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Influence of organic and synthetic fertilizers on soil carbon pool, soil aggregation and associated carbon fractions in conservation agriculture ecosystem: A review

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Abstract

The application of graded doses of NPK from 50% to 150% in the cropping system significantly enhanced SOC, and particulate organic C (POC) fractions in soil. The increase in these C fractions was greater when farmyard manure (FYM) was applied conjointly with 100% NPK. This treatment showed highest amount of SOC and POC in 0–45 cm soil depth. Manure application significantly increased the proportion of large macro-aggregates (> 2000 µm) compared with the control, while leading to a corresponding decline in the percentage of micro-aggregates (53–250 µm). Plots with NPK and NPK + FYM had more labile: recalcitrant C ratios in bulk soils than control, NP and N plots. The NPK+FYM plots also had highest recalcitrant C pools within macro-and micro-aggregates. Moreover, carbon fractions of soil organic carbon (SOC), particulate organic carbon (POC), microbial biomass carbon (MBC), and potential carbon mineralization (PCM). Aggregate proportion was greater in NTCW than in FSTCW in the 4.75- to 2.00-mm aggregate-size class at 0 to 5 cm but was greater in STW-F than in STCW in the 2.00- to 0.25-mm size class at 5 to 20 cm.

No direct or universal relationship was found between the aggregative factors induced by organic/synthetic input decomposition (binding molecules or decomposers of biomass) and temporal a ggregate stability dynamics. This suggests the and can be improved by considering (i) the direct abiotic effect of some organic/synthetic products after the inputs, (ii) the initial biochemical characteristics of the organic/synthetic products and (iii) the effects of organic/synthetic products on the various mechanisms of aggregate breakdown. The application of synthetic fertilizers had no clear effect on SOC and N accumulation or their distribution in particle-size fractions. However, the combined application of pig manure and synthetic fertilizers enhanced the accumulation of SOC and N in all particle-size fractions, and led to a shift of SOC and N from fine to coarse particles. The application of synthetic fertilizers had no clear effect on SOC and N accumulation or their distribution in particle-size fractions. However, the combined application of manure and synthetic fertilizers enhanced the accumulation of SOC and N in all particle-size fractions, and led to a shift of SOC and N from fine to coarse particles. The paper reveals that the micro-aggregate protected C is promising for assessing the impact between manure and synthetic fertilizers long-term fertilization on SOC storage in conservation agriculture ecosystem of *Typic Ustochrept* soil.

Keywords: Soil organic carbon, particle-size fractions, soil aggregates

Introduction

Globally, agricultural soil covers a total area of ~1370 million hectares (Mha) distributed across diverse climatic and edaphic conditions, as well as complex cropping systems and management practices (Potter *et al.*, 2010) [35]. Thus, the C input and SOC turnover are highly variable across spatial-temporal distributions; making the assessment of cropland SOC change more complicated (Tao *et al.*, 2013) [42]. Observed and projected increases in greenhouse gas emissions and their associated effects on global warming and rising of sea levels have heightened interest in identifying mitigation options (Lal, 2006) [24]. The soil organic carbon (SOC) pool is considered a potential major factor driving global climate change because it contains twice the amount of carbon as does the atmospheric pool (Alewel *et al.*, 2009) [3].

Even a relatively slight variation in soil carbon content because of changes in land use, management practices, or natural disturbances may result in a significant net exchange of carbon between the soil carbon reservoir and the atmosphere (Van Hemelryck *et al.*, 2011) [46]. As the most widespread form of soil degradation and the major inducer of SOC dynamics across terrestrial landscapes (Alewel *et al.*, 2009) [3].

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Soil carbon (C) sequestration, the fixing of long-lived C pools in soils for long-term, is a win-win strategy that augments food production and improves soil quality (Lal, 2004) [23]. The options for enhancing soil organic C (SOC) storage are: (1) enhancing the application rates of organic matter in soils, (2) reducing the decomposition rate of organic matter (OM) that enhances long-term SOC storage, and (3) mechanically protecting SOC by improving intra-aggregate and organo-mineral complex stability (Post and Kwon, 2000) [34].

Carbon sequestration is governed by soil structure formation. Soil aggregates are the core of soil structures and their internal pore characteristics create the physical environment enabling or disabling connections and thus C stabilization or loss (Kravchenko *et al*., 2015) [21]. A well-aggregated soil provides optimum condition for plant growth by maintaining good aeration through well balanced pore distribution containing air and water. Regular fertilization, especially integrated nutrient management (INM) increases SOC, hence, increases the stability of soil aggregates. Thus, C inputs through manures, roots and root exudates under different treatments in soils influence the aggregate structure by changing SOC contents and pools (Martens *et al*., 2004). Soil aggregation stabilizes SOC against rapid mineralization by occluding it (Sollins *et al*., 1996) [40], making it inaccessible to microorganisms. Kell (2011) [19] suggested the potential to enhance N storage through the development of deep-rooted plants that would incorporate C directly into the sub-soil. Rasse *et al*. (2005) [36] described the preferential stabilization of root derived C compared to shoot derived C in soils. Despite these facts, there are remarkably little data on the quantity and pools of carbon in deep soils as affected by fertilization.

