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Effects of Tillage; Residue and nutrient management on top soil carbon stocks and soil labile organic carbon fractions in the Indo-gangetic plains of north west India: 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 of North West, India. Therefore, review was presented in this paper to investigate the interactive effects of tillage; residue and nutrient management on top soil carbon stocks and soil labile organic carbon fractions. The proportion of SMBC as mineralizable C decreased with depth. Mean values across soil depths and nutrient supply options, the abundance of these four OOC fractions was in the order C_{NL} (7.04gkg^{-1}) >C_{L} (2.02gkg^{-1}) >C_{VL} (1.35gkg^{-1}) >C_{LL} (0.75gkg^{-1}). The zero tillage practice in wheat increased the organic carbon content and carbon stock as compared to conventional tillage in soils. The zero tillage increased dissolved organic carbon, microbial biomass carbon light and heavy fractions of carbon in soils at upper layers of 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. Soil organic C (SOC) was highly affected by tillage, cropping sequence, and N fertilization. The SOC stock varied under different treatments from 26.9 to 30.8, 17.7 to 21.2, 15.7 to 23.3 and 7.21 to 9.82 Mg ha^{-1} at 0-15, 15-30, 30-45 and 45-60 cm soil depth. The topsoil (0–20 cm) had the maximum levels of cumulative SOC storage in the 1 m soil depth for the CK, N, NP, FYM, NP+S and NP+FYM treatments, accounting for 24%, 23%, 27%, 30%, 31% and 31%, respectively. At the 20–40 cm and 40–60 cm soil layers, the SOC stocks of the NP, FYM, NP+S and NP+FYM treatments were significantly higher by 17%, 21%, 25% and 37% and 5.3%, 8.1%, 7.3% and 11%, respectively, than that of the CK. The SOC stock decreased markedly with increasing soil profile depth irrespective of treatments.

Keywords: Soil organic carbon; carbon stock; total organic carbon; carbon fractions

Introduction

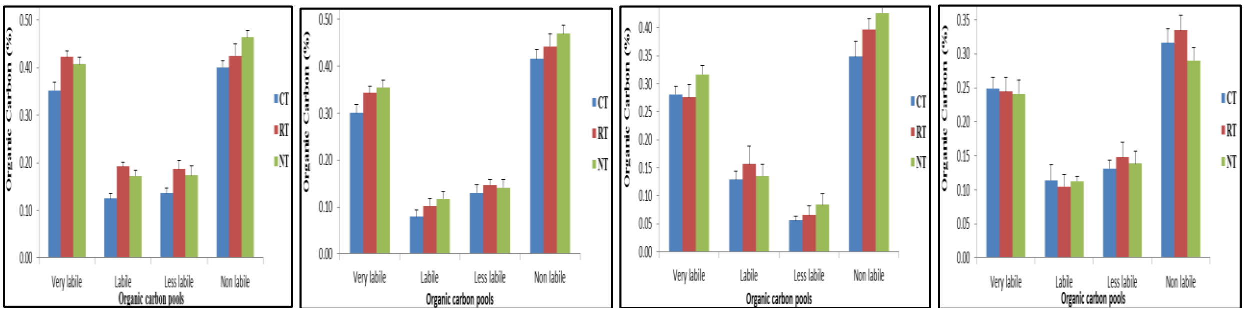
Atmospheric concentration of CO_2 has increased from ~ 280 ppm in pre-industrial era to ~ 385 ppm in 2008 (+ 37.5%) and is presently increasing at the rate of ~ 2 ppm/yr or 3.5 Pg/yr (1 Pg or pentagram = 1 Gt = 1 gigaton = 1 billion metric ton). The increase in CO_2 emission by human activity is attributed to fossil fuel combustion, deforestation and biomass burning, soil cultivation and drainage of wetlands or peat soils. Increase in fossil fuel combustion is caused by high global energy demand of 475 Quads (1 quad = 10^{15} BTU) and increasing at the rate of ~ 2.5%yr^{-1}, especially in emerging economies including China, India, Mexico, Brazil, etc. There exists a strong positive correlation between population growths on the one hand and CO_2 emission or the energy demand on the other. The world population of 6.7 billion in 2008 is increasing at the rate of 1.3% yr^{-1} and is projected to be 9.5 billion by 2050 before stabilizing at ~10 billion towards the end of the 21st century. Because of the anthropogenic perturbations of the global C cycle, there are serious concerns about the risks of global warming and the attendant sea level rise. Thus, identifying viable sinks for atmospheric CO_2 is a high priority with the objective of sequestering it into other C pools with long residence time. Several options of CO_2 sequestration being considered are geologic, oceanic, chemical transformations and terrestrial. In contrast to the engineering techniques (e.g., geologic), C sequestration in terrestrial ecosystems is a natural process. It is also cost-effective and has numerous ancillary benefits (Lal, 2008a) [33].

The adoption of fertilizer management practices, e.g., chemical fertilization, manure application and straw retention, has been recognized to be the most efficient and effective manner to either promote SOC accumulation or reduce the rate of SOC loss. In areas with nutrient deficiency, chemical fertilizers increase the crop yield and biomass and thus the crop residue and root C input to soil (Kätterer *et al*. (2011) [30]. Manure application and stubble retention are among the most predominant management practices driving SOC changes because they directly add C into soil (Liu *et al*., 2014; Maillard and Angers, 2014) [38, 40]. Long-term field experiments have demonstrated that these RMPs significantly enhanced the SOC content (Jiang, *et al*., 2014; Menichetti *et al*., 2015) [29, 44]. Furthermore, with the expansion of conservation tillage (Kassam *et al*., 2009) and organic farming, the residue incorporation and manure application rates are certain to increase in the areas where such RMPs are adopted, consequently promoting soil C sequestration (Powlson *et al*., 2014; Gattinger *et al*., 2012) [56, 23].

Labile soil organic 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) [75]. Because these components can respond rapidly to changes in C supply, they have been suggested as early indicators of the effects of land use on SOM quality Gregorich *et al*. (1994) [25].

Soil organic pools

Kumar, (2016) [32] reported that regardless of tillage system, contribution of different fractions of carbon (C) to the TOC varied from, 33 to 41%; 9.30 to 30.11%; 8.11 to 26%; 30.6 to 45.20% for very labile, labile, less labile and non-labile fractions, respectively at 0-5cm depth [Fig.1a]. For subsurface layer (5-15cm), contribution of different fractions to the TOC varied from 27.8 to 40%; 7.80 to 12.40%; 11.11 to 19.0%; 38.0 to 50.0% for very labile, labile, less labile and non-labile fraction, respectively [Fig.1b]. In general, C contents decreased with increasing depth, mainly for very labile faction which was contributing around 40% or more in surface and surface layers (0–5 and 5–15 cm) as compared to deeper layers (15–30 and 30–45 cm) [Fig 1c & 1d]. Moreover, less labile and non-labile fractions contribute more than 50% of TOC, indicating more recalcitrant form of carbon in the soil.



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

Fig 1: Effect of conservation agriculture on organic carbon pools (%) in a) 0-5 cm, b) 5-15 cm, c) 15-30cm, and d) 30-45 cm depth under different tillage systems

M Liu *et al*. (2016) [49] revealed that both MBC and MBN concentrations were significantly higher in the 0–5 cm soil layer than 5–15 and 15–25 cm layers under grassland, forestland and NT treatments [Fig. 2a, 2b]. These distribution patterns may be attributed to decrease in labile C and N pools with increase in soil depth. Similar patterns of decreased in microbiological parameters with soil depth had been reported for forestland (Agnelli *et al*., 2004) [1], grassland (Fierer *et al*., 2003) [21] and arable land (Taylor *et al*., 2002) [69]. At the top 0–5 cm depth, the MBC: MBN ratio was highest under grassland and lowest under PT [Fig. 2c]. The MBC concentration accounted for 6.79%, 3.90%, 2.84%, and 2.24% of the SOC concentration, while MBN concentration accounted for 3.13%, 3.09%, 2.29%, and 1.55% of TN concentration under grassland, forest, PT and NT, respectively. At the 5–15 cm depth, the MBC: MBN ratio was higher under grassland and forestland than NT and PT [Fig. 2c]. At the 15–25 cm depth, the MBC: MBN ratios were generally lower under PT and NT than grassland and forestland [Fig. 2c]. The MBC concentration accounted for 4.94%, 3.20%, 2.45%, and 1.50% of SOC concentration, while MBN concentration accounted for 2.44%, 1.75%, 1.74%, and 1.78% of TN concentration under grassland, forestland, PT, and NT, respectively. The MBC: MBN ratios were generally not affected by soil depth for grassland, forestland and PT [Fig. 2c]. For NT however, the MBC: MBN ratios significantly decreased with increase in soil depth. These further implied that grassland and forestland would effectively promote soil C forming MBC and avoid more soil C decomposing. Correspondingly, arable land had relatively weak function on SOC sequestration by forming MBC. Among arable land, in the top layer the soil of NT was better than PT on forming MBC to C sequestration.

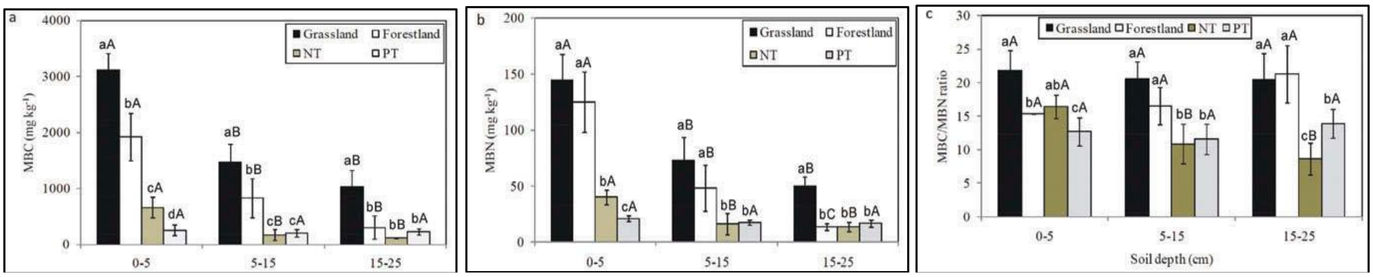


Fig 2: Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) concentrations (gkg^{-1}), and ratios of microbial biomass carbon to microbial biomass nitrogen (MBC/MBN) in the 0–5 cm, 5–15 cm, and 15–25 cm layers expressed as a, b, and c for three land uses (forestland, grassland and arable land) and two tillage systems (NT: no-tillage, PT: plow tillage).

Sharma *et al*. (2015) [64] observed that application of 25 kg N (compost) (1.61) as well as application of 15 kg N (compost) + 10 kg N ha^{-1} (green leaf) both recorded the greatest soil quality index (SQI) of 1.61 [Fig.3a]. Katkar *et al*. (2012) [31] also established that conjunctive nutrient-management practices maintained the greatest SAQI. Irrespective of their statistical significance, the relative order of performance of the nutrient-management treatments in influencing soil quality in terms of SQI was T$_4$ [25 kg N (compost) (1.61)] = T$_9$ [15 kg N (compost) + 10 kg N ha^{-1} (green leaf) (1.61)] > T$_2$ [100% RDN (80 kg Nha^{-1}) (1.48)] > T$_6$ [15 kg N (compost) + 20 kg N ha^{-1} (inorganic) (1.47)] > T7 [15 kg N (green leaf) + 10 kg N ha^{-1} (inorganic) (1.46)] > T$_5$ [15 kg N (compost) + 10 kg N ha^{-1} (inorganic) (1.45)] > T3 [50% RDN (80 kg N ha−1) (1.41)] > T8 [15 kg N (green leaf) + 20 kg N ha^{-1} (inorganic) (1.32)] > T$_1$ [no fertilizer (1.16)]. The average percentage contributions of key indicators toward soil quality indices were available N (13%), available P (32%), available K (34%), exchangeable Ca (9%), and microbial biomass carbon (12%) [Fig.3b].

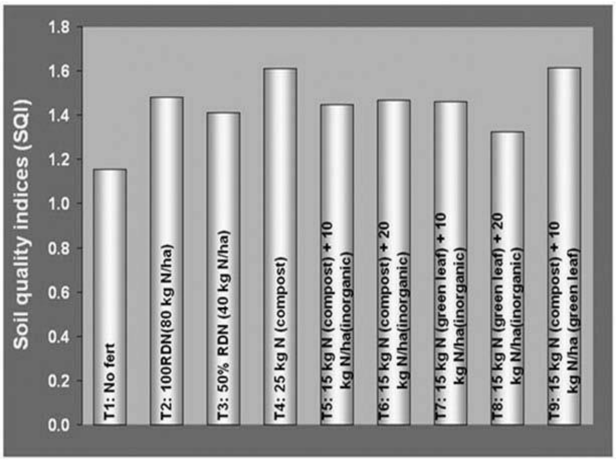


Fig 3(a): Soil quality indices as influenced by different conjunctive nutrient-management treatments in maize–wheat cropping sequence

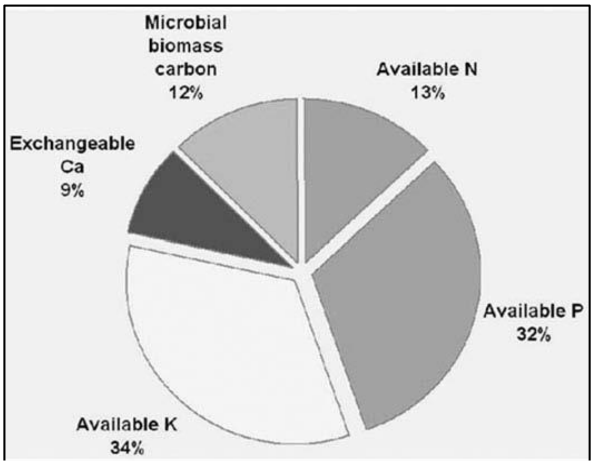


Fig 3(b): Percentage contributions of key soil quality indicators toward soil quality indices as influenced by different conjunctive nutrient-management treatments in maize–wheat cropping sequence

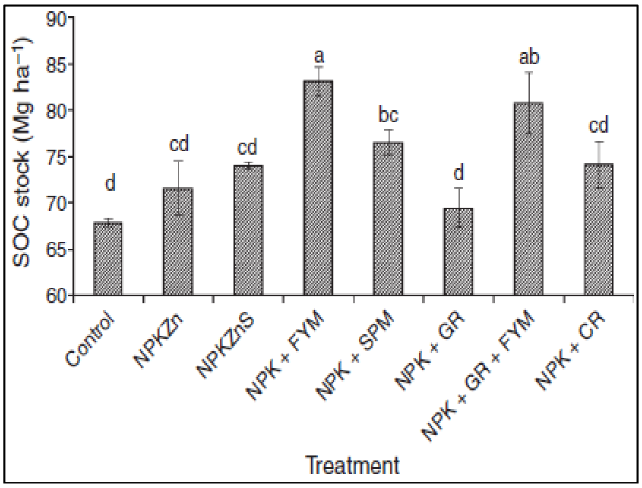


Fig 3(c): Effects of long-term fertilization and manuring on soil organic carbon (SOC) stock (0–60cm soil depth) in the rice–wheat system

Distribution of carbon stock

Venkanna *et al*. (2014) [71] indicated that vertisols and associated soils contained greater total C stocks, followed by inceptisols and alfisols. The soil organic carbon (SOC) stock was highest in alfisols (52.84 Mg ha^{-1}) followed by inceptisols (51.26 Mg ha^{-1}) and vertisols and associated soils (49.33 Mg ha^{-1}), whereas soil inorganic carbon (SIC) stock was highest in vertisols and associated soil (22.9 Mg ha^{-1}) followed by inceptisols (17.5 Mg ha^{-1}) and alfisols (12.4 Mg ha^{-1}) [Fig. 4a, 4b & 4c]. The SIC ranges from 4.14 to 25.54 Mg ha^{-1} with a mean of 12.39 Mg ha^{-1} in alfisols, 7.23 to 34.17 Mg ha^{-1} with a mean of 17.47 Mg ha^{-1} in inceptisols and 9.08 to 71.78 Mg ha^{-1} with a mean of 22.93 Mg ha^{-1} in vertisols and vertic intergrade. In most of the cases, surface SOC is greater than deeper layers, whereas the reverse trend is observed for SIC in most of the cases. Total carbon stock ranges from 30.81 to 116.42 Mg ha^{-1} (mean 65.24 Mg ha^{-1}) in alfisols, 43.12 to 107.20 Mg ha^{-1} (mean 68.73 Mg ha^{-1}) in inceptisols and 39.39 to 145.98 Mg ha^{-1} (mean 72.26 Mg ha^{-}

^{1}) in vertisols and associated soils. Ratio of organic to total carbon stock is maximum in alfisols followed by inceptisols and vertisols. Vertisols and associated soils have relatively greater total soil carbon stock than other soil types, whereas soils of regions with less rainfall show larger inorganic C content than those of regions with more rainfall. Amount of rainfall is significantly related with the amount of organic C stocks as well as soil N. Irrigated agricultural systems with balanced fertilizer application are characterized by higher soil organic stock than areas where rain-fed subsistence agriculture is practiced. Bhattacharyya *et al.* [4] reported that the SOC stock of Entisols ranges between 0.08 and 0.27 Pg in the upper 30 cm to 150cm depth, respectively.

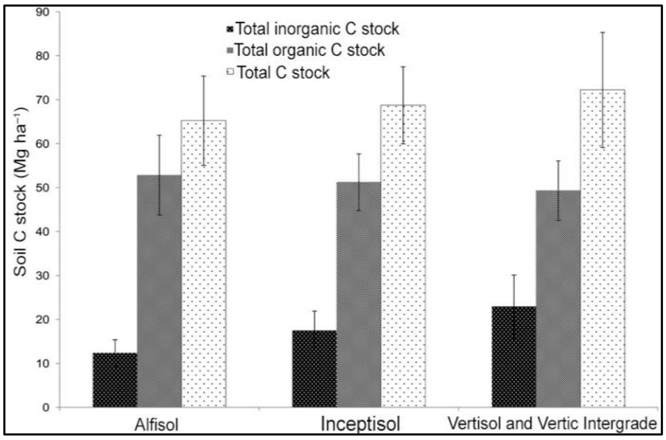


Fig 4(a): Distribution of carbon stock (total, organic and inorganic) in Alfisols, Inceptisols and Vertisols and associated soils for 0–60 cm soil depth.

