0.23±0.15a	1.99±0.21a	3.48±0.31a	5.69±0.05a	0.80±0.04b	0.22±0.04b	0.33±0.06a
	NT	0.34±0.07a	1.06±0.06b	3.50±0.17a	4.90±0.06b	1.33±0.08a	0.19±0.04b	0.17±0.03a
	MP	0.31±0.11a	2.21±0.25a	3.20±0.35ab	5.72±0.14a	1.29±0.03a	0.20±0.06b	0.23±0.07a
	CT	0.15±0.03a	1.83±0.10a	2.38±0.06b	4.36±0.05c	1.21±0.02a	0.96±0.06a	0.26±0.04a

Zheng et al. (2018) also found that aggregate fractal dimension (*D)* varied with soil depth for different treatments and was more variable in the topsoil as compared to lower soil layers (Fig 5a). Aggregate *D* for the ST and NT treatments were significantly lower than for the MP and CT treatments at the 0±10cm depth. This effect for the NT treatment disappeared with increased soil depth; however, the ST treatment still showed lower *D* for the 10-20 and 20-30cm depths. This variation dwindled at lower depths until 50-60cm, where there was no significant difference in *D* between ST, NT, and MP; however, *D* was significantly lower for the CT than for the ST and NT treatments. Moreover, SOC content for different treatments decreased with soil depth (Fig 5b), with significantly higher content in the topsoil than in the sub-layer. At the 0-10cm depth, the mean SOC varied with treatment, with the conservation tillage (ST and NT) significantly higher than conventional tillage (CT). At 10-30cm, especially, the ST treatment was significantly higher. At 20- 30cm, the mean SOC from greatest to smallest was ordered ST>MP>CT>NT, with ST significantly higher than other treatments. The highest SOC storage was for 0.25-1and 1-2mm aggregates because more SOC accumulation occurred in those aggregates. There were more macro-aggregates in the ST and NT treatments than in the MP and CT treatments, which showed more micro-aggregates, with their turnover closely related to SOC storage. Protection and maintenance of the macro-aggregate stability and ratio are of great importance in the sustainability of soil fertility. In addition, the contributing rate of SOC in differently sized aggregates decreased, consistent with the trend of soil aggregate-associated C storage and SOC with increasing soil depth.



(a)



(b)

Fig. 5a: Effect of tillage methods on fractal dimension (*D*) of water-stable aggregates

Fig 5b: Effect of tillage methods on soil organic carbon

Six et al. (1998) [48] concluded that the concentration of free LF C was not affected by tillage, but was on average 45% less in the cultivated systems than NV. Proportions of cropderived C in macro-aggregates were similar in NT and CT, but were three times greater in micro-aggregates from NT than micro-aggregates from CT. Moreover, the rate of macro-aggregates in CT compared with NT leads to a slower rate of micro-aggregate formation within macro-aggregates and less stabilization of new SOM in free micro-aggregates under CT [Fig. 6a]. Zhao et al. (2018) [55] reported that the SOC content of each aggregate class in the 0–20 cm layer was significantly higher than that in the 20–40 cm layer [Fig. 6b]. Increases in the SOC content of aggregate fractions were highest in MRWR, followed by MR, and finally WR [Fig. 6b]. Crop derived organic particles or colloids can combine with mineral matter, binding micro-aggregates into macro-aggregates (Liu et al., 2014) [29]. Fresh straw incorporation provides substrate for microorganisms (An et al., 2015) [2] , and straw input can alter the distribution of SOC and increase the SOC content of aggregates, especially in macro-aggregates (Guan et al., 2015) [14] .