Soil organic matter can be divided into several fractions depending on their densities. Labile fraction (LF) is the most prominent, partly due to its high turnover rate plus it is easily affected by management systems as well as erosion (Wang *et al*., 2014) [49]. Labile fraction has been described in various ways by soil scientists, including particulate organic carbon (POC) (53–2000 μm), light fraction organic carbon (LFOC) (density of < 2.0 g cm^{-2}), readily oxidized carbon (ROC) (easily oxidized by potassium permanganate), soil microbial biomass carbon (SMBC) and dissolved organic carbon (DOC), etc. (Mirsky *et al*., 2008) [30].The labile fraction (LF) consists of the mineral-free SOM composed of partly decomposed plant and animal residues which turn over rapidly and have a specific density that is comparatively lower than that of soil minerals (Alvarez and Alvarez, 2000) [4]. Agricultural soils have been identified as having the lowest LF (Vieira *et al*., 2007) [47], due to high disturbances by tillage practices and harvesting of crop residues. Stable fraction (SF) accounts for 90% of the total organic carbon (TOC) in terms of particle size distribution. Most studies show that SF due to its recalcitrant nature is not easily affected by land use or management practices (Bayer *et al*., 2002) [9] whiles others show that this fraction is more affected than the labile portion (Klotzbücher *et al*., 2011) [20]. The SF arguable is said to be resistant to management systems due protection from external factors by sorption on fine particles. Its inaccessibility to decomposing microbes is due to dominance of clay particles that strongly adsorb the carbon protecting it from enzymatic action leading to the humification process (Allen *et al*., 2010) [2].

In modern agriculture, to attain high crop yields and satisfy the demand of an increasing population, a significant amount of synthetic fertilizers is applied to croplands (Gruzdeva *et al*., 2007) [17]. However, the inputs of synthetic fertilizers are disadvantageous to develop long-term sustainability in agro-ecosystems (Sarkar *et al*., 2003) [37]. Organic inputs are widely accepted as one of the sustainable agricultural practices that improve soil fertility and soil biological properties (Talgre *et al*., 2012; Wang *et al*., 2013; Zhang *et al*., 2014) [41, 48, 52]. Considering the requirement for both crop yields and sustainable agro-ecosystems, the combined application of synthetic fertilizers with organic materials is regarded as a reasonable and effective approach to achieve both goals (Gentile *et al*., 2008) [13]. Chivenge *et al.* (2011) [12] concluded that the reasonable application of synthetic fertilizers with organic resources can increase soil fertility and crop yields. The objectives of this review study were (i) to evaluate how long-term applications of manure and/or synthetic fertilizers affect the sequestration or depletion of SOC in the particle-size pools; (ii) to clarify the role of soil particle-size separates in SOC storage and stabilization, and (iii) to explore the interaction mechanism of SOC mineralization shaped by conservation agriculture ecosystem and depositional patterns.

Aggregate-size Distribution

Ogunwole, (2008) [33] revealed that soils amended with FYM + NPK had significantly more dry-sieved aggregates > 2.0 mm than the unamended and NPK amended soils. The mean water-stable aggregate fraction was highest for the >2.0 mm size range, next was < 0.1 mm and lowest was for 0.5–2.0mm size range. In the >2.0 mm size range significantly higher water-stable aggregate fraction was recorded with FYM amended soil than all the other amended soils. In the 0.5–2.0 mm size range significantly greater water-stable aggregate fraction was recorded with NPK amended soil than the other treatments. At the< 0.1mm size range the FYM+NPK amended soil had significantly higher aggregate fraction than the other treatments. The MWD of the water-stable aggregates was significantly lower for unamended soil and soils amended with FYM + NPK.

Aulakh *et al*. (2013) [7] revealed that the proportion of macro-aggregates in the size class of 0.25 to >2 mm was higher as compared to micro-aggregate in the size class 0.11-0.25 mm. Among the macro-aggregates, 0.25 -0.50 mm fraction constituted the greatest proportion followed by 0.5 -1.0, 1.0 - 2.0, and >2 mm fraction constituted the least proportion in both 0 - 5 cm and 5 -15 cm soil layers under both CT and CA system. Integrated use of organic and inorganic fertilizers significantly increased total WSA which was highest in all the macro-aggregate size fractions in 0 - 5 cm and 5 - 15 cm soil layer.

Das *et al*. (2014) [56] reported that the higher LM was recorded in T_7 and T_8 in 0–7.5 (34–36%), 7.5–15 (19%) and 15–30 (17%) cm layers. These treatments had proportionally less SM and significantly lower amounts of mi and sc fractions. The T_5 has significantly higher SM and lower LM in 0–7.5 and 7.5–15 cm layers, while higher mM contents were recorded in T_6, T_7 and T_8 (70.17, 74.34 and 74.76 g 100 g^{-1} of soil, respectively) in the layer 0–7.5 cm compared to zero and 100% inorganic N treatments. In rest of the layers, T_8 had larger effects while other organic treatments had nearly similar impacts as in inorganic N application.

Tripathi *et al*. (2014) [45] also found that the aggregate size distribution was significantly affected by the application of FYM and inorganic fertilizers compared to unfertilized control. An aggregate fraction of 0.25–0.5 mm made up the largest (27.36–31.36%) whereas 0.1–0.053 mm fraction made the least contribution (2.10–3.87%) in total WSA percentage at two sampling depths. Application of FYM alone or in combination with inorganic fertilizers significantly improved the formation of macro and meso-aggregates compared to unfertilized control at both sampling depths. The incorporation of FYM alone increased the occurrence of macro-aggregates (5–2 mm) by 165.33% whereas meso-aggregates increased by 130.68% in 2–1 mm fraction, by 282.83% in 1–0.5 mm fraction over unfertilized control in 0–15 cm soil layer. The proportion of micro-aggregates (0.25–0.1 mm and 0.1–0.053 mm) was less in FYM + inorganic fertilized plots than the plots applied with inorganic fertilizer alone. The application of FYM decreased the micro-aggregate fraction of 0.25–0.1 mm by 0.35 to 9.94% and micro-aggregate fraction of 0.1–0.053 by 0.4–30.63% compared to unfertilized control in the surface soil. The increase in the proportion of water stable macro-aggregates (>2 mm) by FYM + inorganic fertilizer application could be attributed to the input of additional organic residues and available C to the soils.

