

Review Article

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Effects of Manure and Synthetic Fertilizer with Residue Returning on Soil Organic Carbon Storage; Interactions with Intra-Aggregate Pore Structure and Water Stable Aggregates in High Input Cropping System: A Review

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ABSTRACT

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Soil organic carbon (SOC) and its labile fractions are strong determinants of chemical, physical, and biological properties, and soil quality. 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. The average concentration of particulate organic carbon (POC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in organic manure plus inorganic fertilizer treatments (NP+S and NP+FYM) in 0–60 cm depth were increased by 64.9–91.9%, 42.5–56.9%, and 74.7–99.4%, respectively, over the CK treatment. After 18 yr, manure increased the OM level of the whole soil and favored formation of slaking-resistant macro-aggregates (250–1000 μ m). This effect was primarily a result of the OM added by the manure. In contrast, NPK fertilizer did not affect soil OM level or macro-aggregation. The increase in OM induced by manure application was observed primarily in macro-aggregates, and both as mineral-associated and particulate OM. However, manure did not change OM located in the fraction <53 μ m confirming that recently deposited OM preferentially accumulates within the aggregate structure and not in the finely or non-aggregated material. The mean soil organic carbon storage of the 0–60 cm soil layers were significantly increased with H, M, and L, by 21.40%, 20.38% and 8.21% compared with CK, respectively. Straw incorporation increased 0.25 mm water-stable macro-aggregates level, geometric mean diameter, mean weight diameter and the aggregate stability, which were ranked in order of increasing straw incorporation rates: H/M > L > CK. Therefore review study shown that most of the C in cattle manure is composed of coarse particles, we hypothesize that manure-derived OM first enters the soil primarily as particulate material, then, during decomposition, is transformed within the aggregate structure into mineral associated material thereby contributing to aggregate stabilization.

Introduction

Soil organic carbon (SOC) is a key indicator of soil fertility, and changes in SOC content leads to soil aggregation modification. SOC influences soil aggregation because of its binding function (Tisdall and Oades, 1982), and in turn, soil aggregation affects SOC sequestration. As such, SOC enhancement is a strategy that can be used to mitigate climate change (Almaraz *et al.*, 2009). In this regard, soil aggregation and SOC sequestration has gained increased research attention. In agricultural ecosystems, among many factors those affect aggregation process and SOC sequestration, the alternation in land use and fertilizer management practices might be of the most important ones. Both management practices exert profound direct and indirect effects on the growth and biodiversity of vegetation and microbial organisms, thereby increasing the organic input into the soil. Arable land abandonment has been reported one of the most important global land use strategies in the past decades (Raiesi 2012). Several studies showed that cropland abandonment increases the amount of macro-aggregates (>0.25 mm) and improves aggregate stability in the top soil layer (0–10, 0–20 and 0–30 cm) over time (Li and Pang 2010; Raiesi 2012).

Labile fractions of C in soils, such as microbial biomass C (MBC), water soluble C (WSC), light fraction C (LFC) and particulate organic matter (POM) can respond rapidly to changes in C inputs (Bolinder *et al.* 1999). Thus, these have been suggested as early indicators of the effects of land use changes on soil organic matter quality (Gregorich *et al.*, 1994). In general, the labile C pool has a greater turnover rate of several weeks to months or years compared with more recalcitrant pools (Paul *et al.*, 2001) and therefore, labile C pool is much smaller in size. The WSC, a labile C

pool, is the main energy source for soil microorganisms, a primary source of mineralizable N, P, and S, and it influences the availability of metal ions in soils by forming soluble complexes (Stevenson, 1994). While the MBC constitutes living micro-organisms that are smaller than 5–10 μm^3 , these microorganisms help in aggregate formation by producing gums and mucilage's (Watts *et al.*, 2005). The LFC (free or uncomplexed) is considered to include decomposing plant and animal residues that have rapid turnover rate and thus can be an important source of plant nutrients (Wander *et al.*, 1994), however, LFC has lower specific density than soil minerals. The differences in C fractions resulting from different management practices can provide knowledge about the mechanisms of C sequestration (Six *et al.*, 2002). The management practices that increase the sequestration of C in soils are also found to have favorable effects on soil structure (Rasool *et al.*, 2007). The loss of SOC, particularly the labile C fractions, due to unsuitable management practices can adversely affect soil physical properties. A well aggregated soil provides physical protection to SOC. Therefore, the maintenance of soil aggregation can help to sequester greater amounts of C in soils and improve soil quality. Therefore, the main objective of the present review study was to assess the impact of long-term manure and synthetic fertilization and residue retention on SOC storage, soil aggregation and responses of SOC fractions in the *Typic Ustochep* soil of Northwest India.

Soil organic carbon storage

SOC storage is usually measured in terms of total C stored, but how much C is stored and for how long this C can be stored depends on the pools (active/labile vs. recalcitrant/passive) and their cycling (Six *et*

al., 2001; Gleixner *et al.*, 2002), form of stabilization (chemical/physical), and physical location (inter/intra-aggregate vs. free) (Six *et al.*, 2001) of the C in the soil. Kanchikerimath and Singh, (2001) also found that inorganic fertilizers plus organic material increased the SOC content of the soil. The reasons for the higher SOC in manure soils at deeper depths include the following. First, the crop rooting depth between organic manure and inorganic fertilizer soils differ. The organic manure soils can be favorable for the growth of roots into deeper layers due to the relatively loose soil and high soil water content. Second, SOC in organic manure soils can also move to lower depths through earthworm burrows and leaching. Gami *et al.*, (2009) also reported a significant increase in SOC stocks to 60 cm depth under three 23–25-year-old long-term fertility experiments in the Nepal, with application of manure and inorganic fertilizer. Within 1 m soil depth, the cumulative distribution of SOC in the CK, N, NP, FYM, NP+S and NP+FYM treatments were by 50%, 46%, 51%, 53%, 54% and 55% in the 0–40 cm layer, and 68%, 68%, 71%, 72%, 73% and 74% in the 0–60 cm layer, respectively. The SOC storage in the 60–100 cm layer was statistically similar among different treatments. On average the estimate of soil C accumulation to 60 cm depth were 267% and 41% greater than that for soil C accumulated to 20 cm depth and to 40 cm depth.