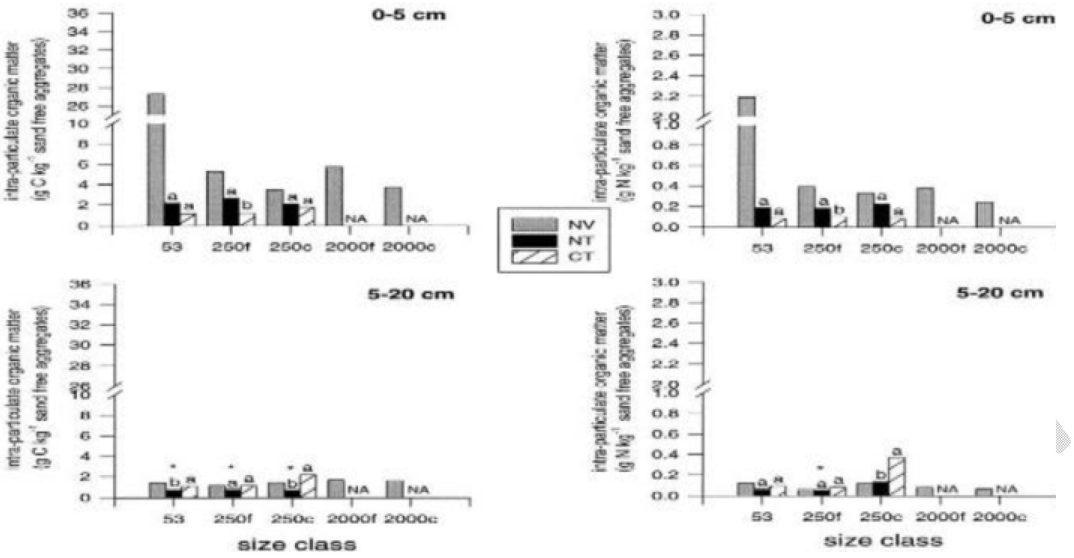


Fig 6 (a): Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems

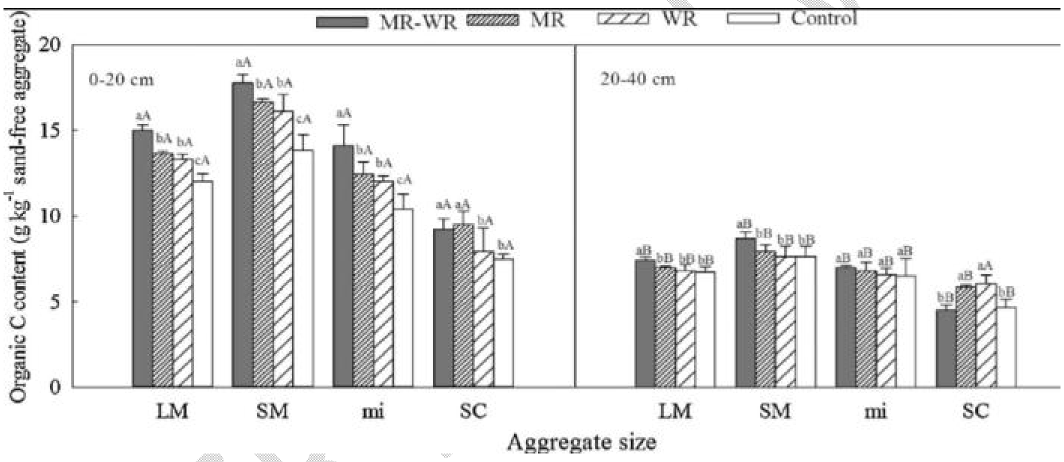


Fig 6 (b): Organic C content (g kg−1 aggregate) of aggregates: LM, SM, mi, and SC in the 0–20 cm and 20–40 cm soil layers under MR-WR, MR, WR, and Control

Mazumdar et al. (2015) [34] also found that the Concentration of C was higher in macro-aggregates as compared to micro-aggregates. Irrespective of treatments, C concentration was highest in 1-2 mm followed by 0.5-1mm size of macro-aggregates and the concentration decreased as the aggregates became smaller in size [Fig. 7a]. 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 [Fig.7a]. Zhao et al. (2018) revealed that the straw return treatments, particularly MRWR, increased the proportions of mSOM and fine iPOM within small macro-aggregates and micro-aggregates, especially in the 0–20 cm layer [Fig. 7b]. The carbon content of iPOM was much lower at 20–40 cm than at 0–20 cm [Fig. 7b].

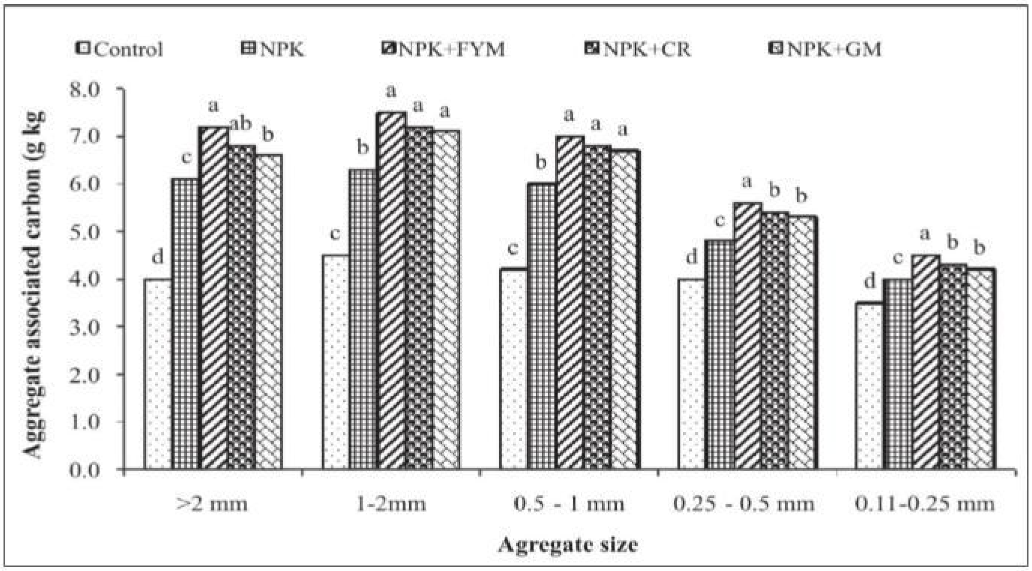


Fig 7 (a): Effects of long term integrated nutrient management practices on aggregate associated carbon in the soil