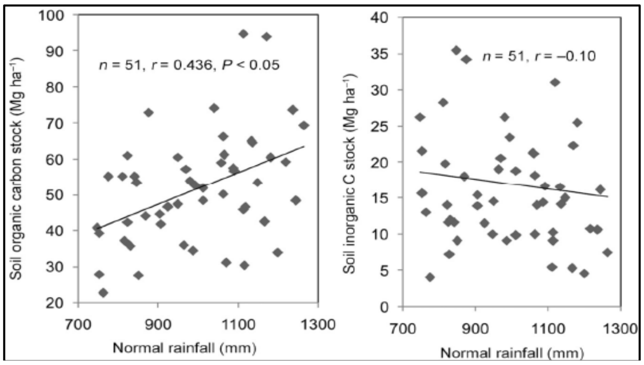


Fig 4(b): Relationship between mean annual rainfall and soil inorganic and organic carbon stock

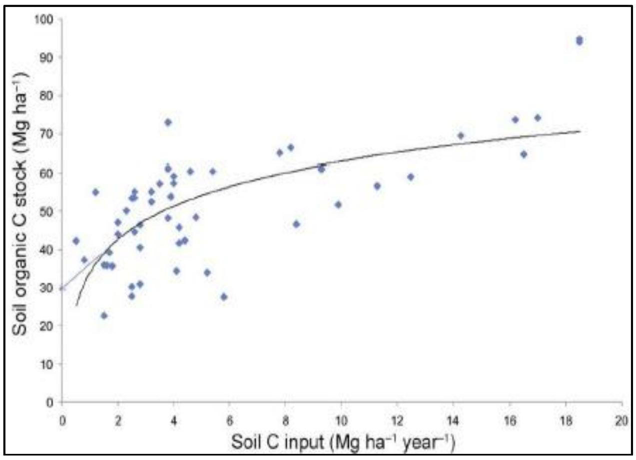


Fig 4(c): Soil organic carbon stock (Mg ha^{-1}) expressed as a function of carbon input levels (Mg ha^{-1} yr^{-1}) for the semiarid tropical region of South India.

Bhattacharyya *et al*. (2012) reported that the plots under NT–NT, NT–CT, and CT–NT had nearly 16, 12, and 10% higher total SOC content compared with CT-CT (∼12 g kg^{-1} soil) in the 0-to 5-cm soil layer. However, tillage had no impact on total SOC content in the subsurface (5- to 15-cm) soil layer.

Saikia *et al*. (2017) [62] observed that PTR with residue retention and GM and zero tillage wheat with 100% residue retention (ZTWR$_{100}$) significantly increased oxidisable soil organic carbon in surface (0-7.5 cm) and sub-surface (7.515 cm) soil layer. Averaged across five wheat growth stages, oxidizable organic carbon increased under PTR$_{W25}$+GM/ZTW$_{R100}$ by 50.1% in surface soil layer and 52.05% in sub-surface soil layer, respectively, as compared to PTR without residue and GM followed by conventionally tilled wheat [Fig.5a]. Islam, (2016) [28] also found that after Crop 1 and 4, the highest SOC concentrations was measured in BT, 39% and 44% higher than that in BF in the depth of 0-15 cm [Fig.5b]. After Crop 7, the SOC concentrations of BT were higher by 69% in 0-7.5 cm depth while by 38% in 0-15 cm depth than that in BF [Fig.5b]. On the other hand, the SOC concentrations of BT decreased significantly (10%) than that of BF in the 7.5-15 cm depth after Crop 7 [Fig.5b]. The SOC concentrations at 0-15 cm soil depth increased from 0.73% to 0.79% with ST and 0.73% to 0.83% with BP. The SOC concentrations slowly decreased with CT and were significantly lower than ST and BP from the end of Crop 1 and onwards [Fig.5c]. After Crop 4, the SOC-stocks were significantly greater by 9% in ST than CT [Fig.5c]. After Crop 7, the SOC-stocks were greater in ST by 25% at 7.5-15 cm depth and by 13% for the 0-15 cm depth (average of 0-7.5 cm and 7.5-15 cm) than CT [Fig.5c]. In all the treatments, the SOC-stocks decreased with soil depth [Fig.5c]. A minimum of 1 Mg Cha^{-1}yr^{-1} under ST condition and 7.7 Mg Cha^{-1}yr^{-1} for CT are required to compensate for SOC loss, only the ST treatment showed a net C sequestration ranging between 0.65 and 0.05 Mg Cha^{-1} [Fig. 5d]. Hou *et al*. (2012) [27]; Singh *et al*. (2016) [66] suggested that soil at 0-30 cm depth required about 5-6 years to establish a new balance between C inputs and outputs after converting from CT to NT in double cropping systems in temperate and tropical soils. After four years, Das *et al*. (2013) [18] found an increase in total SOC-stocks under ZT and partial or full residue retention in a cotton-wheat system.

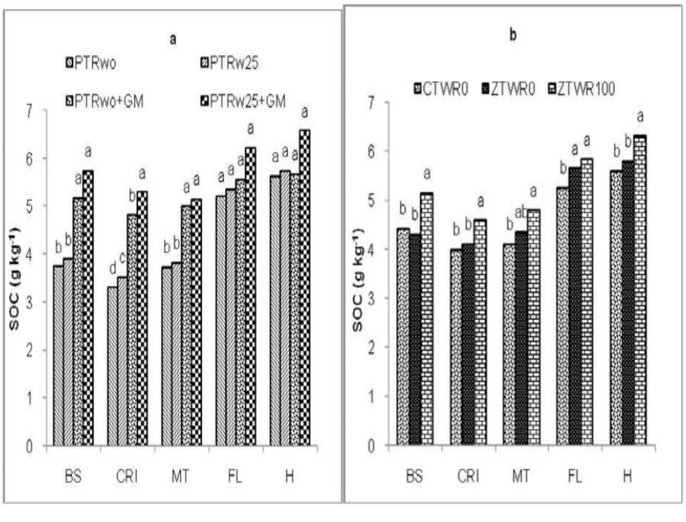


Fig 5(a): Soil organic carbon as affected by (a) Wheat straw and green manure practices in rice (b) Tillage and rice straw management practices in wheat in surface soil layer at different wheat growth stages.

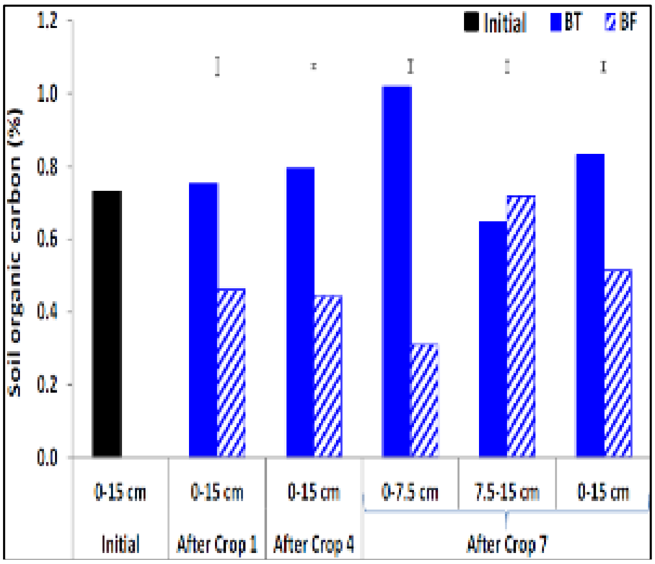


Fig 5(b): Variation of soil organic carbon concentrations at different cropping seasons.

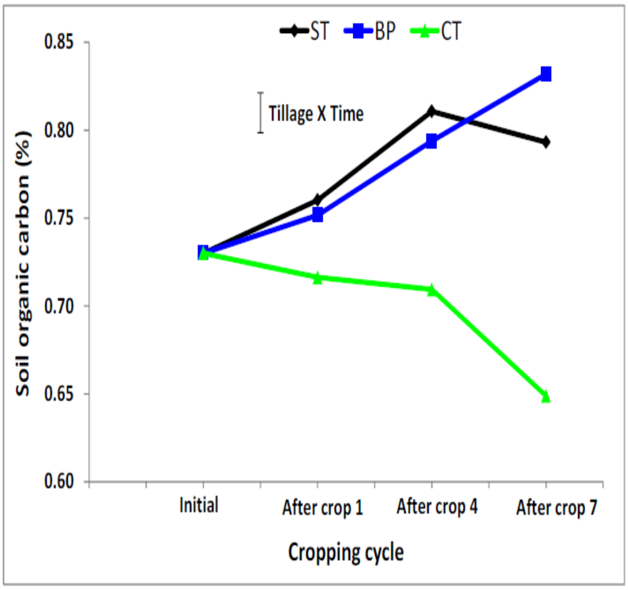


Fig 5(c): Temporal variation of soil organic carbon (SOC).

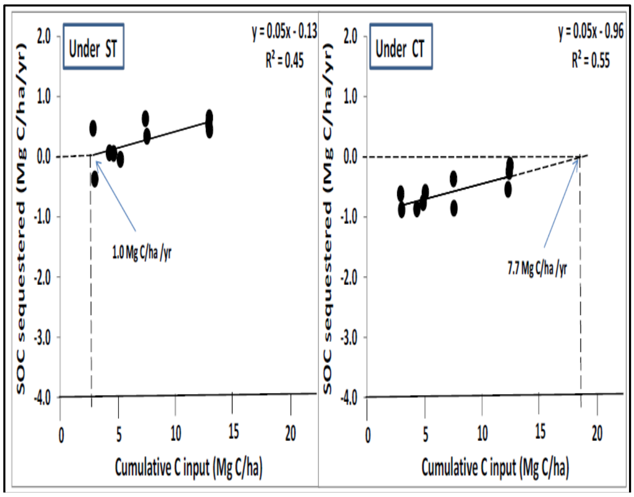


Fig 5(d): Relationship between cumulative C input and SOC sequestration during under ST and CT conditions of cereal-dominated rice–based system.

Zhang *et al.* (2015) [77] reported that in the control treatment (initial soil organic carbon content = 21.43 t C ha^{-1}), maize-derived soil organic carbon accumulated to 2.2 t C ha^{-1} over the first 10 years of the experiment, and eventually reached 5.6 t C ha^{-1} after another 17 years; a rate of change in the range of 0.20–0.22 t C ha^{-1} yr^{-1} (Fig. 3a). With mineral fertilizer application (NPK and 2NPK), maize-derived soil organic carbon accumulated to 3.2–3.5 t C ha^{-1} over the first 10 years and reached 8.2 t C ha^{-1} in 2012; a rate of change of 0.30 t C ha^{-1}. After 10 years, about 11% of original soil organic carbon had been replaced with maize-derived carbon in the control, whereas this was 15–16% in the NPK and 2NPK treatments [Fig. 6a]. After 27 years of maize double-cropping, 26% of soil organic carbon had been replaced by maize-derived carbon in the control, and this value was 34–35% in the mineral fertilizer treatments. In the NPKM treatment, manure-derived soil organic carbon comprised about 30% of total soil organic carbon and original soil organic carbon accounted for 43%, with the remainder derived from maize. Moreover, showed that the retention rate of maize-derived carbon in mineral fertilizer treatments was only about one-third of that in the control. Assuming the priming effect of long-term continuous organic manure input on original soil organic carbon turnover was insignificant which indicate that about 5.1% of manure-derived carbon was converted into soil organic carbon [Fig. 6b]. The average retention of the maize-derived carbon plus manure-derived carbon over the first 11 years of the trial was relative high (10%) compared to over the full 27 years (5.1–6.3%); regression analysis showed that the retention rate declined significantly with time [Fig. 6c]. The average retention rate of maize-derived carbon plus manure-derived carbon was about 5.1% over the period 1986–2012. Cai *et al*. (2016) [10] showed that long-term manure application significantly increased SOC and total N content and enhanced C and N mineralization in the three particle-size fractions. The content of SOC and total N followed the order 2000–250μm> 250–53μm> 53μm fraction, whereas the amount of C and N mineralization followed the reverse order. In the <53μm fraction, the M_{60}NPK treatment significantly increased the amount of C and N mineralized (7.0 and10.1times, respectively) compared to the M_0CK treatment. Long-term manure application, especially when combined with chemical fertilizers, resulted in increased soil microbial biomass C and N [Fig. 7a, 7b & 7c]. As a general trend N mineralization increased with manure application, showing more N mineralized from <53 μm fraction under the M_{30} NPK and M_{60} NPK treatments. There was no relationship between the storage of SOC or total N and the C or N mineralization from the bulk soil [Fig 8a]. Interestingly, N mineralization was strongly related to total N storage in the 250–53 μm and <53 μm fractions and C mineralization was significantly positive related to SOC storage in the 2000–250μm and <53μm fractions. Total organic carbon (TOC) content at different soil depths was significantly affected by the nutrient supply options (Table 4.1.4). On average, TOC content was highest (1.35%) in top (0-7.5 cm) soil and the lowest (0.32%) at 45-60 cm soil depth. Among treatments TOC under control and sole fertilizer treatments was statistically similar, whereas integrated nutrient options, except NPK+GR, increased the TOC significantly over control in 0-7.5 cm soil layer. The TOC in 0-7.5 cm soil under integrated nutrient supply, except NPK+GR and NPK+SPM, was even greater than sole fertilizer treatments. At other soil depths also, TOC under these treatments was significantly greater than control, although the differences were not as spectacular as in the top soil [Fig.8b]. The SOC stock varied under different treatments from 26.9 to 30.8, 17.7 to 21.2, 15.7 to 23.3 and 7.21 to 9.82 Mg ha^{-1} at 0-15, 15-30, 30-45 and 45-60 cm soil depth, respectively [Fig 8c]. The SOC stock decreased markedly with increasing soil profile depth irrespective of treatments. The higher SOC stock in the surface as compared to deeper soil layers may possibly be associated with C inputs through organic sources. Zhu, *et al*. (2007) [79] showed that while mineral fertilizer application can maintain high yields, a combination of chemical fertilizers plus manure was required to enhance soil C sequestration. The content of SOC and total N in soil particle-size fractions declined with a decrease in particle-size, indicating that larger-size soil fractions were the main pool of SOC and total N (Cambardella and Elliott, 1994) [12], with the less decomposable SOC and N associated with fine soil particles Puget *et al*. (1995) [57].

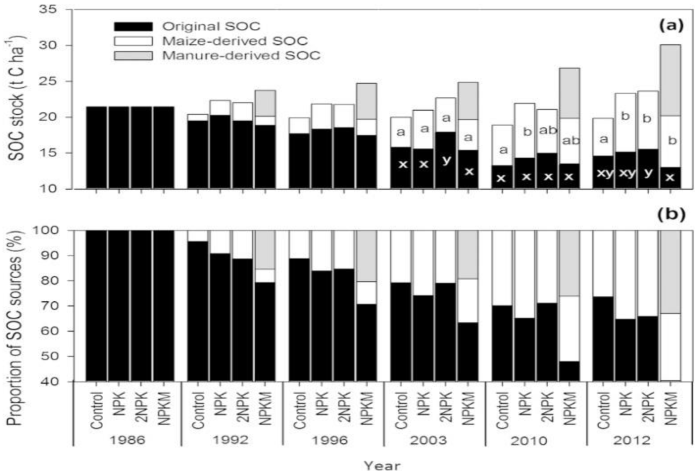


Fig 6 (a): Changes in stock of original, maize-derived, and manure-derived soil organic carbon (SOC) (t C ha^{-1}) (a) and their proportions (b) from 1986 to 2012

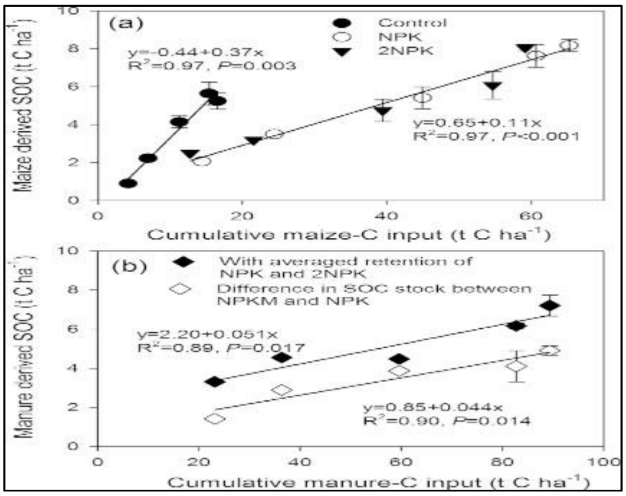


Fig 6(b): Relationship between maize-derived soil organic carbon (SOC) and cumulative maize carbon input as determined by δ^{13}C measurements for the Control, NPK, and 2NPK treatments (a) and manure-derived SOC and cumulative manure-C inputs

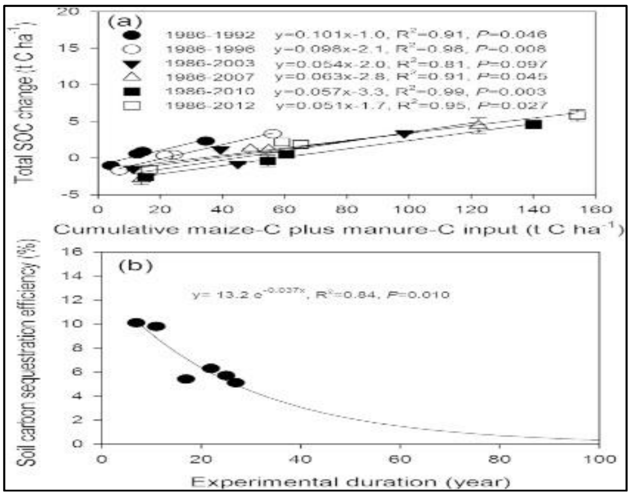


Fig 6c): Relationships between total soil organic carbon (SOC) and cumulative maize-derived C plus manure-derived C input for the periods 1986–1992, 1986–1996, 1986–2003, 1996–2007, 1986–2010, and 1986–2012.