Ghosh *et al*. (2016) [16] revealed that macro-aggregates accounted for >51% of total aggregates. In topsoil (0–5 cm soil layer), these were the dominant water-stable aggregates (WSA). Significantly higher (60%) water-stable macro-aggregates were recorded in T_4 plots compared with T_1 in the topsoil, with a concurrent decrease in micro-aggregates in the T_2 and T_3 plots. A similar trend also was recorded in sub-surface soil. Small macro-aggregates were the greatest proportion of the whole soil, followed by aggregates <53 mm in topsoil. Plots under T4 had significantly more large and small micro-aggregates than T_1 plots in both soil layers.

Tian *et al*. (2018) [43] reported that the increased organic carbon concentrations in each size fraction. Organic C concentrations in the <0.053-, 0.053- to 0.25-, 0.25- to 2.0-, and >2.0-mm fractions were 14.012.0, 14.4, 24.1% greater, respectively, in OF than in CF. Organics also significantly increased the organic C concentrations of micro-aggregates occluded with in macro-aggregates. Organic C concentrations in the <0.053 and 0.053 to 0.25 micro-aggregates were 14.0 and 13.8%greater, respectively, in OF than in CF. Moreover, the combining the four aggregate size classes, the total amount of soil organic C storage was 20% greater in OF (5.60 kg m^{-2}) than in CF (4.67 kg m^{-2}). Zhou *et al*. (2020) [53] also found that the lowest aggregate content was found in the $MSA_{<0.106}$ mm, accounting for about 2%. The highest proportions in $MSA_{>5\ mm}$, $MSA_{2\text{-}5\ mm}$, and $MSA_{1\text{-}2\ mm}$ were obtained in FS (50.2%), FC (24.8%), and FC (14.6%) treatments, respectively. Meanwhile, SC treatment retained the highest proportion in the $MSA_{0.5\text{-}1mm}$ (17.4%), $MSA_{0.25\text{-}0.5\ mm}$ (6.5%), $MSA_{0.106\text{-}0.25\ mm}$ (2.9%), and $MSA_{<0.106\ mm}$ (2.3%). On the other hand, the lowest proportions in the $MSA_{>5\ mm}$ and $MSA_{2\text{-}5mm}$ in FC treatment (34.7%) and CC treatment (18.5%), respectively. The FS treatment had the lowest proportions in the $MSA_{1\text{-}2mm}$ (11%),$MSA_{0.5\text{-}1mm}$ (11.8%), $MSA_{0.25\text{-}0.5mm}$ (1.9%), $MSA_{0.106\text{-}0.25mm}$ (0.8%), and $MSA_{<0.106\ mm}$ (1.2%).

Distribution Patterns of SOC in Particle-size Fractions

Ogunwole, (2008) [33] reported that FYM + NPK amended soil recorded significantly the highest bulk SOC concentration followed by FYM and NPK amended soils, whose SOC concentrations were similar to but higher than that of the unamended soil. The SOC concentration of the different sizes of dry aggregate show that the FYM+NPK amended soil was highest in virtually all the aggregate sizes particularly, in the large aggregate size range. Thus suggesting that increased fraction of large macro-aggregates (> 2.0mm) be the result primarily of the SOC content of the bulk soil.

Yan *et al*. (2012) [51] revealed that the distribution of SOC pools among the particle-size fractions indicated that the clay and silt fractions comprised major SOC pools in the soils with 61.6% of the total SOC. In three finer fractions, the fine clay fraction accounted for 0.93%, the coarse clay fraction contained 25.0%, and the silt fraction was 35.7% of total SOC, respectively. About 38.5% of total SOC was found in the two sand fractions. The large variation of SOC distribution in the particle-size fractions indicated that the vertisol contained different pools of SOC. However, significant increase in SOC concentrations was evidenced in the plots with manure application, which mainly occurred in coarse sand fraction. Higher level of manure had a more pronounced effect than the lower level in the coarse sand. The SOC contents in bulk soil increased by 33% and 52% in M_1 and M_2, respectively, relative to the control.

It is known that the increase in the SOC resulting from manure application can also be attributed to the increased crop residue return because manure applications may increase plant biomass (Whalen and Chang 2002) [50]. Zhu *et al*. (2007) [55] reported that farmyard additions produced higher grain yields compared to the no farmyard treatments. As above-ground biomass was completely removed, root biomass could also contribute positively to SOC accumulation (Yang *et al*. 2003) [58]. Gerzabek *et al*. (2001) [14] and Antil *et al*. (2005) [5] also reported that manure caused an increase of SOC content, and the most OC introduced by the addition of manure remained in the silt fraction.

Nayak *et al*. (2012) [32] also found that the continuous application of FYM along with N–P–K (NPK+ FYM) resulted in a significantly higher soil MBC over NPK. The MBC content of plots which received CR along with NPK (NPK+ CR) was at par with NPK+ FYM. However, the MBC content of surface soil in NPK+ GM treatments was significantly lower than NPK+ FYM, where it was at par. The MBC content of surface soil in NPK+ GM plots was at par with NPK+ CR where it was significantly lower. The highest MBC content of 515.4 g g^{-1} at surface soil (0–15 cm) was observed in NPK plots.

Liu *et al*. (2013) [27] observed that the SOC concentration in 0–20, 20–40 and 40–60 cm depths increased significantly by farmyard manure or straw application. At the 0–20 and 20–40 cm soil depths, SOC was highest in NP+FKM followed by NP+S and FYM treatments and the least in CK treatment.

Liang *et al*. (2014) [26] also found that the total SOC increased with treatment: no fertilizer<inorganic fertilizers alone<farmyard manure. SOC increased by 19% in the inorganic fertilizer treatments relative to the control. However, the SOC concentration in the farmyard manure treatment was almost twice of that in the no-fertilizer treatment. SOC concentration was the highest in the MNPK treatment and lowest in the control treatment. Zhu *et al*. (2014) [54] observed that the contents of soil TOC and labile organic C fractions, where PD generally had the highest contents of TOC, DOC, MBC and EOC at the three soil depths. Crop straw return treatments (PR, PW, PD, RR, RW, RD) had consistently higher amount of TOC and labile organic C fractions at the three soil depths than without crop straw return treatments (PN, RN). Moreover, PN had significantly lower TOC, DOC, MBC and EOC at 0–7 cm and 7–14 cm, and RN had the lowest TOC and MBC at 14–21 cm compared to other treatments.