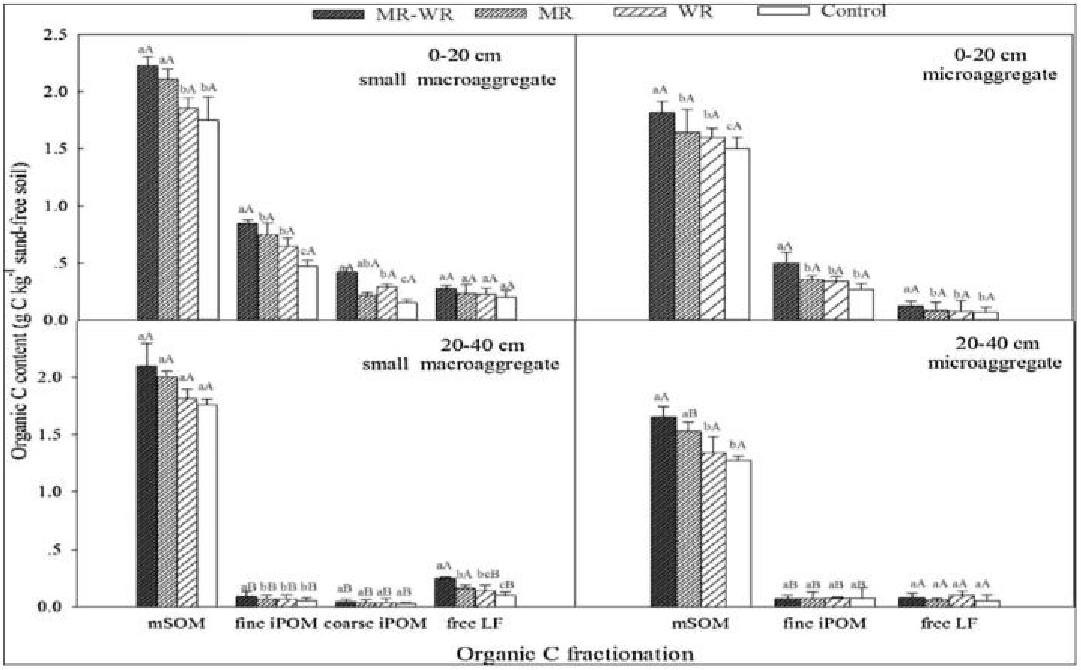


Fig 7(b): Organic C content (g kg−1 soil) of the SOC fractions: coarse iPOM, fine iPOM, mSOM, and free LF of small macro-aggregates and micro-aggregates in the 0–20 cm and 20–40 cm soil layers under MR-WR, MR, and WR

Naresh et al. (2015) also found that conservation tillage practices significantly influenced the total soil carbon (TC), total inorganic carbon (TIC), total soil organic carbon (SOC) and oxidizable organic carbon (OC) content of the surface (0 to 15 cm) soil. Wide raised beds transplanted rice and zero-till wheat with 100% (T_9) or with 50% residue retention (T_8) showed significantly higher TC, SOC content of 11.93 and 10.73 g kg^{-1} inT_9 and 10.98 and 9.38 gkg^{-1}, respectively inT_8 as compared to the other treatments.

Irrespective of residue incorporation/retention, wide raised beds with zero till wheat enhanced 40.5, 34.5, 36.7 and 34.6% of TIC, TC, SOC and OC in surface soil as compared to CT with transplanted rice cultivation. Kumar et al. (2018) also found that the ZTR (zero till with residue retention) (T_1) and RTR (Reduced till with residue retention) (T_3) showed significantly higher BC, WSOC, SOC and OC content of 24.5%, 21.9%,19.37 and18.34 gkg^{-1}, respectively as compared to the other treatments. Irrespective of residue retention, wheat sown in zero till plots enhanced 22.7%, 15.7%, 36.9% and 28.8% of BC, WSOC, SOC and OC, respectively, in surface soil as compared to conventional tillage. Simultaneously, residue retention in zero tillage caused an increment of 22.3%, 14.0%, 24.1% and 19.4% in BC, WSOC, SOC and OC, respectively over the treatments with no residue management. Similar increasing trends of conservation practices on different forms of carbon under sub-surface (15– 30cm) soil were observed however, the magnitude was relatively lower.

Carbon fractions and C–stabilization

Naresh et al. (2017) revealed that WSC was found to be 3.74% higher in surface soil than in sub-surface soil. In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to conventional tillage, PRB and ZT coupled with 6tha^{-1} CR increased 39.6% WSC in surface soil and 37.4% in sub surface soil. Among all the treatments, T_6 had significantly higher (20.15%) proportion of WSC than the other treatments compared. Plots under ZT had about 32% higher POC than CT plots (620 mg kg^{-1} bulk soil) in the surface soil layer. In 0 - 5 cm soil layer of tillage system, T_1, and T_4 treatments increased POC content from 620 mgkg^{-1} in CT (T_7) to 638 and 779 mgkg^{-1} without residue retention and to 898, 1105, 1033 and 1357 mgkg^{-1} in ZT and PRB with residue retention (T_2, T_3, T_5, and T_6), respectively. In subsurface layer (5-15 cm), similar increasing trends were observed; however, the magnitude was relatively lower. It is evident that the POC contents in both surface and sub-surface soil were significantly higher in plots receiving 50% RDN as CF+50% RDN as FYM (F_5) treated plots compared to 50% RDN as CF+50% RDN as GM/SPM (F_6) fertilizer and unfertilized control (F_1) plots. The values of LFOC in surface soil were 81.3, 95.7, 107.8, 155.2, 128.8, 177.8 and 52.7 mgkg^{-1} in ZT and PRB without residue retention, ZT and PRB with 4 and 6 tha^{-1} residue retention and conventional tillage (CT) treatments. In 5- 15 cm layer, the increasing trends in LFOC content due to use of tillage practices and residue retention were similar to those observed in 0-5cm layer; however, the magnitude was relatively lower. Significant increase in LFOC in surface soil (0–5 cm) was maintained in plots receiving 50% RDN as CF+50% RDN as FYM (F_5) and integrated use of 50% RDN as CF+50% RDN as GM/SPM (F_6) fertilizer over 1/3rd N as CF+1/3rd N as FYM+1/3rd N as GM/SPM (F7) over unfertilized control plots (F_1). In general, the impact of applied fertilizer, organic sources and residue retention in improving WSC, POC, PON, LFOC and LFON content was significant in 0 - 5 cm soil layer and was substantially higher than in 5 - 15 cm soil layer under both ZT and PRB and CT system.