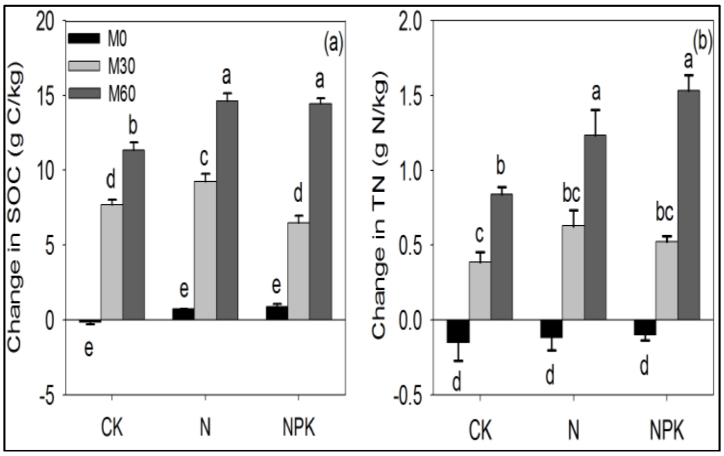


Fig 7(a): Change in soil organic carbon (SOC, a) and total nitrogen (N) (b) in bulk soil from the control (CK) or soil that has received 32 years of chemical fertilizer application (N, P: phosphorus, K: potassium) and either 0 (M$_0$), 30 (M$_{30}$) or 60 (M$_{60}$) t manure ha^{-1} yr^{-1}

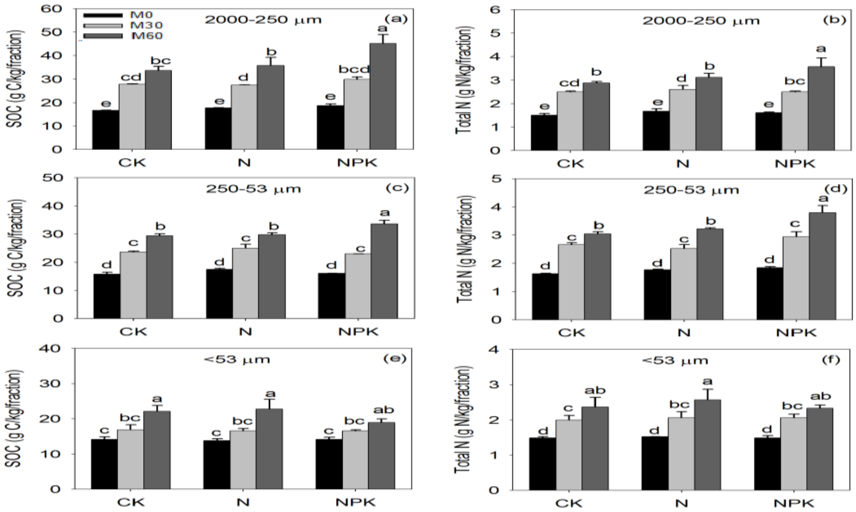


Fig 7(b): The content of soil organic carbon (SOC) in 2000–250µm (a), 250–53µm (c), <53µm (e) fraction and total nitrogen (N) in 2000–250µm (b), 250–53µm (d), <53µm (f) fraction from the control (CK) or soil that received 32 years of chemical fertilizer application (N, P: phosphorus, K: potassium) and either 0 (M_0), 30(M_{30}) or 60 (M_{60}) t manure ha^{-1} yr^{-1}

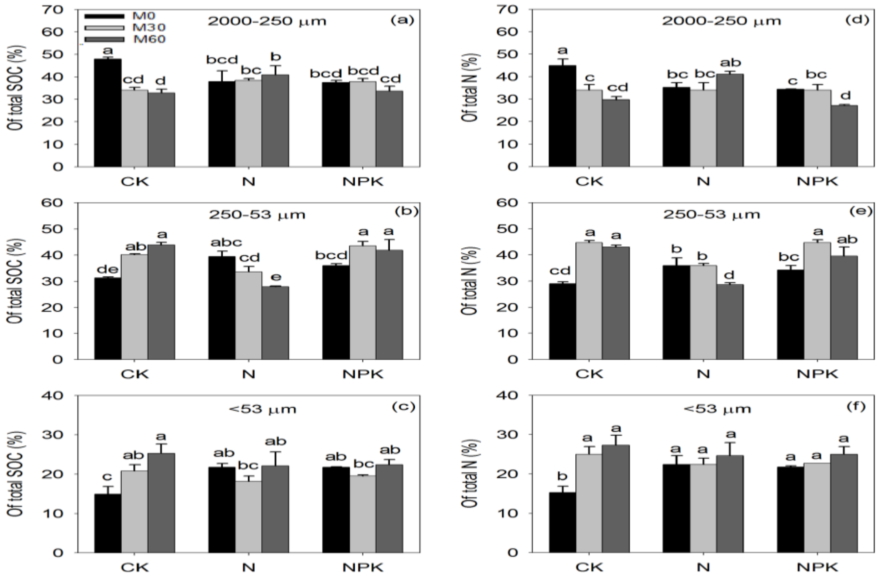


Fig 7(c): The percent (%) of soil organic carbon (SOC) in 2000–250µm (a), 250–53µm (c), <53µm (e) fraction and total nitrogen (N) in 2000–250µm (b), 250–53µm (d), <53µm (f) fraction from the control (CK) or soil that received 32 years of chemical fertilizer application (N, P:phosphorus, K: potassium) and either 0 (M_0), 30 (M_{30}) or 60 (M_{60}) t manure ha^{-1} yr^{-1}

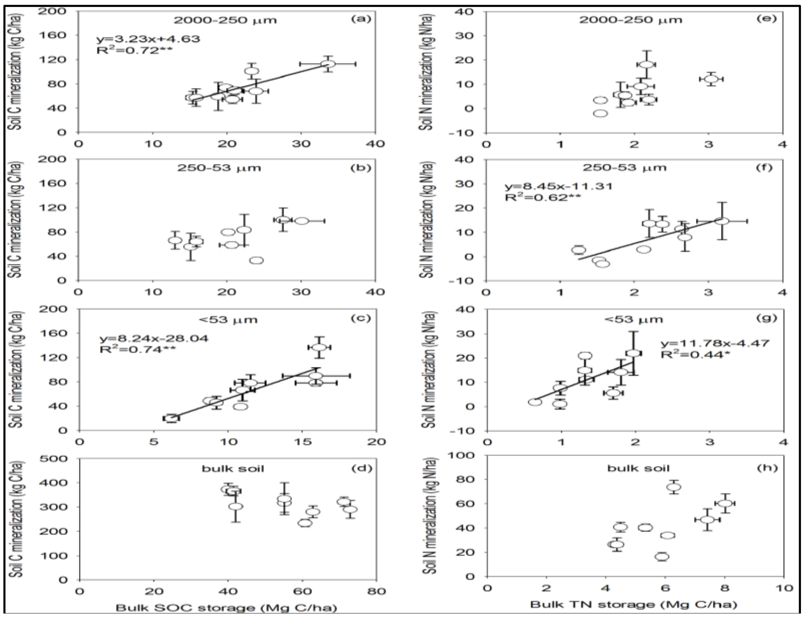


Fig 8(a): Relationship between soil organic carbon (SOC) storage vs potential carbon (C) mineralization, and total N storage, potential nitrogen (N) mineralization in 2000–250µm, 250–53µm, <53µm fraction and bulk soil after 32 years of manure fertilization

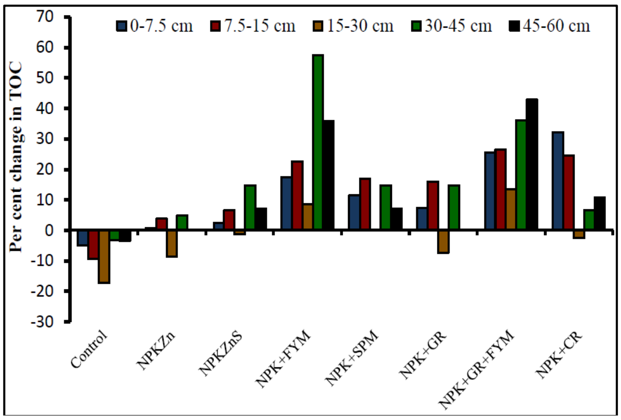


Fig 8(b): Per cent change in TOC over uncultivated soil after 18 rice-wheat crop cycles

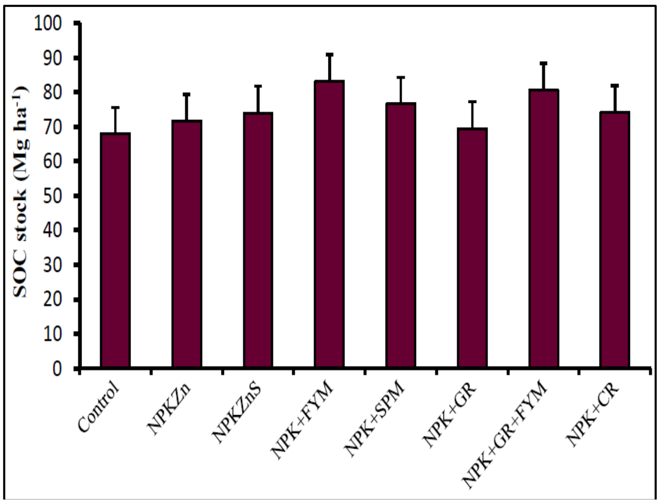


Fig 8(c): Effect of long-term fertilization and manuring on SOC stock (0-60 cm soil depth) in rice-wheat system

Depth distribution of SOC

Mazumdar *et al*., (2015) [41, 45] reported that organic C distribution in soil profile differed significantly among the treatments and with depths [Table 1]. At the surface (0-15 cm) layer, NPK+FYM contained the highest SOC concentration (7.7 g kg^{-1}) followed by NPK+CR (7.5 g kg^{-1}) and NPK+GM (7.4 g kg^{-1}). There was a significant reduction in SOC concentration with the sole application of inorganic fertilizers (NPK) compared with those in the mixed organic and inorganic treatments. The lowest SOC concentration (3.6 g kg^{-1}) in 015 cm layer was observed in treatment of a continuous cropping of rice-wheat over 25 years without any amendments. Mean SOC concentration in the profile increased from 2.4 g kg^{-1} in control to 4.1 g kg^{-1} in NPK+FYM. All the treatments showed higher accumulation of SOC in surface layer. Significant variations in SOC content were also observed in the sub-soil layers; mean SOC content decreased from 6.4 at surface 0-15 cm to 1.8 g kg^{-1} at 45-60 cm soil layer. Zhao *et al*. (2018) [78] revealed that the SOC content in each soil aggregate size class in the 0–20 cm layer significantly increased in the straw return treatments compared with no straw return. Moreover, 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. 9a]. Increases in the SOC content of aggregate fractions were highest in MR, WR, followed by MR, and finally WR [Fig. 9a]. All three straw return treatments (MR-WR, MR and WR) largely improved the SOC stock in each aggregate fraction in the 0–20 cm depth; increases were highest in MR-WR, followed by MR, and finally WR [Fig. 9b]. In the 20–40 cm layer, the SOC stock of small macro-aggregates significantly increased in MR-WR, but the SOC stock in the silt plus clay fraction decreased relative to other three treatments. Straw return treatments, particularly MR-WR, increased the proportions of mSOM and fine iPOM within small macro-aggregates and micro-aggregates, especially in the 0–20 cm layer [Fig. 9c]. The carbon content of iPOM was much lower at 20–40 cm than at 0–20 cm [Fig. 9c]. Higher OC content of micro-aggregates due to straw return may be beneficial to long-term SOC sequestration because micro-aggregates have a longer turnover time and higher stability relative to macro-aggregates (Qiao *et al*., 2015) [58]. The carbon content of soil aggregates was much lower in the 20–40 cm layer than in the 0–20 cm layer because the field machinery used mainly distributed straw within the topsoil.

Table 1: Long term effect of fertilizer and organic matter application on SOC content, SOC stock and SOC sequestration rate under rice-wheat cropping system [Mazumdar *et al*., 2015] [41, 48]

Treatments	**SOC content (g kg^{-1})**				**SOC stock (Mg ha^{-1})**				**Total SOC stock (Mg ha^{-1})**	**C build up (per cent)**	**SOC sequestration rate (Mg C ha^{-1} yr^{-1})**
	0-15	**15-30**	**30-45**	**45-60**	**0-15**	**15-30**	**30-45**	**45-60**			
Control	3.6c	2.3d	2.0d	1.7b	8.4	5.5	4.7	4.0	22.5	-	-
NPK	5.6b	3.1c	2.3c	1.7b	12.3	7.0	5.2	3.8	28.3	25.7	0.231
NPK+FYM	7.7a	3.8a	2.8a	2.0a	15.9	8.4	6.4	4.7	35.4	57.2	0.515
NPK+CR	7.5a	3.6ab	2.6b	1.7b	15.3	7.9	6.0	4.0	33.1	47.1	0.424
NPK+GM	7.4a	3.5b	2.5b	1.7b	15.5	7.7	5.7	4.0	32.9	32.9	0.413

FYM: Farmyard manure; CR: Crop residue; GM: Green manure; Means in a column followed by the same lower case letter do not differ significantly at $P<0.05$ according to Duncan's Multiple Range test.

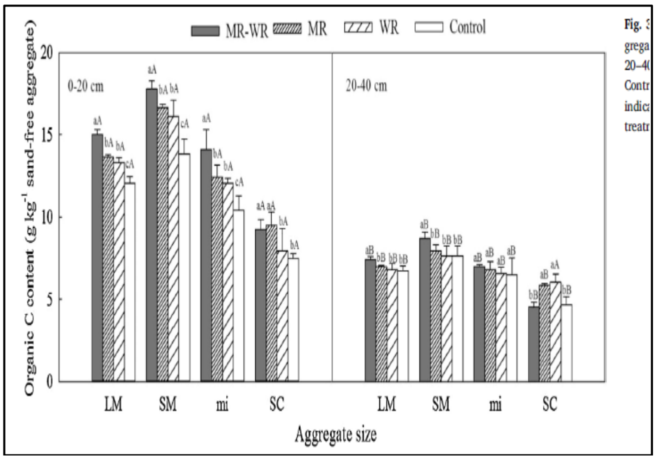


Fig 9(a): Organic C content (g kg^{-1} aggregate) of aggregates: LM, SM, mi, and SC in the 0–20 cm and 20–40 cm soil layers under MR-WR, MR, WR, and Control.

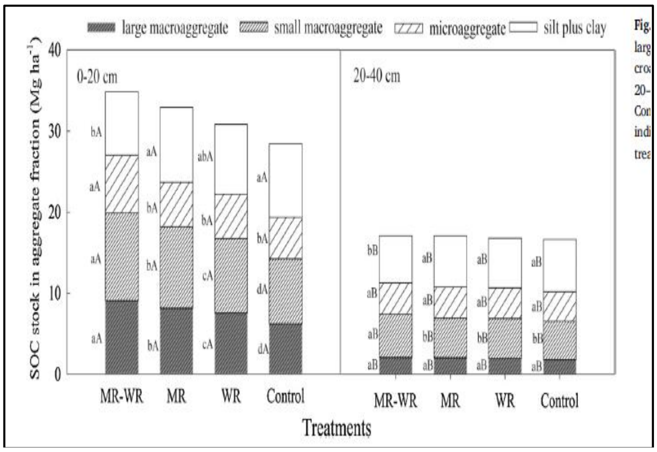


Fig 9(b): SOC stock of aggregate fractions (Mg ha^{-1}): large macro-aggregates, small macro-aggregates, micro-aggregates, and silt plus clay in the 0–20 cm and 20–40 cm soil layers under MR-WR, MR, WR, and Control.

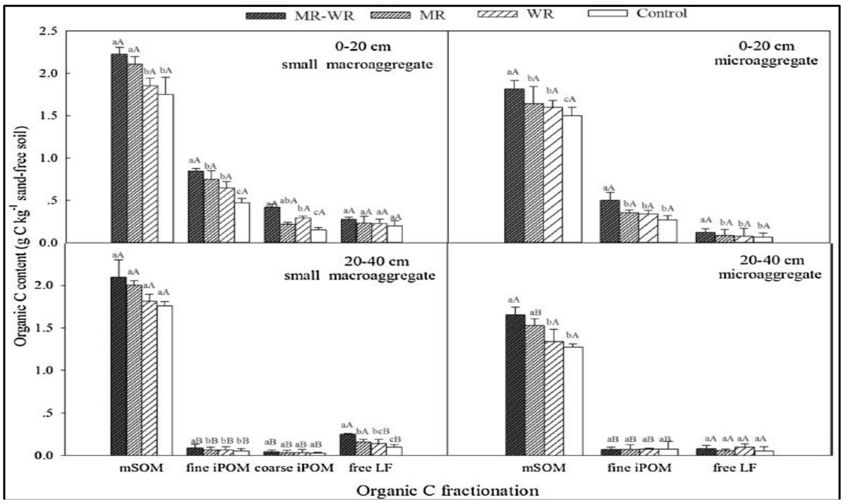


Fig 9(c): Organic C content (gkg^{-1} soil) of the SOC fractions: coarse iPOM, fine iPOM, mSOM, and free LF of small macro-aggregates and micro-aggregates in the 0–20 cm and 20–40 cm soil layers under MR-WR, MR, and WR

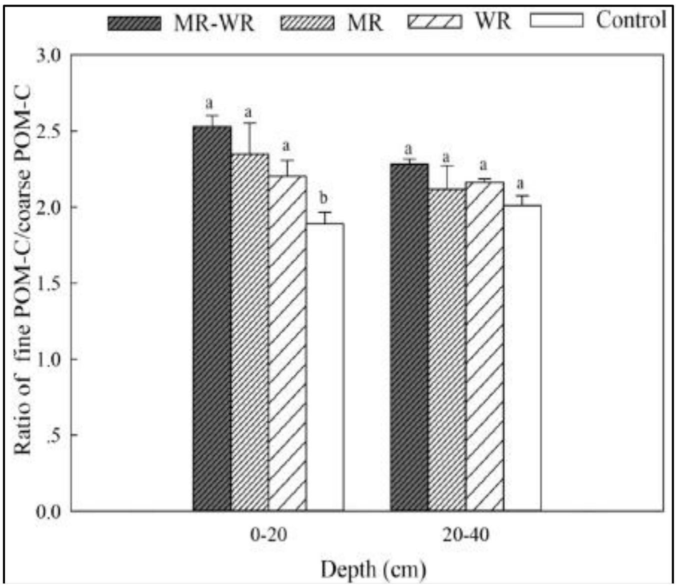


Fig 10 (a): Ratio of fine iPOM-C to coarse iPOM-C under MR-WR, MR, WR, and Control in the 0–20 and 20–40cm soil layers Soil light fraction organic carbon.

