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# Impact of conservation tillage on soil organic carbon storage and soil labile organic carbon fractions of different textured soils under rice-wheat cropping system: A review

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## Abstract

Conservation management approaches focusing on minimizing soil disturbance maximizing soil cover, and stimulating biological activity can be achieved with different cropping choices and production goals in different environments all around the Indo-Gangetic Plains, India. The conservation tillage practice in wheat increased the organic carbon content and carbon stock as compared to conventional tillage in soils. The Conservation tillage increased dissolved organic carbon, microbial biomass carbon light and heavy fractions of carbon in soils at both the depths. The light and heavy fraction carbon values were observed to be lower in lighter textured soil which increased with increase in fineness of the texture. The total nitrogen was highest in clay loam under conservation tillage at 0-15 cm depth as compared to conventional tillage. 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. However, higher SOC content of 8.14 g $kg^{-1}$ of soil was found in reduced tilled residue retained plots followed by 10.34 g $kg^{-1}$ in furrow irrigated raised beds with residue retained plots. Whereas, the lowest level of SOC content of 5.49 g $kg^{-1}$ of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots. 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 $ha^{-1}$ $yr^{-1}$. Long term conservation tillage significantly increased 66.1%, 57.9%, 50.9%, 38.3%, 37.3% and 32% LFOC, SOC, PON, TN, LFON, DOC and POC, over conventional tillage ($T_7$) treatment and WSC 39.6% in surface soil and 37.4% in subsurface soil. Under RWCS, TOC contents were similar in 50% RDN as CF+50% RDN as GM/SPM ($F_6$) and1/3rd N as CF+1/3rd N as FYM+1/3rd N as GM/SPM ($F_7$) and 75% RDN as CF+25% RDN as FYM ($F_3$) plots and significantly higher than those in control (no manure and fertilizer) ($F_1$) plots (by 50.4% 48.3%, and 43.3% respectively). Manure addition further enhanced TOC contents, which were highest following the 50% RDN as CF+50% RDN as FYM ($F_5$) treatment (21.37 $gkg^{-1}$). Therefore, conservation agriculture in rice-wheat system can help directly in building–up of soil organic carbon, labile organic carbon fractions and improve the fertility status of soil.

**Keywords:** organic matter fractions; soil health, soil organic carbon, total carbon stocks

## Introduction

Agricultural management practices influence organic matter in soil (Reicosky and Lindstrom, 1995) [57], micro- and macro-aggregates distribution, rate of soil organic matter (SOM) turnover, saturation limit and SOM stability and their steady state level (Stewart *et al*., 2007) [70]. Agriculture and intensive tillage have caused a decrease in soil C of between approximately 30 and 50 per cent due to the fact that many soils were brought into cultivation more than a 100 years ago (Schlesinger, 1986) [58]. Soil aggregation can provide physical protection of organic matter against rapid decomposition (Pulleman and Marinissen, 2004) [56]. Soil aggregation itself and consequently the C stock, soil organic carbon (SOC) dynamics and organic matter quality is strongly influenced by agricultural management intensity (Bono *et al*., 2008; Simon *et al*., 2009) [10, 63]. Soil structure and organic matter storage are also affected by the quality and quantity of organic inputs and the use of pesticides, fertilizers and manure (Droogers and Bouma, 1997) [21]. In addition, SOM and soil structure are mutually related: SOM binds with mineral particles to form soil aggregates and, in turn, stable aggregation can provide physical protection of otherwise mineral sable SOM (Beare *et al*., 1994b) [8]. Since the start of large-scale farming in the 20th century, agricultural practices have caused the loss of SOM from cultivated soils (Smith *et al*., 2000) [69]. Apart from the detrimental effects on soil structure and soil quality (Six *et al*., 1998) [67], the released organic C contributes to global

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warming (IPCC, 2007) [32]. An important objective of sustainable use of soil resources is, therefore, to increase the pool of soil organic C (Paustian *et al*., 1997) [55]. However, the understanding of the mechanisms of SOM protection in aggregates and the management conditions that favors this process needs to be improved.

## Soil organic carbon in water-stable aggregates

Simansky *et al*. (2017) [61] 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]. Khorramdel *et al*. (2013) [39]; Abdollahi *et al*. (2014) [1] showed that an application of organic and mineral fertilizers increased the average content of SOC in WSA $_{ma}$ by 22%, 9% and 6% in T+FYM, G+NPK3 and G+NPK1, respectively, as compared to control. Tong *et al*. (2014) [72] reported that the soils under NPK and NP treatments significantly increased SOC stocks. However, fertilizers may also decrease C content as compared to unfertilized soil. Shimizu *et al*. (2009) [60] also indicates C loss which is connected with the higher use of chemical fertilizers – especially nitrogen (Yang 2011) [80]. On the other hand, higher nutrient contents through biomass production can increase SOC in the higher size fractions of WSA $_{ma}$, especially in the short term (Simansky & Pollakova, 2012) [62].

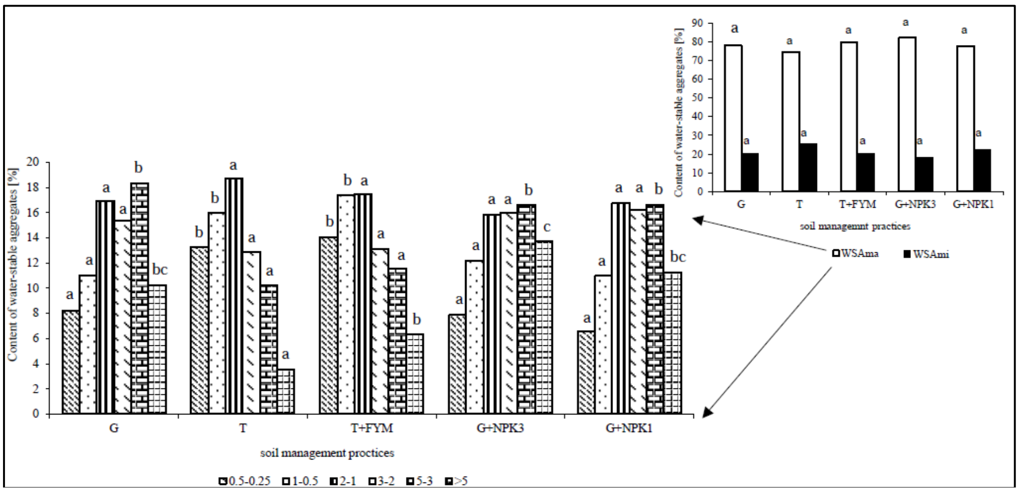


**Fig 1:** water-stable aggregates contents under different soil-management practices

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 $1^{st}$ intensity for vineyards; WSA $_{ma}$ – water-stable macro-aggregates; WSA $_{mi}$ – water-stable micro-aggregates.

Hui-Ping Ou *et al*. (2016) [29] reported that tillage systems obviously affected the distribution of soil aggregates with different sizes [Fig. 1]. The proportion of the >2 mm aggregate fraction in NT+S was 7.1 % higher than that in NT-S 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 <0.053 mm aggregate compared to the MP system for the 0.00-0.20 m layer. The proportion 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.2]. Huang *et al*. (2010) [30]; Jiang *et al*. (2011) [34]; Vogelmann *et al*. (2013) [73] revealed that the higher proportion of >2 mm aggregates and lower proportion of <0.053 mm aggregates under NT systems might be the result of the higher soil hydrophobicity, low intensity of wetting and drying cycles, higher soil C concentration or the physical and chemical characteristics of large macro-aggregates making them more resistant to breaking up. Naresh *et al*. (2017) [53] 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 (F5) followed by 50% RDN as CF+50% RDN as GM/SPM (F6) 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 1]. 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 $kg^{-1}$) > 1/3 $^{rd}$ N as CF+1/3 $^{rd}$ N as FYM+1/3 $^{rd}$ N as GM/SPM (21.40 $gkg^{-1}$) >75% RDN as CF+25% RDN as FYM (19.64 $gkg^{-1}$) > unfertilized control (10.99 $gkg^{-1}$). Higher soil organic carbon content in residue retention could be attributed to more annual nutrient recycling in respective treatments and decreased intensity of mineralization (Kaisi and yin, 2005) [35]. Carbon input in the form of crop residue had primary factor for stabilization of soil carbon (Singh, 2011) [66]. 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.

**Table 1:** 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 [53]]

| 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 ($P < 0.05$).

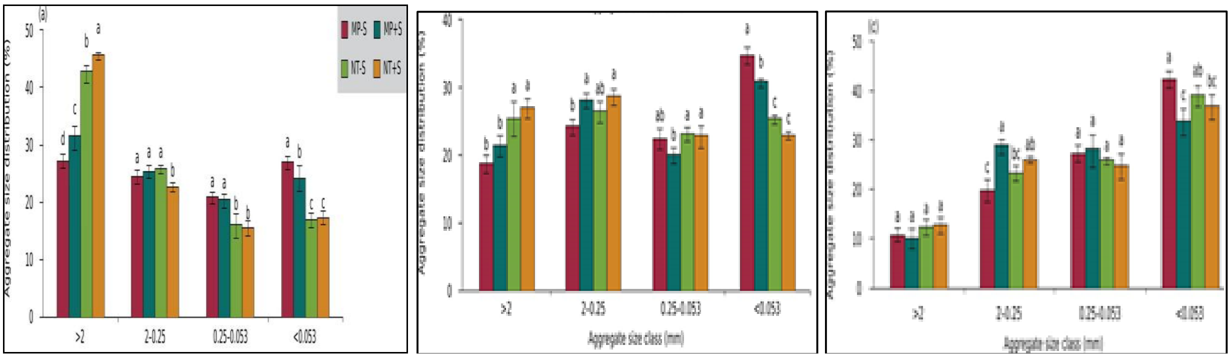


**Fig 2:** Distribution (%) of water-stable aggregates with different sizes in different soil layers as influenced by tillage treatments. (a) 0.00-0.05 m; (b) 0.05-0.20 m; (c) 0.20-0.30 m. MP-S: moldboard plow without straw; MP+S: moldboard plow with straw; NT-S: no-tillage without straw; NT+S: no-tillage with straw

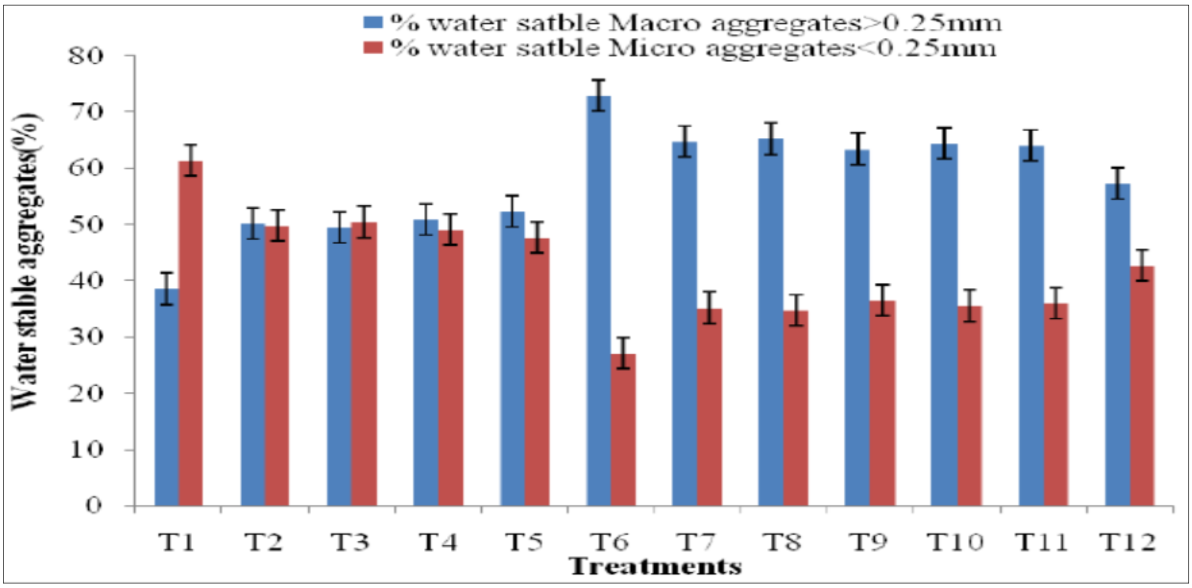


**Fig 3:** Influence of Organic amendments on distribution of Water Stable Macro and Micro Aggregates ($T_1$–control (no fertilizer no organic manure); $T_2$–50% recommended dose of fertilizers (RDF) to both rice and wheat; $T_3$– 50% RDF to rice and 100% RDF to wheat; $T_4$– 75% RDF to both rice and wheat; $T_5$– 100% RDF to both rice and wheat; $T_6$– 50% RDF + 50% N through farm yard manure (FYM) to rice and 100% RDF to wheat; $T_7$– 75% RDF + 25% N through FYM to rice and 75% RDF to wheat; $T_8$– 50% RDF + 50% N through paddy straw to rice and 100% RDF to wheat; $T_9$– 75% RDF + 25% N through paddy straw to rice and 75% RDF to wheat; $T_{10}$– 50% RDF + 50% N through green manuring to rice and 100% RDF to wheat; $T_{11}$– 75% RDF + 25% N through green manuring to rice and 75% RDF to wheat; $T_{12}$– Conventional farmer's practice)