Nandan et al. (2019) reported that tillage based crop establishment practices and residue management treatments strongly influenced TOC and soil C–fractions, C–pools, and C–management indices. Residue retention treatment increased C_{frac1}, C_{frac2}, C_{frac3}, C_{frac4}, and TOC by 18, 24, 5, 10, and 12%, respectively, over residue removal treatment. Conservation tillage treatments (NPTPR–ZT, ZTTPR–ZT and ZTDSR–ZT) had 13–21%, 12–16%, 5–7%, 9–13%, and 9–14% higher C_{frac1}, C_{frac2}, C_{frac3}, C_{frac4}, and TOC, respectively, over CTTPR–CT. ZTDSR–ZT and ZTTPR–ZT treatments increased active C–pool, LI and CMI over CTTPR–CT. Irrespective of the cropping system, ZTDSR–ZT or ZTTPR–ZT with crop residue retention had 29–30% higher TOC over conventional CTTPR–CT without residue retention. Stabilization of added carbon in soil was the highest in ZTDSR–ZT and reduced progressively to the order of ZTDSR–ZT > ZTTPR–ZT ≥ NPTPR–ZT > CTTPR–CT.

Jat et al. (2019) showed that the SOC was increased by 69.7%, 40.7% and 9.0% under CSA-based scenarios; Sc4, Sc3 and Sc2, respectively compared to Sc1 (16.2 Mg C ha^{-1}) at 0–15 cm soil depth. In surface soil layer, active and passive pool carbon (18.6 and 10.2 Mg C ha^{-1}) was higher by 90% and 59%, with Sc4 compared to Sc1 (9.8 Mg C ha^{-1} and 6.4 Mg C ha^{-1}), respectively. However, Sc4 (12.4 Mg C ha^{-1}) and Sc3 (10.6 Mg C ha^{-1}) recorded highest very labile C (C_{VL}) which was about 82% and 56% higher compared with Sc1 (6.8 Mg C ha^{-1}). Sc4 conserved significantly higher C_L (110%), C_{LL} (39%) and C_{NL} (71%) at surface soil layer compared with Sc1. Highest active pool (CAP) (72%) and passive pool (CPP) carbon (47%) as per cent of SOC were recorded with Sc3 and Sc2, respectively at 0–15 cm soil depth. Sc3 showed higher C_{VL} (45–47%) and C_L (23–25%) carbon content as per cent of SOC compared to other scenarios. Highest C_{LL} (18%) and C_{NL} (29%) carbon were associated with Sc2 at 0–15 cm soil depth. At 15–30 cm depth, SOC concentration was about 8% higher in Sc2 (12.5 Mg C ha^{-1}) where crop residues were incorporated into the soil during puddling operation compared with Sc3 and Sc4 where residues were retained on soil surface. Sc2 also showed highest CAP (8.6 Mg C ha^{-1}), CPP (3.9 Mg C ha^{-1}) and C_{VL} (7.6 Mg C ha^{-1}) than the other scenarios at 15–30 cm soil depth.

Maharjan et al. (2017) also found that the total soil organic C was highest in organic farming (24 mg C g^{-1} soil) followed by conventional farming (15 mg C g^{-1} soil) and forest (9 mg C g-1 soil) in the topsoil layer (0–10 cm depth). Total C content declined with increasing soil depth, remaining highest in the organic farming soil al all depths tested. A similar trend was found for total N content in all three land uses [Fig.8a], with organic farming soil possessing the highest total N content in both top and subsoil. Similarly, microbial C and N were also highest under organic farming, especially in the topsoil layer (350 and 46 mgg-1 soil, respectively), [Fig.8a]. However, conventional farming and forest soils had similar microbial biomass content. Microbial biomass C and N in topsoil followed the order: organic farming > conventional farming = forest soil which contradicts hypothesis (ii). Higher soil C and N in organic farming is mainly due to the regular application of farmyard manure and vermin-composting [Fig.8b]. Farmyard manure supplies readily available N, resulting higher plant biomass.