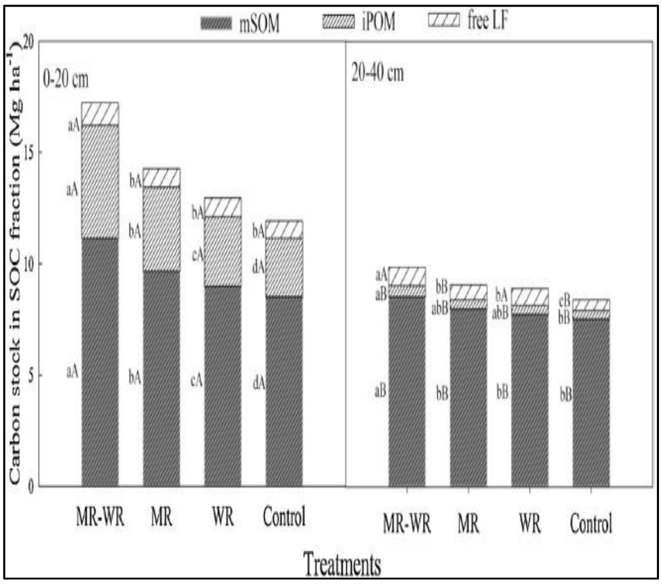


Fig 10(b): Carbon stock of mSOM, iPOM, and free LF (small macro-aggregates and micro-aggregates) in the 0–20 and 20–40 cm soil layers under MR-WR, MR, WR, and Control.

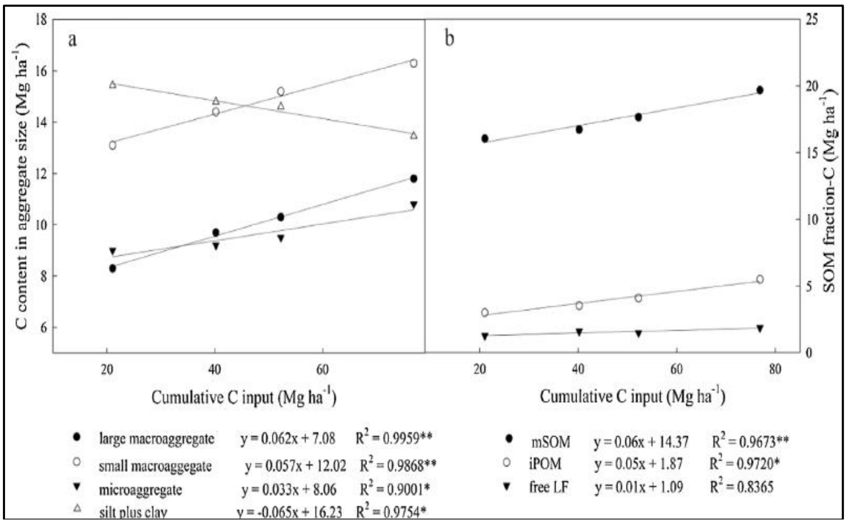


Fig 10(c): Relationships between cumulative C inputs and C stock of the aggregate sizes and SOM fractions within the 0–40 cm soil layer over 7 years long-term cropping system.

Zhao *et al*. (2018) [78] also found that relative to the control, straw return (MR-WR, MR, and WR) increased the ratio of fine iPOM-C to coarse iPOM-C in small macro-aggregates in the 0–20 cm soil layer [Fig. 10a]. Continuous straw return, particularly MR-WR, also greatly increased the proportions of mSOM-C, iPOM-C and free LF-C [Fig. 10b]. In both the 0–20 and 20–40 cm layers, mSOM-C contributed to the majority (67.0–71.9% and 86.3–89.6%) of the total SOC stock within small macro-aggregates and micro-aggregates [Fig. 10b]. In the 0–20 cm layer, mSOM-C was 31%, 13.6% and 5% higher in MR-WR, MR, and WR relative to the control, respectively [Fig.10b]; in the 20–40 cm depth, the corresponding values were13.2%, 6.1% and 2.8%. In the 0–20 cm layer, iPOM-C was 75.9%, 36.7%, and 33.3% higher in MR-WR, MR and WR relative to the control, respectively; in the 20–40 cm layer, the corresponding values were 30.7%, 7.1%, and 8.9%. Free LF-C was 30.8%, 5.1%, and 3.8% higher in MR-WR, MR, and WR relative to the control, respectively; in the 20–40 cm layer, the corresponding values were 74.5%, 35%, and 56.4%. Therefore, straw return had much greater impact on the proportions of mSOM and iPOM compared with that of free LF, and the iPOM fraction was the most sensitive to different straw return modes and soil depth. The carbon content of large macro-aggregates, small macro-aggregates, and micro-aggregates [Fig. 10c], as well as mSOM and iPOM [Fig. 10c], increased with increasing cumulative C input. However, the carbon content of the silt plus clay fraction decreased with increasing C input, and free LF-C remained stable. Thus, high C input mainly increased the C content of large aggregates [Fig.10c]. Based on the slope of the regression equations, the effect was highest for mSOM (slope = 0.06), followed by iPOM (slope = 0.04). Duval *et al*. (2016), who found a strong linear relationship between residue C input and SOC change (R^2 =0.61; $P < 0.05$) as well as between C input and labile soil organic fractions (R^2 = 0.81; $P < 0.001$). Despite C addition (3.00 Mg ha^{-1} yr^{-1}) through roots, stubble, and rhizo deposition, SOC stock in the control decreased over the experimental period. Although inorganic fertilizers may indirectly increase SOM by increasing crop biomass and C return to soils, the amount of aboveground crop residue returned to the soil was insufficient to maintain soil organic carbon level (Xie *et al*., 2014) [74]. Furthermore, the addition of inorganic fertilizers alone increased microbial biomass and DOC and N availability (Qiu *et al*., 2016) [59], thereby promoting SOC decomposition (Lu *et al*., 2014) [39]. The increased SOC stock under WR, MR, and MR-WR only accounted for 4.7%, 5.4%, and 8.1% of the cumulative C input, respectively, indicating large C losses.

Samal *et al*. (2017) [63] reported that the S3 scenario registered highest total organic carbon (TOC) stock of 47.71 Mg C ha^{-1} and resulted in significant increase of 14.57% over S1(Farmer's practice) in 0–30 cm soil depth after 7years of field trial. The S4 scenario having intensified cropping systems recorded lowest TOC of 39.33 Mg C ha^{-1} and resulted in significant depletion of 17.56% in C stock with respect to S3 in 0–30 cm soil depth. The TOC enrichment was higher in S2, S3 and S4 scenario in the surface soil (0–10 cm) compared to S1. At lower depth (20–30 cm), the TOC enrichment was significantly higher in S2 (12.82 Mg C ha^{-1}) and S3 (13.10 Mg C ha^{-1} soil) over S1 scenario [Table 2]. Maximum increase in TOC stock under S3 might be due to the highest addition of crop residues coupled with conservation tillage (Ghosh *et al*., 2012) [24]. Ploughing of soil causes breakage of macro-aggregates into micro-aggregate and silt and clay size particles inside soil exposing protected organic carbon inside macro-aggregate for oxidation (Six *et al*., 2000).

Bäumler *et al*. (2005) [5] found that the vertical distribution of SOC density under forests was more homogeneous than grassland and shrub lands [Fig. 11a] probably due to high OM inputs from both above- and below ground biomass, slow decomposition and SOC complications with andic and spodic properties of non-volcanic andosolic soils. Egli *et al*. (2009) [20] reported that the mean SOC density values were variable in their ranges under different aspect directions, viz: 2.8–10.6 kg·m^{-2} (north-facing slopes), 2.6–9.0 kg·m^{-2} (east-facing slopes), 1.9–8.5 kg·m^{-2} (south-facing slopes) and 1.5–8.5 kg·m^{-2} (west-facing slopes) [Fig. 11b]. At all depths, the northern aspect had relatively large mean SOC density than other aspect directions. The larger SOC density on the north-facing slopes could be ascribed to rich biodiversity, high OM inputs, faunal abundance and more soil moisture on the northern aspect compared to other aspect directions. Begum *et al*. (2010) [6] observed that the mean SOC density under different altitudinal zones was relatively large under 4000–5520 m (4.8–13.2 kg·m^{-2} for first three depths) and 3500–4000 m zones (3.4–11.7 kg·m^{-2}) compared to 3000–3500 m (2.2–11.6 kg·m^{-2}), 2500–3000 m (1.7–7.0 kg·m^{-2}) and 1769–2500 m zones (2.0–7.1 kg·m^{-2}) [Fig. 11c]. The increase in SOC density with altitudinal zone was largely due to increase in SOC concentration with altitude resulting from higher OM inputs from above- and belowground biomass, slow decomposition due to low temperature [Bäumler *et al*. (2005) [5] and more translocation of OC into deeper layers.

Table 2: Depth wise (0–10, 10–20, 20–30 cm) distribution of total organic carbon stock (Mg C ha^{-1} soil) (Mean ± SD) as affected by different tillage and crop management practices followed in four scenarios [Samal *et al*., 2017] [63].

Scenarios	0-10 cm	10-20 cm	20-30 cm	Total
S1: TPR-CTW	16.22 ± 0.60^{b}	15.06 ± 0.92a	10.36 ± 1.07^{b}	41.65 ± 0.13^{BC}
S2: TPR/MTNPR+R-ZTW+R-CTMB+ R	16.53 ± 0.78^{b}	14.56 ± 0.65^{a}	12.82 ± 1.10^{a}	43.91 ± 0.84^{B}
S3: ZTDSR+R-ZTW+R-ZTC/ZTMB+R	19.41 ± 1.84^{a}	15.20 ± 0.73^{a}	13.10 ± 0.21^{a}	47.71 ± 2.46^{A}
S4: NPTPR/ZTDSR+R-CT(P+M)/ZTM +R-ZTC/ ZTM+R	16.56 ± 1.71^{b}	12.61 ± 0.10^{b}	10.16 ± 0.80^{b}	39.33 ± 2.40^{C}

Different capital letters and small letters denote significant difference among the values of total and depths respectively, across the scenarios.

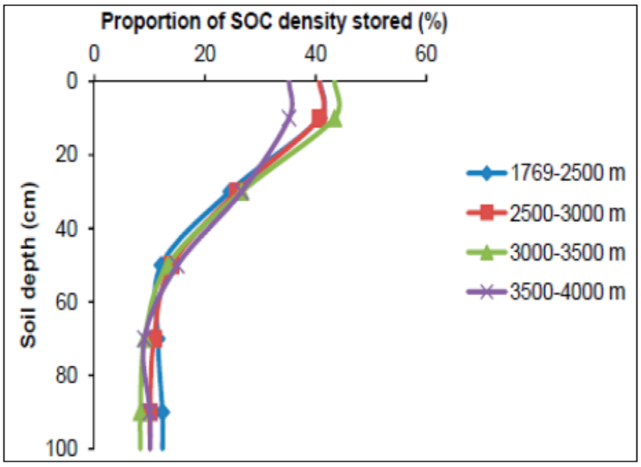


Fig 11(a): Proportion of SOC density (kg·m^{-2}) stored at different depth intervals under different LULC types

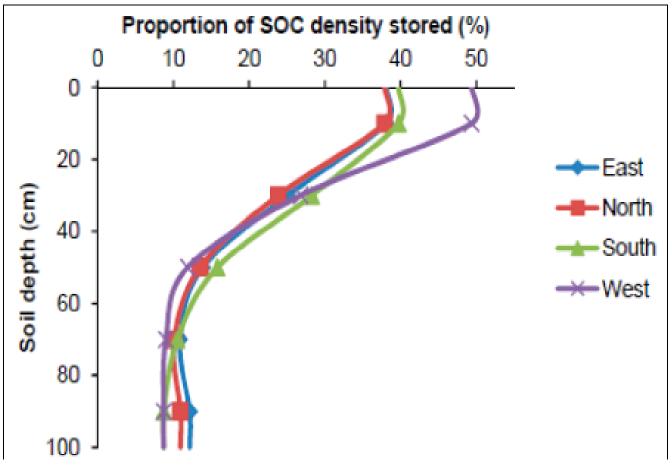


Fig 11(b): Proportion of SOC density (kg·m^{-2}) stored at different depth intervals under different aspect directions

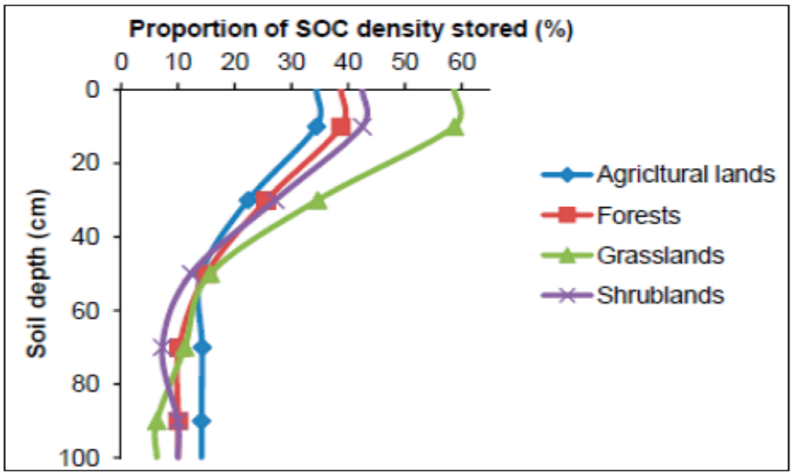
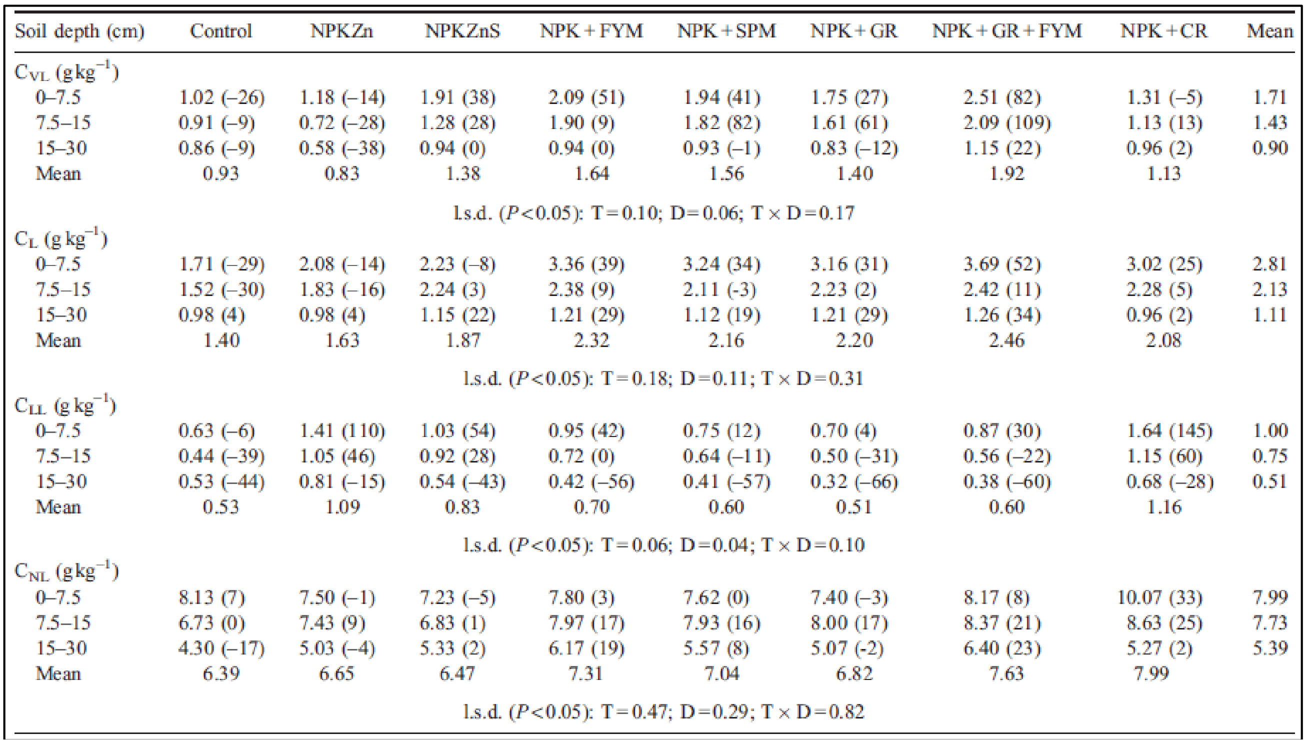


Fig 11(c): Proportion of SOC density (kg·m^{-2}) stored at different depths under different altitudinal zones

Labile organic carbon fractions

Das *et al*. (2016) [17] reported that the 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 [Table 3]. Among the OOC fractions (Table 5), C_{VL} in the 0–7.5, 7.5–15 and 15–30cm soil depths was in the range 1.02–2.51, 0.72–2.09 and 0.58–1.15gkg^{-1} respectively, with corresponding mean values of 1.71, 1.43 and 0.90gkg^{-1}. At the 0–7.5cm soil depth, the lowest CVL was seen in the unfertilized control treatment (1.02gkg^{-1}) and CVL increased significantly under IPNS treatments, with particularly high values (2.51gkg^{-1}). Mean values across soil depths and nutrient supply options, the abundance of these four OOC fractions was in the order C_{NL} (7.04gkg^{-1}) >C_{L} (2.02gkg^{-1}) >C_{VL} (1.35gkg^{-1}) >C_{LL} (0.75gkg^{-1}) [Fig. 12b]. Mandal *et al*. (2013) [46] reported that the TOC of soil under NPK did not change over control even after 5 years of pigeon-pea–wheat cropping at 0–15 and15–30 cm depths on a Typic Haplustept soil of the IGP. Mtambanengwe and Mapfumo (2008) [45] reported that the effects of fertilization and manure application on PmOC varied with the nature of the organics added. A much narrower C: N ratio of FYM and GR compared with CR may be an important reason for higher PmOC content under the NPK+ GR+FYM treatment than under the NPK+CR treatment (Verma *et al*. 2010) [72]. 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) [51].