Mazumdar *et al*. (2015) [29] reported that organic C distribution in soil profile differed significantly among the treatments and with depths. At the surface (0-15 cm) layer, NPK+FYM contained the highest SOC concentration (7.7 gkg^{-1}) followed by NPK+CR (7.5 gkg^{-1}) and NPK+GM (7.4gkg^{-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 0-15 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 4.1g 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 45-60cm soil layer.

Awanish, (2016) [8] reported that the greater variations among carbon fractions were observed at surface layer (0-5 cm). F_1= very labile, F_2 =labile, F_3= less labile and, F_4=non-labile. At this depth, C fraction in vertisols varied in this order: $F_4>F_1>F_2=F_3$. Below 5 cm, the carbon fraction was in the order: $F_4>F_1>F_3>F_2$. For 15-30 cm depth it was in the order $F_4>F_1>F_2>F_3$. At lower depth, almost similar trend was followed as that of 30-45 cm. 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. 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. In general, C contents decreased with increasing depth, mainly for very labile faction (F_1) 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). Moreover, less labile and non-labile fractions contribute more than 50% of TOC, indicating more recalcitrant form of carbon in the soil.

Cai *et al*. (2016) [11] also found that the amount of SOC and N mineralized differed among particle-size fractions and under different fertilizer application treatments. For the CK treatments, there were no differences among the three soil fractions under manure application. However, there was more C mineralized from the<53µm fraction with manure applied at 60t $ha^{-1}yr^{-1}(M_{60})$, com-pared with no manure (M_O). As a general trend N mineralization increased with manure application, showing more N mineralized from<53µm fraction under the M_{30} NPK and M_{60} NPK treatments.

Effect of Fertilization on the Distribution and Enrichment of SOC among Particle-size Separates

Yan *et al*. (2012) also found that plots receiving manure, the silt-sized fraction accounted for 36.6% of whole SOC and clay fraction accounted for 25.4% of whole SOC. Obviously, silt fraction acted as the major sink for SOC due to the large proportion of silt in the investigated soil, though SOC was not enriched in silt fraction. Nevertheless, the redistribution of SOC between particle-size separates may, more or less, be characterized by a shift from clay towards coarse sand associated SOM in the soil amended with different amounts of manure. However, it is a general feature that the redistribution of SOM between particle-size separates induced by cultivation is characterized by a shift from coarser towards finer fractions (Gulde *et al*., 2008) [18]. The finding suggests that manure application had a more pronounced impact on the redistribution of SOC among particle size separates compared with cultivation.

The synthetic fertilizer application did not affect the relative contribution of different particle-size particles to SOC storage. This was very clear when we interpreted the data of SOC concentrations and enrichment together. In general, SOC associated with coarse fractions were readily mineralized to supply nutrients for crop growth in long-term cropping systems (Ashagrie *et al*., 2005) [6], consequently there should be a shift of SOC from coarse to fine particles. However, its indicate that the addition of synthetic fertilizers neither change the concentrations of SOC and in the particle-size fractions, nor lead to the shift between the fractions. In this context, we can also argue that even at low organic input systems the application of synthetic fertilizers could not cause significant change in either SOC concentrations or redistribution. The combined application of manure and synthetic fertilizer tended to decrease the pool size of SOC in the clay and silt fractions, whereas the pool size in the coarse sand fraction increased compared with the control. This phenomenon was closely related to the manure input, i.e., higher manure application resulted in more change. Compared to the application of manure or synthetic fertilizers alone the combined application promoted relatively large changes in SOC storage. Therefore, it is conceivable to say that there is a clear interactive impact between manure and synthetic fertilizers on the contribution of particle-size separates to SOC storage.

Naresh *et al*. (2015) [31] reported that the highest SOC concentration was obtained for 0–5 cm depth and decreased with sub surface depth for all treatments. The SOC concentration in 0–5 and 5– 15 cm depths increased significantly by farmyard manure or GM/SPM application. At the 0–5 and 5–15 cm soil depths, SOC was highest in 50% RDN as CF+50% RDN as FYM (F_5) followed by 50% RDN as CF+50% RDN as GM/SPM (F_6) treatments and the least in Control. This might be due to more turn-over of root biomass in 50% RDN as CF+50% RDN as FYM treatment because of better growth and higher average yields obtained during the study period of both the crops in 50% RDN as CF+50% RDN as FYM treatment as compared to 50% RDN as CF+50% RDN as GM/SPM treatment.

Das *et al*. (2016) [57] revealed that among the OOC fractions, C_{VL} in the 0–7.5, 7.5–15 and 15–30 cm soil depths was in the range1.02–2.51, 0.72–2.09 and 0.58–1.15 g kg^{-1} respectively, with corresponding mean values of 1.71, 1.43 and 0.90 g kg^{-1}. At the 0–7.5 cm soil depth, the lowest C_{VL} was seen in the unfertilized control treatment (1.02 g kg^{-1}) and C_{VL} increased significantly under IPNS treatments, with particularly high values (2.51 g kg^{-1}) under the NPK + GR + FYM treatment. This treatment also had the highest C_{VL} values at the 7.5–15 and 15–30 cm depths (2.09and 1.15 g kg^{-1} respectively). At 7.5–15 and 15–30 cm soil depths, the lowest C_{VL} values were observed under the NPKZn treatment (0.72 and 0.58 g kg^{-1} respectively) rather than in the unfertilized control. Compared with uncultivated soil, the C_{VL} content was lower under control or NPKZn treatments, but was invariably greater under treatments using combinations of FYM, GR or SPM with NPK fertilizers. The percentage change in C_{VL} over uncultivated soil varied from–38% to 109% at different depths. However, the C_{NL} content at the 0–7.5, 7.5–15 and15–30cm soil depths varied, with values in the range7.23–10.07, 6.73–8.63 and 4.30–6.40 g kg^{-1} respectively, and corresponding mean values of 7.99, 7.73 and 5.39 g kg^{-1}.Averaged across treatments, the C_{NL} content at the 0–7.5 and7.5–15 cm depths was similar, but decreased significantly at the15–30 cm soil depth. Averaged across soil depths, C_{NL} content under the NPK + CR and NPK + GR + FYM treatments (7.99and 7.63 g kg^{-1} respectively) was significantly higher than in the other treatment groups. Compared with uncultivated soil, the change in C_{NL} under different nutrient supply options was inconsistent, although C_{NL} content increased under the NPK + CR treatment by 25–