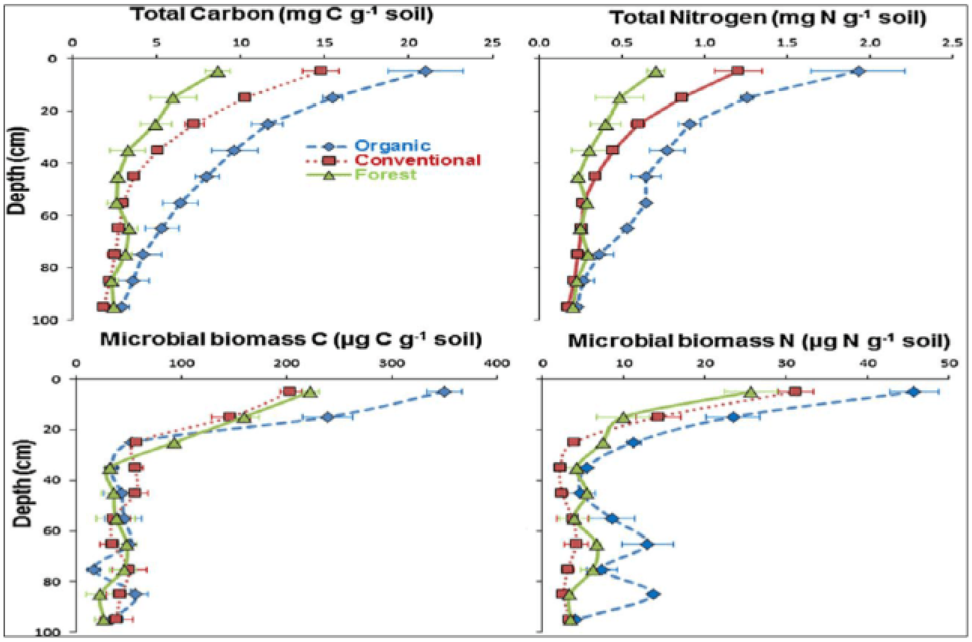


Fig 8(a): Total C, N, and microbial biomass C and N depending on land use and depth

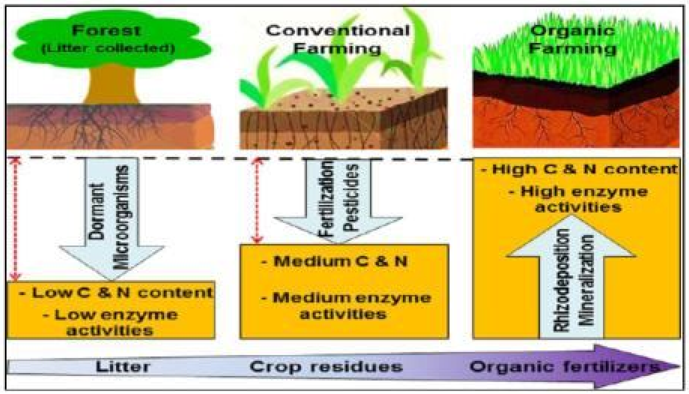


Fig 8(b): Conceptual diagram representing the effect of land use on carbon and nitrogen content in soil

Tillage system influence on soil microbial biomass and soil organic carbon storage

Microbial biomass (bacteria and fungi) is a measure of the mass of the living component of soil organic matter. The microbial biomass decomposes plant and animal residues and soil organic matter to release carbon dioxide and plant available nutrients. Microbial biomass represents a relatively small standing stock of nutrients, compared to soil organic matter, but it can act as a labile source of nutrients for plants, a pathway for incorporation of organic matter into the soil, and a temporary sink for nutrients. Microbial biomass is the main agent that controls the flow of C and cycling of nutrient elements in terrestrial ecosystems. The large size of the soil microbial biomass implicates it as a major nutrient sink during C immobilization and as a source during mineralization.

Dou et al., (2008) reported that SMBC was 5to 8%, mineralized C was 2%, POM C was 14to 31%, hydrolyzable C was 53 to 71%, and DOC was 1 to 2% of SOC. No-till significantly increased SMBC in the 0- to 30-cm depth, especially in the surface 0 to 5 cm. Under NT, SMBC at 0 to 5 cm was 25, 33, and

22% greater for CW, SWS, and WS, respectively, than under CT, but was 20 and8% lower for CW and WS, respectively, than under CT at the 5- to 15-cm depth. At the 15-to 30-cm depth, no consistent effect of tillage was observed. Enhanced cropping intensity increased SMBC only under NT, where SMBC was 31 and 36% greater for SWS and WS than CW at 0 to 30 cm. Bhattacharya et al. (2015) reported that tillage-induced changes in POM C were distinguishable only in the 0- to 5-cm soil layer; the differences were insignificant in the 5- to 15-cm soil layer. Plots under ZT had about 14% higher POM C than CT plots (3.61 g kg^{-1} bulk soil) in the surface soil layer.

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 of15.86 g kg^{-1} of soil were found in puddle transplanted rice followed by wheat planted under conventionally tilled plots. 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 (15–30cm) 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

Kumar et al. (2018) reported that potentially mineralizable nitrogen (PMN) and microbial biomass nitrogen (MBN) content showed that in 0- 15cm soil layer T_1 and T_3 treatments increased from 6.7 and 11.8 $mgkg^{-1}$ in conventional tillage (T_6) to 8.5, 14.4 and 7.6, 14.1 $mgkg^{-1}$ in ZT and RT without residue retention and 12.4, 10.6, 9.3 and 20.2, 19.1,18.2 mg kg^{-1} ZT and RT with residue retention and CT with residue incorporation (T_1, T_3, T_5), respectively. Zhang et al. (2013) reported that soil microbial communities promote the accumulation of C directly and indirectly through MBC, and the input level of microbial-derived C and MBC regulate SOC within aggregates. Xu et al. (2011) observed that the SOC stocks in the 0–80 cm layer under NT was as high as 129.32 Mg C ha^{-1},significantly higher than those under PT and RT. The order of SOC stocks in the 0–80 cm soil layer was NT > PT > RT, and the same order was observed for SCB; however, in the 0–20 cm soil layer, the RT treatment had a higher SOC stock than the PT treatment.