Table 3: Oxidisable organic C fractions under long-term fertilization (NPK, NPKZn, NPKZnS) and manure treatments in an Inceptisol of Modipuram, India [Das *et al*., 2016] [17]



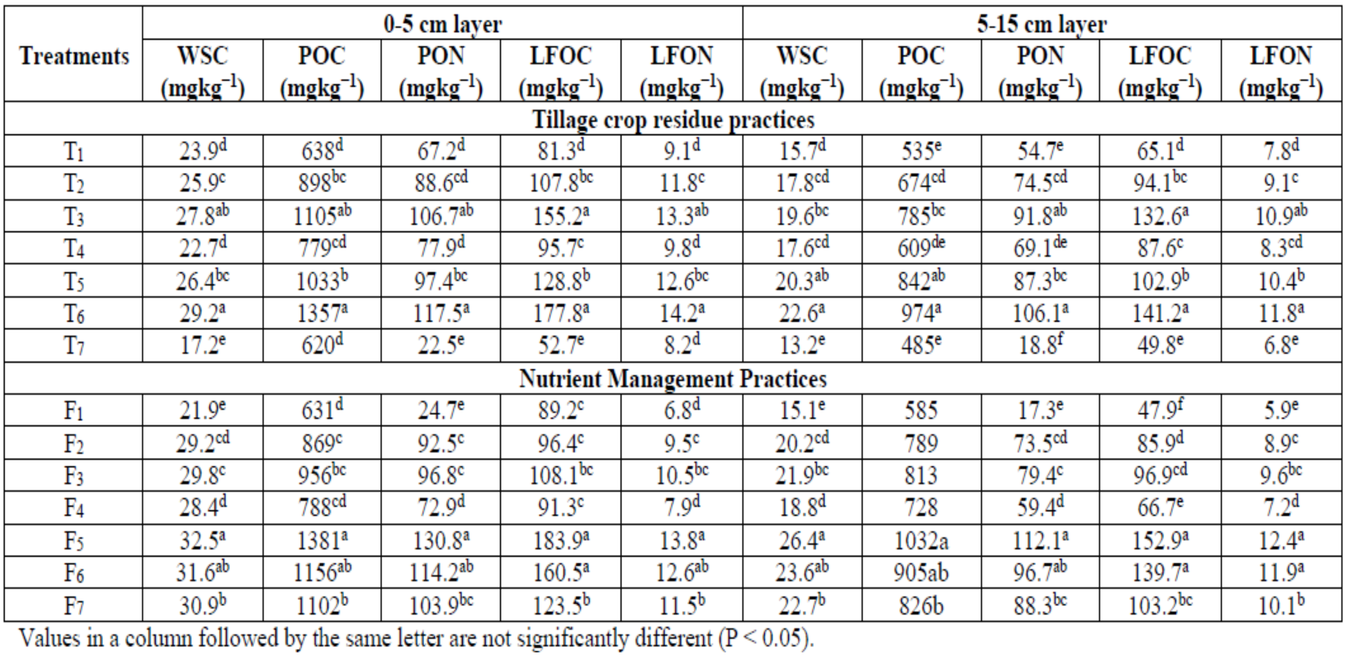
Soil depth (cm)	Control	NPKZn	NPKZnS	NPK + FYM	NPK + SPM	NPK + GR	NPK + GR + FYM	NPK + CR	Mean
C_{VL} ($g\,kg^{-1}$)									
0–7.5	1.02 (–26)	1.18 (–14)	1.91 (38)	2.09 (51)	1.94 (41)	1.75 (27)	2.51 (82)	1.31 (–5)	1.71
7.5–15	0.91 (–9)	0.72 (–28)	1.28 (28)	1.90 (9)	1.82 (82)	1.61 (61)	2.09 (109)	1.13 (13)	1.43
15–30	0.86 (–9)	0.58 (–38)	0.94 (0)	0.94 (0)	0.93 (–1)	0.83 (–12)	1.15 (22)	0.96 (2)	0.90
Mean	0.93	0.83	1.38	1.64	1.56	1.40	1.92	1.13	
l.s.d. ($P<0.05$): T = 0.10; D = 0.06; T × D = 0.17									
C_L ($g\,kg^{-1}$)									
0–7.5	1.71 (–29)	2.08 (–14)	2.23 (–8)	3.36 (39)	3.24 (34)	3.16 (31)	3.69 (52)	3.02 (25)	2.81
7.5–15	1.52 (–30)	1.83 (–16)	2.24 (3)	2.38 (9)	2.11 (-3)	2.23 (2)	2.42 (11)	2.28 (5)	2.13
15–30	0.98 (4)	0.98 (4)	1.15 (22)	1.21 (29)	1.12 (19)	1.21 (29)	1.26 (34)	0.96 (2)	1.11
Mean	1.40	1.63	1.87	2.32	2.16	2.20	2.46	2.08	
l.s.d. ($P<0.05$): T = 0.18; D = 0.11; T × D = 0.31									
C_{LL} ($g\,kg^{-1}$)									
0–7.5	0.63 (–6)	1.41 (110)	1.03 (54)	0.95 (42)	0.75 (12)	0.70 (4)	0.87 (30)	1.64 (145)	1.00
7.5–15	0.44 (–39)	1.05 (46)	0.92 (28)	0.72 (0)	0.64 (–11)	0.50 (–31)	0.56 (–22)	1.15 (60)	0.75
15–30	0.53 (–44)	0.81 (–15)	0.54 (–43)	0.42 (–56)	0.41 (–57)	0.32 (–66)	0.38 (–60)	0.68 (–28)	0.51
Mean	0.53	1.09	0.83	0.70	0.60	0.51	0.60	1.16	
l.s.d. ($P<0.05$): T = 0.06; D = 0.04; T × D = 0.10									
C_{NL} ($g\,kg^{-1}$)									
0–7.5	8.13 (7)	7.50 (–1)	7.23 (–5)	7.80 (3)	7.62 (0)	7.40 (–3)	8.17 (8)	10.07 (33)	7.99
7.5–15	6.73 (0)	7.43 (9)	6.83 (1)	7.97 (17)	7.93 (16)	8.00 (17)	8.37 (21)	8.63 (25)	7.73
15–30	4.30 (–17)	5.03 (–4)	5.33 (2)	6.17 (19)	5.57 (8)	5.07 (-2)	6.40 (23)	5.27 (2)	5.39
Mean	6.39	6.65	6.47	7.31	7.04	6.82	7.63	7.99	
l.s.d. ($P<0.05$): T = 0.47; D = 0.29; T × D = 0.82									

Values in parentheses indicate the percentage change over uncultivated soil. Control, unfertilized plots; FYM, farmyard manure; SPM, sulfitation press-mud; GR, green gram residue; CR, cereal residue; C_{VL}, very labile C fraction; C_L, labile C fraction; C_{LL}, less-labile C fraction; C_{NL}, non-labile C fraction; T, treatment; D, depth

Naresh *et al*. (2017) [54] revealed that WSC was found to be 3.74% higher in surface soil than in sub-surface soil [Table 4]. 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 [Table 4]. In 0 - 5 cm soil layer of tillage system, T_1, and T_4 treatments increased POC content from 620 mgkg^{-1} in CT (T7) 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 [Table 4]. 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 [Table 4].

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 [Table 3]. 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 [Table 4].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 (F_7) over unfertilized control plots (F_1) [Table 4]. 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& PRB and CT system. Six *et al*. (2002) [67] reported that the decrease in the disruption of soil macro-aggregates under ZT plots permitted a greater accumulation of SOC between and within the aggregates. Thus, less soil disturbance is the major cause of higher POC in the ZT and PRB plots compared with the CT plots in the 0- to 5-cm soil layer. This phenomenon might lead to micro-aggregate formation within macro-aggregates formed around fine intra-aggregate POC and to a long-term stabilization of SOC occluded within these micro-aggregates. Because increased POC is regarded as a potential indicator of increased C accumulation. Rudrappa *et al*., (2006) [61] [reported that the additional organic carbon input could enhance the POC accumulation. Rajan *et al*., (2012) [60] concluded that FYM can increase the root biomass and microbial biomass debris which is the main source of POC. The continuous replacement of organic manure on the soil creates a favorable environment for the cycling of C and formation of macro-aggregates. Furthermore, POC acts as a cementing agent to stabilize macro-aggregates and protect intra-aggregate C in the form of POC Six *et al*. (2002) [67].

Table 4: Effect of 15 years of application of treatments on contents of various labile fractions of carbon in soil [Naresh *et al*., 2017] [54]



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 ($P < 0.05$).

WSC = water soluble C, POC = particulate organic C, PON = particulate organic N, LFOC = light fraction organic

Guo *et al*. (2016) [26] revealed that compared with CT treatments, NT treatments did not affect SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly increased the SOC concentration of bulk soil in the 0−5 cm soil layer [Table 5]. In comparison with NS treatments, S treatments had not significant effects on SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly enhanced the SOC concentration of bulk soil in the 0−5 cm soil layer [Table 5]. Therefore, this study only investigated the effects of conservation tillage on microbial metabolic characteristics and the relationships between the metabolic characteristics and SOC within aggregates in the 0−5 cm soil layer. NT treatments significantly increased MBC of bulk soil, >0.25 mm and <0.25 mm aggregates by 11.2%, 11.5% and 20.0%, respectively, compared with CT treatments. DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under NT treatments were 15.5%, 29.5%, and 14.1% higher than those under CT treatments, respectively. In comparison with NS treatments, S treatments significantly increased SOC concentrations of bulk soil by 12.8%, >0.25 mm aggregate by 11.3%, and <0.25 mm aggregate by 14.1%. In addition, MBC of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under S treatments were 29.8%, 30.2%, and 24.1% higher than those of NS treatments, respectively. S treatments exhibited 25.0%, 37.5%, and 23.2% higher DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate compared with NS treatments, respectively. In the 0−5 cm soil layer, there were significant interactions of tillage and straw returning on SOC concentration of >0.25 mm and <0.25 mm aggregates, MBC of bulk soil and <0.25 mm aggregate, and DOC concentration of >0.25 mm aggregate [Table 5].

Li *et al*. (2018) [34] reported that organic manure alone evolved greater cumulative amounts of CO_2-C (C_{min}) from soils after 21 days of incubation (467 mg CO_2-C g^{-1} soil for DMA and 279 mg CO_2-C g^{-1} soil for SMA) than other treatments and the lowest C_{min} concentrations (109 mgCO_2-C g^{-1} soil) were found in the CK treatment. Application of mineral fertilizers combined with organic manure (1/2SMF + 1/ 2SMA) significantly increased C mineralization by 81% compared to the SMF treatment and by 32% compared to the DMF treatment [Fig. 12a]. MBC ranged from 168.84 to 471.04 mgkg^{-1}, constituting about 1.74–2.32% of total SOC [Fig.12a].The long-term application of N through organic manure alone (DMA and SMA) resulted in a significant increase in MBC compared to mineral-fertilized plots (DMF and SMF) and CK, meanwhile, the MBC concentration significantly increased with increasing rate of organic manure application. Similarly, substitution of 50% N through manure (1/2SMF + 1/2SMA) also increased the POC concentration compared to SMF. Increasing manure input levels resulted in higher levels of DOC with a concentration1.17 times higher under DMA compared with SMA. The integrated treatment (1/2SMF +1/2SMA) markedly increased DOC content compared to CK. DOC comprised the smallest proportion (0.84–1.19%) of SOC and was significantly affected by different fertilizer treatments, with the highest proportion in the SMA treatment and the lowest in the 1/2SMF +1/2SMAtreatment. Pure organic manure treatments (DMA and SMA) showed significantly higher concentrations of POC as compared to integrated (1/ 2SMF + 1/2SMA) and mineral-fertilized plots (DMF and SMF) ($P \leq 0.05$). POC constituted 10.20 to 23.65% of total SOC with a mean value of 16.43%. Highest proportion of POC was observed under DMA, followed by SMA, which was not significantly different from DMF; 1/ 2SMF + 1/2SMA and SMF had a lower proportion of POC and the lowest proportion was found in the CK treatment. In the surface soil (0–20 cm), the LFOC concentration was 60% higher under DMA than under CK. Other treatments showed no significant effects on LFOC concentrations relative to CK [Fig.12b]. The proportion of $KMnO_4$-C varied from 14.48 to 21.89% with the mean value of 18.39% of total SOC. The impacts of different fertilizer treatments on the proportion of $KMnO_4$-C were similar to POC, with highest proportions in DMA and lowest in CK [Fig.12b]. Although they account for only a small proportion of SOC (generally 0.80–12.00% for C_{min} 0.05–0.50% for DOC and 0.30–4.00% for MBC) in agricultural soils, these measures of soil C are considered good indicators of the soil's potential to cycle nutrients, a key ecosystem service (Moharana *et al*., 2012; Benbi *et al*., 2015) [50, 7]. Significant increases in C_{min}, DOC and MBC were observed after organic manure addition, suggesting that organic manure alone or combined with mineral fertilizers had beneficial effects on the activity of microorganisms probably by providing a readily-available source of C substrate and improving the soil physical environment e.g. porosity (Yang *et al*., 2012) [76].

Table 5: Changes in SOC fractions within aggregates under different tillage and residue treatments [Guo *et al*., 2016] [26]

Organic C	Soil fractions	CTNS	CTS	NTNS	NTS	T	S	T×S
SOC (0–5 cm soil layer)	Bulk soil	19.60±0.55 d	21.29±0.12 b	20.33±0.46 c	21.75±0.18 a	*	*	ns
(g kg^{-1})	>0.25 mm	19.70±0.10 c	21.30±0.10 b	20.43±0.06 c	23.37±0.06 a	**	**	**
	<0.25 mm	17.28±0.06 d	19.48±0.12 b	18.41±0.17 c	21.24±0.18 a	**	**	**
SOC (5–10 cm soil layer)	Bulk soil	17.84±0.56 a	18.10±0.20 a	17.87±0.87 a	18.31±0.17 a	ns	ns	ns
(g kg^{-1})	>0.25 mm	/	/	/	/			
	<0.25 mm	/	/	/	/			
SOC (10–20 cm soil layer)	Bulk soil	15.67±0.47 a	15.97±0.41a	15.53±0.41 a	15.50±0.20 a	ns	ns	ns
(g kg^{-1})	>0.25 mm	/	/	/	/			
	<0.25 mm	/	/	/	/			
MBC (0–5 cm soil layer)	Bulk soil	1846±5.84 d	2366±38.58 b	2024±11.40 c	2657±28.71 a	**	**	*
(mg kg^{-1})	>0.25 mm	1962±3.68 d	2538±27.09 b	2173±57.73 c	2844±22.90 a	**	**	ns
	<0.25 mm	1517±10.56 c	1820±14.42 b	1758±11.33 b	2245±33.86 a	*	**	**
DOC (0–5 cm soil layer)	Bulk soil	1.09±0.04 d	1.33±0.03 b	1.22±0.03 c	1.56±0.04 a	**	**	ns
(g kg^{-1})	>0.25 mm	1.05±0.05 d	1.43±0.03 b	1.34±0.01 c	1.86±0.01 a	**	**	*
	<0.25 mm	0.89±0.03 d	1.10±0.02 b	1.01±0.02 c	1.25±0.02 a	**	**	ns

Different letters in a line denote significant differences among treatments.

**, $P<0.01$

*, $P<0.05$

ns, not significant. CTNS, conventional intensive tillage with straw removal; CTS, conventional intensive tillage with straw returning; NTNS, no-tillage with straw removal; tillage; NTS, no-tillage with straw returning. T, tillage; S, straw; SOC, soil organic C; MBC, microbial biomass C; DOC, dissolved organic C; values are mean ± standard errors.