Liu *et al.*, (2013) also found that 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.

Song *et al.*, (2015) reported that Soil organic C content was highest in the topsoil (0–0.2 m), and then decreased rapidly with soil depth (Fig. 1a). In the topsoil layer, SOC content in MNPK, FAL and SNPK was significantly higher than that in the unfertilized control by 50.7, 25.6 and 12.4%, respectively, whereas no significant difference was found between the unfertilized control and NPK. In the subsoil (0.2–0.4 m) layer, SOC contents in MNPK and FAL were significantly higher than for the unfertilized control, NPK and SNPK, but no significant differences were observed among the unfertilized control, NPK and SNPK treatments. In the 0.4–0.6 m and 0.6–0.8 m layers, MNPK had the highest SOC content among the treatments (Fig.1a). The increasing trend of C content in soils could be explained by the amount of C input. Firstly, soil mineralization rate is usually stable, thus the rate of SOC change is directly related to C input from organic amendments (Jastrow *et al.*, 2007). The higher amount of organic matter input in MNPK and SNPK treatments promoted SOC concentration in the soil (Li *et al.*, 2010). Secondly, the average maize yields over the experimental duration in MNPK and SNPK treatments were significantly higher than in the unfertilized control consequently providing higher amounts of root residues and exudates in the soil (Fan *et al.*, 2005). Therefore, higher organic matter and root biomass and exudation input in MNPK and SNPK treatments contributed to the increases in C content in the soil. In addition, straw incorporation concentrated less C in the soil

compared to the MNPK treatment, which might have resulted from low soil temperature and moisture in this region, which restricted straw mineralization (Ogle *et al.*, 2005). Moreover, the fractions of large- and macro-aggregates in FAL were significantly higher than in the unfertilized control, NPK, SNPK and MNPK, whereas the fractions of micro- and silt +clay aggregates (<53 µm) in FAL were significantly lower than in other treatments (Fig.1b). There were no significant differences in aggregate-size distribution among the unfertilized control, NPK, SNPK and MNPK treatments, except for the higher fraction of micro-aggregates and lower fraction of silt +clay aggregates in SNPK (Fig.1b). The proportion of aggregates >250 µm was similar and not significantly different to the proportion of aggregates <250 µm in the FAL treatment. However, the proportion of aggregates <250 µm in the unfertilized control, NPK, SNPK and MNPK treatments, ranging from 65.0 to 71.3%, was significantly higher than the proportion of aggregates >250 µm. Cropping practices lead to larger aggregate breakdown into smaller aggregates, thus, micro- and silt +clay aggregates are dominant in cropland soils (Liang *et al.*, 2009).

Zhang *et al.*, (2014) revealed that the sum of SOC storage in 0–60 cm layers with the three incorporation treatments were higher than CK, i.e., 7.71%, 11.14 and 1.70% in 2008, 15.15%, 24.00% and 6.86% in 2009, and 21.40%, 20.38% and 8.21% in 2010, respectively (Fig.2a). The SOC storage increased with the number of years of incorporation, i.e., the SOC storage (0–60 cm depth) in 2010 had increased by 6.19–12.48% compared with 2008, and decreased with the soil layer depth, i.e., by 3.75–25.68% in 2008, 11.85–21.70% in 2009 and 13.51–26.64% in 2010. The SOC storage of H and M was slightly higher than CK in 2008, although the difference was significant in 40–60 cm layer

only. In 2009, compared with CK, H and M significantly increased the SOC storage by 11.01% and 21.74% in 0–20 cm layer, 14.94% and 18.81% in 20–40 cm layer, and 20.40% and 32.47% in 40–60 cm layer, respectively, and L was significantly increased by 7.89% in 40–60 cm layer only. However, Fig. 2b shows that the fractal dimensions with the three incorporation treatments decreased significantly after three years of straw incorporation. The fractal dimensions (0–40 cm layer) with the incorporation treatments were lower than those of CK during 2008–2010, i.e., 0.16%, 0.11% and 0.02% in 2008, 0.14%, 0.16% and 0.06% in 2009, and 0.24%, 0.26% and 0.06% in 2010, respectively. The fractal dimensions also increased with the soil layer depth and decreased with the number years of incorporation, i.e., the H, M, L and CK in 2010 was 0.20%, 0.27%, 0.17% and 0.12% higher than that in 2008. The fractal dimensions in the 0–10 cm layers with the four treatments were ranked in the order: H, M, L, and C K in 2008. The fractal dimensions with H and M were significantly lower than CK, i.e., 0.33%, 0.17% and 0.06%, respectively.

Xie Jun-yu *et al.*, (2015) reported that SOC storage in <0.25 mm aggregates was not affected by nutrient management at both soil layers, except for the NPK treatment at 0–10 cm depth, which yielded significantly higher value than that of CK (Fig. 4a). However, SOC storage in soil aggregates treated with NP, NPK and MNPK was lower in >1 mm aggregates compared with those treated with CK at both soil depths. Higher SOC partitioning proportions were also observed in 0.25–1 mm aggregates at 0–10 cm and 0.25–0.5 mm aggregates at 10–20 cm depth in soil treated with MNPK than those in CK (Fig. 3a). Moreover, total nitrogen (TN) concentrations in 1–2 and 0.25–0.5 mm aggregates were higher under Abandonment

than those under Cropping at 0–10 cm soil depth. Fallow showed significantly lower TN concentration in >1 mm aggregates than Cropping and Abandonment. At 10–20 cm soil depth, TN concentrations in >0.5 mm aggregates were significantly lower under Abandonment than those under Cropping (Fig. 3b).