Mitran *et al*. (2018) [52] reported that an enrichment of organic carbon content in the larger size aggregates (>2 mm) compared to smaller aggregates (<0.25 mm). Higher proportion of organic carbon was occluded within small macro aggregates (0.25-2.0mm) than fine micro aggregates (0.050.2mm) as well as silt plus clay sized soil separates (<0.05mm). The effects were more pronounced in organically amended soils rather than unfertilized and solely fertilized soil. Within a size class, aggregated C concentrations of the organically amended treatments were in the order of FYM>PS≥GLM. In all the cases 50% substitution of N by organic amendments recorded much higher values than 25% substitution of N [Fig. 3 and 4]. (Liu *et al*., 2014; Sui *et al*., 2012; Fang *et al*., 2014) [47, 71] reported that the formation of aggregate associated carbon in small aggregates occurs more quickly than in large aggregates, but ultimately SOC content in large aggregates is greater than in small aggregates. The micro aggregates formed within macro-aggregates could contribute significantly to SOC stabilization. Carbon accumulation in the fine micro aggregates fractions not only as a result of C loading through organics but also due to a transfer of carbon from macro aggregated carbon. The bio polymers (e.g. lignin, polyphenols etc.) derived from roots and hyapae as well as added organics exhibit a high degree of resistance to microbial degradation as compared to cellulose poly- saccharides in macro aggregated carbon and seemed to be stabilized in fine micro aggregates (Bandyopadhyay *et al*., 2010).

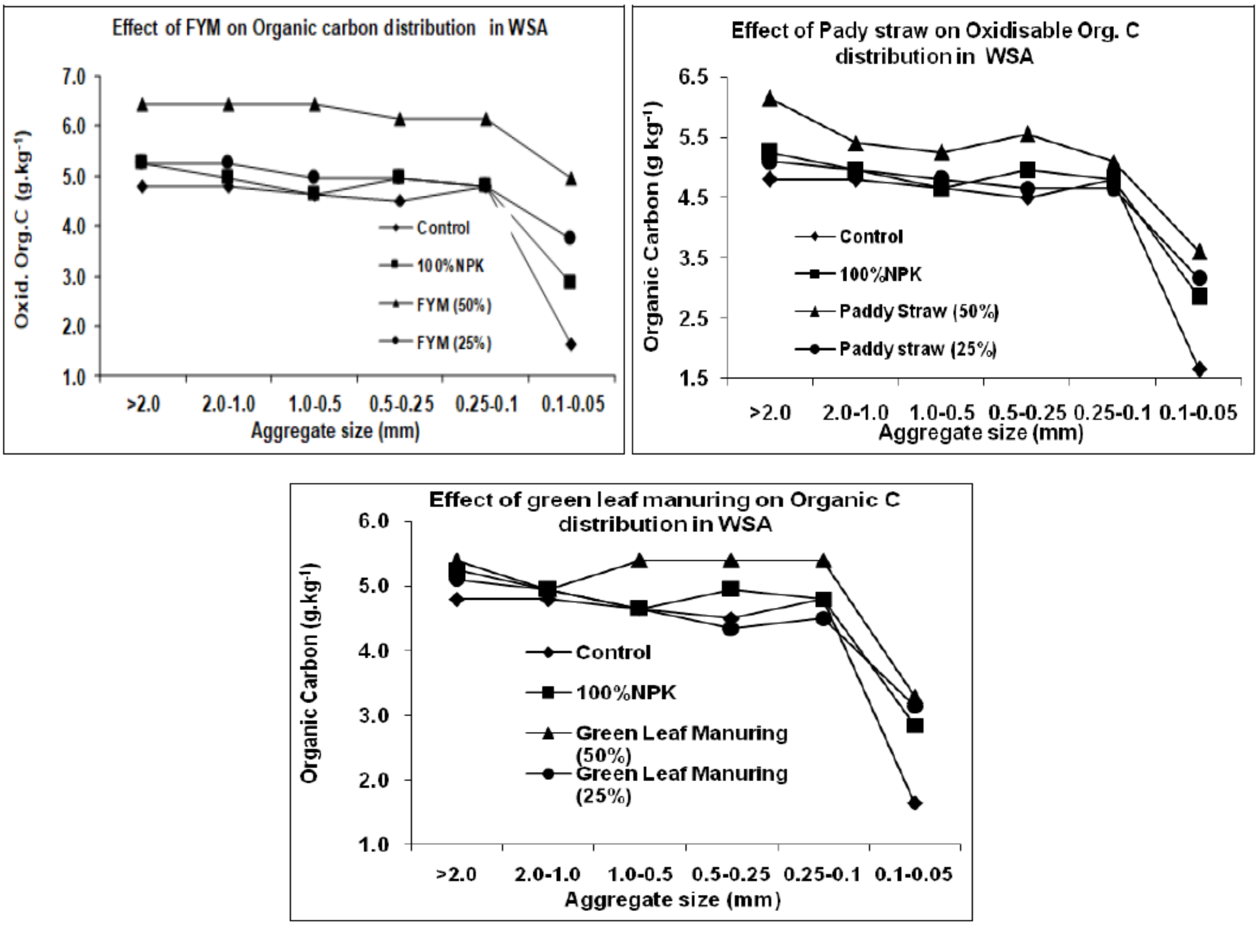
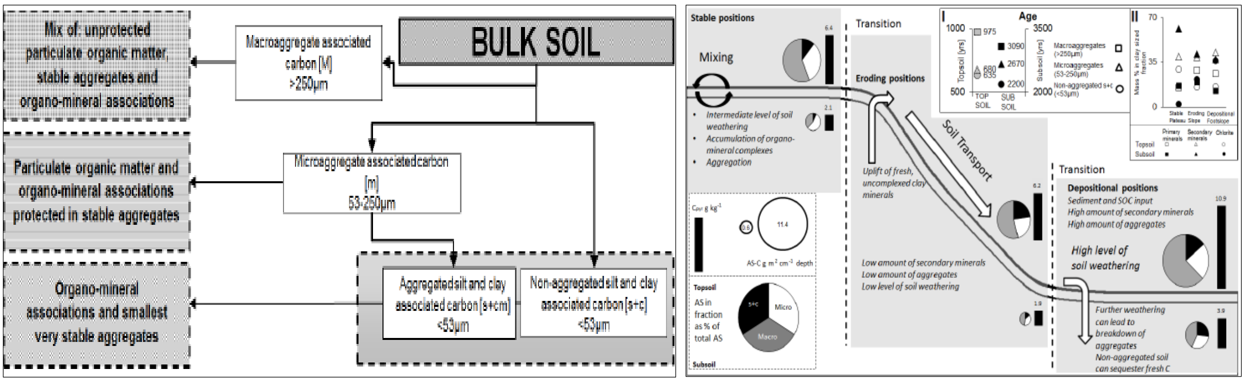


**Fig 4:** Distribution of Organic Carbon within water stable aggregates under various treatments

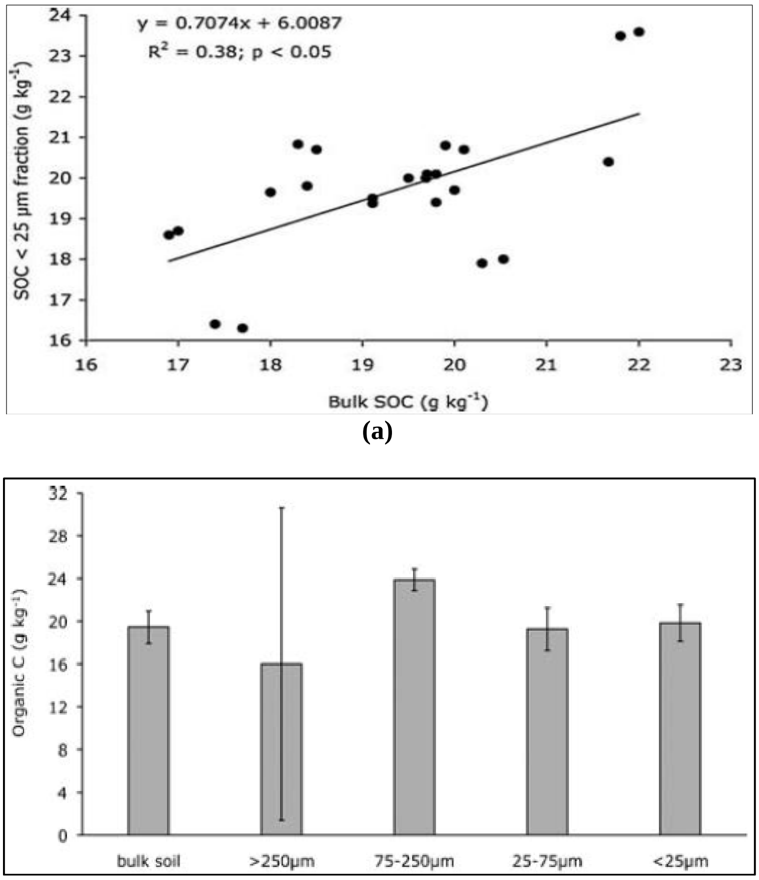
Doetterl *et al*. (2015) [19] revealed that mineral alteration and the breakdown of aggregates limit the protection of C by minerals and within aggregates temporally [Fig 5 a & b]. Barbera *et al*. (2010) [7] also found that the small differences were found for the 25–75 and 75–250µm fractions between the treatments. Regarding the C contribution of the particle size fractions (aggregate) to the bulk SOC, the following order was obtained: 0–25>25–75µm>75–250>250– 2000µm. The higher accumulation of SOC in the finest fraction was due to the higher mass of the silt-clay fraction in the soils while the sandy fractions in general account less for the total soil mass [Fig. 6a]. However, taking the average SOC concentration of each fraction into account, then the 75–250µm aggregate size showed an SOC enrichment compared to the bulk SOC concentration (23.9gkg$^{-1}$), while the corresponding values of the 25–75 and <25µm fractions did not statistically differ (19.3 and 19.8gkg$^{-1}$, respectively) [Fig. 6b]. The average SOC concentration of the fraction >250µm was the lowest. Kong *et al*. (2005), however, reported a preferential stabilization of SOM in the micro-aggregate fraction. The treatments only affected the SOC content of large micro-aggregates and coarser fractions. In fact, crop residues incorporated into the soil were first stored in >75µm fractions and were then transferred to the silt and clay fractions. The differences among the CSs W and WB were not significant. Tillage seemed, however, to influence the SOC concentration in the large macro-aggregate (75–250µm) fraction. Moreover, the contribution of large macro-aggregates (>250µm) to the total SOC is definitely influenced by the tillage and CSs.