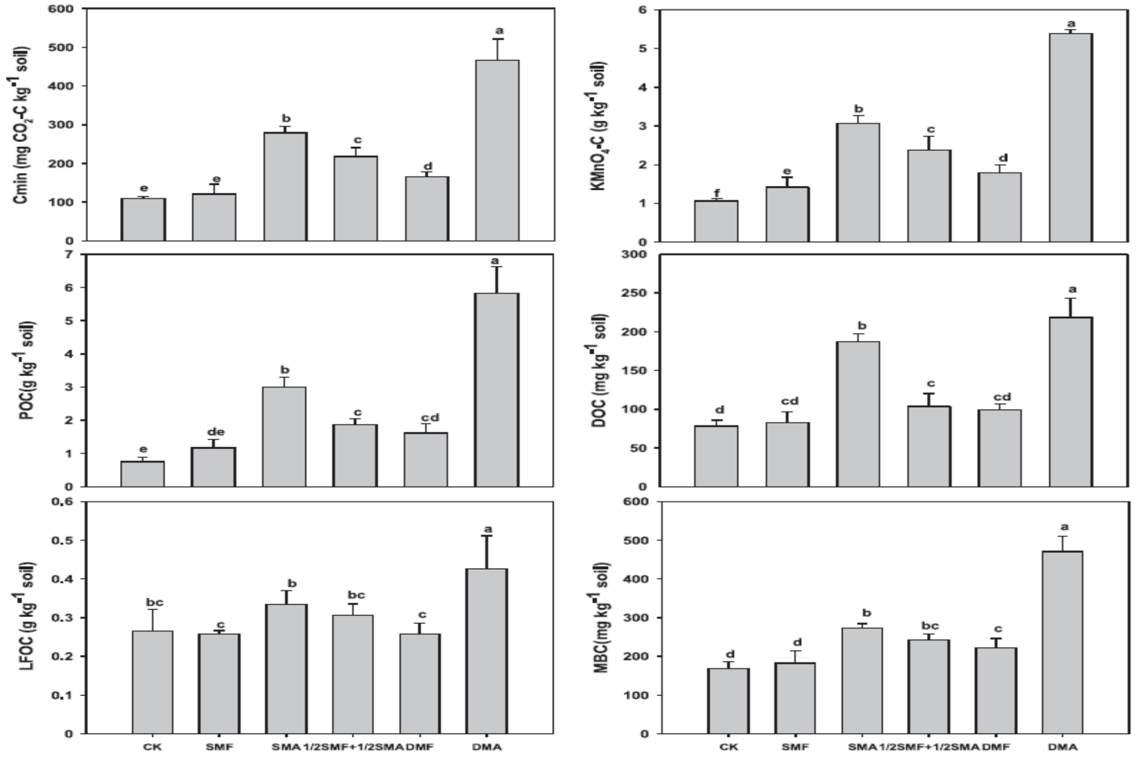


Fig 12(a): Effects of long term fertilization regimes on labile organic C fractions (C_{min}, cumulative carbon mineralization in a 21-day incubation experiment; $KMnO_4$-C, permanganate oxidizable carbon; POC, particulate organic carbon; DOC, dissolved organic carbon; LFOC, light fraction organic carbon; MBC, microbial biomass carbon) in soil at 0–20 cm depth in intensive Chinese maize/wheat rotations. (CK, control with no amendment addition; SMF, standard rate of mineral fertilizer treatment that reflect local farmer practice; SMA, standard rate of organic manure treatment with N input rate equal to SMF; 1/2SMF + 1/2SMA, half the standard rate of mineral fertilizer plus half the standard rate of organic manure treatment; DMF, double standard rate of mineral fertilizer treatment; DMA, double standard rate of organic manure treatment.

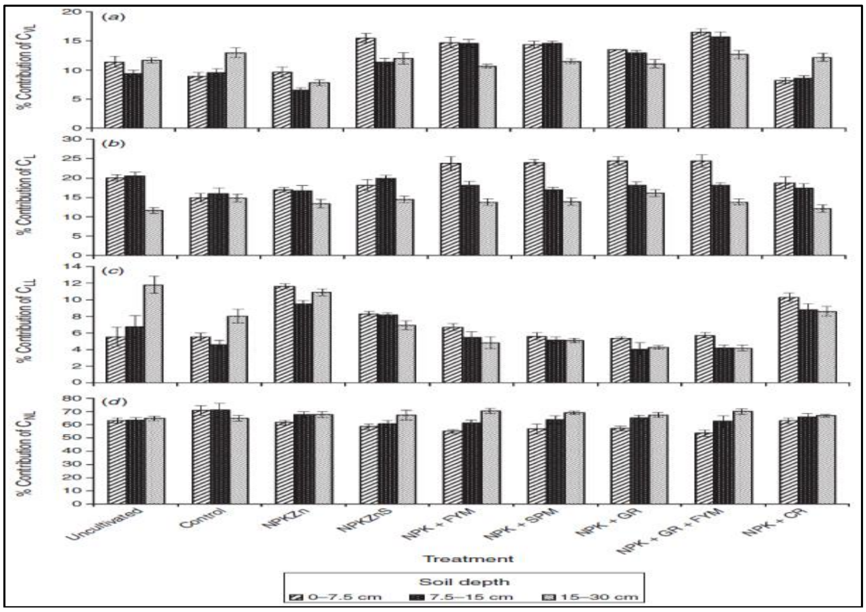
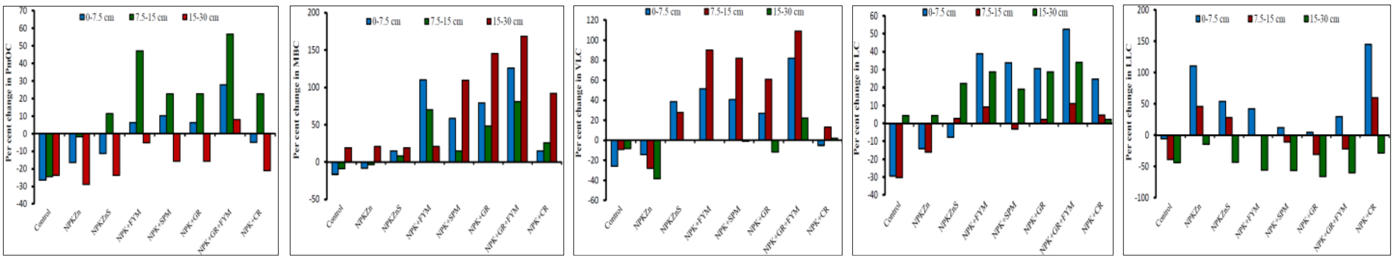


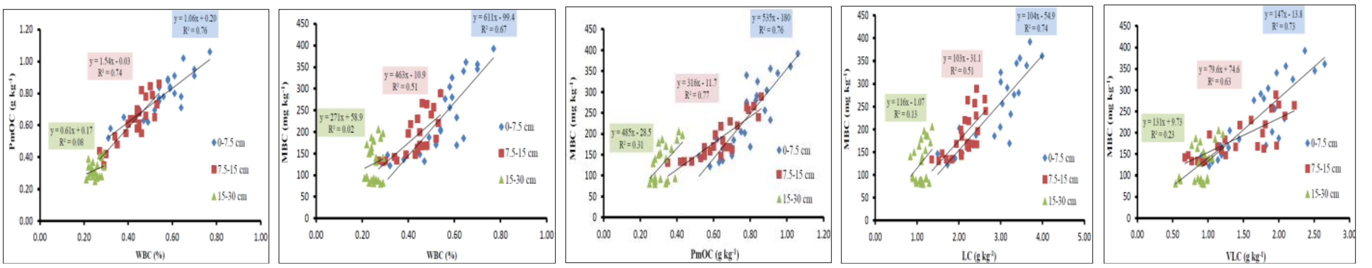
Fig 12(b): Contribution of (a) very labile C (C_{VL}), (b) labile C (C_L), (c) less-labile C (C_{LL}) and (d) non-labile C (C_{NL}) to total organic carbon under different nutrient supply options and soil depths. Control, unfertilized plots; FYM, farmyard manure; SPM, sulfitation press-mud; GR, green gram residue; CR, cereal residue.

Das, (2012) [16] reported that microbial biomass carbon (MBC) fraction in surface soil layer (0-7.5 cm) ranged between 135 mg kg^{-1} in control to 366 mg kg^{-1} in NPK+GR+FYM [Fig.13]. In general, treatment effects on MBC followed trends similar to PmOC and the lowest MBC was noticed in NPK+CR amongst the INM treatments. Averaged across the treatments, different OOC fractions in the 0-7.5 cm soil were in the order: LLC (1.00 g kg^{-1}) < VLC (1.71 g kg^{-1}) < LC (2.81 g kg^{-1}). Similar order of OOC fractions was recorded in other soil depths also. Moreover, positive and significant correlations were observed between WBC, VLC, LC and PmOC at 0-7.5 and 7.5-15 cm soil depths [Fig.14]. At these soil depths, TOC was also positively and significantly correlated with WBC, NLC, LC and PmOC. The relationships between different fractions at 15-30 cm depth were generally inconsistent. Highly significant relationship of WBC with MBC and PmOC, and between PmOC and MBC suggested the possibility of predicting PmOC from WBC, and MBC from WBC or PmOC at 0-7.5 cm and 7.5-15 cm soil depths. Similarly, LC and V_{LC} could also be helpful in predicting MBC. Among organics, FYM and GR were comparatively more effective in increasing the labile pools of SOC, whereas incorporation of CR i.e. rice or wheat straw mostly added non-labile fraction of SOC. Results further suggest that in the areas where regular green manuring is not possible for one or the other reason, incorporation of residues of short duration summer greengram after pod-picking could be an alternative option to improve soil health by increasing labile SOC. Majumder *et al*. (2007) [47] showed a large proportion of passive pools (63%) in different NPK and FYM treatments. Such variations in the results are explainable in view of large variability in the composition of organic materials, cropping systems, and climate and soil conditions.



(a). (b). (c). (d). (e).

Fig 13: Per cent change in **a)** PmOC, **b)** MBC, **c)** V_{LC}, **d)** LC, and **e)** L_{LC} over uncultivated soil after 18 rice-wheat crop cycles



(a) **(b)** **(c)** **(d)** **(e)**

Fig 14: Relationship between **a)** WBC and PmOC, **b)** WBC and MBC, **c)** PmOC and MBC, **d)** LC and MBC, and **e)** VLC and MBC at different soil depths

Dou *et al*. (2005) [19] reported that Soil microbial biomass C was more affected by tillage than by crop intensity or N fertilization in wheat, sorghum, and soybean systems [Fig. 15a]. In wheat systems, SMBC under NT was 18, 25, and 13% greater in CW, SWS, and WS, respectively, than with CT at 0- to 5-cm depth, but was 26, 5, and 10% lower in CW, SWS, and WS, respectively, than with CT at 5- to 15-cm depth. At the 15- to 30-cm depth, however, there was no consistent difference between CT and NT. Balota *et al*. (2004) [4] suggested that the accumulation of crop residues at the soil surface provides substrate for soil microorganisms, which accounts for the higher SMBC in surface soil under NT. The effect of tillage and cropping intensity on SMBC also varied with cropping systems. The most significant difference in SMBC between CT and NT was observed in surface soil in sorghum systems, where SMBC under NT was 73 and 40% greater than with CT for C Sorghum and SWS, respectively. Increased SMBC with increasing cropping intensity regardless of tillage was also only observed in sorghum systems. Franzluebbers *et al*. (1994) [22] reported increases in SMBC with increased crop intensity under both NT and CT in wheat systems. Soil microbial biomass C is generally considered an active pool which is more impacted by factors such as crop and tillage management practices, climate, season, and so on.

SMBN was significantly affected by tillage under the three crops. For example in the wheat systems, SMBN under NT was 50, 123, and 108% greater than CT in CW, SWS, and WS at the 0- to 5-cm depth, respectively [Fig. 15c]. Greater differences between NT and CT for SMBN than SOC may reflect that SMBN was more sensitive to management. Across wheat cropping sequences and tillage, N fertilization increased SMBN by 29% compared with the no N control. At the 5- to 15-cm depth, however, NT significantly decreased SMBN compared to CT [Fig. 15c]. One possible reason may be lower crop residue input with depth under NT compared with CT, where tillage partially added surface crop residue into this depth. No significant differences were observed for depth of 15 to 30 cm. similar trends were also observed in sorghum and soybean systems.

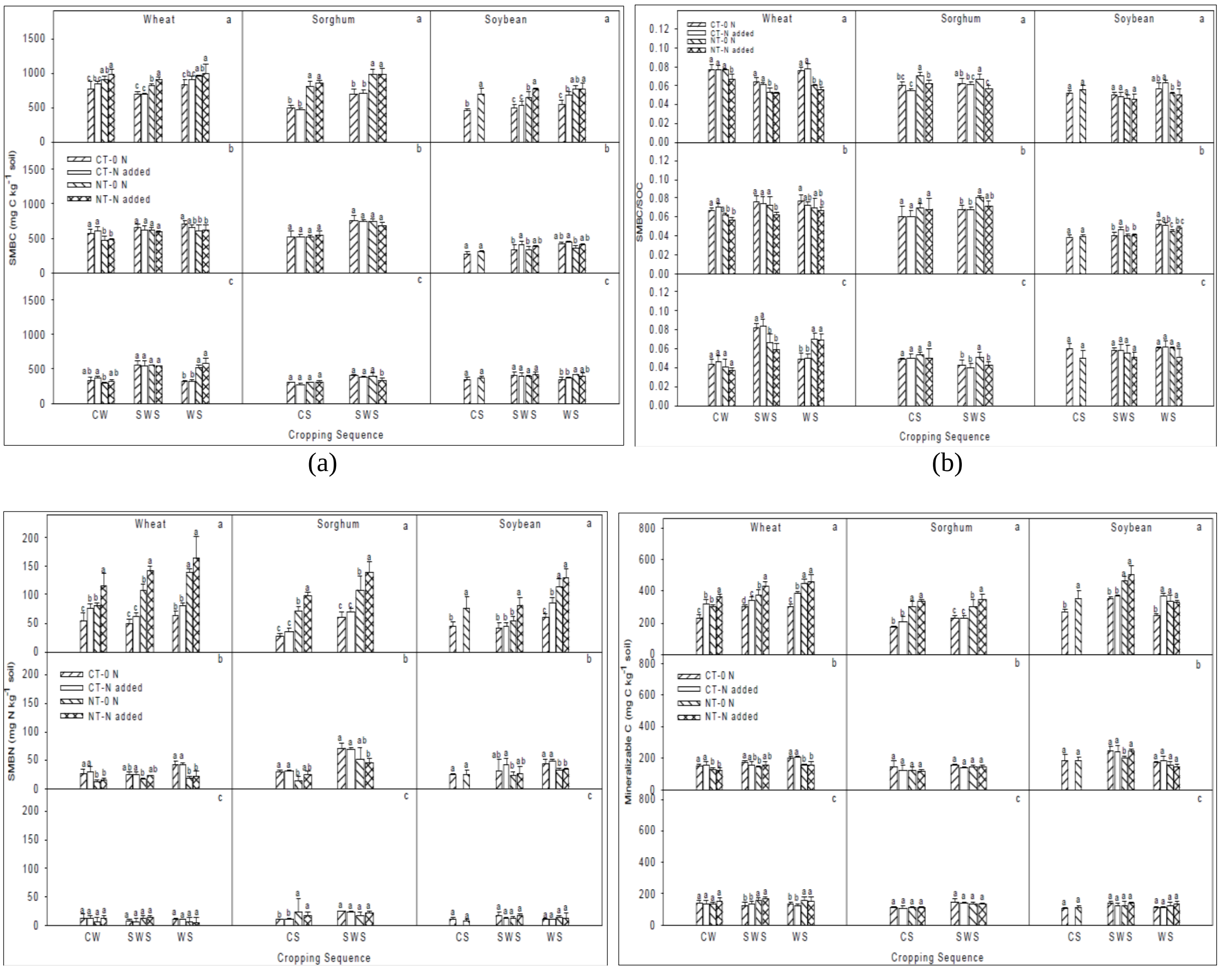
Unlike SOC or SMBC, soil microbial biomass N decreased faster with depth in all studied crop systems. For example in the wheat systems, SMBN at 5- to 15- and 15- to 30-cm was only 26 and 9% of that in surface soil, respectively. Similar tends were observed in sorghum and soybean systems. The faster decline in SMBN with increasing depth has also been observed in other studies (Spedding *et al*., 2004). NT significantly increased mineralizable C in surface soil. Mineralizable C in surface soil increased with increasing cropping intensity under both tillage and N fertilization regimes, except for soybean in WS [Fig. 15d]. Franzluebbers *et al*. (1994) [22] observed that mineralizable C was sensitive to changes in SOM quantity and quality due to increased crop residue input with increased cropping intensity. This indicated that mineralizable C was more sensitive than SOC or SMBC to management factors. At the 5- to 15-cm depth, mineralizable C was greater under CT than NT in all crop systems. Cropping intensity and N fertilization had little effect on mineralizable C of this depth. Mineralizable C was also affected by soil depth and crop species. Mineralizable C decreased faster with soil depth than SOC or SMBC. This result was in accordance with the observation that mineralizable C was more sensitive to crop management practices than SOC and SMBC.

At the 0- to 5-cm depth, no-till significantly increased POM C in wheat, sorghum, and soybean systems compared with CT [Fig. 16a]. For example, POM C under NT in wheat systems was 43, 58, and 92% greater for CW, SWS, and WS, respectively, compared to CT. Compared with CW, POM-C was greater for SWS or WS after wheat regardless of tillage, indicating that soil POM C increased with enhanced cropping intensity. Similar differences were also observed for sorghum and soybean systems. Differences in POM- C caused by N fertilization were minimal except in sorghum systems, where a significant interaction between tillage and N fertilization was observed. POM-C under NT was 39% and 44% greater in C sorghum and SWS, respectively, with than without N fertilization, while no differences due to N were observed with CT. The relationship between tillage and POM-C in the 5- to 15-cm depth was quite different from that in the surface soil (0 to 5 cm) for wheat. POM-C was 45, 86, and 106% lower for NT compared with CT. POM-C in the deeper layer 15 to 30 cm showed a similar pattern as in the surface soil, although differences were smaller [Fig. 16a]. Chan (1997) [13] also found that NT increased POM-C at the soil surface but decreased it in deeper layers. Increased POM-C with depth with CT partially results from burying plant resid ue with plowing. Based on the observation that C inputs from crop production were not different between tillage treatments, Cambardella and Elliott (1992) [11] suggested that lower POM under CT was due to more rapid decomposition than with NT. The proportion of SOC as POM-C followed similar patterns as for POM-C, except that the differences tended to be less distinct [Fig. 16b]. The proportion of SOC as POM-C with wheat averaged 30, 15, and 25% for 0- to 5-, 5- to 15-, and 15- to 30-cm depths, respectively. Compared to CT with wheat, the proportion under NT was 15%greater in surface soil, but was 80% lower at 5 to 15 cm. No significant tillage difference was observed for this characteristic at 15 to 30 cm. Particulate organic matter N (POM-N) was highly related to POM-C, and decreased significantly with depth in all crop systems . Trends for POM-N in wheat systems were very similar to these of POM-C, especially in the first two depths. No tillage and N fertilization increased POM-N at 0 to 5 cm, but NT decreased this characteristic at 5 to 15 cm compared with CT.