Wang *et al.*, (2020) also found that different return patterns had different effects on SOC storage (Fig. 4a). RR could significantly increase SOC storage by 10.1%, 8.7%, and 8.0% when residues were returned once in a single cropping system (OSCS), in a double cropping system (ODCS) and twice in a double cropping system (TDCS) when compared to residue removal, respectively. When all residue from the previous growing season was returned to the field (All) and when only half the amount was returned (Half), the effects on SOC storage were similar, with a significant increase by 11.4% and 11.2%, respectively. Residue return duration had a great impact on SOC storage. Short-term RR significantly increased SOC storage by 10.7%, and this effect was slightly lower for medium-term RR which was 9.3%. The effect of long-term RR was highest 13.5% (Fig. 4a). Residues from maize, wheat, and rice significantly increased SOC storage by 9.7%, 10.6%, and 9.2%, respectively however, return of different crop residues had little impacts on SOC storage. However, SOC storage was closely related to the cropping pattern (Fig.4b). After 6–10 yrs of RR without crop rotation, SOC storage increased highly significant 16.7%, while after 6–10 yrs of RR with crop rotation, SOC storage slightly increased (8.1%. Compared to production without crop rotation, the application of crop rotation had a lower impact on the increase in SOC storage in >5 yrs of adoption of RR. As returning duration >10 yr, SOC sequestration rate showed decline in fields without crop rotation, which shows that soil reached its

maximum potential to store C. This indicated the phenomenon of “C saturation”. Regarding the cropping system, SOC storage dramatically increased in single cropping systems under RR 12.6%. More SOC was consumed by crop growth in double cropping systems, and therefore, SOC storage was significantly increased by 10.1% under RR (Fig.4b). Cultivation of maize, wheat, and rice had similar effects on SOC storage under RR, with significant increases by 10.5%, 10.3%, and 12.4%, respectively.

Cai *et al.*, (2016) 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 2000–250 μm > 250–53 μm > 53 μm fraction, whereas the amount of C and N mineralization followed the reverse order. In the <53 μm fraction, the M₆₀NPK treatment significantly increased the amount of C and N mineralized (7.0 and 10.1times, respectively) compared to the M₀CK treatment. Long-term manure application, especially when combined with chemical fertilizers, resulted in increased soil microbial biomass C and N [Fig. 5a and 5b].

Cai *et al.*, (2016) also found that 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.6a]. 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 6a]. 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. Dou *et al.*, (2005) 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. 6b]. 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.

Water stable aggregates

Ogunwole, (2008) 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 < 0.1 mm 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.

Whalen *et al.*, (2003) reported that in 2000, the proportion of WSA >4 mm was greater in soils receiving compost than soils that did not receive compost and there were fewer WSA >0.25 mm in compost amended than unamended soils (Fig. 7). In addition, there were fewer WSA between 0.25 and 1mm in compost-amended than unamended soils in 2001. Long-term applications of animal

manure increased the soil organic C level and favor the formation of WSA >0.25 mm under field conditions.

Zhang *et al.*, (2014) also found that the average MWD and GMD values under the incorporation treatments were higher in the 0–40 cm layers than CK during 2008–2010, i.e., 1.46–3.65% and 0.39–1.54% in 2008, 1.09–2.90% and 0.62–1.55% in 2009, 1.77–11.35% and 0.77–3.83% in 2010, respectively (Fig.8a and 8b). The MWD and GMD values decreased with the soil layer depth and increased with the number of years of incorporation, i.e., the H, M, L and CK in 2010 was 10.56% and 3.04% (P,0.05), 7.47% and 2.29%, 3.24% and 1.15%, and 2.92% and 0.77% higher than that in 2008. The MWD and GMD values of treatments in the 0–10 and 10–20 cm layers were ranked in the order: H > M > L > CK. The MWD and GMD values in the 30–40 cm layers under the incorporation treatments were increased by 1.87%, 3.75%, 3.37% and 0.76%, 1.76%, 0.78% in 2008, 0.37%, 0.01%, 0.73% and 0.73%, 0.45%, 0.45% in 2009, 8.09%, 7.35%, 2.21% and 2.32%, 1.93%, 0.77% in 2010, compared with CK, respectively.

Aoyama *et al.*, (1999) revealed that the largest portion of the OM occurred in the large micro-aggregates (53–250 mm) (Figs. 9a and 9b). The amounts of both the particulate and mineral-associated C and N were greater in treatments receiving manure than in the non-manured one. This was particularly true in the small macro-aggregates (250–1000 mm) reflecting the greater amounts of soil material and greater C and N concentrations in this fraction from the manured soils. The application of NPK also increased somewhat the particulate and mineral associated C and N in macro-aggregates. The amount of particulate C and N in any aggregate fraction was usually less than those of the mineral-associated, except for C in the large macro-

aggregates (>1000 μm). The ratio of particulate/mineral-associated C or N decreased with decreasing aggregate size class. The different treatments had a significant effect on this ratio only for the aggregates >1000 μm .

Tripathi *et al.*, (2014) 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 increased the occurrence of macro-aggregates (5–2 mm) by 165.33% whereas meso-aggregates increased by 130.68% in 2–1mm 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. Tian *et al.*, (2018) 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 14.01, 14.0, 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 mm 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).

Labile and recalcitrant carbon pool

Ghosh *et al.*, (2018) 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. 10a). 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% and 20.7%, 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. 10b).