33% at the 0–7.5 and 7.5–15 depths. Considering overall mean values across soil depths and nutrient supply options, the abundance of these four OOC fractions was in the order C_{NL}(7.04 gkg^{-1})> C_{L}(2.02gkg^{-1})> C_{VL}(1.35 gkg^{-1}) > C_{LL}(0.75 g kg^{-1}).

Kumar, (2016) [22] 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 andnon-labile fractions, respectively at 0-5cm depth. In 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. 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). Moreover, less labile and non-labile fractions contribute more than 50% of TOC, indicating more recalcitrant form of carbon in the soil.

Shen *et al*. (2018) [39] revealed that SOC, EOC, DOC, and MBC decreased with increasing soil depth, and significant difference were only observed in the SOC and DOC contents among the three soil layers. The EOC content in the 0–10cm layer was significantly higher than that in the other soil layers. In the 0–10 cm soil layer, SOC content under the LIT and HIT treatment were significantly lower than those in the CK and SC plots, but in 0–30 cm soil layer, significant difference between the HIT and CK treatment was only observed. The contents of DOC under the SC and HIT treatment were significantly higher than those in CK and LIT treatment in 0–10 cm soil layer and the corresponding values in the 10–20 cm layer were significantly higher than those in the CK. The content of EOC in the 0–10 cm layer was significantly higher in the HIT treatment than that in other three treated plots.

Tiwari *et al*. (2018) [44] also found that POC reduction was mainly driven by a decrease in fine POC in topsoil, while DOC was mainly reduced in subsoil. Fine POC, LFOC and microbial biomass can be s for subsoil. Reduced proportions of fine POC, LFOC, DOC and microbial biomass to soil organic useful early indicators of changes in topsoil organic C. In contrast, LFOC and DOC is useful indicator C reflected the decline in soil organic C quality caused by tillage and straw Management practices. 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}.

The annual greenhouse gas emissions from fossil carbon are estimated at 8.9 giga tonnes C (8.9 × 10^{15} g), and a global estimate of soil C stock to 2 m of soil depth of 2400 giga tonnes (2400 × 10^{15} g) (Batjes, 1996) [10]. Taking the ratio of global anthropogenic C emissions and the total SOC stock (8.9/2400), results in the value of 0.4% or 4‰ (4 per mille) (Fig. 1a). Increasing SOC has been proposed to mitigate climate change with an additional benefit of improving soil structure and conditions (Lal, 2016) [25]. If we take the land area of the world as 149 million km^2, it would be estimated that on average there are 161 tonnes of SOC per hectare. So 4 per mille of this equates to an average sequestration rate to offset emissions at 0.6 tonnes of C per hectare per year. This 4 per mille blanket value cannot be applied everywhere as soil varies widely in terms of C storage, which includes desert, peat-lands, and mountains, etc. Soil types, aboveground vegetation, climate, and how quickly the soil biota uses the carbon collectively impact C storage. The 4 per mille initiative was based on a blanket calculation of the whole global 2 m profile C stock, which amounts to an annual sequestration rate of 9.6 Gt C. However the potential to increase SOC is mostly on managed agricultural lands. If we consider top 1 m of 3900 to 4900 Mha of global agricultural land, its SOC stock estimate is between 480 to 790 Gt, and 4 per mille of this stock is 1.9-3.1 Gt C.

Scharlemann *et al*. (2014) [14] observed that SOC stock fluctuates with latitude and longitude with greater stocks at higher latitudes, decreases in the mid-latitudes, and increases in the humid tropics (Fig.1b). The high value in the humid tropics is due to the high precipitation while, the high SOC content at high latitudes corresponds to the low temperature regimes. Lal (2016) [25] posed some challenges for the 4 per mille initiative, including: paucity of scientific data, the finite capacity of soil carbon sinks, resource-poor farmers and small landholders and implementation.

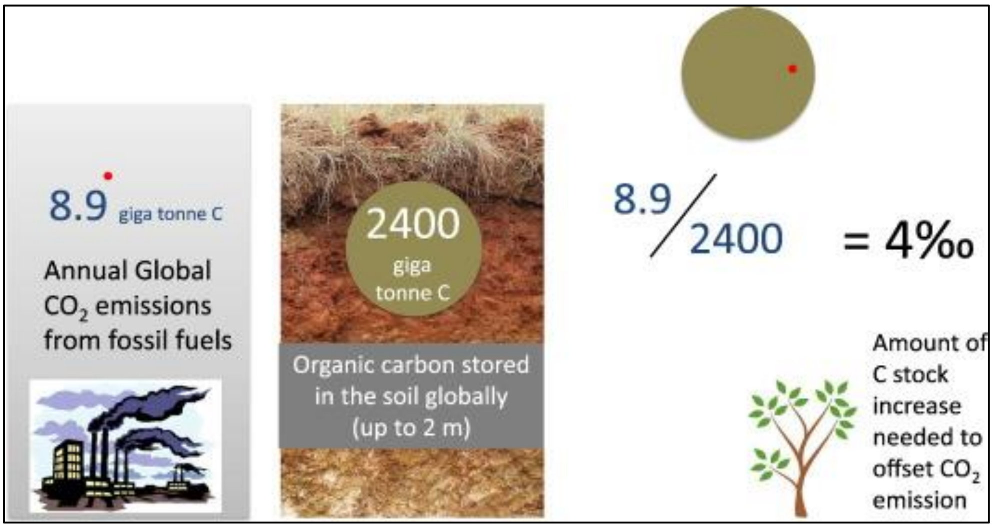


Fig 1(a): The 4 per 1000 soil carbon sequestration initiative [Source: Ademe, 2015].