(a) (b)

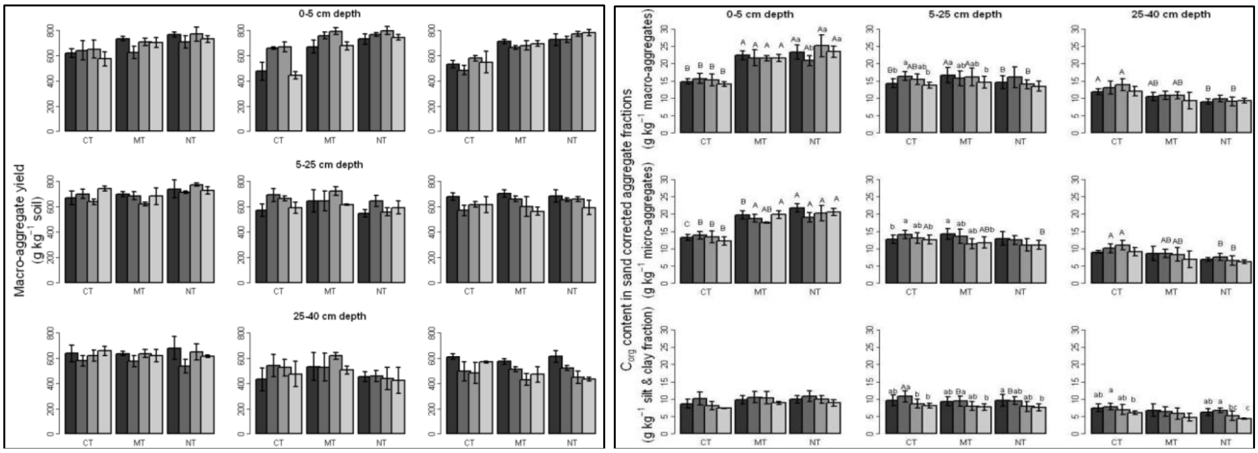
**Fig. 5 (a):** Fractions of the applied fractionation scheme and interpretation of the present carbon stabilization mechanisms in each fraction
**Fig. 5(b):** Conceptual figure showing the mineralogical changes along the slope in relation to the abundance of AS in non-aggregated silt and clay (s + c), micro-aggregates, and macro-aggregates

Wagner *et al*. (2007) [74] 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.7a]. 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. 7b]. 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. 7b].



(b)

**Fig. 6(a):** Relationship between the organic C concentration in the bulk soil and in <25µm fraction of all samples
**Fig. 6(b):** Average SOC concentrations (with standard deviation) in the different soil fractions



(a) (b)

**Fig. 7(a):** Average dry matter yields of the macro-aggregate (>250 µm) 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. 7(b):** Average $C_{org}$ content in sand corrected macro-aggregate (>250 µm) and micro-aggregate (250-53 µm) fractions and of the silt and clay sized (<53 µm) fractions of the different tillage treatments

### Aggregate-associated SOC concentration

Hui-Ping Ou *et al*. (2016) [29] also found that in the 0.00-0.05 m layer, SOC concentration in macro-aggregates showed the order of NT+S>MP+S = NT-S>MP-S, whereas the NT system was superior to the MP system. However, the NT system significantly reduced the SOC concentration in the 2.00-0.25 mm fraction in the 0.05-0.20 m layer. A similar trend was observed in the 0.25-0.053 mm fraction in the 0.20-0.30 m layer. Across all the soil layers, there was no difference in the <0.053 mm fraction between NT-S and MP-S, as well as between NT+S and MP+S, indicating that the NT system did not affect the SOC concentration in the silt+ clay fraction. In average across the soil layers, the SOC concentration in the macro-aggregate was increased by 13.5 % in MP+S, 4.4 % in NT-S and 19.3 % in NT+S, and those in the micro-aggregate (<0.25 mm) were increased by 6.1 % in MP+S and 7.0 % in NT+S compared to MP-S. For all the soil layers, the SOC concentration in all the aggregate size classes was increased with straw incorporation, by 20.0, 3.8 and 5.7 % under the MP system, and 20.2, 6.3 and 8.8 % under the NT system [Fig.8]. Du *et al*. (2013) [23]; Conceicao *et al*. (2015) [13] reported that the NT system resulted in stratification of SOC, while the MP system resulted in a more homogeneous distribution in the 0.00-0.20 m layer. When considering the whole 0.00-0.30 m layer, however, the differences in SOC stock were not significant between NT-S and MP-S as well as between NT+S and MP+S. This indicates that the NT system did affect the SOC stock distribution in the soil profile but not the total quantity.

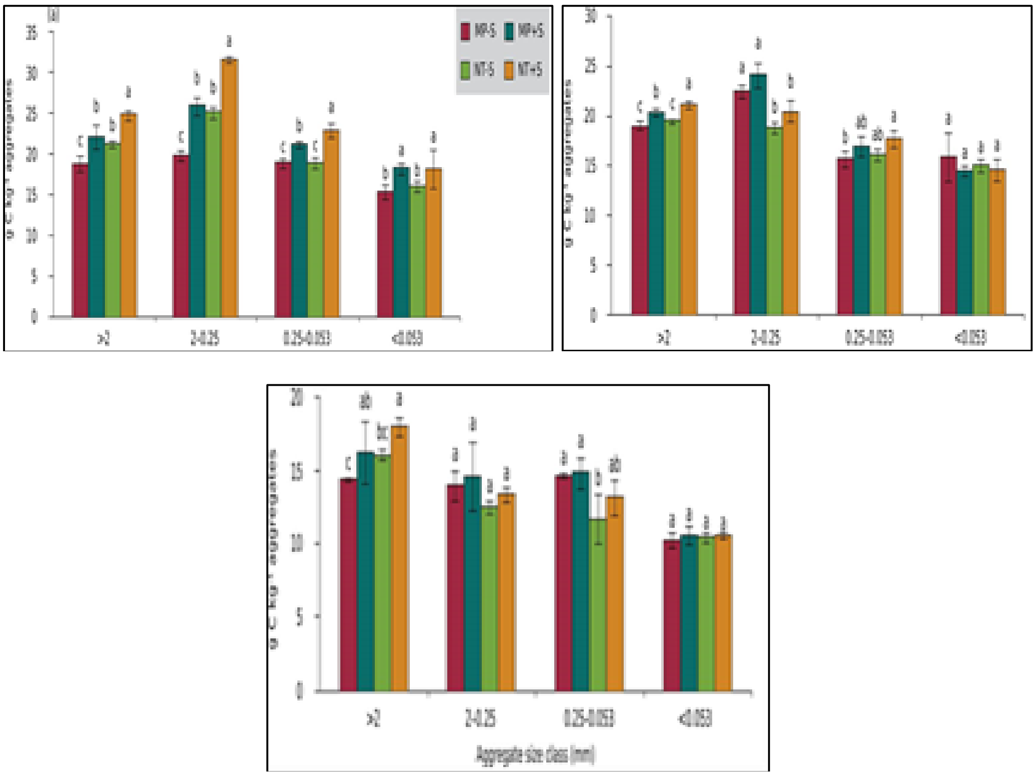
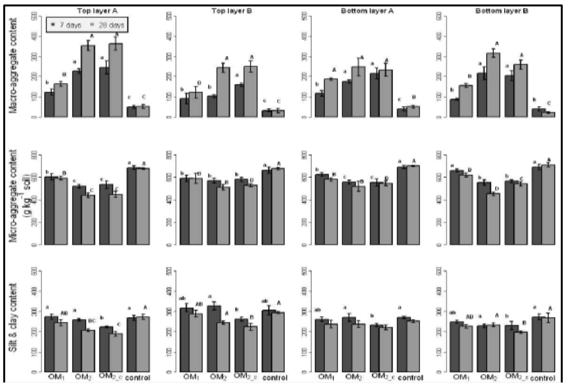


**Fig. 8:** Aggregate-associated SOC concentration in different layer intervals as influenced by tillage treatments. (a) 0.00-0.05 m; (b) 0.05-0.20 m; (c) 0.20-0.30 m. MP-S: moldboard plow without straw; MP+S: moldboard plow with straw; NT-S: no-tillage without straw; NT+S: no-tillage with straw



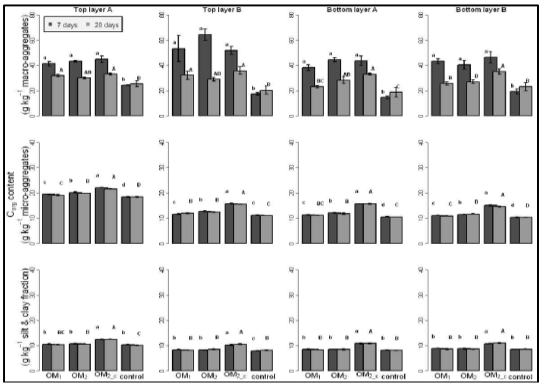


**Fig. 9 (a):** Mean dry matter yields of macro-aggregate (>250 µm), micro-aggregate (250-53 µm) and silt & clay sized (<53 µm) fractions of different soils at 0-5 and 5-25 cm soil depth and treatments (OM1: addition of OM: pre-incubated wheat straw at a rate of 4.1 g C kg$^{-1}$ soil, OM2: addition 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. 9 (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

Zotarelli *et al*. (2007) [84] revealed that the amount of C within the macro-aggregates was still markedly higher after 7 and 28 days of incubation [Fig. 9a] 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.9b]. 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. Luo *et al*. (2010) found in their meta-analysis of a global data set from 69 paired tillage experiments no significant differences between $C_{org}$ stocks of CT and NT soils. They especially focused on studies with soil sampling deeper than 40 cm and revealed that conversion from CT to NT significantly increased the $C_{org}$ stocks in 0-10 cm depth, whereas the $C_{org}$ stocks between 10 and 40 cm depth were significantly lower. Also Embacher *et al*. (2007) showed an increased $C_{org}$ content in the upper cm of a Eutric Cambisol after 10 years of NT.

## Soil labile carbon fractions

Reflecting the different extent of litter incorporation, the average fLF contents were significantly higher for the MT treatment than for the CT treatment and decreased in the order MT (3.9 g (kg soil)$^{-1}$) > NT (2.7 g (kg soil)$^{-1}$) > CT (1.5 g (kg soil)$^{-1}$) in 0-5 cm soil depth [Table 2]. The fLF contents decreased with increasing soil depth. In 5-25 cm and 25-40 cm soil depths, the fLF contents followed a different order than in the top 5 cm with higher contents under MT and CT due to litter in corporation and the lowest contents under NT. The oLF content was significantly higher for the NT and MT treatments, with 7.4 g (kg soil)$^{-1}$ and 6.7 g (kg soil)$^{-1}$, respectively, than for the CT treatment with 4.1 g (kg soil)$^{-1}$ in 0-5 cm soil depth. The $C_{org}$ content of the fLF fraction decreased in 0-5 cm and 25-40 cm soil depths in the order: CT > NT > MT and in 5-25 cm soil depth in the order NT > CT > MT. Soils of the CT treatment showed an increased $C_{org}$ content of the oLF fraction, and the MT and NT treatments ranged around the same contents [Table 1]. On average, 2.5 and 12.2% of $C_{org}$ of the bulk soil were recovered in the fLF and oLF fractions, respectively, the rest consisting of mineral associated C in the heavy fraction.

**Table 2:** Average contents of the free light fraction (fLF), the occluded light fraction (oLF), the fLF/oLF ratio and the organic carbon ($C_{org}$) content of the fLF and oLF.

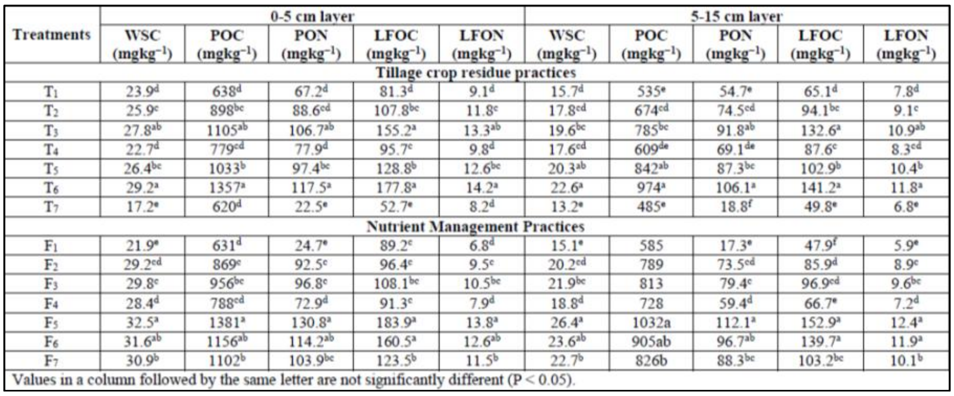
| Treatment | fLF content | oLF content | fLF/oLF ratio | $C_{org}$ content | $C_{org}$ content |
|---|---|---|---|---|---|
| 0-5 cm | | | | | |
| CT | 1.5 (0.7)$^b$ | 4.1 (1.1) $^b$ | 0.4 (0.3) | 237 (67) | 294 (7)$^a$ |
| MT | 3.9 (1.4)$^a$ | 6.7 (1.3) $^a$ | 0.6 (0.3) | 180 (16) | 284 (9)$^b$ |
| NT | 2.7(1.2)$^{ab}$ | 7.4(1.5)$^a$ | 0.4(0.3) | 207(9) | 285(3)$^b$ |
| 5-25 cm | | | | | |
| CT | 0.8 (0.4) | 5.1 (1.4)$^a$ | 0.2 (0.1) | 243 (71) | 299 (7) |
| MT | 1.0 (0.6) | 5.3 (1.2)$^a$ | 0.2 (0.1) | 194 (66) | 293 (3) |
| NT | 0.6(0.1) | 3.9(1.3)$^b$ | 0.2(0.1) | 254(59) | 295(14) |
| 25-40 cm | | | | | |
| CT | 0.5 (0.3)$^{ab}$ | 3.8 (1.4) | 0.1 (0.1) | 226 (72) | 298 (8) |
| MT | 0.6 (0.3)$^a$ | 3.6 (2.0) | 0.2 (0.1) | 191 (51) | 277 (28) |
| NT | 0.3(0.1)$^b$ | 3.0(2.3) | 0.2(0.1) | 216(90) | 284(19) |