Wang et al. (2018) reported that tillage system change influenced SOC content, NT, ST, and BT showed higher values of SOC content and increased 8.34, 7.83, and 1.64 $Mg\cdot C\cdot ha^{-1}$, respectively, compared with CT. Among the 3 changed tillage systems, NT and ST showed a 12.5% and 11.6% increase in SOC content then BT, respectively. Tillage system change influenced SOC stratification ratio values, with higher value observed in BT and NT compared CT but ST. Therefore, in loess soil, changing tillage system can significantly improve SOC storage and change profile distribution. Mahajan et al. (2019) reported that the increased SOC stock in the surface 50 kg m^{-2} under ZT and PRB was compensated by greater SOC stocks in the 50-200 and 200- 400 kg m^{-2} interval under residue retained, but SOC stocks under CT were consistently lower in the surface 400 kg m^{-2} .Soil organic carbon fractions (SOC), microbial biomasses and enzyme activities in the macro-aggregates are more sensitive to conservation tillage (CT) than in the micro-aggregates. Responses of macro-aggregates to straw return showed positively linear with increasing SOC concentration. Straw-C input rate and clay content significantly affected the response of SOC.

Sirisha et al. (2019) also found that NT treatments increased MBC by 11.2%, 11.5%, and 20%, and dissolved organic carbon (DOC) concentration by 15.5%, 29.5%, and 14.1% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively. Compared with NS treatments, S treatments significantly increased MBC by 29.8%, 30.2%, and 24.1%, and DOC concentration by 23.2%, 25.0%, and 37.5% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively. Conservation tillage (NT and S) increased microbial metabolic activities in >0.25 and <0.25 mm aggregates in the 0−5 cm soil layer. Maximum and significant improvement in microbial parameters was recorded in T_4 with 44, 24, 27 and 24.6% increase in total nitrogen (total N), mineralizable nitrogen (MN), microbial biomass nitrogen (MBN), and microbial biomass carbon (MBC) after a 10 day incubation period over the T_3, respectively, in the surface soil and 10%, 21%, 24% and 24.2% increase in the corresponding microbial parameters in the sub soil.

CONCLUSIONS

The conservation tillage (ST and NT) treatments effectively improved the soil structure and strengthened the stability of water-stable soil aggregates. In addition, they increased the SOC content and storage in aggregates of different sizes with comparison of MP and CT. Furthermore, long-term adoption of conservation tillage methods significantly increased the content of water-stable macro-aggregates and increased the SOC content, ratio of, and storage in the macro-aggregates. In particular, the ST treatment increased the SOC content and enriched the newly formed C in macro-aggregates.

Soil management through the use of different tillage systems affects soil aggregation directly by physical disruption of the macro-aggregates, and indirectly through alteration of biological and chemical factors. Crop residue plays an important role in improving soil organic matter. Tillage reduction and residue retention sequestration, increasing both increased the proportion of soil organic matter as microbial biomass. Microbial immobilization of available-N during the early phase of crops enhanced the degree of synchronization between crop demand and N supply. The organic carbon content under no-tillage and reduced tillage system increased compared to conventional tillage due to retention of residues and minimum disturbance in the former system. The no-tillage system showed a trend to accumulate organic carbon near the soil surface layer. Conventional tillage reduced soil organic C stocks and that of its labile fractions both in top and subsoil (20-100 cm). POC reduction was mainly driven by a decrease in fine POC in topsoil, while DOC was mainly reduced in subsoil. Fine POC, LFOC and microbial biomass can be useful early indicators of changes in topsoil organic C. Rice-Wheat cropping system in western Uttar Pradesh of India has depleted a significant amount of SOC and threatened the sustainability of agriculture in the region of different textured soils. Conservation tillage practices such as reduced- and no-tillage and crop residue addition increased SOC accumulation and improved sustainability of agricultural systems.

No-tillage increased soil aggregation, improved other soil properties, and favorably influenced SOC accretion. Effects of crop residue addition are often observed when it was integrated with reduced-tillage systems. This review study also revealed several challenges and research opportunities impacts of alternative tillage and crop residue management practices to improve SOC concentration and stock and enhance soil carbon pools.