Labile pools in surface soil such as SMBC, mineralizable C, POM-C, and hydrolyzable C were significantly and positively correlated with SOC [Fig.16c]. Mclauchlan and Hobbie (2004) [42] observed that SMBC, acid hydrolyzable C, light fraction C, mineralizable C in a 12-day incubation, and SOC were all positively correlated with each other. On average, SMBC was 5% of SOC, mineralizable C in 24-day incubation was 3% of SOC, POM-C was 35% of SOC, and hydrolyzable C was 45% of SOC.

Sensitivity of different labile pools to changes in SOC varied with CT or NT [Fig. 16c]. Compared with NT, the slopes for regressions between SOC and SMBC and hydrolyzable C were significantly greater with CT. Under NT, the slope between SOC and POMC was significantly greater than that with CT, increasing almost three times more per unit of SOC.

Si *et al*. (2018) [65] reported that similar to the SOC, the NTSM treatment increased POM-C in the 0–5 cm layer by 33.2% compared with the CT treatment [Fig. 17a]. The NTSM treatment also resulted in significantly higher POM-C in the 5–10 cm layer (23.7% higher). However, no significant difference has been observed in POM-C content between NTSM and CT treatments at the deeper layers (10 cm sections between 10 and 60 cm). Moreover, DOC was significantly greater following the NTSM treatment compared to the CT treatment at 0 to 10 cm [Fig. 17a]. In the 0–5 cm layer, DOC following the NTSM treatment (112 mg kg^{-1}) increased by 37.3% compared to that following the CT treatment (82 mg kg^{-1}), while in the 5–10 cm layer, DOC increased by only 14.9% compared that following the CT treatment. MBC varied from 16 to 250 mg kg^{-1} following the NTSM treatment and from 15 to 150 mg kg^{-1} was following the CT treatment [Fig. 17a]. At the 0–5 and 5–10 cm soil layers, MBC was significantly higher for the NTSM treatment compared to the CT treatment. In the 0–5 cm layer, MBC was 66.3% higher following the NTSM treatment (250 mg kg^{-1}) compared to the CT treatment (150 mg kg^{-1}). Chen *et al*. (2009) [15] 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) [36]. Meenakshi, (2016) [43] showed that under conventional tillage, the heavy fraction carbon in the surface 0-15 cm soil layer was 3.8, 4.2and 4.9 gkg^{-1} which decreased to 2.0, 2.2and2.6g/kg in 15-30 cm soil layer in sandy loam, loam and clay loam, respectively. The heavy fraction carbon was highest in the surface layer in all the three soils and decreased with depth under both tillage treatments. The zero tillage resulted in an increase in heavy fraction carbon at both the depth. In the surface 0-15 cm, it increased the heavy fraction carbon significantly from 3.8 to 4.9, 4.2 to 4.9 and 4.9 to 5.1 g/kg and in 15-30 cm soil depth from 2.0 to 2.9, 2.2 to 3.4 and 2.6 to 3.9 g kg^{-1} in sandy loam, loam and clay loam, respectively [Fig. 17b]. Relatively higher amount of heavy fraction carbon was observed in heavier textured soil at both the depths. Liang *et al*. (1998) [35] reported that ratios of LF of C and SOC were greater in light-textured soils than in fine-textured soils. LF of C is directly proportional to sand content. The lower disturbance in ZT systems can promote the interaction between clays and slower decomposing C inputs to form soil aggregates.



(a) (b)

(c) (d)

Fig 15: Soil microbial biomass C (SMBC**) a);** proportion of SOC as soil microbial biomass C (SMBC) **b);** Soil microbial biomass N (SMBN) **c);** and mineralizable C in 24-day incubation **d)** with depth as affected by cropping sequence, tillage, and N fertilization at **i)** 0- to 5-, **ii)** 5- to 15-, and **ii)** 15- to 30-cm depths. CW, SWS, and WS indicate continuous wheat, sorghum-wheat-soybean, and wheat-soybean, respectively. CS in sorghum and soybean refers to continuous sorghum and soybean, respectively. CT and NT refer to conventional and no tillage. SMB, mineralizable C and N, POM, and hydrolyzable C were highly correlated with each other and SOC, but their slopes were significantly different, being lowest for mineralizable C and highest for hydrolyzable C, suggesting that different methods included different fractions of total SOC. The labile C pools exhibited varying sensitivity to soil tillage regime. Compared with NT, SMBC, mineralizable C, and hydrolyzable C exhibited greater slopes with increasing SOC under CT.

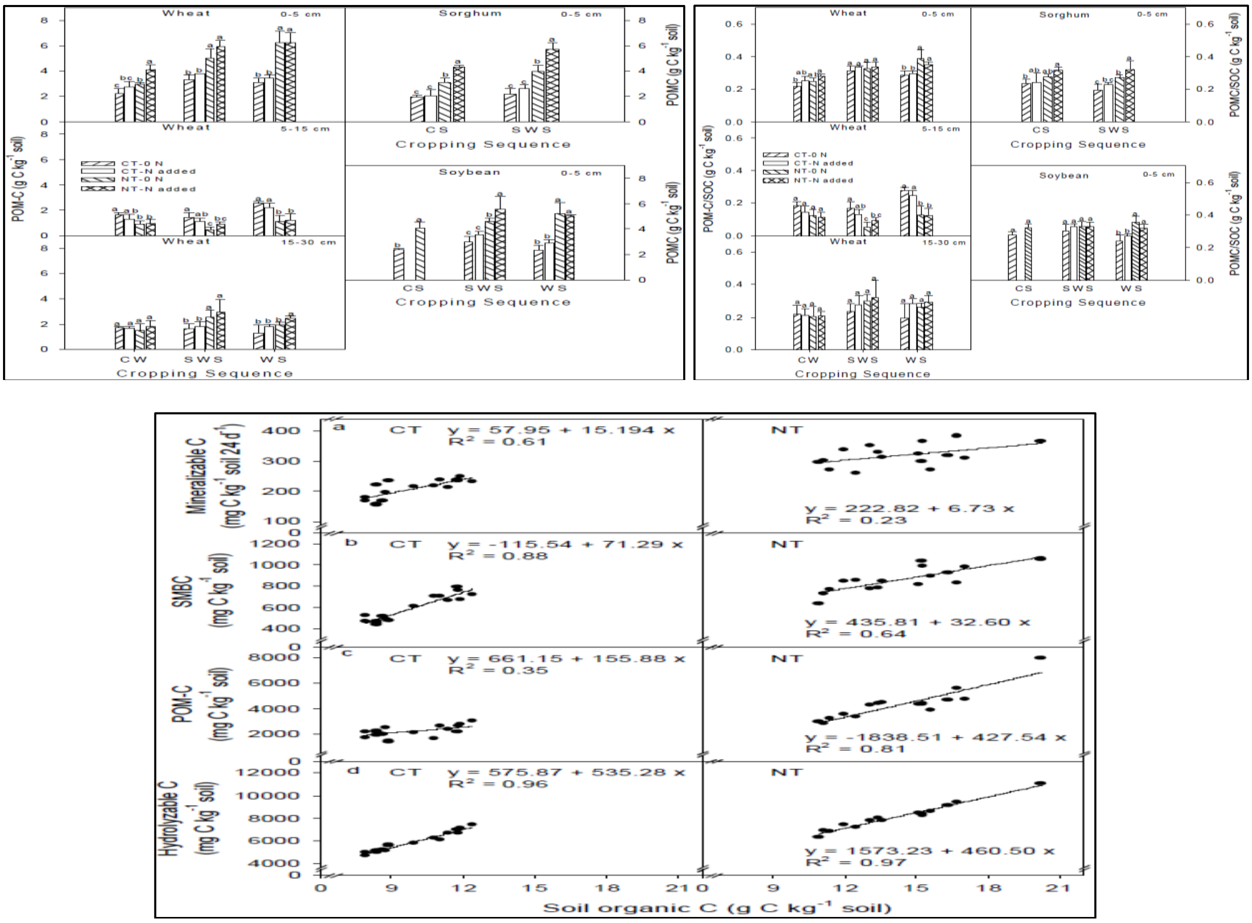


Fig 16: Particulate organic matter C (POM-C) **a);** proportion of soil organic C (SOC) as particulate organic matter (POM) C **b);** with depth and linear regression of soil organic C (SOC) and labile SOC in surface soil (0 to 5 cm) **c)** as affected by cropping sequence, tillage, and N fertilization. CW, SWS, and WS indicate continuous wheat, sorghum-wheat-soybean, and wheat-soybean, respectively

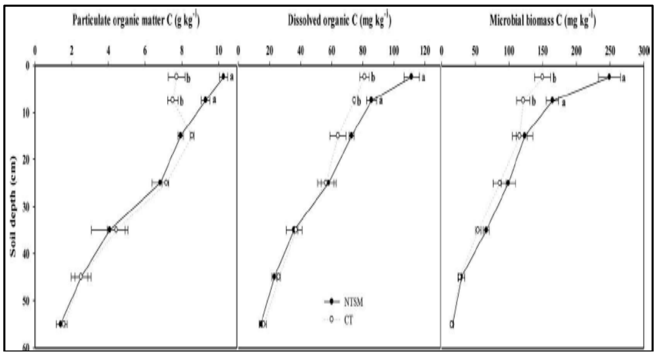


Fig 17(a): Soil particulate organic matter C (POM-C), dissolved organic C (DOC) and microbial biomass C (MBC) under no-tillage with straw mulch and conventional tillage

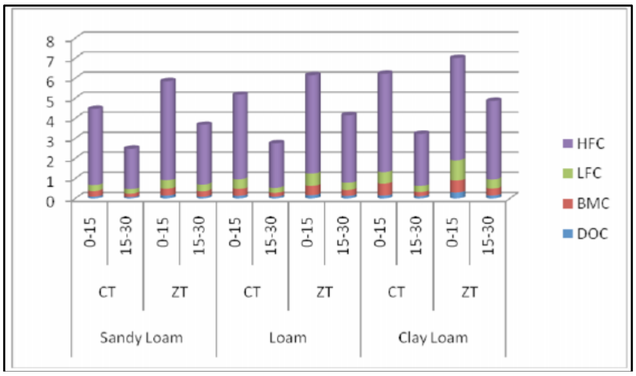


Fig 17(b): Different fractions of organic carbon (gkg^{-1}) at 0-15 and 15-30 cm soil depths under conventional (CT) and zero (ZT) tillage practice in different textured soils

Water-stable macro-aggregates over soil depth

Andruschke witsch, (2013) [2] reported that the macro-aggregate (>250 µm) contents in the top 5 cm were significantly higher for soils of the NT and MT treatments than for soils of the CT treatment and decreased in the order NT (711 g (kg soil)$^{-1}$) > MT (666 g (kg soil)$^{-1}$) > CT (518 g (kg soil)$^{-1}$) [Table 6]. Differences between the treatments were less pronounced in deeper soil layers. However, for the CT treatment it was higher in the 5-25 cm soil layer than in the top 5 cm, which is in line with the oLF contents.

The C_{org} contents in the macro-aggregates in 0-5 cm depth were significantly higher in soils of the MT and NT treatment with 19 and 20 g (kg aggregates)$^{-1}$, respectively, than the contents in the soils of the CT treatment with 13 g (kg aggregates)$^{-1}$ [Table 6]. With increasing depth the C_{org} contents in the macro-aggregates of the MT and NT treatments decreased to the level of the CT treatment. In 25-40 cm soil depth the CT treatment showed even a significantly higher C_{org} content in the macro-aggregates (10 g (kg aggregates) $^{-1}$) than the NT treatment (7 g (kg aggregates) $^{-1}$). The C_{org}/N_{tot} ratio of the macro-aggregates in 5-25 cm soil depth was significantly increased for the CT treatment in comparison to the NT treatment with 9.9 and 9.5, respectively [Table 6]. The C_{org}/N_{tot} ratio of the micro-aggregates in 0-5 cm soil depth was significantly higher for the MT treatment than for the CT treatment, with 9.7 and 9.4, respectively.

In 0-5 cm soil depth the CT treatment was separated from the MT and NT treatments due to lower C_{org} and macro-aggregate contents. This was also valid for the correlation of the macro-aggregate content against the oLF content and against the fLF content, respectively. However, in 5-25 cm soil depth the tillage treatments had no further effect on these relationships. Macro-aggregate content was distributed equally among the tillage treatments, but the higher oLF and fLF contents under CT and MT led to a separation on the y-axis in 5-25 cm soil depth, reflecting the different amounts of incorporated crop residues [Fig.18a]. Wagner *et al*. (2007) [73] 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.18b]. 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 [Fig. 18b].

Table 6: Average macro-aggregate (>250 µm) contents, organic carbon (C_{org}) contents in macro-aggregates, relative C_{org} contribution in macro-aggregates to whole C_{org} content and C_{org}/total N (N_{tot}) ratios for macro- and micro-aggregates [Andruschkewitsch, 2013] [2]

Depth (cm)	Treatment[a]	Aggregate content >250 µm (g kg^{-1} soil)	C_{org} content in aggregates >250 µm (g kg^{-1} aggregates)	C_{org} content in aggregates >250 µm (% of C_{org} bulk soil)	C_{org}/N_{tot} ratio in aggregates >250 µm	C_{org}/N_{tot} ratio in aggregates <250 µm
0-5	CT	518 (76.5) b	13 (2) b	60 (6) b	10.0 (0.7)	9.4 (0.4) b
	MT	666 (79.2) a	19 (3) a	75 (13) a	10.4 (0.7)	9.7 (0.3) a
	NT	711 (59.1) a	20 (3) a	81 (4) a	10.5 (0.3)	9.5 (0.5) ab
5-25	CT	606 (86.1)	12 (3)	69 (10)	9.9 (0.8) a	9.6 (0.4)
	MT	636 (94.7)	14 (2)	71 (10)	9.7 (0.7) ab	9.3 (0.7)
	NT	639 (88.8)	12 (2)	72 (8)	9.5 (0.6) b	9.1 (0.8)
25-40	CT	533 (105.4)	10 (3) a	64 (7)	9.5 (1.2)	9.4 (0.6)
	MT	530 (108.3)	9 (3) ab	60 (14)	9.3 (1.0)	9.7 (1.3)
	NT	563 (101.8)	7 (2) b	66 (7)	9.2 (0.9)	8.7 (1.0)

[a]CT: conventional tillage, MT: mulch tillage, NT: no-tillage

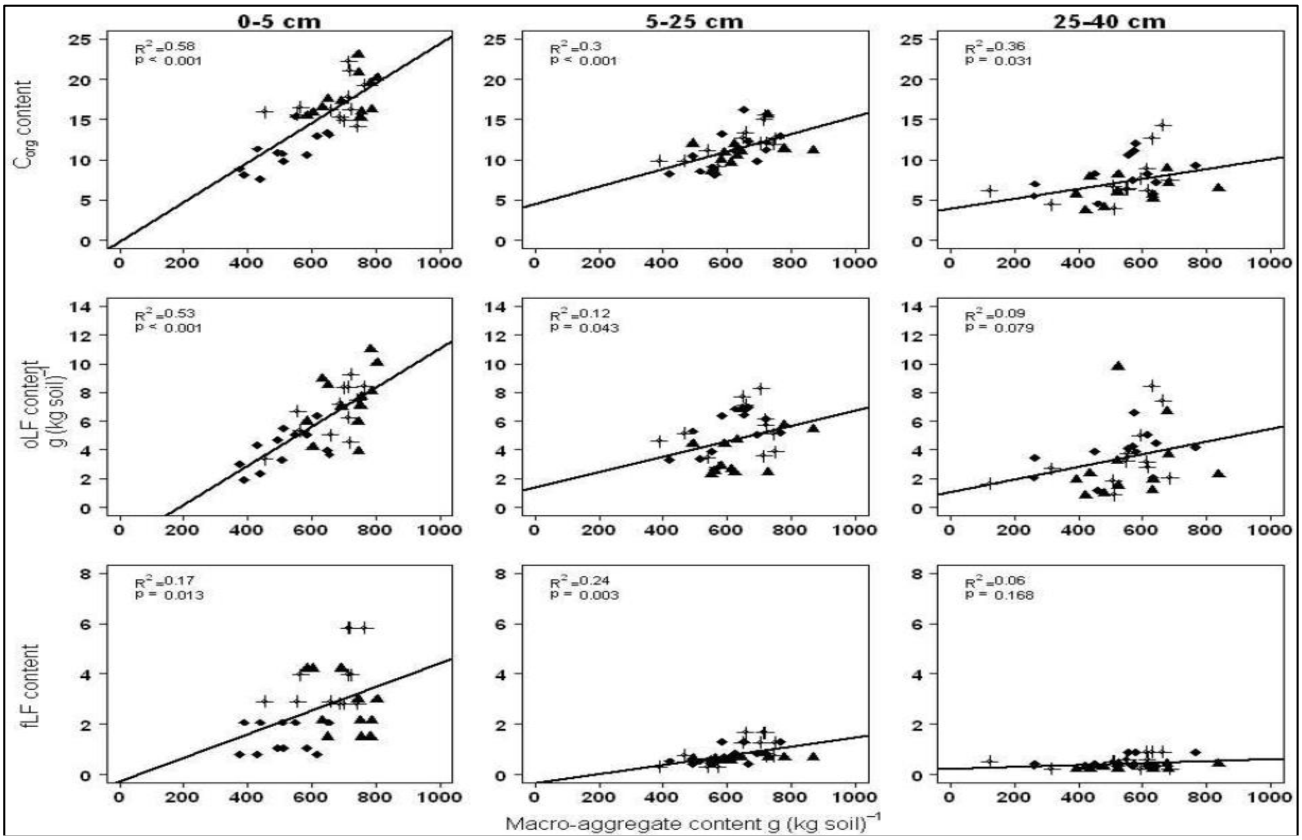


Fig 18 (a): Correlation of the macro-aggregate (>250µm) content with the contents of organic carbon (C_{org}), free light fraction (fLF), and occluded light fraction (oLF) for different soil depths. Tillage treatments are marked as follows (♦ = conventional tillage, + = mulch tillage, ▲ = no-tillage)