Nayak *et al.*, (2012) 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. Zhu *et al.*, (2014) 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.

Das *et al.*, (2016) 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 range 1.02–2.51, 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 CVL 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 CVL values at the 7.5–15 and 15–30 cm depths (2.09 and 1.15 g kg⁻¹ respectively). At 7.5–15 and 15–30 cm soil depths, the lowest CVL 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 CVL over uncultivated soil varied from–38% to 109% at different depths. However, the C_{NL} content at the 0–7.5, 7.5–15 and 15–30cm soil depths varied, with values in the range 7.23–10.07, 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 and 7.5–15 cm depths was similar, but decreased significantly at the 15–30 cm soil depth. Averaged across soil depths, C_{NL} content under the NPK + CR and NPK + GR + FYM treatments (7.99 and 7.63 g kg⁻¹ respectively) were 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 g kg⁻¹) > C_L (2.02 g kg⁻¹) > C_{VL} (1.35 g kg⁻¹) > C_{LL} (0.75 g kg⁻¹).

Mazumdar *et al.*, (2015) 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 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 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. Fertilizer application has played an important role in improving the total SOC and labile C pools content in the soil.

Because there was low SOC content in the Northwest of India, the long-term application of organic manure and inorganic fertilizer increased the content of SOC. SOC concentrations and storage were highest in surface soil and depth interval down to 60 cm under NP+FYM and NP+S, below which concentrations did not change with depth.

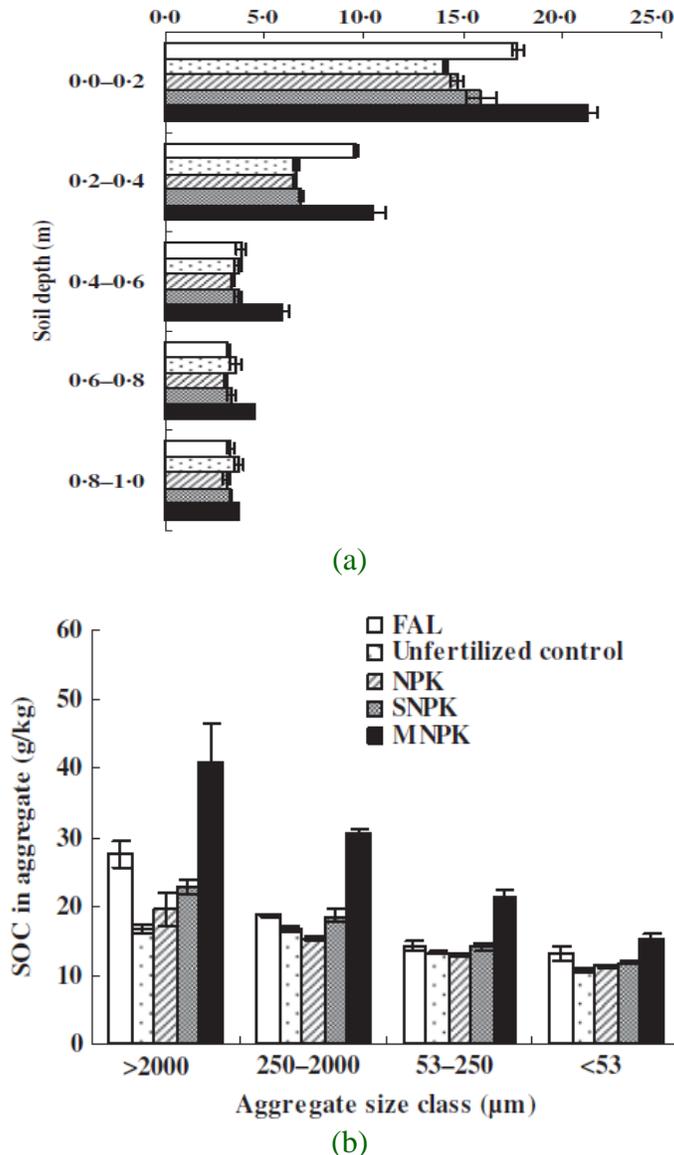


Fig.1 (a) Soil organic carbon (SOC) contents in top 1.0m soil under different fertilization treatments. NPK, balanced inorganic N, P, K fertilizers; SNPK, balanced inorganic fertilizers plus maize straw residues; MNPK, balanced inorganic fertilizers plus farmyard manure
 (b) Soil aggregate distribution in the topsoil (0–0.2 m) under different treatments