REFERENCES

- Abid, M. and Lal, R. 2008. Tillage and drainage impact on soil quality: I. Aggregate stability, carbon and nitrogen pools. Soil Tillage Res., 100, 89–98.
- Al-Kaisi MM, Douelle A, Kwaw-Mensah D. 2014. Soil micro-aggregate and macro-aggregate decay over time and soil carbon change as influenced by different tillage systems. J Soil Water Cons., 69(6):574-580.
- An T, Schaeffer S, Zhuang J, Radosevich M, Li SY, Li H *et al*. 2015. Dynamics and distribution of ^{13}C-labeled straw carbon by microorganisms as affected by soil fertility levels in the black soil region of Northeast China. Biol. Fertil. Soils., 51:605-613
- Barrios, E. 2007. Soil biota, ecosystem services and land productivity. *Ecol. Econ.* 64, 269–285.
- Blanco-Canqui, H., Lal, R., Sartori, F., and Miller, R.O. 2007. Changes in Organic Carbon and Physical Properties of Soil Aggregates under Fiber Farming. Soil Sci., 172, 553–564.
- Bhattacharyya R, Das TK, Sudhishri S, Dudwal B, Sharma AR, Bhatia A *et al*. 2015. Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. European J Agron., 70:11-21.
- Bronick CJ,and Lal R.2005. Soil structure and management: a review. Geodema. 2005; 124:3-22.
- Caesar-TonThat TC, Sainju UM, Wright SF, Shelver WL, Klberg RL, West M. 2011. Long-term tillage and cropping effects on microbiological properties associated with aggregation in a semi-arid soil. Bio Fertil Soils., 47:157-165.
- Dou F, Wright AL, Hon's FM. 2008. Sensitivity of labile soil organic carbon to tillage in wheat-based cropping systems. Soil Sci Soc Am J., 72:1445-1453.
- Dou S, Li K, Guan S. 2011. A review on organic matter in soil aggregates. Acta Pedologica Sinica., 48 (2):412-418.
- Guan S, Dou S, Chen G, Wang G, Zhuang J. 2015. Isotopic characterization of sequestration and transformation of plant residue carbon in relation to soil aggregation dynamics. Appl. Soil Ecol., 96:18-24.
- Hui-Ping Ou, Xi-Hui Liu, Qiu-Shi Chen, Yan-Fei Huang, Ming-Ju He, Hong-Wei Tan *et al*. 2016. Water-Stable Aggregates and Associated Carbon in a Subtropical Rice Soil under Variable Tillage. Rev. Bras. Ciênc. Solo, 40. http:// dx. doi. Org/ 10.1590/ 18069657 rbcs 20150145
- Huang DD, Liu SX, Zhang XP, Xu JP, Wu LJ, Lou YJ. 2012. Constitute and organic carbon distribution of soil aggregates under conservation tillage. J Agro-Environ Sci.31 (8):1560-1565.

- Humberto BC,and Lal, R. 2004. Mechanism of carbon sequestration in soil aggregates. Plant Sciences. 23(6):481-504.
- Jat HS, Datta A, Choudhary AK, Yadav V, Choudhary PC, Sharma MK, Gathala ML, et al. 2019. Effects of tillage, crop establishment and diversification on soil organic carbon, aggregation, aggregate associated carbon and productivity in cereal systems of semi-arid Northwest India. Soil Tillage Res., 190:128-138
- Jiang, X., Hu, Y., Bedell, J.H., Xie, D., and Wright, A.L. 2010. Soil organic carbon and nutrient content in aggregate-size fractions of a subtropical rice soil under variable tillage. Soil Use Manag. 27, 28–35.
- Jiang, X., Wright, A.L., Wang, J., and Li, Z. 2011. Long-term tillage effects on the distribution patterns of microbial biomass and activities within soil aggregates. Catena, 87, 276–280.
- Lal L. 2007. Constraints to adopting no-till farming in developing countries. Soil Tillage Res., 94:1-3.
- Liu C, Lu M, Cui J, Li B, Fang C.2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Change Biol., 20(62):1366-1381.
- Kumar V, Naresh RK, Satendra Kumar, Sumit Kumar, Sunil Kumar, Vivak Singh SP *et al*. 2018. Tillage, crop residue, and nitrogen levels on dynamics of soil labile organic carbon fractions, productivity and grain quality of wheat crop in *Typic ustochrept* soil. J Pharmacog Phytochem. 7(1):598-609.
- Liu XL, He YQ, Li CL, Jang CL, Chen PB.2009. Distribution of soil water-stable aggregates and soil organic C, N and P in upland red soil. Acta Ecologica Sinica., 46(2):255-262
- Maharjana M, Sanaullaha M, Razavid BS, Kuzyakov Y. 2017. Effect of land use and management practices on microbial biomass and enzyme activities in subtropical top-and sub-soils. Appl Soil Ecol., 113:22-28.
- Mandal B, Majumde RB, Adhya TK, Bandyopadhyay PK, Gangopadhyay A, Sarkar D *et al*.2008. The potential of double-cropped rice ecology to conserve organic carbon under subtropical climate. Glob Change Biol., 14:2139-2151.
- Moharana P.C., Sharma B.M., Biswas D.R., Dwivedi B.S., and Singh R.V. 2012. Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a6-year-old pearl millet–wheat cropping system in an Inceptisol of subtropical India. Field Crops Res 136: 32–41
- Mazumdar SP, Kundu DK, Nayak AK, Ghosh D. 2015. Soil Aggregation and Associated Organic Carbon as Affected by Long Term Application of Fertilizer and Organic Manures under Rice-Wheat System in Middle Gangetic Plains of India. J Agric Phy., 15(2):113-121.
- Nakajima, T., Shrestha, R.K., Jacinthe, P.A., Lal, R., Bilen, S., and Dick, W. 2016. Soil organic carbon pools in ploughed and no-till Alfisols of central Ohio. Soil Use Manag. 32, 515–524.