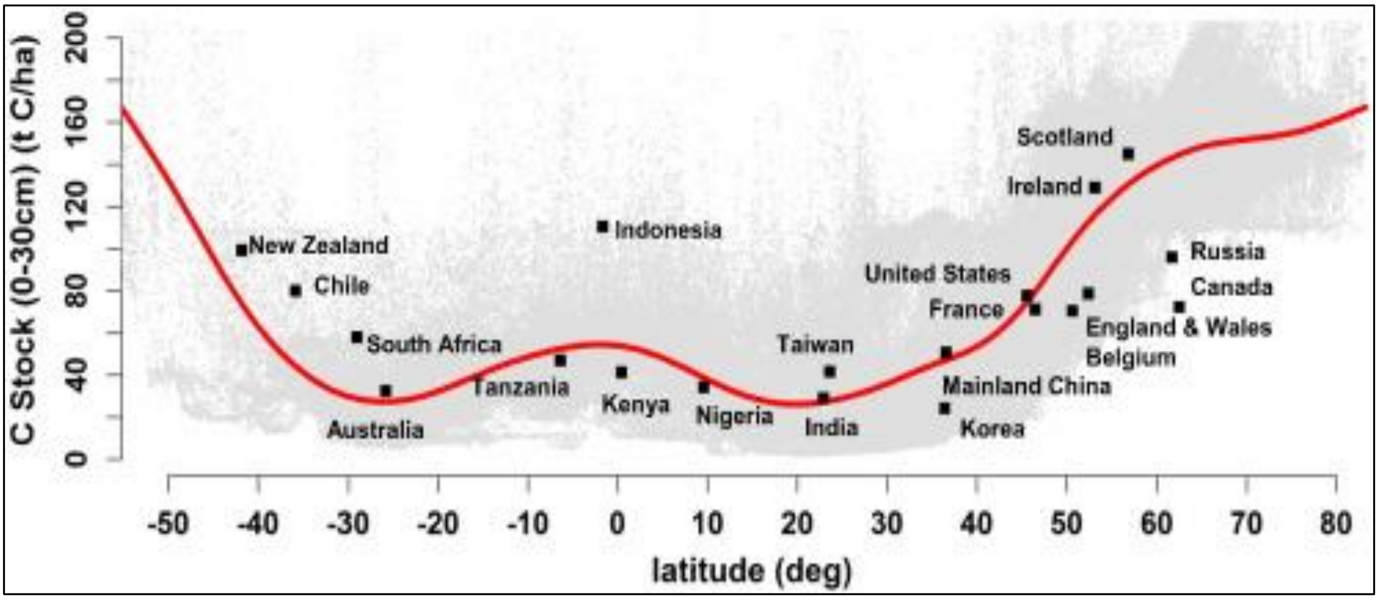


Fig 1(b): Soil C stock (0–30 cm) as a function of latitude.

Labile and recalcitrant carbon pool

Ghosh *et al*. (2018) [15] reported that in both 0–15 and 15–30 cm soil layers, plots with NPK + FYM had significantly higher labile and recalcitrant C pools than control and NP plots (Fig. 2a). Plots with NPK + FYM also had higher labile C than 150% NPK in the 15–30 cm soil layer, but both plots had similar recalcitrant C pools. While NPK + FYM had significantly higher non-labile C pool than all other treatments in soil surface, all plots had similar non-labile C pools in 15–30 cm soil layer. On average, the relative preponderance of the fractions of SOC, extracted under a gradient of oxidizing conditions was: Pool 4 > Pool 1 > Pool 3 (less labile C) > Pool 2 (labile C) in surface soil layer constituting about 33.4%, 24.6%, 21.3% and20.7%, respectively, of the total SOC. However, macro-aggregates of NP plots in soil surface had 1.36 and 1.38 times greater SOC enrichment than NPK+FYM and NPK treated plots. Whereas, macro-aggregates from N plots had 1.12 and 1.18 times greater C enrichment than NPK+FYM and NPK plots, respectively, in sub-surface soil. Carbon enrichment factor of soil micro-aggregates from all plots were<1, indicating net C depletion (Fig. 2b).