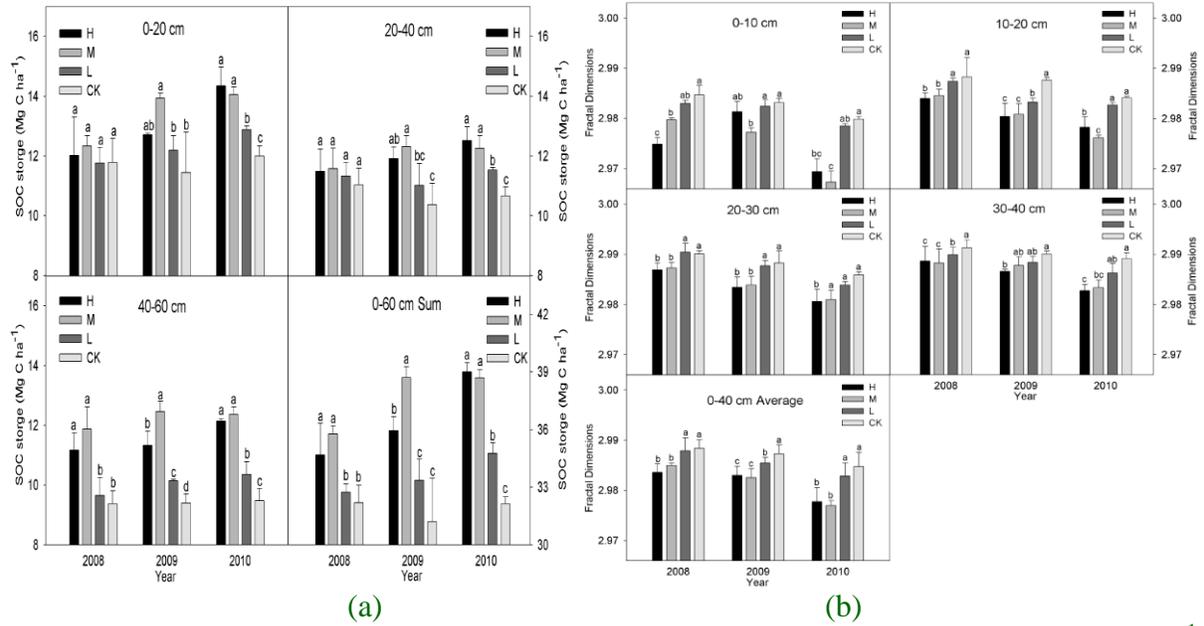


Fig.2 (a) Soil organic carbon storage with different straw incorporation treatments (Mg C ha^{-1}) (b) Fractal dimensions (D) of soil aggregates with different straw incorporation treatments

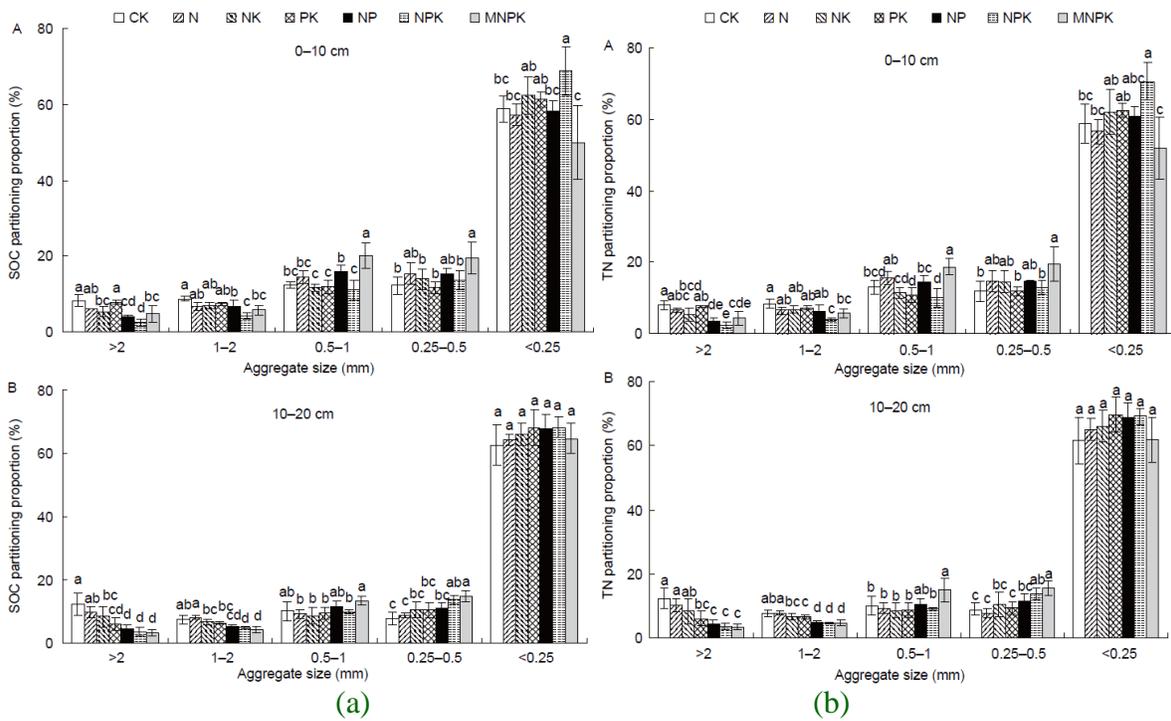


Fig.3 (a) Soil organic carbon (SOC) partitioning proportions (%) in water-stable aggregates in 0–10 cm (A) and 10–20 cm (B) soil horizons under different fertilizer treatments. CK, no nutrient input; N, nitrogen only; NK, nitrogen and potassium; PK, phosphorus and potassium; NP, nitrogen and phosphorus; NPK, nitrogen, phosphorus and potassium; MNPK, manure plus NPK (b) Total nitrogen (TN) partitioning proportions (%) in water-stable aggregates in 0–10 cm (A) and 10–20 cm (B) soil horizons under different fertilizer treatments