- Nandan R, Singh V, Singh SS, Kumar V, Hazra KK, Nath CP, et al.2019. Impact of conservation tillage in rice– based cropping systems on soil aggregation, carbon pools and nutrients. Geoderma. 340:104-114.
- Naresh RK, Gupta Raj K, Gajendra Pal, Dhaliwal SS, Kumar, D., etal. 2015. Tillage crop establishment strategies and soil fertility management: resource use efficiencies and soil carbon sequestration in a rice-wheat cropping system. Eco. Env. & Cons. 21:127-134
- Naresh RK, Arvind Kumar, Bhaskar S, Dhaliwal SS, et al. 2017.Organic matter fractions and soil carbon sequestration after 15- years of integrated nutrient management and tillage systems in an annual double cropping system in northern India. J. Pharmacog Phytochem. 6(6):670-683.
- Naresh RK, Jat PC, Kumar V, Singh SP, Kumar Y. 2018. Carbon and nitrogen dynamics, carbon sequestration and energy saving in soils under different tillage, stubble mulching and fertilizer management in rice–wheat cropping system. J Pharmacog Phytochem.,7(6):723-740
- Naresh RK, Bhaskar S, Dhaliwal SS, Kumar A, Gupta RK, and Vivek. 2018. 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. J Pharmacogn Phytochem 7:248–259.
- Naresh RK, Gupta RK, Vivek Rathore RS, Singh SP, Kumar A, Kumar S, et al. 2018. Carbon, Nitrogen Dynamics and Soil Organic Carbon Retention Potential after 18 Years by Different Land Uses and Nitrogen Management in RWCS under Typic ustochrept Soil. Int. J Curr. Microbiol. App. Sci., 7(12):3376-3399
- Paudel Madhab, Sah Shrawan Kumar, AndrewMcDonald, and Chaudhary Narendra Kumar.2014. Soil Organic Carbon Sequestration in Rice-Wheat System under Conservation and Conventional Agriculture in Western Chitwan, Nepal. World J Agri Res 2, (6A): 1- 5.
- Saikia, R., Sharma, S., Thind, H. S., Sidhu, H. S. and Singh, Y.2019. Temporal changes in biochemical indicators of soil quality in response to tillage, crop residue and green manure management in a rice-wheat system. *Ecol. Ind.* 103, 383–394.
- Saikia, R., Sharma, S., Thind, H. S. and Singh, Y. 2019. Tillage and residue management practices affect soil biological indicators in a rice–wheat cropping system in north-western India. *Soil Use Manag.* 36, 157–172.
- Sharma, S., Vashisht, M., Singh, Y. and Thind, H. S. 2019. Soil carbon pools and enzyme activities in aggregate size fractions after seven years of conservation agriculture in a rice–wheat system. *Crop Pasture Sci.* 70, 473–485.
- Simansky V, Horak J, Clothier B, Buchkina N, Igaz D. Soil organic-matter in water-stable aggregates under different soil-management practices. Agriculture *(Poľnohospodárstvo),* 2017; 63(4):151-162.

- Sirisha, L., Naresh, R.K., Kancheti, M., Mahajan, N.C., et al. 2019. Tillage and residue management practices on soil carbon, nitrogen mineralization dynamics and changes in soil microbial community under RWCS: A review. Int. J Chem Stu., 7(3): 4974-4994
- Six J, Elliott ET, Paustian K. 1998. Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems. Soil Sci Soc Am J., 63(5):1350-1358.
- Six J, Elliot ET, Paustian K. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J., 63:1350-1358.
- Wagner S, Cattle SR, Scholten T. 2007. Soil-aggregate formation as influenced by clay content and organic-matter amendment. J Plant Nutr. Soil Sci., 170(1):173–180
- Wang H, Wang S, Zhang Y, Wang X, Wang R, Li J.2018. Tillage system change affects soil organic carbon storage and benefits land restoration on loess soil in North China. Land Degrad Dev., 29:2880-2887.
- Xu M, Lou Y, Sun X, Wang W, Baniyamuddin M, Zhao K. 2011. Soil organic carbon active fractions as early indicators for total carbon change under straw incorporation. Biol Fertility Soils., 47:745-752.
- Zhao H, Shar AG, Li S, Chen Y, Shi J, Zhang X, Tian X.2018. Effect of straw return mode on soil aggregation and aggregate carbon content in an annual maize-wheat double cropping system. Soil Tillage Res. 2018; 175:178-186.
- Zheng ZC, Wang YD, Li TX, Yang YM. 2011. Effect of abandoned cropland on stability and distributions of organic carbon in soil aggregates. J Nat Res., 26(1):119-127.
- Zheng H, Liu W, Zheng J, Luo Y, Li R, Wang H, et al. 2018. Effect of long-term tillage on soil aggregates and aggregate-associated carbon in black soil of Northeast China. PLoS ONE 13(6): e0199523. https://doi.org/10.1371/journal.pone.0199523
- Zhou H, Lu YZ, Li BG. 2009. Advancement in the study on quantification of soil structure. Acta Ecologica Sinica. 46(3):501-506.
- Zhou P, and Pan GX. 2007. Effect of different long-term fertilization treatments on particulate organic carbon in water-stable aggregates of Paddy Soil. Chinese J Soil Sci., 38(2):256-261.
- Zotarelli L, Alves BJR, Urquiaga S, Boddey RM, Six J. 2007. Impact of tillage and crop rotation on light fraction and intra-aggregate soil organic matter in two Oxisols. Soil till Res., 95(1-2):196-206.
-