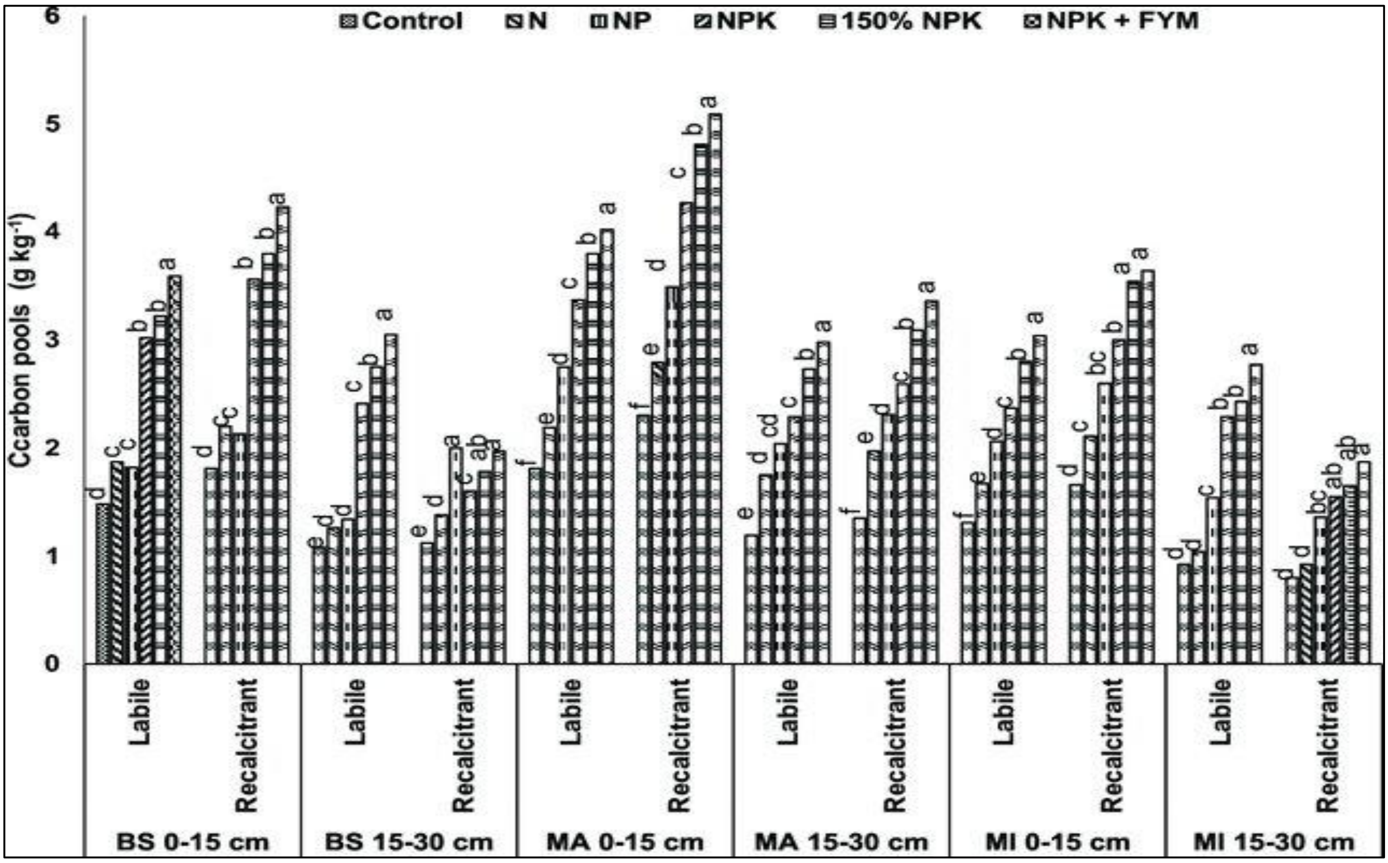


Fig 2(a): Labile and recalcitrant carbon pools in bulk soils and aggregates as affected by long-term fertilization in the 0-15 and 15-30 cm soil layers under a wheat-based cropping system in an Inceptisol

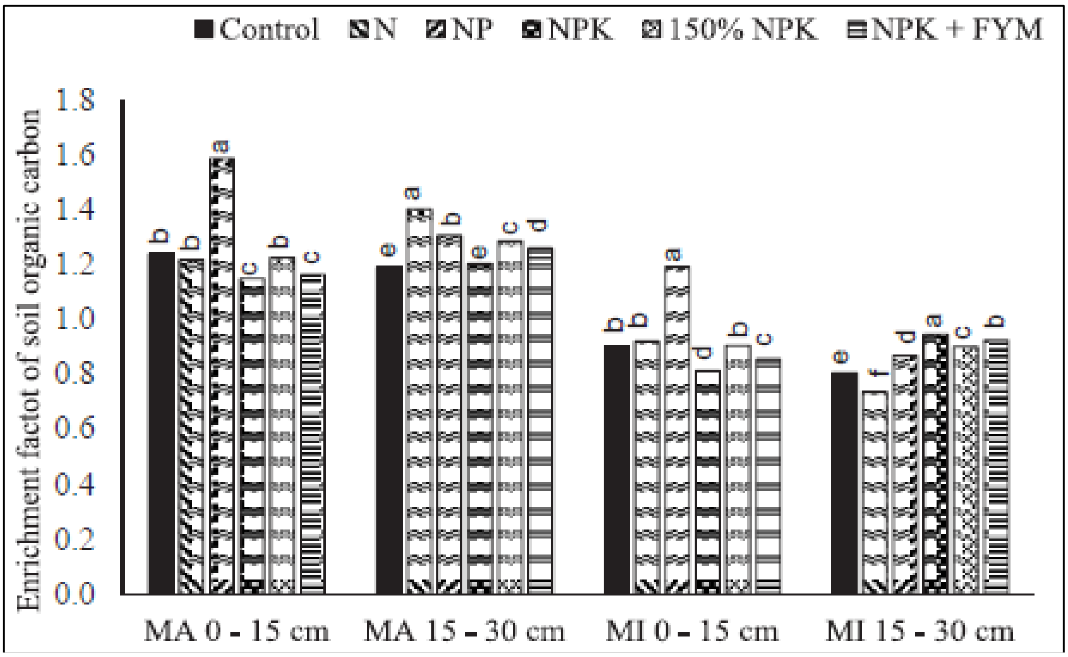
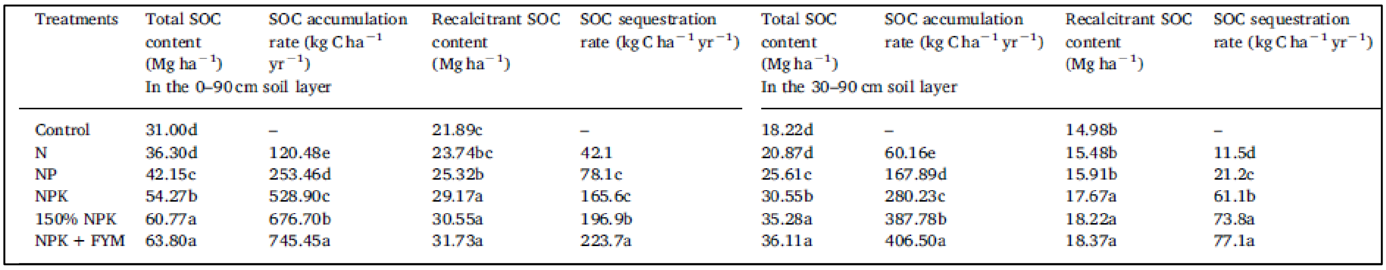


Fig 2(b): Enrichment factor of soil organic C (SOC) in aggregates of fertilization under a wheat based cropping system in an Inceptisol. MA: Macro-aggregates, MI: Micro-aggregates, MA 0–15 cm: Macro-aggregates of 0–15 cm soil depth, and so on.