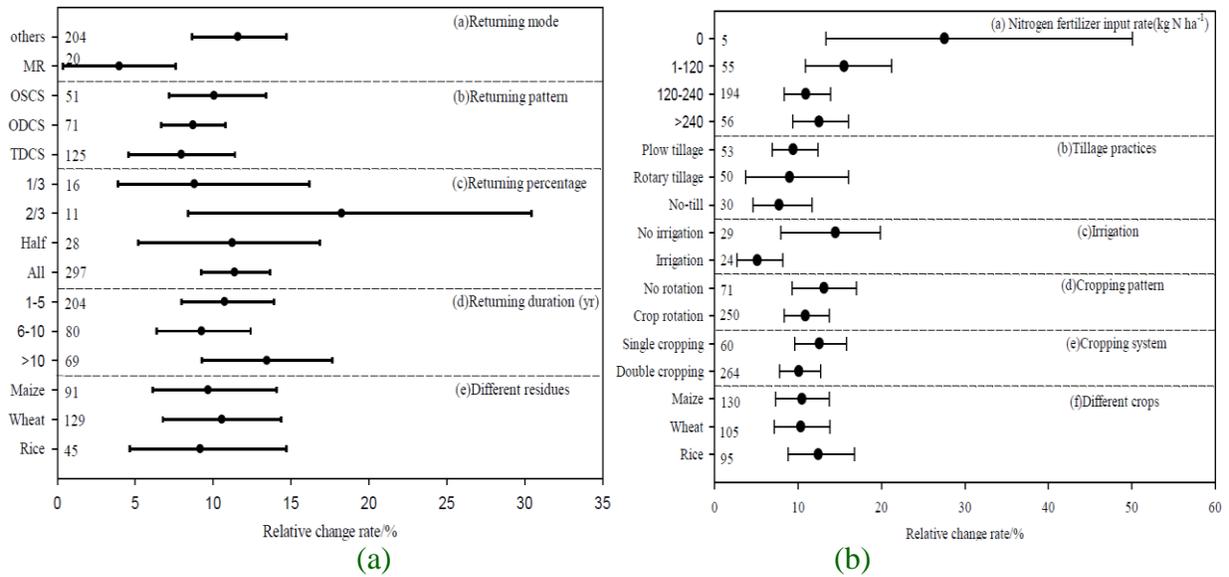


Fig.4 (a) Relative change rate of SOC storage responding to residue retention
 (b) Relative change rate of SOC storage responding to residue retention under field management practices

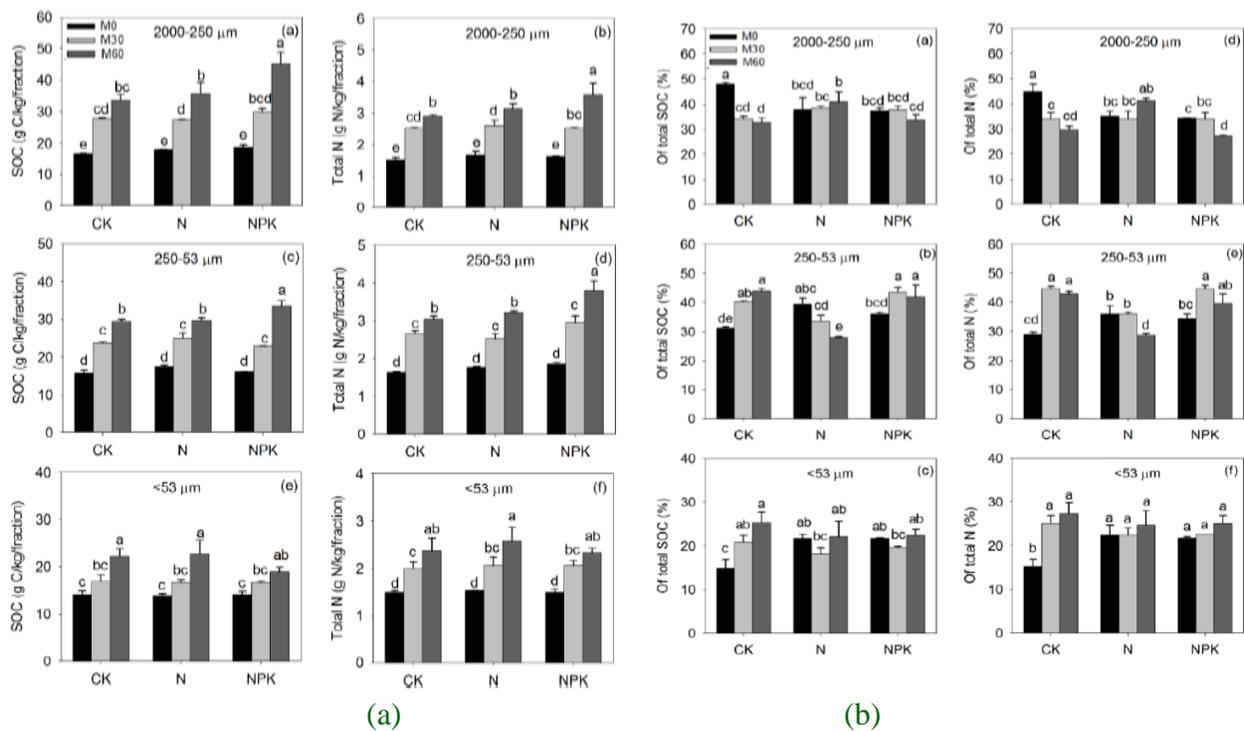


Fig.5 [a] The content of soil organic carbon (SOC) in 2000–250μm (a), 250–53μm (c), <53μm (e) fraction and total nitrogen (N) in 2000– 250μm (b), 250–53μm (d), <53μm (f) fraction from the control (CK); [b] The percent (%) of soil organic carbon (SOC) in 2000–250μm (a), 250–53μm (c), <53μm (e) fraction and total nitrogen (N) in 2000– 250μm (b), 250–53μm (d), <53μm (f) fraction from the control (CK)