Si *et al*. (2018) [64] reported that differences in SOC concentration and stock were primarily evident in the 0 -10 cm layer. The particulate organic matter carbon (POM-C), dissolved organic carbon (DOC), and microbial biomass carbon (MBC) levels in the top layers (0–10 cm) under the NTSM treatment were 28.5, 26.1 and 51.0% higher than CT. A positive correlation was observed between these labile C fractions and the SOC, and POM-C was the much more sensitive indicator of SOC quality than MBC and DOC [Fig. 10 a and b]. Blanco-Canqui and Lal (2007a) [9] showed that approximately 33% of all C from wheat residues returned to a silt loam soil during a 10-yr experiment was sequestered in the SOC pool, while Courtiermurias *et al.* (2013) [14] concluded that the application of crop residues increased total organic C content by 10% compared to the un-amended soil. Dou *et al*. (2008) [20], who observed that POM-C, DOC and MBC were all positively correlated with SOC. Chen *et al*. (2009) [12], reported that SOC was positively correlated with POM-C, DOC and MBC. The improvement or depletion in the labile C fractions could also provide an effective early warning of changes in SOC. On the other hand, these correlations indicated that SOC was a major determinant of the labile C fractions (Liang *et al*. 2012) [44]. Li *et al*. (2018) [46] revealed that the application of chemical fertilizers (NP) alone did not alter labile C fractions, soil microbial communities and SOC mineralization rate from those observed in the CK treatment. Whereas the use of straw in conjunction with chemical fertilizers (NPS) became an additional labile substrate supply that decreased C limitation, stimulated growth of all PLFA-related microbial communities, and resulted in 53% higher cumulative mineralization of C compared to that of CK. The SOC and its labile fractions explained 78.7% of the variance of microbial community structure. Yang *et al*. (2012) [81] reported that the significant increases of MBC were observed after manure or straw addition, suggesting that organic amendments had beneficial effects on growth of the microbial biomass probably by providing a readily-available source of C substrate and improving the soil environment. Xu *et al*. (2013) [77] also found that the changes of MBC/MBN could be related to changes in microbial species and populations. However, the larger N input originating from urea, crop residues and manure resulted in decreases in C/N ratios of labile fractions.

Naresh *et al*. (2017) [53] revealed that significantly increased 66.1%, 50.9%, 38.3%, 37.3% and 32% LFOC, PON, LFON, DOC and POC, over $T_7$ treatment and WSC 39.6% in surface soil and 37.4% in subsurface soil [Table 3]. The proportion of MBC ranged from 16.1% to 21.2% under ZT and PRB without residue retention and 27.8% to 31.6% of TOC under ZT and PRB system with residue retention, which showed gradual increase with the application of residue retention treatments and was maximum in 6 tha$^{-1}$ residue retention treatment under both tillage systems [Table 4]. Kang *et al*., (2005) [37] also found that application of organic residues increased PMN, which was positively related to increase in TOC content of soil. DOC is believed to be derived from plant roots, litter and soil humus and is a labile substrate for microbial activity Kalbitz *et al*., (2000) [36]. The concentration of DOC varied widely among all the treatments and a significant increase was observed in surface soils under different fertilizer treatments compared with unfertilized control. Schjonning *et al*. (2002) [59] reported that the highest MBC content of 515.4 µg g$^{-1}$ at surface soil (0–15 cm) was observed in FYM+NPK plots. It is known that the microbial fraction of clay soils is often greater than it is in sandy soils due to the protective effect of clays on microbial biomass.

Banger *et al*. (2010) [6] reported that compared to the control treatment, the increase in SOC was 36, 33, and 19% greater in organic, integrated, and NPK treatments. The 16-years application of fertilizers and/or FYM resulted in much greater changes in water soluble C (WSC), microbial biomass C (MBC), light fraction of C (LFC), and particulate organic matter (POM) than SOC. Of the SOC, the proportion of POM was highest (24–35%), which was followed by LFC (12–14%), MBC (4.6–6.6%), and WSC (0.6–0.8%).

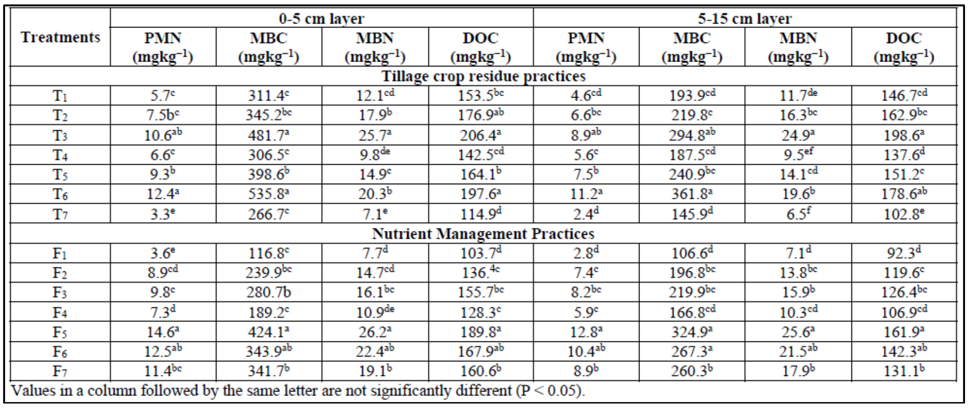
**Table 3**: Effect of 15 years of application of treatments on contents of various labile fractions of carbon in soil [Naresh *et al*., 2017 [53]]



| Treatments | 0-5 cm layer | | | | | 5-15 cm layer | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | WSC (mgkg$^{-1}$) | POC (mgkg$^{-1}$) | PON (mgkg$^{-1}$) | LFOC (mgkg$^{-1}$) | LFON (mgkg$^{-1}$) | WSC (mgkg$^{-1}$) | POC (mgkg$^{-1}$) | PON (mgkg$^{-1}$) | LFOC (mgkg$^{-1}$) | LFON (mgkg$^{-1}$) |
| Tillage crop residue practices | | | | | | | | | | |
| $T_1$ | $23.9^{d}$ | $638^{d}$ | $67.2^{d}$ | $81.3^{d}$ | $9.1^{d}$ | $15.7^{d}$ | $535^{e}$ | $54.7^{e}$ | $65.1^{d}$ | $7.8^{d}$ |
| $T_2$ | $25.9^{c}$ | $898^{bc}$ | $88.6^{cd}$ | $107.8^{bc}$ | $11.8^{c}$ | $17.8^{cd}$ | $674^{cd}$ | $74.5^{cd}$ | $94.1^{bc}$ | $9.1^{c}$ |
| $T_3$ | $27.8^{ab}$ | $1105^{ab}$ | $106.7^{ab}$ | $155.2^{a}$ | $13.3^{ab}$ | $19.6^{bc}$ | $785^{bc}$ | $91.8^{ab}$ | $132.6^{a}$ | $10.9^{ab}$ |
| $T_4$ | $22.7^{d}$ | $779^{cd}$ | $77.9^{d}$ | $95.7^{c}$ | $9.8^{d}$ | $17.6^{cd}$ | $609^{de}$ | $69.1^{de}$ | $87.6^{c}$ | $8.3^{cd}$ |
| $T_5$ | $26.4^{bc}$ | $1033^{b}$ | $97.4^{bc}$ | $128.8^{b}$ | $12.6^{bc}$ | $20.3^{ab}$ | $842^{ab}$ | $87.3^{bc}$ | $102.9^{b}$ | $10.4^{b}$ |
| $T_6$ | $29.2^{a}$ | $1357^{a}$ | $117.5^{a}$ | $177.8^{a}$ | $14.2^{a}$ | $22.6^{a}$ | $974^{a}$ | $106.1^{a}$ | $141.2^{a}$ | $11.8^{a}$ |
| $T_7$ | $17.2^{e}$ | $620^{d}$ | $22.5^{e}$ | $52.7^{e}$ | $8.2^{d}$ | $13.2^{e}$ | $485^{e}$ | $18.8^{f}$ | $49.8^{e}$ | $6.8^{e}$ |
| Nutrient Management Practices | | | | | | | | | | |
| $F_1$ | $21.9^{e}$ | $631^{d}$ | $24.7^{e}$ | $89.2^{c}$ | $6.8^{d}$ | $15.1^{e}$ | 585 | $17.3^{e}$ | $47.9^{f}$ | $5.9^{e}$ |
| $F_2$ | $29.2^{cd}$ | $869^{c}$ | $92.5^{c}$ | $96.4^{c}$ | $9.5^{c}$ | $20.2^{cd}$ | 789 | $73.5^{cd}$ | $85.9^{d}$ | $8.9^{c}$ |
| $F_3$ | $29.8^{c}$ | $956^{bc}$ | $96.8^{c}$ | $108.1^{bc}$ | $10.5^{bc}$ | $21.9^{bc}$ | 813 | $79.4^{c}$ | $96.9^{cd}$ | $9.6^{bc}$ |
| $F_4$ | $28.4^{d}$ | $788^{cd}$ | $72.9^{d}$ | $91.3^{c}$ | $7.9^{d}$ | $18.8^{d}$ | 728 | $59.4^{d}$ | $66.7^{e}$ | $7.2^{d}$ |
| $F_5$ | $32.5^{a}$ | $1381^{a}$ | $130.8^{a}$ | $183.9^{a}$ | $13.8^{a}$ | $26.4^{a}$ | 1032a | $112.1^{a}$ | $152.9^{a}$ | $12.4^{a}$ |
| $F_6$ | $31.6^{ab}$ | $1156^{ab}$ | $114.2^{ab}$ | $160.5^{a}$ | $12.6^{ab}$ | $23.6^{ab}$ | 905ab | $96.7^{ab}$ | $139.7^{a}$ | $11.9^{a}$ |
| $F_7$ | $30.9^{b}$ | $1102^{b}$ | $103.9^{bc}$ | $123.5^{b}$ | $11.5^{b}$ | $22.7^{b}$ | 826b | $88.3^{bc}$ | $103.2^{bc}$ | $10.1^{b}$ |