Ghosh *et al.* (2018) [15] observed that SOC accumulation rates in plots under NPK+FYM and NPK in the 0–90 cm soil profile were ~745 and 529 kg ha^{-1} yr^{-1}, respectively (Table 1). However, C sequestration rates in the 0–90 cm soil profile for NPK and NPK+FYM treatments were only ~167 (31% of the accumulated SOC) and 224 kg ha^{-1} yr^{-1}, respectively. Interestingly, NPK, 150% NPK and NPK+FYM treated plots had similar recalcitrant C contents in the said soil profile, but had significantly different C accumulation rates. Nearly 54% of the accumulated SOC and 34% of the sequestered SOC under NPK+FYM plots were observed within deep soils (30–90 cm soil layer), implying role of INM on C sequestration in deep soils

Table 1: Total soil organic carbon (SOC) accumulation and sequestration rates (kg C ha^{-1} $year^{-1}$) over unfertilized control plots as affected by long-term fertilization.



Treatments	Total SOC content ($Mg\ ha^{-1}$)	SOC accumulation rate ($kg\ C\ ha^{-1}\ yr^{-1}$)	Recalcitrant SOC content ($Mg\ ha^{-1}$)	SOC sequestration rate ($kg\ C\ ha^{-1}\ yr^{-1}$)	Total SOC content ($Mg\ ha^{-1}$)	SOC accumulation rate ($kg\ C\ ha^{-1}\ yr^{-1}$)	Recalcitrant SOC content ($Mg\ ha^{-1}$)	SOC sequestration rate ($kg\ C\ ha^{-1}\ yr^{-1}$)
	In the 0–90 cm soil layer				In the 30–90 cm soil layer			
Control	31.00d	–	21.89c	–	18.22d	–	14.98b	–
N	36.30d	120.48e	23.74bc	42.1	20.87d	60.16e	15.48b	11.5d
NP	42.15c	253.46d	25.32b	78.1c	25.61c	167.89d	15.91b	21.2c
NPK	54.27b	528.90c	29.17a	165.6c	30.55b	280.23c	17.67a	61.1b
150% NPK	60.77a	676.70b	30.55a	196.9b	35.28a	387.78b	18.22a	73.8a
NPK + FYM	63.80a	745.45a	31.73a	223.7a	36.11a	406.50a	18.37a	77.1a

Means with similar lower-case letters within a column are not significantly different at $P < 0.05$ according to Tukey's HSD test.

Conclusion

The accumulation of C in soil was related to soil aggregation and the distribution of carbon in aggregates. By significantly improving soil aggregation and associated carbon content, the potential of conservation agriculture (CA) systems in an Inter-play between aggregation and the formation of mineral-associated SOC is the key to under-standing changes in amounts and stability of SOC upon depth, occlusion within aggregates, and associated organic carbon fractions. Organic carbon concentrations in the <0.053-,0.053-to 0.25-,0.25-to 2.0,and >2.0-mm fractions were 14.0, 12.0, 14.4, 24.1% greater, respectively, in CA than in CF. The contents of SOC,LOC, DOC, POC and EOC by 14.73%, 16.5%, 22.5%, 41.5% and 21% in the 0-40 cm soil layer, and by 17%, 14%, 19%, and 30% in the 0-100 cm soil layer. These results suggest that over time, the MBC and MBC-derived C under the fine-sized residue treatment may constitute a significant source of stable SOC through strong physical and chemical bonding to the mineral soil matrix.

The organic and synthetic fertilizers increased total SOC concentrations due to substantial increments not only in the macro-aggregates and labile C pools, but also in the micro-aggregates and recalcitrant C pools. Increased labile and recalcitrant C in aggregates under organic and synthetic fertilizers is of specific importance, as it would reduce CO_2 emission from soils. Organic and synthetic fertilizers also had a positive effect on the redistribution of SOC among the particle-size fractions, with obvious depletion of SOC in fine particles and pronounced enrichment in macro-aggregates. However, the enrichment factors of SOC in macro-aggregates of all treatments were>1 and that of micro-aggregates were<1 in both soil layers, indicating C sequestration in macro-aggregates and C depletion from micro-aggregates. Hence, the enrichment factor of SOC is a better indicator than the labile: recalcitrant C to assess C sequestration within aggregates.

Average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+FYM treatment and increased enzyme activities, which potentially influence soil nutrients dynamics under field condition. A regular input of biomass-C along with chemical fertilizers is essential to improving soil quality in the semi-arid tropics of India, and for minimizing the depletion of SOC stock under continuous cropping. Use of organic amendments is essential to enhancing the SOC sequestration. The minimum input of 1.1 Mg C ha^{-1} $year^{-1}$ is needed to maintain SOC at the initial level (with no change). In view of the decreasing availability of FYM, however, application of 10.7 Mg ha^{-1} of FYM (equivalent to 60 kg N) on dry weight basis is difficult. Thus, conjunctive use of FYM or other crop residues along with 50% recommended dose of fertilizers is a viable option for curbing SOC depletion and sustaining crop production.

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