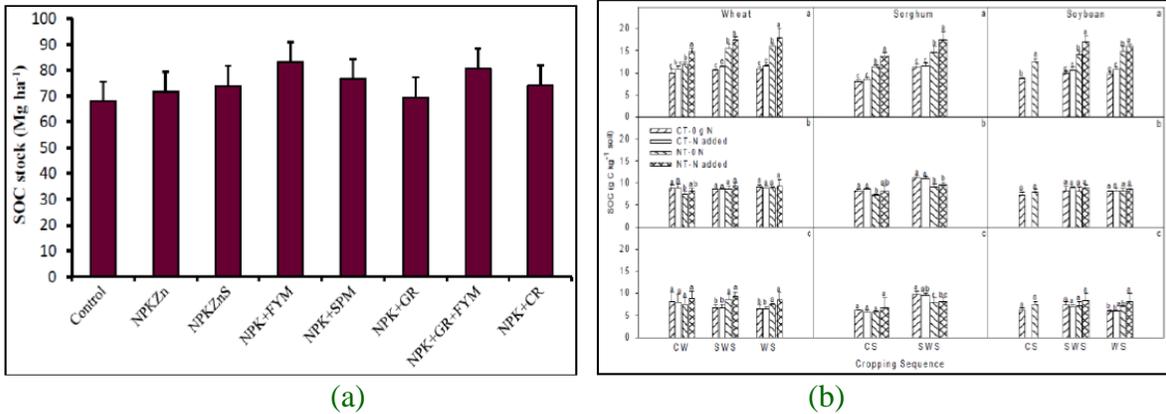


Fig.6 (a) Effect of long-term fertilization and manuring on SOC stock (0-60 cm soil depth) in rice-wheat system; (b) Soil microbial biomass C (SMBC) a); proportion of SOC as soil microbial biomass C (SMBC)

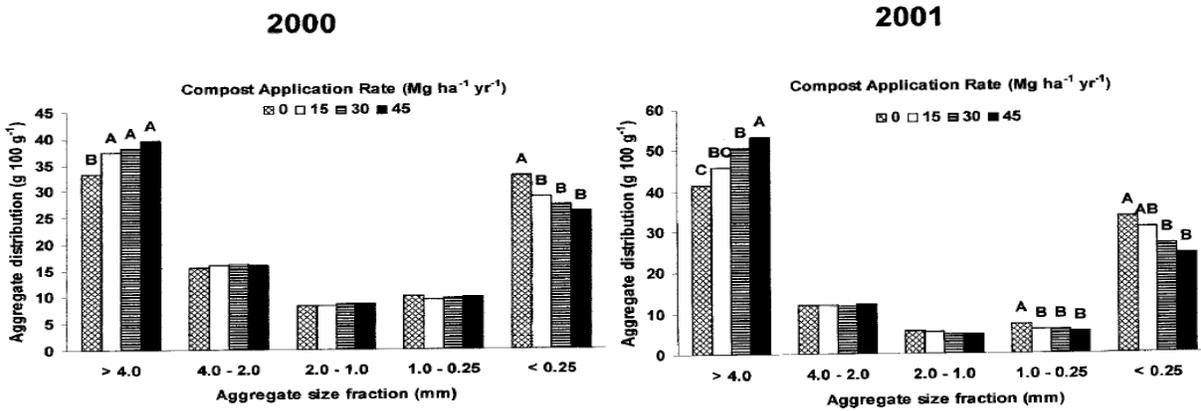


Fig.7 Effect of compost applications on the distribution of water- stable aggregates in 2000 and 2001

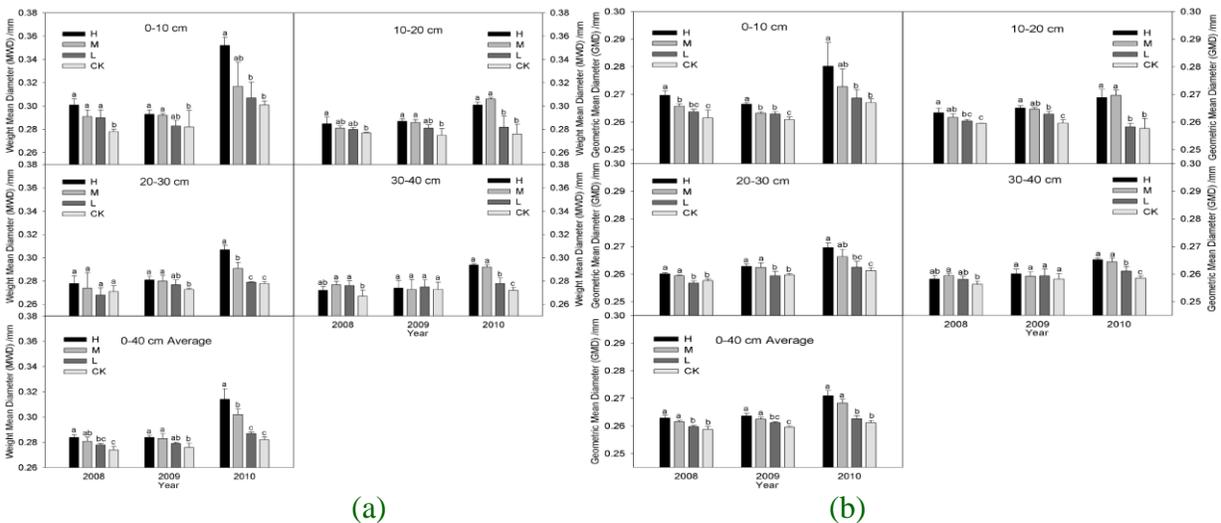


Fig.8 (a) MWD values with wet sieving under the different straw incorporation treatments (b) GMD values with wet sieving under the different straw incorporation treatments