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

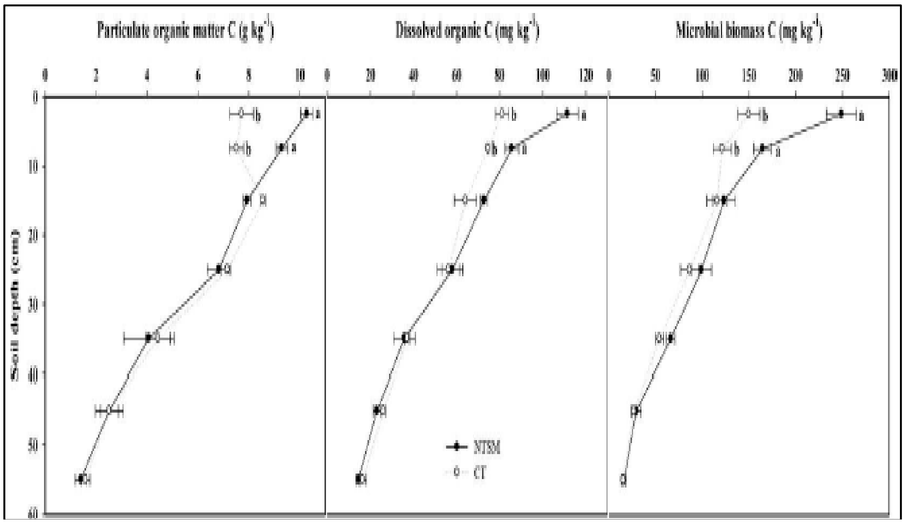
**Table 4:** Effect of 15 years of application of treatments on contents of various biological fractions of carbon in soil [Naresh *et al*., 2017 [53]]



| Treatments | 0-5 cm layer | | | | 5-15 cm layer | | | |
|---|---|---|---|---|---|---|---|---|
| | PMN (mgkg$^{-1}$) | MBC (mgkg$^{-1}$) | MBN (mgkg$^{-1}$) | DOC (mgkg$^{-1}$) | PMN (mgkg$^{-1}$) | MBC (mgkg$^{-1}$) | MBN (mgkg$^{-1}$) | DOC (mgkg$^{-1}$) |
| Tillage crop residue practices | | | | | | | | |
| $T_1$ | $5.7^{c}$ | $311.4^{c}$ | $12.1^{cd}$ | $153.5^{bc}$ | $4.6^{cd}$ | $193.9^{cd}$ | $11.7^{de}$ | $146.7^{cd}$ |
| $T_2$ | $7.5b^{c}$ | $345.2^{bc}$ | $17.9^{b}$ | $176.9^{ab}$ | $6.6^{bc}$ | $219.8^{c}$ | $16.3^{bc}$ | $162.9^{bc}$ |
| $T_3$ | $10.6^{ab}$ | $481.7^{a}$ | $25.7^{a}$ | $206.4^{a}$ | $8.9^{ab}$ | $294.8^{ab}$ | $24.9^{a}$ | $198.6^{a}$ |
| $T_4$ | $6.6^{c}$ | $306.5^{c}$ | $9.8^{de}$ | $142.5^{cd}$ | $5.6^{c}$ | $187.5^{cd}$ | $9.5^{ef}$ | $137.6^{d}$ |
| $T_5$ | $9.3^{b}$ | $398.6^{b}$ | $14.9^{c}$ | $164.1^{b}$ | $7.5^{b}$ | $240.9^{bc}$ | $14.1^{cd}$ | $151.2^{c}$ |
| $T_6$ | $12.4^{a}$ | $535.8^{a}$ | $20.3^{b}$ | $197.6^{a}$ | $11.2^{a}$ | $361.8^{a}$ | $19.6^{b}$ | $178.6^{ab}$ |
| $T_7$ | $3.3^{e}$ | $266.7^{c}$ | $7.1^{e}$ | $114.9^{d}$ | $2.4^{d}$ | $145.9^{d}$ | $6.5^{f}$ | $102.8^{e}$ |
| Nutrient Management Practices | | | | | | | | |
| $F_1$ | $3.6^{e}$ | $116.8^{c}$ | $7.7^{d}$ | $103.7^{d}$ | $2.8^{d}$ | $106.6^{d}$ | $7.1^{d}$ | $92.3^{d}$ |
| $F_2$ | $8.9^{cd}$ | $239.9^{bc}$ | $14.7^{cd}$ | $136.^{4c}$ | $7.4^{c}$ | $196.8^{bc}$ | $13.8^{bc}$ | $119.6^{c}$ |
| $F_3$ | $9.8^{c}$ | 280.7b | $16.1^{bc}$ | $155.7^{bc}$ | $8.2^{bc}$ | $219.9^{bc}$ | $15.9^{b}$ | $126.4^{bc}$ |
| $F_4$ | $7.3^{d}$ | $189.2^{c}$ | $10.9^{de}$ | $128.3^{c}$ | $5.9^{c}$ | $166.8^{cd}$ | $10.3^{cd}$ | $106.9^{cd}$ |
| $F_5$ | $14.6^{a}$ | $424.1^{a}$ | $26.2^{a}$ | $189.8^{a}$ | $12.8^{a}$ | $324.9^{a}$ | $25.6^{a}$ | $161.9^{a}$ |
| $F_6$ | $12.5^{ab}$ | $343.9^{ab}$ | $22.4^{ab}$ | $167.9^{ab}$ | $10.4^{ab}$ | $267.3^{a}$ | $21.5^{ab}$ | $142.3^{ab}$ |
| $F_7$ | $11.4^{bc}$ | $341.7^{b}$ | $19.1^{b}$ | $160.6^{b}$ | $8.9^{b}$ | $260.3^{b}$ | $17.9^{b}$ | $131.1^{b}$ |

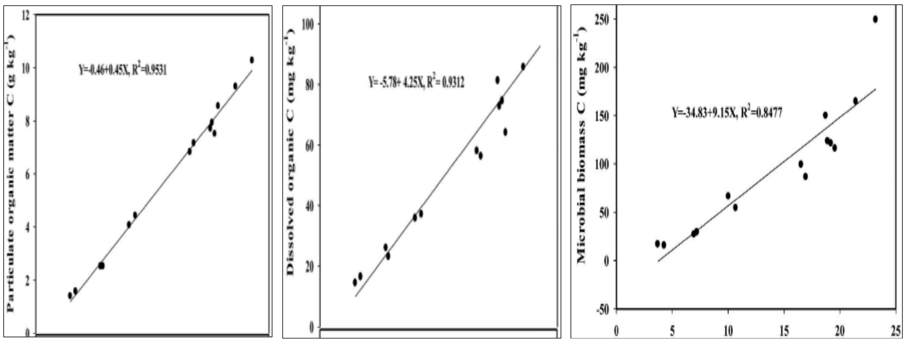
Values in a column followed by the same letter are not significantly different ($P < 0.05$).

Kumar *et al*. (2018) [40] reported that the Conventional tillage without residue treatment resulted in significantly lower SOC by 24% and labile C fractions by 27–48% than $T_2$ and $T_3$, respectively. However, treatment $T_1$ markedly increased all labile C fractions by 32–52% except POC relative to $T_3$, but treatments $T_1$ and $T_3$ resulted in similar SOC contents (21.2 g $kg^{-1}$ and 20.3 g $kg^{-1}$, respectively). Of the four C fractions, LFOC and DOC were the most sensitive indicators of changes in SOC induced by the tillage crop establishment methods. Under $T_1$, SOC contents were in 200kg $Nha^{-1}$>160kg $Nha^{-1}$ > and 120kg $Nha^{-1}$plots, and significantly higher than those in control plots (by 37, 33 and 21%, respectively). Labile C fractions were also significantly higher following the treatments including residue retention/ incorporation than following applications solely of chemical fertilizers [Table 5 & 6]. Li *et al*. (2012) [45] explained that crop residue might enter the labile C pool, provide substrate for the soil microorganisms, and contribute to the accumulation of labile C. Lewis *et al*. (2011) [43] also found that the increasing tillage intensity could reduce DOC levels in soils as a result of destruction of soil macro-aggregates and elevated respiration. Lower amount of DOC, hence is likely under CT due to increased soil disturbances subjecting aggregated protected SOC fraction to rapid decomposition via oxidation.



**(a)**

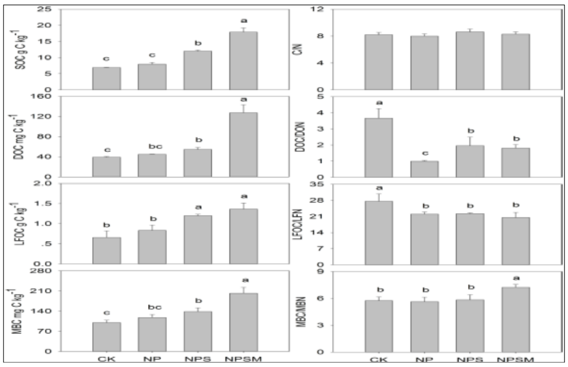
**Fig. 10 (a):** Soil particulate organic matter C (POM-C), dissolved organic C (DOC) and microbial biomass C (MBC) under no-tillage with straw mulch and conventional tillage [Fig. 11a and b]

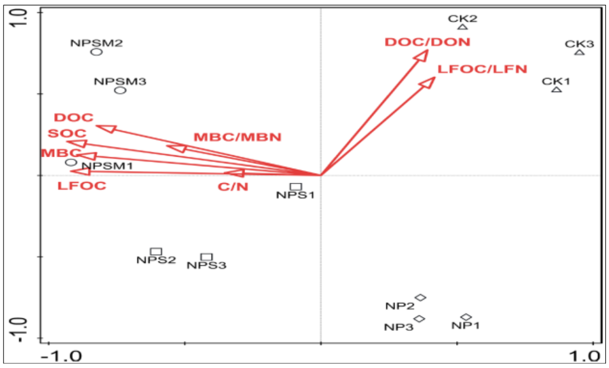


**(b)**

Soil organic carbon ($gkg^{-1}$)

**Fig. 10 (b):** Relationship between soil organic carbon and different labile SOC pools





**(a)** **(b)**

**Fig 11 (a):** Organic C contents and C/N ratios of bulk soil and labile fractions under different fertilization regimes

**Fig. 11 (b):** Redundancy analysis (RDA) of the soil microbial communities constrained by labile organic C fractions

**Table 5:** Effect of different treatments on contents of various labile fractions of carbon in soil [Kumar *et al*., 2018] [40]

| Treatments | POC (mgkg$^{-1}$) | | PON (mgkg$^{-1}$) | | LFOC (mgkg$^{-1}$) | | LFON (mgkg$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-15 cm | 0-5 cm | 5-15 cm | 0-5 cm | 5-15 cm | 0-5 cm | 5-15 cm |
| Tillage Practices | | | | | | | | |
| $T_1$ ZTR | 1342.8 | 967.9 | 119.5 | 108.1 | 194.7 | 154.8 | 14.8 | 12.3 |
| $T_2$ ZTWR | 981.1 | 667.4 | 94.6 | 86.5 | 120.5 | 104.7 | 11.8 | 10.3 |
| $T_3$ RTR | 1230.2 | 836.9 | 109.7 | 97.8 | 170.9 | 144.9 | 13.7 | 11.6 |
| $T_4$ RTWR | 869.4 | 604.4 | 82.6 | 76.6 | 107.1 | 97.3 | 9.7 | 8.6 |
| $T_5$ CTR | 1099.1 | 779.4 | 98.4 | 89.3 | 143.8 | 115.9 | 12.8 | 10.9 |
| $T_6$ CT | 617.5 | 481.8 | 69.2 | 57.6 | 90.8 | 73.6 | 9.6 | 7.9 |
| Nitrogen Management | | | | | | | | |
| $F_0$ Control | 709.7 | 658.6 | 31.7 | 26.3 | 123.9 | 104.3 | 6.4 | 5.8 |
| $F_1$ 80 kg N ha$^{-1}$ | 860.7 | 785.6 | 68.4 | 56.2 | 132.8 | 116.1 | 7.6 | 6.9 |
| $F_2$120 kg N ha$^{-1}$ | 952.2 | 808.9 | 89.5 | 78.5 | 150.6 | 127.6 | 9.7 | 8.6 |
| $F_3$ 160 kg N ha$^{-1}$ | 1099.5 | 823.8 | 96.8 | 83.4 | 168.5 | 145.7 | 10.2 | 9.8 |
| $F_4$ 200 kg N ha$^{-1}$ | 1153.1 | 898.4 | 103.9 | 97.3 | 176.2 | 152.9 | 11.7 | 10.6 |

**Table 6:** Effect of different treatments on contents of various biological fractions of carbon in soil [Kumar *et al*., 2018] [40]

| Treatments | PMN (mgkg$^{-1}$) | | MBC (mgkg$^{-1}$) | | MBN (mgkg$^{-1}$) | | DOC (mgkg$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | 0-15 cm | 15-30 cm | 0-15 cm | 15-30 cm | 0-15 cm | 15-30 cm | 0-15 cm | 15-30 cm |
| Tillage Practices | | | | | | | | |
| $T_1$ ZTR | 12.4 | 11.2 | 562.5 | 471.1 | 20.2 | 18.9 | 198.6 | 183.6 |
| $T_2$ ZTWR | 8.5 | 7.6 | 350.4 | 302.1 | 14.1 | 12.6 | 167.1 | 159.2 |
| $T_3$ RTR | 10.6 | 9.9 | 490.2 | 399.3 | 19.1 | 17.2 | 186.4 | 171.6 |
| $T_4$ RTWR | 7.6 | 6.6 | 318.1 | 299.8 | 14.4 | 13.7 | 159.5 | 148.7 |
| $T_5$ CTR | 9.3 | 8.5 | 402.9 | 354.4 | 18.2 | 16.6 | 175.9 | 168.9 |
| $T_6$ CT | 6.7 | 5.6 | 307.9 | 289.5 | 11.8 | 9.7 | 142.5 | 134.6 |
| Nitrogen Management | | | | | | | | |
| $F_0$ Control | 3.6 | 2.8 | 218.3 | 202.9 | 10.8 | 10.4 | 103.7 | 92.3 |
| $F_1$ 80 kg N ha$^{-1}$ | 5.3 | 4.4 | 241.1 | 199.4 | 14.9 | 12.2 | 128.3 | 116.9 |
| $F_2$120 kg N ha$^{-1}$ | 8.9 | 7.6 | 282.7 | 220.9 | 16.5 | 16.1 | 136.8 | 123.6 |
| $F_3$ 160 kg N ha$^{-1}$ | 9.8 | 8.4 | 343.9 | 262.9 | 19.4 | 18.1 | 164.8 | 148.9 |
| $F_4$ 200 kg N ha$^{-1}$ | 10.4 | 9.7 | 346.3 | 269.6 | 22.7 | 21.7 | 155.7 | 136.4 |