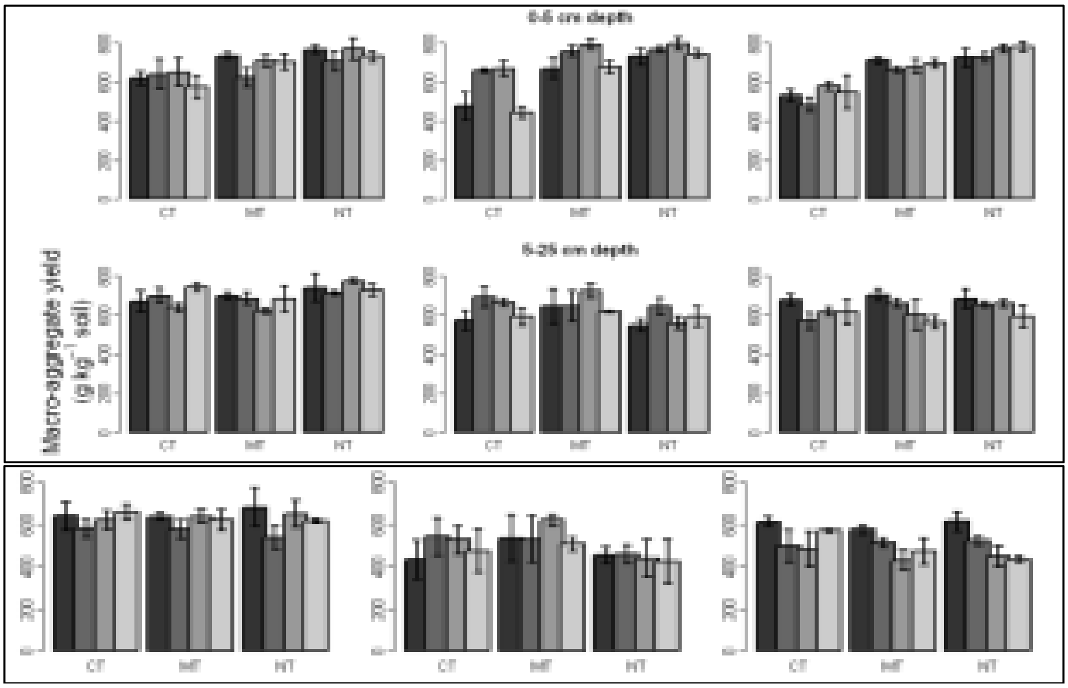


Fig. 18(b): Average dry matter yields of the macro-aggregate (>250 µm) fractions of the different tillage treatments. CT with annual mould-board plowing to 25-30 cm; MT with a cultivator or disc harrow 10-15 cm deep, and NT with direct drilling.

Aulakh *et al*. (2013) [3] showed total WSA after 2 years of the experiment in 0 - 5 cm soil layer of CT system, T_2 and T_4 treatments increased total WSA from 71% in control (T_1) to79 and 81% without CR, and to 82 (T_6) and 83% (T_8) with CR. The corresponding increase of total WSA under CA system was 75% in control (T_9) to 81 (T_{10}) and 82% (T_{12}) without CR and 83 (T_{14}) and 85% (T_{16}) in with CR. Naresh *et al*. (2012) [52] showed significant effects of NT and residue retention on soil aggregate stability in western Uttar Pradesh under an alternative wheat production system. Mazumdar *et al*. (2015) [41, 48] found that he MWD was significantly higher in plots receiving 50%NPK+ 50% N through FYM in rice (1.36 mm), 100% NPK in wheat or 50%NPK+ 50% N through CR in rice (1.28 mm), 100% NPK in wheat or 50%NPK+ 50% N through GM in rice (1.29), 100% NPK in wheat (1.18mm) as compared to control (0.89 mm). Naresh *et al*. (2016) [53] revealed that the small macro-aggregates accounted for >30% of the total aggregates (mean of both main plots) in the surface soil layer. Silt- plus clay-sized aggregates comprised the greatest proportion of the whole soil, followed by the small macro-aggregates. The amount of water stable large and small macro-aggregates in the FIRB and ZT plots were significantly higher than in the CT plots in the 0- to 5-cm soil layer. These differences may be attributed to the different planting systems. A reduced presence of macro aggregates (>0.25 mm) under TT was partly due to excessive tillage and heavy traffic, which hindered the soil biological activity (Tisdall and Oades, 1982) [70].

Chaudhary *et al*. (2014) [14] reported that compared to conventional tillage, water stable macro-aggregates in conservation tillage (reduced and zero-tillage) in wheat coupled with direct seeded rice (DSR) was increased by 50.13% and water stable micro-aggregates of the later decreased by 10.1% in surface soil. Residue incorporation caused a significant increment of 15.65% in total water stable aggregates in surface soil (0–15 cm) and 7.53% in sub-surface soil (15–30 cm). Song *et al*., (2016) [68] reported that compared to conventional tillage, the percentages of >2mm macro aggregates and water-stable macro-aggregates in rice-wheat double- conservation tillage (zero-tillage and straw incorporation) were increased 17.22% and 36.38% in the 0–15 cm soil layer and 28.93% and 66.34% in the 15–30 cm soil layer, respectively. In surface soil (0–15cm), the maximum proportion of total aggregated carbon was retained with 0.25–0.106mm aggregates, and rice-wheat double-conservation tillage had the greatest ability to hold the organic carbon (33.64g kg^{-1}).

Soil organic carbon storage

Liu *et al*. (2013) [37] reported that he effects of fertilization on SOC storage showed a similar trend to SOC concentration [Fig. 19a]. The topsoil (0–20 cm) had the maximum levels of cumulative SOC storage in the 1 m soil depth for the CK, N, NP, FYM, NP+S and NP+FYM treatments, accounting for 24%, 23%, 27%, 30%, 31% and 31%, respectively. At the 20–40 cm and 40–60 cm soil layers, the SOC stocks of the NP, FYM, NP+S and NP+FYM treatments were significantly higher by 17%, 21%, 25% and 37% and 5.3%, 8.1%, 7.3% and 11%, respectively, than that of the CK. The differences of SOC storage between different treatments were not significant in the 60–80 cm and 80–100 cm soil layers. SOC storages were significantly different between fertilization treatments in the 0–100 cm profile. Compared with the CK treatment, SOC storages of the NP+FYM, NP+S, FYM and NP treatments within the 0–100 cm soil depth were increased by nearly 30, 24, 20 and 12%, respectively [Fig.19a].

Compared to surface soil (0 to 5 cm), concentrations of SOC in wheat systems decreased with depth [Fig. 19b]. Few differences in SOC concentration between treatments were noted at a depth of 5 to 15 cm (Fig. 2.2b). However, at 15 to 30 cm, NT significantly increased SOC for SWS and WS compared to CT. Different crop species also differentially affected SOC storage. SOC with CW was greater than with continuous sorghum or soybean, regardless of tillage treatment [Fig. 19c]. In surface soil, SOC under CT was 25 and 21% greater with CW than with continuous sorghum and soybean, respectively. Under NT, however, the difference in SOC was significantly smaller [Fig. 19c]. Differences decreased with depth and were smallest at 5- to 15-cm soil depth. The return of aboveground crop Stover was greater with continuous sorghum than CW. Si *et al*. (2018) [65] revealed that SOC was higher under the NTSM treatment compared to the CT treatment at a depth over 10 cm [Table 7]. The SOC in the NTSM treatment (23.2 g kg^{-1} in 0–5 cm and 21.4 g kg^{-1} in 5–10 cm) were significantly 23.9 and 11.7% higher than that in the CT treatment (18.7 g kg^{-1} in 0–5 cm and 21.4 g kg^{-1} in 5–10 cm) at the 0–5 cm depths and 5–10 cm depth, respectively. No significant differences were found in SOC between the NTSM and CT treatments at the 10–60 cm depths. After 8 years, the NTSM treatment (103.1 Mg C ha^{-1}) showed approximately 7.1% higher cumulative carbon stocks at 0–60 cm than the CT treatment (96.3 Mg C ha^{-1}). Plaza *et al*. (2012) [55] reported that the SOC level was obviously higher in the soil amended with crop residues than un-amended soil after 34 years. This was mainly attributed to surface residue returned to the soil. Balota (2004) [4] demonstrated that soil disturbances under CT treatment usually increased organic matter oxidation and reduce soil structure by degrading aggregates, which was important protector of SOC. The decreases of SOC with increasing soil depth were probably due to the accumulation of organic material on the soil surface during the NTSM treatment.

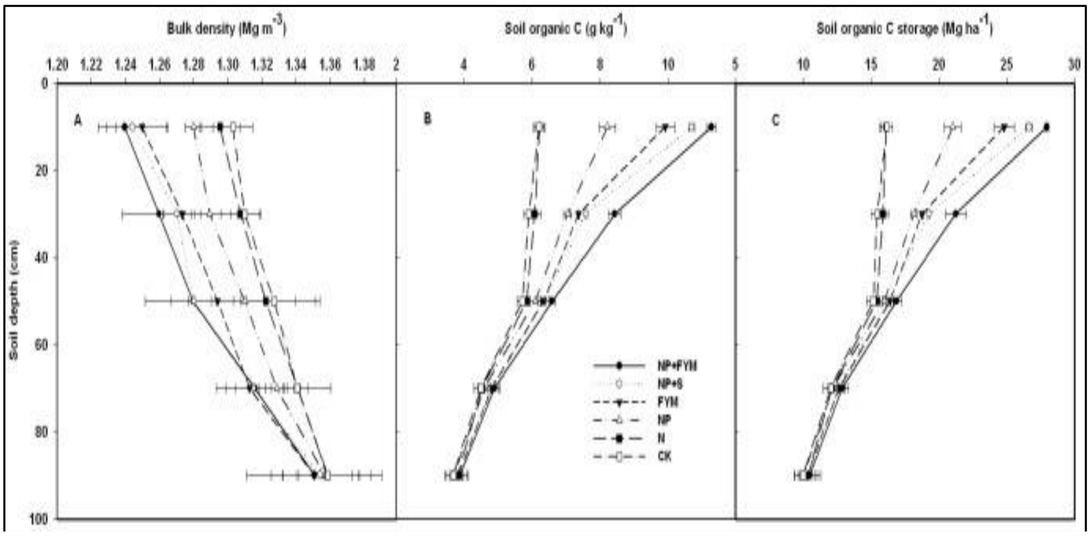


Fig 19(a): Effect of long-term fertilizer applications on depth distribution of bulk density (A), soil organic C (B) and soil organic C storage (C)

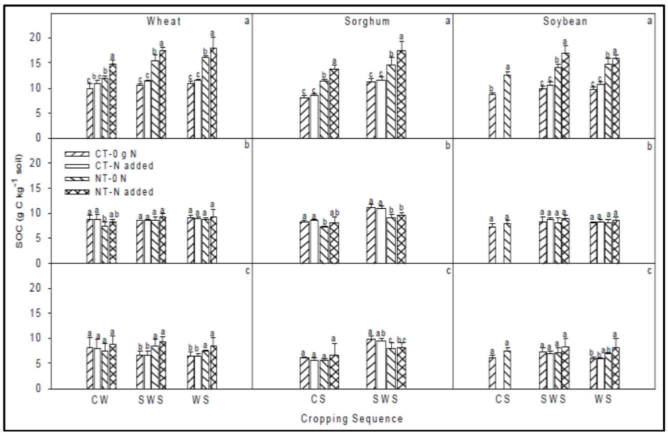


Fig 19(b): Soil organic C (SOC) with depth as affected by cropping sequence, tillage, and N fertilization at a) 0- to 5-, b) 5- to 15-, and c) 15- to 30-cm depths. CW, SWS, and WS indicate continuous wheat, sorghum-wheat-soybean, and wheat-soybean, respectively. CS in sorghum and soybean refers to continuous sorghum and soybean, respectively

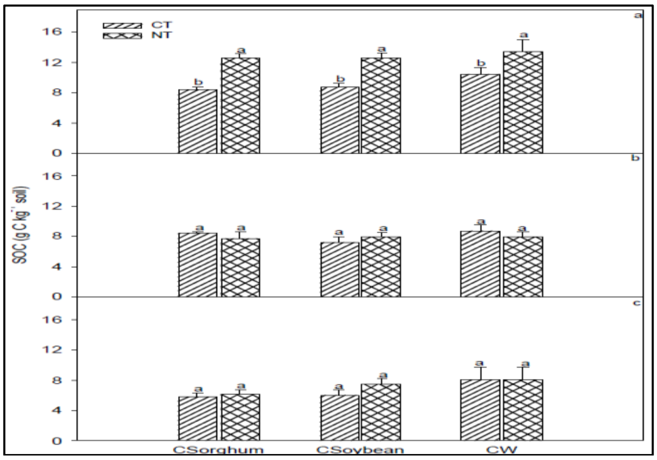


Fig 19: (c): Soil organic C (SOC) with depth as affected by cropping sequence, and tillage at a) 0- to 5-, b) 5- to 15-, and c) 15- to 30-cm depths. C Sorghum, C Soybean, and CW indicate continuous sorghum, soybean, and wheat, respectively. CT and NT refer to conventional and no tillage.

Table 7: Soil organic carbon concentrations and stocks under no-tillage with straw much (NTSM) and conventional tillage (CT) soil in 2011 [Si *et al*., 2018] [65]

	NTSM		CT	
Depths (cm)	SOC (g kg^{-1})	SOC stock (Mg C ha^{-1})	SOC (g kg^{-1})	SOC stock (Mg C ha^{-1})
0–5	23.2 (1.01)a	12.2 (0.68)	18.7 (0.26)b	9.8 (0.19)
5–10	21.4 (0.38)a	12.3 (0.24)	19.2 (0.17)b	10.9 (0.14)
10–20	18.9 (0.23)	22.8 (0.32)	19.6 (0.31)	23.2 (0.32)
20–30	16.5 (0.87)	22.6 (0.58)	16.9 (0.75)	22.4 (0.21)
30–40	10.0 (0.38)	15.9 (0.37)	10.7 (0.64)	14.6 (0.44)
40–50	7.2 (0.54)	11.0 (0.26)	6.9 (0.38)	9.7 (0.33)
50–60	3.7 (0.28)	6.3 (0.14)	4.3 (0.08)	5.9 (0.12)

Conclusion

Soil conservation management improved the quality of the soil by enhancing the labile and total organic carbon fractions and biological status, especially in 0-5cm upper layer. Results of several studies indicate that the content of TOC, SOC, LFON, DOC and POC decreased with soil depth, and thin surface layer (0 – 5 cm) contained much higher concentration of these labile pools than 5 - 15 cm subsurface layer. The surface soil layer had substantially higher levels of all soil health parameters than subsurface layer, presumably due to higher retention of crop stubbles, fallen leaves and root biomass. The enhanced proportions of WSC, POC, LFOC, MBC in TOC with the supply of optimum and balanced N and organic manures and retention of crop residues indicate that the improvement in labile forms of both C and N was relatively rapid than control suggesting that active C and N pools reflect changes due to integrated nutrient management (INM).The macro-aggregates increased by 39% and micro-aggregates decreased by 9% in PRB plots compared with CT plots. Decrease in micro-aggregates and increase in macro-aggregates with application of conservation tillage might have enhanced soil aggregation processes and compared to conventional tillage (CT), zero-tillage and permanent raised beds (PRB) could significantly improve the SOC content in cropland and the POC, LFOC, LFON, and MBC concentrations were greatly influenced by ZT in the surface (0 - 5 cm) and subsurface (5 - 15 cm) soil layer.

Any type of soil and crop management practices that could enhance carbon contents in soils should be considered and recommended for farmers' practice. Use of crop residues, animal manures, biochar, minimum or zero tillage, crop rotation, balanced fertilization and many other available organic sources may replenish and increase carbon stock in soils and bring multitude of benefits for agricultural sustainability. Long-term fertilization significantly influenced SOC concentrations and storage to 60 cm depth. Below 60 cm, SOC concentrations and storages were statistically not significant between all treatments. The concentration of SOC at different depths in 0–60 cm soil profile was higher under NP+FYM follow by under NP+S, compared to under CK. The SOC storage in 0–60 cm in NP+FYM, NP+S, FYM and NP treatments were increased by 41.3%, 32.9%, 28.1% and 17.9%, respectively, as compared to the CK treatment. Organic manure plus inorganic fertilizer application also increased labile soil organic carbon pools in 0–60 cm depth. Treatment involving 50 per cent recommended dose of N supplied through chemical fertilizers and another 50 per cent through FYM reduced the depletion of SOC stocks. The SOC concentration was highest in small macro-aggregates, intermediate in macro-aggregates, and lowest in micro-aggregates (0.25–0.05 mm). Approximately >50% of total SOC was stored in micro-aggregates (0.25–0.05 mm) and sand +silt fractions (< 0.05 mm) after treatment without FYM but >60% of total SOC was stored in macro-aggregates (>0.25 mm) after treatment with FYM. Management and improvement of soil quality are imperative for the vastly growing population who conservatively depends on the soil resources for a constant supply of food. There is a need for farmers to be made aware them about the facts of soil carbon in agriculture so they can make a proper decision for adopting a suitable management practices for enhancement of productivity and fertility of soil simultaneously.

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