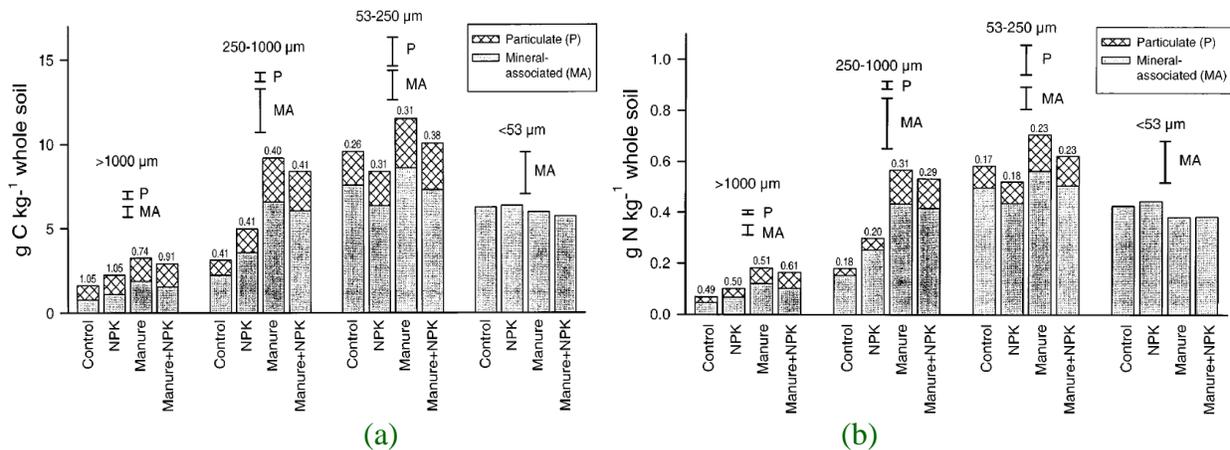


Fig.9 (a) Amount of particulate and mineral-associated C per kg of whole soil
(b) Amount of particulate and mineral-associated N per kg of whole soil

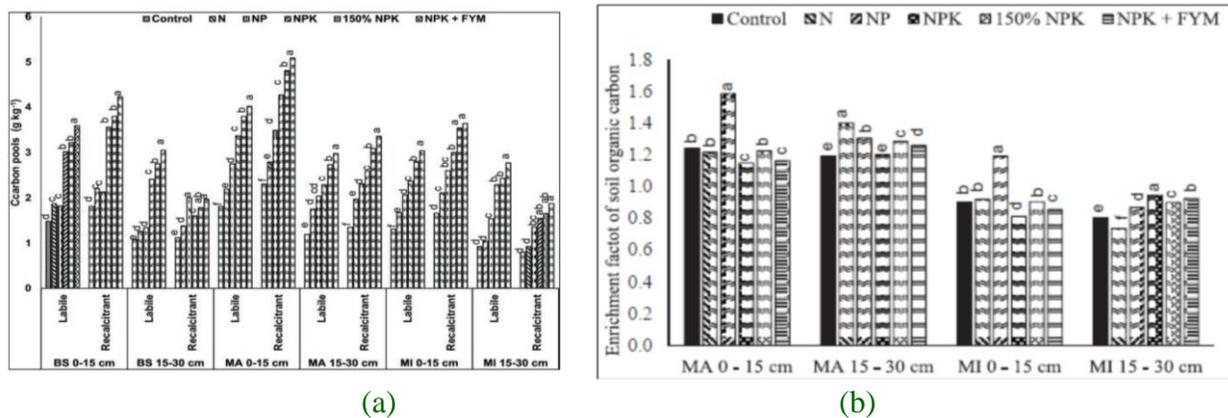


Fig.10 (a) Labile and recalcitrant carbon pools in bulk soils and aggregates as affected by long-term fertilization in the 0-15 and 15-30 cm soil layers under a wheat-based cropping system in an Inceptisol; (b) Enrichment factor of soil organic C (SOC) in aggregates of fertilization under a wheat based cropping system in an Inceptisol. MA: Macro-aggregates, MI: Micro-aggregates, MA 0-15 cm: Macro-aggregates of 0-15 cm soil depth.

At the same time, on average the estimate of soil C storage to 60cm depth was higher than that for soil C accumulated to 20 cm depth and to 40 cm depth, respectively. These findings suggest that the estimate of soil C accumulation to 60 cm depth was more effective than that for soil C accumulated to 20 cm depth and to 40 cm depth. NP+FYM were the most efficient management system for sequestering SOC. A large amount of C was also sequestered in soil under NP+S treatment. Soil microbial biomass C, POC and DOC were all significantly greater under organic manure (farmyard manure or straw)

plus inorganic fertilizers, especially in the surface. The labile fraction organic C contents decreased significantly with increasing soil depth. These labile pools were highly correlated with each other and SOC, indicating that they were sensitive to changes in SOC.

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, 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. 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 CO₂ 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-aggregate

The integrated and organic treatments significantly increased the SOC fractions as compared to the chemical fertilizers alone. This suggests that the inclusion of organic manures in fertilization programs can enhance C sequestration in soils. The sensitivities or changes of labile C fractions (WSC, MBC,

LFC and POM) were much greater than the SOC following the application of fertilizers and/or FYM. Thus, the labile fractions of C may be used as indicators of change in C accumulation following application of fertilizers and/or manures. The application of fertilizers and/or FYM provided another benefit of increase in soil aggregates, which will provide physical protection to SOC resulting in less C emissions from agricultural soils. The SOC storage, 0.25 mm macro-aggregates, MWD and GMD also increased with higher straw incorporation rates. The fractal dimension decreased with increasing straw incorporation rates. The sensitivities or changes of labile C fractions (WSC, MBC, LFC and POM) were much greater than the SOC following the application of fertilizers and/or FYM. Thus, the labile fractions of C may be used as indicators of change in C accumulation following application of fertilizers and/or manures. The application of fertilizers and/or FYM provided another benefit of increase in soil aggregates, which will provide physical protection to SOC The large scale implementation of the straw or manure plus inorganic fertilizer amendments will help to enhance the capacity of carbon sequestration in the region. Therefore, local government should encourage farmers to manage the nutrients and soil fertility based on integrated nutrient management by combining organic matter with inorganic fertilizer to improve soil carbon pools for long-term.

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