Ibrahim *et al*. (2015) reported that rice straw under a range of water regimes markedly improved the transformation of soil organic carbon and labile organic carbon pools such as dissolved organic carbon, microbial biomass carbon, light fraction organic carbon, particulate organic carbon, and permanganate oxidizable carbon. Yang *et al*. (2005) [79] that soil PMOC, LFOC, and POC under water regime of continuous water-logging decreased by 30.6, 8.3, and 10.6 % in wheat straw treatment, respectively, as compared to the water regime of alternative wetting and drying. This confirmed that the adoption of soil water regimes is an important factor to improve the transformation of soil organic carbon pools after the addition of rice straw. Yang *et al*. (2012) [81] showed that LFOC, POC, and PMOC were improved by 2.25, 1.84, and 2.15 times after the addition of wheat straw or maize stalk in a silt clay loam soil. They also mentioned that PMOC was higher in wheat straw or maize stalk-amended soil than the control could be explained by the higher labile organic carbon inputs, which associated with the straw and stalk. Mandal *et al*. (2013) [50] reported that averaged across fertilization and manure treatments, MBC varied significantly with soil depth, with mean values of 239, 189 and 127 mg kg$^{-1}$ at 0–7.5, 7.5–15 and 15–30 cm depths respectively. Surface soil had higher MBC than deeper soil layers, due primarily to the addition of leftover CRs and root biomass to the topsoil. When averaged across soil depths, the MBC content under the different treatments was in the order: NPK +GR +FYM>NPK+FYM=NPK +GR> NPK +SPM> NPK+CR> PKZnS >NPKZn = control. Incorporation of CR slows mineralization processes; hence, microbes take longer to decompose the residue and use the released nutrients. Conversely, incorporation of GR, with a narrow C: N ratio, hastened mineralization by enhancing microbial activity in the soil (Nayak *et al*. 2012) [54].

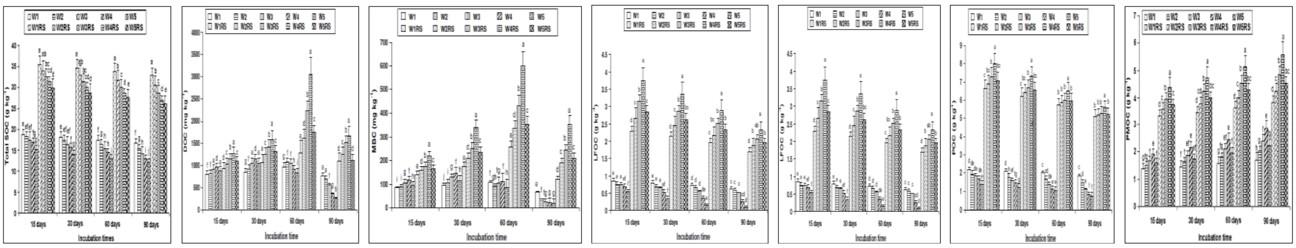
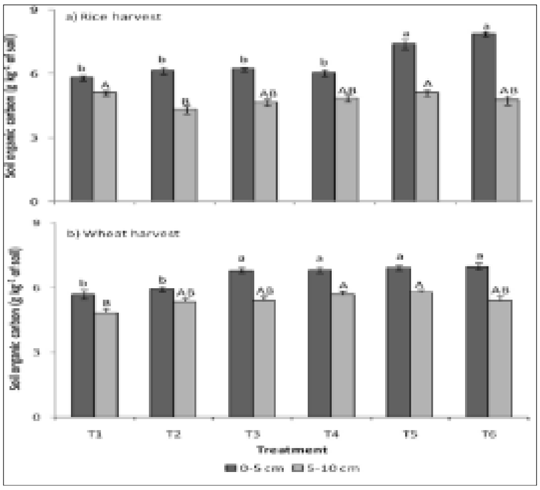


**Fig 12:** Effect of rice straw on soil total SOC, DOC, MBC, LFOC, POC and PMOC at different water regimes. SOC= soil organic carbon, DOC= dissolved organic carbon, MBC = microbial biomass carbon, LFOC light fraction of organic carbon, POC= particulate organic carbon, PMOC permanganate oxidizable carbon W= water regime, and RS= rice straw

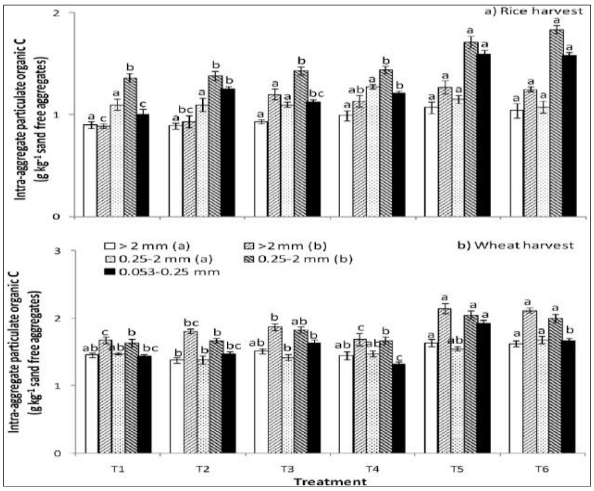
## Soil carbon pools

Mamta Kumari *et al*. (2011) [49] reported that macro-aggregates increased under a ZT rice (direct-seeded or transplanted) and wheat rotation with the 2- to 4-mm fraction greater than that of the 0.25- to 2-mm fraction. Bulk and aggregate associated C increased in ZT systems with greater accumulation in macro-aggregates. The fine (0.053–0.25 mm) intra-aggregate particulate organic C (iPOM-C), in 0.25- to 2-mm aggregates, was also higher in ZT than conventional tillage. A higher amount of macro-aggregates along with greater accumulation of particulate organic C indicates the potential of ZT for improving soil carbon over the long-term in rice-wheat rotation [Fig. 13 a & b]. Grandy and Robertson, (2006) [26] also found that the iPOM-C is physically better protected than other POM-C fractions in soil. A significantly higher amount of fine iPOM-C mostly associated with small macro-aggregates indicated slower turnover under ZT, resulting in the formation and stabilization of fine intra-aggregate C particles. The increased fine iPOM-C could be regarded as a potential indicator of increased C accumulation (Six *et al*., 1999) [68]. Lu *et al*. (2015) [48] indicated that compared with straw removal (SR), SI significantly increased soil C storage by 12 %. Moreover, incorporation of chopped straw with tillage treatment (ploughing and rotary tillage) increased C storage compared to un-chopped straw without tillage treatment. SI implementation with upland cropping, in the northwest and northeast resulted in higher C storage compared with rice cropping, and in the northern and southern regions. Changes in soil C were observed based on SI variables, including tillage and straw amounts in fine-textured soils, however straw amount rather than tillage treatment exhibited a greater influence on soil C in coarse-textured soils [Fig. 14 a& b].

Wingeyer *et al*. (2012) [75] reported straw decomposition rates were closely related to SI depths, in decreasing order from 5 to 15 cm to the surface soil. Thus, compared with NT, tillage treatments have increased the potential to promote straw C conversion into soil C. Wu *et al*. (2004) [76] observed that soils suffering from C loss or further from C saturation have greater potential for soil C sequestration following SI implementation. Moreover, rice-cropping systems were associated with a warmer climate and anaerobic conditions, which accelerated $CH_4$ emissions and straw decomposition. Hernanz *et al*. (2009) [28] evaluated the soil organic carbon variations in three different tillage systems and found that soil organic carbon was 14% higher in no-till systems than in minimum tillage as well as conventional tillage systems after a period of 20 years. Huang *et al*. (2010) [31] reported that C distributions in the soil were dominated by macro aggregates, which accounted for 64.4% and 64.1% of the soil. Ladha *et al*. (2016) [42] revealed that Cereals harvested a total of 1551 Tg of N, of which 48% was supplied through fertilizer-N and 4% came from net soil depletion. An estimated 48% (737 Tg) of crop N, equal to 29, 38, and 25 kg $ha^{-1}$ $yr^{-1}$ for maize, rice, and wheat, respectively, is contributed by sources other than fertilizer- or soil-N. Non-symbiotic N2 fixation appears to be the major source of this N, which is 370 Tg or 24% of total N in the crop, corresponding to 13, 22, and 13 kg $ha^{-1}$ $yr^{-1}$ for maize, rice, and wheat, respectively. Manure (217 Tg or 14%) and atmospheric deposition (96 Tg or 6%) are the other sources of N [Fig. 16 a, b & c].



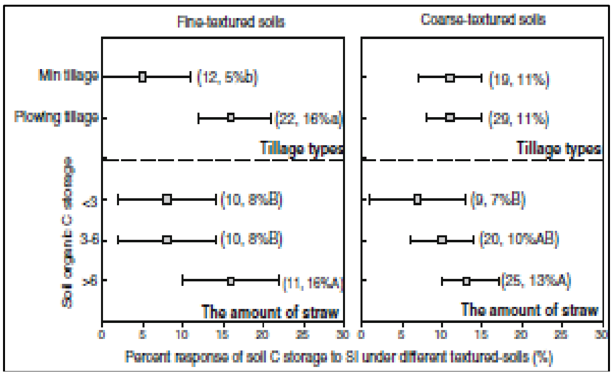
**(a)**



**(b)**

**Fig 13 (a):** Soil organic C (g $kg^{-1}$ of bulk soil) as influenced by tillage practices at (a) rice and (b) wheat harvest

**Fig. 13 (b):** Intra-aggregate particulate organic matter (iPOM) C (g $kg^{-1}$ of sand-free aggregates) in aggregate-size fractions at the 0- to 5-cm soil depth at (i) rice and (ii) wheat harvest. '(a)' and '(b)' in legend refer to coarse (0.25–2 mm) and fi ne (0.053–0.25 mm) iPOM in the respective size of aggregates



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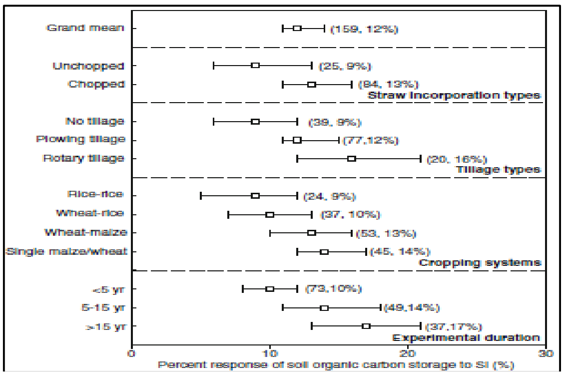
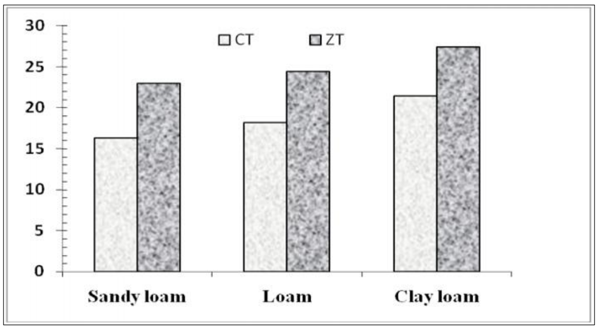


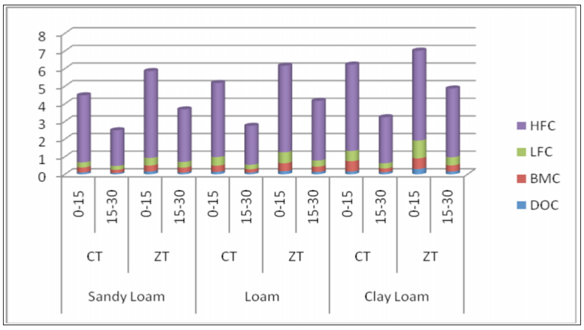
**(b)**

**Fig. 14 (a):** Response of soil organic C storage to SI under different SI types, tillage types, rotation types, and experimental duration

**Fig. 14 (b):** Response of soil C to SI under different tillage types, and straw amount in fine and coarse textured soils. The unit of straw amount is t $ha^{-1}$

Khairul *et al*. (2016) [38] also found that after 4 years, ZT under WDT and WMT significantly increased soil organic matter (SOM) at 0–150 mm depth [Fig. 17 a]. Soil organic carbon (C) increased at a rate of 1.17 and 1.14 tha$^{-1}$yr$^{-1}$ in ZT under WDT and WMT, respectively, while CT and DT under WFT were almost unchanged. After 4 years of tillage and rice– wheat systems, TOC ranged from 16·28 t/ha in CT under WFT to 21·47 t/ha in ZT under WDT, while in ZT under WMT it was 21·35 t/ha. In the surface 150 mm of soil, TOC increased by 28 and 27% in ZT under WDT and WMT cropping systems [Fig 17 b]. Singh *et al*. (2014) [65] obtained a similar result during their experiment on clay loam soil under semi-arid climatic conditions. Gonzalez-Sanchez *et al*. (2012) [24] also produced a similar result, which they correlated with soil texture, temperature for higher residue production, residue retention and absence of tillage. Govaerts *et al*. (2007) [25] and Zhu *et al*. (2014) [83], who stated that ZT coupled with residue retention created conditions favorable for a significant increase in MBC. Balota *et al*. (2003) [4] attributed the MBC increase in ZT over CT and DT under sub-tropical conditions to several factors, such as a lower temperature, higher moisture content, greater soil aggregation and higher C content, adding that the minimal disturbance in ZT probably supplied a stable source of OC to support the microbial community compared to DT/CT where a sudden flush of microbial activity with each tillage event causes significant losses of C as $CO_2$.

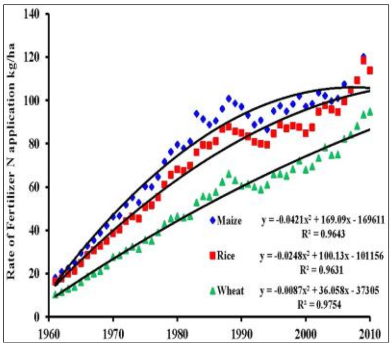


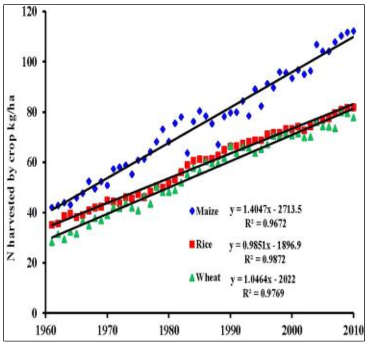


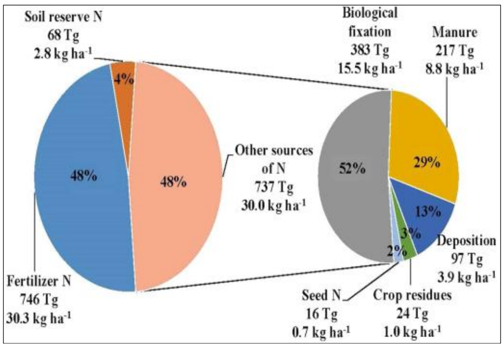
(a) (b)

**Fig. 15 (a):** Soil organic carbon stock (Mg C ha$^{-1}$) in 0-30 cm soil depth in different textured soil under conventional (CT) and zero tillage (ZT) practices

**Fig.15 (b):** Different fractions of organic carbon (gkg$^{-1}$) at 0-15 and 15-30 cm soil depths under conventional (CT) and zero (ZT) tillage practice in different textured soils





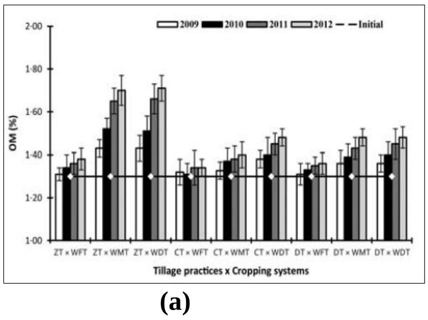


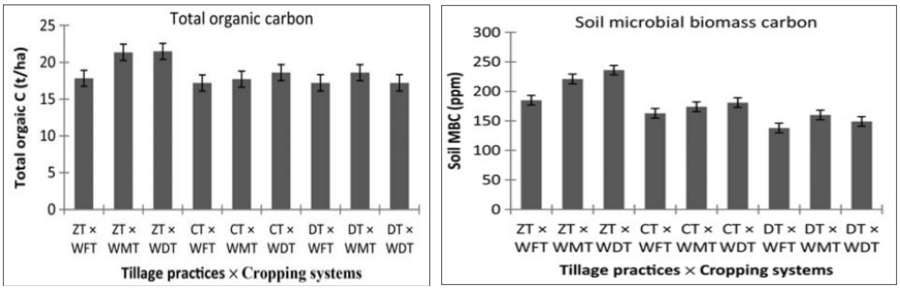
(a) (b) (c)

**Fig. 16 (a):** Trends in global averages of fertilizer-N application rates in maize, rice, and wheat

**Fig. 16 (b):** Trends in global averages of total N harvest by maize, rice, and wheat

**Fig. 16 (c):** Global estimates of sources of N in crop harvest of maize, rice, and wheat production systems: total (Tg) for 50 years (1961–2010) with percentages and per hectare (kg ha$^{-1}$)





(a) [I] (b) [II]

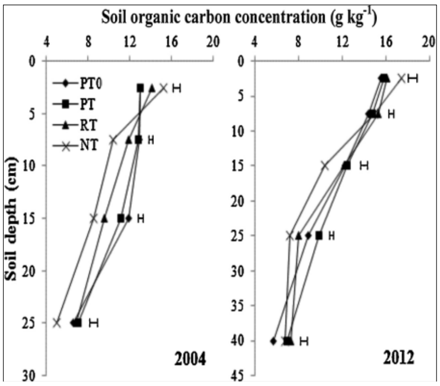
**Fig. 17 (a):** Effect of tillage depths and cropping systems on soil organic matter content over 4 years of cropping [ZT, zero tillage; CT, conventional tillage; DT, deep tillage; WFT, wheat–fallow–T. aman; WMT, wheat– mungbean–T. aman; WDT, wheat–dhaincha–T. aman]

**Fig.17 (b):** Total soil organic carbon (I) and soil microbial biomass (II) C after 4 years of tillage practices and cropping systems

## Soil organic carbon concentration and stock

Dikgwatlhe *et al*. (2014) [17] compared with PTO and PT, significantly higher SOC and N concentrations were observed in surface layer (0-10 cm depth) under NT and RT. In 2004, the SOC stocks were lower under NT and RT than under PT and PTO, however, the opposite trend was observed in 2012. Compared with 2001, the net profile (0-30 cm) SOC sequestration rate was 10.60, 13.95, 13.65, and 14.92 Mg ha$^{-1}$ in 2012 under PTO, PT, RT, and NT, respectively. As for stocks in the 0-50 cm profile, no significant differences were observed among NT, RT, and PT. The trends in N stocks in profile (0-30, 0-50 cm depth) were NT>TR>PT>PTO in both the years. Compared with other treatments, SOC and N stocks were the lowest under PTO. Therefore, crop residues play an important role in SOC and N management, and improvement of soil quality [Fig. 18 a, b, c & 7d]. (Du *et al*., 2010; Mishra *et al*., 2010) [22, 51] reported that Higher SOC and N concentrations un the surface layer under NT than those under RT and PT systems can be attributed to a combination of less soil disturbance and reduced litter decomposition due to less soil/residue interaction. Blanco-Canqui and Lal, (2008) revealed that the lower SOC stock under at > 5-10 cm depth in 2004 and >10-30 cm in 2012 than those under PT and RT may be because of the duration of the study, and lower the stratified SOC concentration with depth. In fact, the higher SOC and N stocks under tilled systems probably resulted from incorporation of crop residues into the subsoil layers. Similarly

SOC and N stocks at 0-50 cm profile were higher under residue retained treatments probably due to cumulative increase in humification and storage of SOM from residues (Mishra *et al*., 2010) [51].



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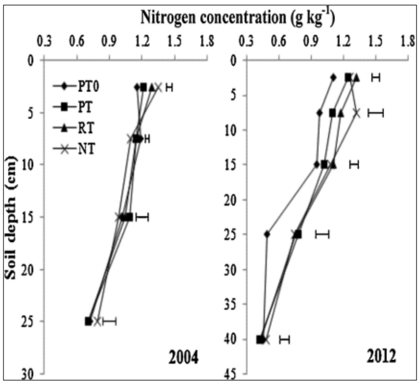

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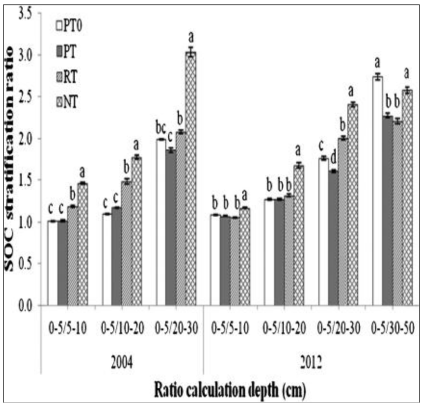

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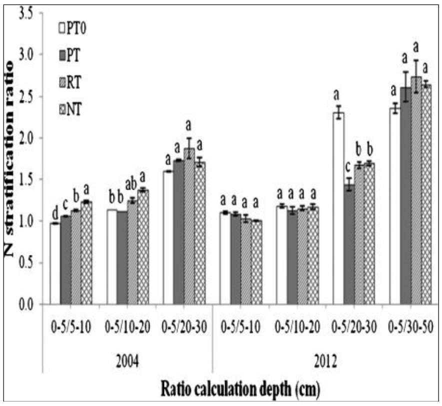


(d)

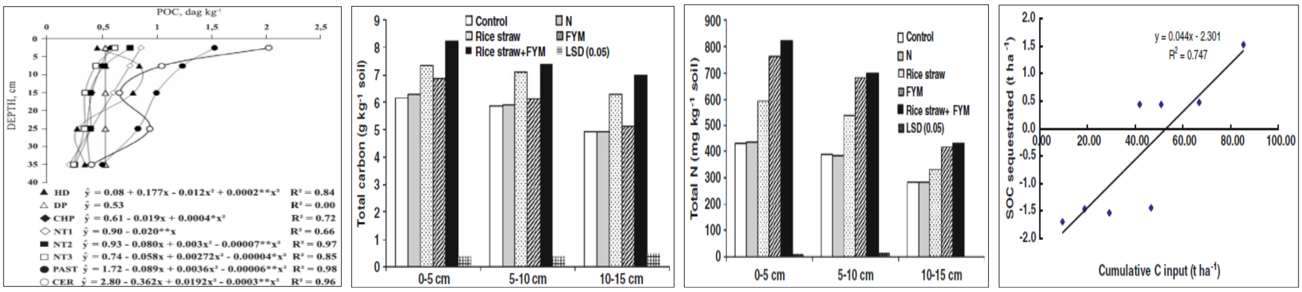
**Fig. 18 (a):** Depth distribution of soil organic carbon (SOC) concentration under different tillage systems in 2004 and 2012

**Fig. 18 (b):** Depth distribution of nitrogen (N) concentration under different tillage systems in 2004 and 2012

**Fig. 18 (c):** Soil organic carbon (SOC) stratification under different tillage systems in 2004 and 2012

**Fig. 18 (d):** Nitrogen (N) stratification under different tillage systems in 2004 and 2012

Cícero Célio de Figueiredo *et al*. (2010) [11] reported that stratification was minimal in the no-tillage systems [Fig. 19a]. The better distribution of POC in the profile under no-tillage preceded by management systems including disk and moldboard plows, which promote chemical and physical corrections and increase organic matter and consequent changes in biological activity to a greater depth in the soil profile. Dinesh and Senapati, (2010) [18] observed that an application of FYM along with inorganic fertilizer resulted in a net C sequestration of 0.44 t ha$^{-1}$ in the plough layer after 7 years of rice–wheat cropping. Carbon sequestration was greater (1.53 t ha$^{-1}$) when both rice straw and FYM along with inorganic fertilizers were applied annually [Fig. 19 b & c]. Dick and Gregorich (2004) [16] stated that organic manures have already undergone some decomposition and organic C in these substances has already been converted to recalcitrant forms. This allows for more C being sequestered in the soil. Yang *et al*. (2004) [78] showed that the total C in paddy soil was 40–60% higher in the combined organic sources and chemical fertilizers treatment against the sole chemical fertilizers treatment. Haer and Benbi (2003) [27] showed that the organic N mineralization rate in the regional soils is higher by an order of magnitude as compared to that reported for US soils. Kundu *et al*. (2007) [19] and Huang *et al*. (2010) [31] reported that the highest carbon sequestration after the FYM application is connected with the higher size fractions of WSA$_{ma}$. Tong *et al*. (2014) [72] also found that the soils under NPK and NP treatments significantly increased SOC stocks. Das *et al*. (2017) [15] revealed that the total organic C increased significantly with the integrated use of fertilizers and organic sources (from 13 to 16.03 g $kg^{-1}$) compared with unfertilized control (11.5 g $kg^{-1}$) or sole fertilizer (NPKZn; 12.17 g $kg^{-1}$) treatment at 0–7.5 cm soil depth [Fig 20a]. Oxidisable organic C fractions revealed that very labile C and labile C fractions were much larger in the NPK+FYM or NPK+GR+FYM treatments, whereas the less-labile C and non-labile C fractions were larger under control and NPK+ CR treatments [Fig. 20b]. Wang *et al*. (2012) [45] and Naresh *et al*. (2018) [40] that an increase in SOC stock is directly linked to the amount and quality of organic residues, as well as manure application and fertilization.



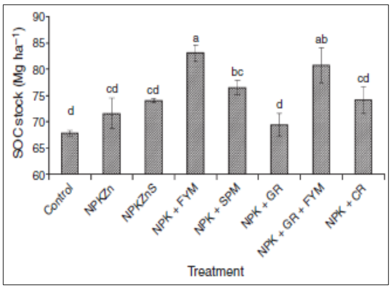
(a) (b) (c)

**Fig. 19(a):** Distribution of levels of particulate organic carbon (POC) in the profiles of the different management systems

**Fig.19 (b):** Influence of rice straw, farmyard manure (FYM) and fertilizer nitrogen (N) application on total carbon and total N in whole soil after 7 years of RWCS in northwest India

**Fig. 19 (C):** Relationship between cumulative C input and soil C sequestration after 7 years of RWCS

Anaya *et al*. (2015) [2] reported that long-term cultivation did not alter soil aggregate structure, or litter C content; however it reduced significantly litter N content in sugarcane compared to forest plots. After 20 years of cultivation, SOC and soil N stocks dropped by 25% at 0–10 cm soil depth compared to current C stocks in forest soils. After 50 years of cultivation, pooled over 0–20 cm, SOC stocks were similar in sugarcane and forest plots, while soil N stocks remained 12–19% lower in sugarcane than in forest plots. The mineral-associated organic C fraction remained unaffected by land use change. Forest conversion to sugarcane, depleted the free light particulate organic matter (POM) C fraction at 0–10 cm depth. Forest intra-aggregate POM C concentration declined after 20 years of cultivation and then recovered after 50 years of cultivation at 0–10 cm depth [Fig.21 a, b & c]. Jaiarree *et al*. (2011) [33] reported that conversion of tropical forest to maize and 12 years of cultivation kept SOC stocks 47% lower than in the original forest in the top 0–10 cm soil layer. Ashagrie *et al*. (2007) [3] found a greater loss in free POM than in intra-aggregate POM after conversion of forest to croplands. They suggested that this was due to the lack of physical protection of free POM within aggregates and to the lower input of organic matter in croplands than in forest. Zhang *et al*. (2016) [82] reported that an application of inorganic fertilizers (NPK) plus animal manure over 20-30 years significantly increased SOC stocks to 20-cm depth by 32-87% whilst NPK plus wheat/maize straw application increased it by 26-38% compared to controls. The efficiency of SOC sequestration differed between regions with 7.4-13.1% of annual C input into the topsoil [Fig.22a & b]. Ruis *et al*. (2017).



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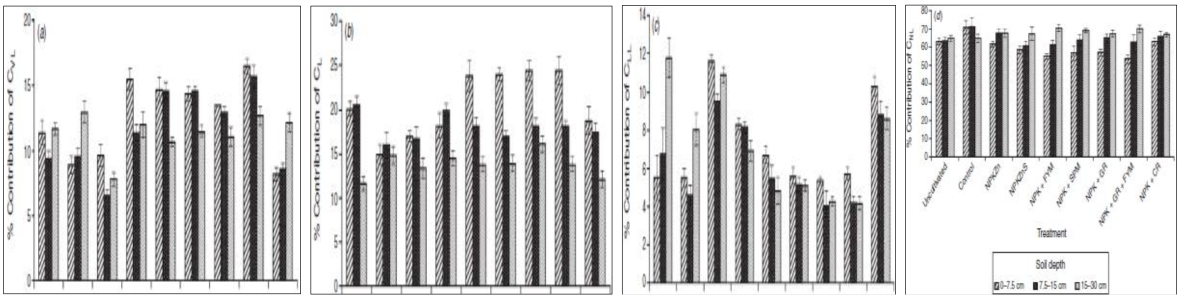
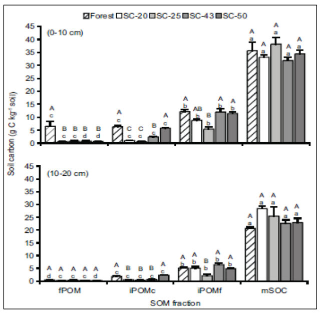


(b)

**Fig. 20(a):** Effects of long-term fertilization and manuring on soil organic carbon (SOC) stock (0–60 cm soil depth) in the rice–wheat system

**Fig. 20(b):** Contribution of (*a*) very labile C ($C_{VL}$), (*b*) labile C ($C_L$), (*c*) less-labile C ($C_{LL}$) and (*d*) non-labile C ($C_{NL}$) to total organic carbon under different nutrient supply options and soil depths



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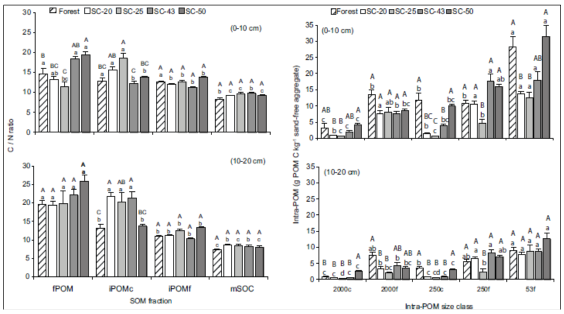

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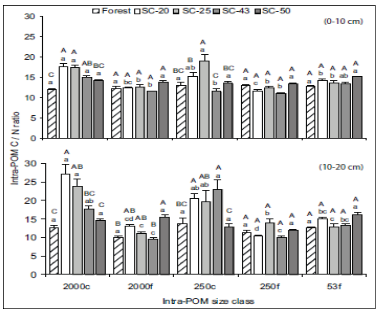
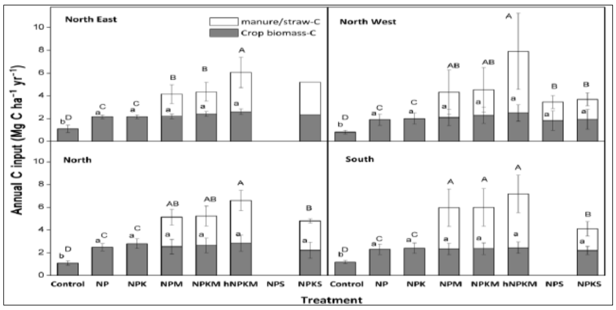


(c)

**Fig. 21(a):** Total soil organic carbon (C) concentration divided into soil organic matter C (SOM) fractions of a native forest and four sugarcane (SC) plots with 20, 25, 43, and 50 years of cultivation at two soil depths

**Fig. 21(b):** Carbon to nitrogen ratios (C:N ratio) of SOM fractions and Intra-aggregate particulate organic matter carbon (iPOM) at two soil depths of a native forest and four sugarcane (SC) plots with 20, 25, 43, and 50 years of agricultural use

**Fig. 21 (c):** Average carbon to nitrogen ratios (C/N) of iPOM fractions at two soil depths of a native forest and four sugarcane (SC) plots with 20, 25, 43, and 50 years of agricultural use



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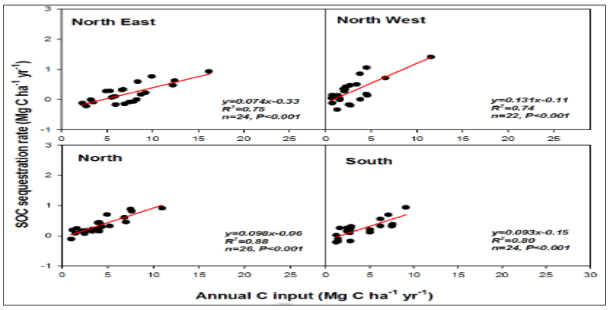
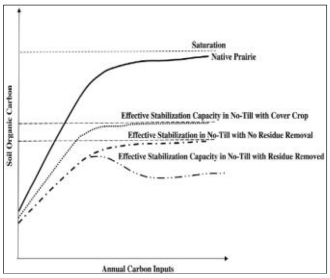
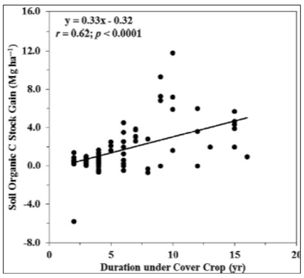


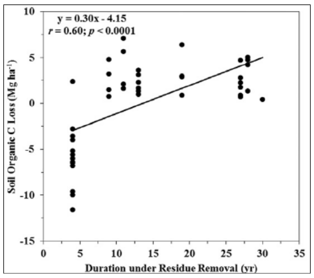
(b)

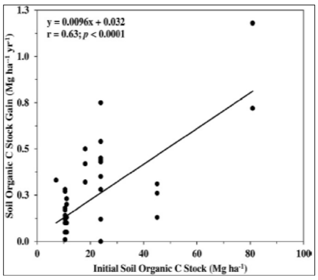
**Fig. 22(a):** Annual C inputs from crop residues and manure/straw in different regions

**Fig. 22(b):** Relationships between total cumulative C inputs and the increase in SOC stocks over the experimental period in different regions









(a) (b) (c) (d)

**Fig. 23 (a):** Effective stabilization capacity of soil organic carbon (SOC) under no-till systems with and without cover crop or residue removal

**Fig. 23(b):** The correlation between rate of soil organic carbon stock gain and duration under cover crop

**Fig. 23 (c):** Change in soil organic carbon (SOC) stock with duration under residue removal

**Fig. 23(d):** Correlation between soil organic carbon (SOC) stock gain and initial SOC stock under cover crops

## Conclusions

Conservation tillage proved to be highly effective in enhancing SOC under the semi-arid conditions prevailing in western Uttar Pradesh. Carbon and nitrogen dynamics in soils are complex phenomenon, which vary depending on soil and crop management practices and may have profound effects on global warming and climate change. Farm yard manure was found efficient to increase carbon and nitrogen in soils compared to rice-wheat straw, which decreased with increased soil depths irrespective of residues. Positive trend of carbon enrichment in soils was found while, FYM and rice-wheat straw were applied, which could be monitored and maintained through regular replenishment of organic materials in soils. Any type of soil and crop management practices that could enhance carbon contents in soils should be considered and recommended for farmers' practice.

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 management systems such as reduced- and no-tillage, crop residue addition, FYM incorporation, and integrated nutrient management 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 or with improved nutrient management. This review study also revealed several challenges and research opportunities impacts of alternative tillage, crop residue, and nitrogen management practices to improve SOC concentration and stock and enhance soil carbon pools. Evaluating SOC dynamics of rice-wheat and other crop based systems under alternative management practices, and their potential impacts on agricultural system sustainability would substantially benefit producers, researchers, and policy makers. More research evaluating impacts of alternative management systems on SOC dynamics is required. Specifically, understanding SOC and nutrient dynamics during transition from conventional to conservation systems are required.

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