The Pharma Innovation Journal 2021; SP-10(12): 739-756

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2021; SP-10(12): 739-756

www.thepharmajournal.com
Received: 11-10-2021
Accepted: 14-11-2021

Conservation tillage and integrated nutrient management impact on soil organic carbon fractions, labile soil organic matter pools and microbial community under rice-wheat cropping system: A review

Rajaram Choudhary, RK Naresh, M Sharath Chandra, Nimay Chandra Giri, K Lokeshwar and Himanshu Tiwari

Rajaram Choudhary
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

RK Naresh
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

M Sharath Chandra
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Nimay Chandra Giri
Department of ECE & CREE, Centurion University of Technology and Management, Odisha, India

K Lokeshwar
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Himanshu Tiwari
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Corresponding Author
Rajaram Choudhary
Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Abstract
Soil tillage can affect the stability and formation of soil aggregates by disrupting soil structure. Frequent tillage deteriorates soil structure and weakens soil aggregates, causing them to be susceptible to decay. Physical, chemical, and biological fractions of SOC pools, such as coarse particulate organic matter C (CPOM-C), microbial biomass carbon (MBC), and mineralizable C (C_{min}) respond to changes in management practices and provide sensitive indication of changes in the SOC dynamics than commonly reported total soil C alone. POC reduction was mainly driven by a decrease in fine POC in topsoil, while DOC was mainly reduced in subsoil. Fine POC, LFOC and microbial biomass can be useful early indicators of changes in topsoil organic C. In contrast, LFOC and DOC are useful indicators for subsoil. Reduced proportions of fine POC, LFOC, DOC and microbial biomass to soil organic 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 difference of total SOC stocks between NT and CT decreased with soil depth, confirming that the SOC benefits of NT are concentrated to the immediate topsoil still subject to direct seeding.

The plots under ZT had nearly 11% and12% higher total SOC and particulate organic matter-C (POM-C) concentrations, respectively, compared with CT (~12 and 4 g kg^{-1} soil, in that order) plots in the 0- to 5-cm soil layer. Plots under F_4 and F_5 had significantly higher total SOC and POM-C contents than F_2 and F_3 treated plots in both soil layers. Although the labile pools of SOC were positively affected by ZT and fertilization, the recalcitrant pool was not. Plots under ZT had higher macro-aggregates, mean weight diameter (MWD), and macro-aggregate-associated SOC compared with CT in the surface soil layer only. Similarly, F_4 or F_5 treated plots had higher macro-aggregates, MWD, and macro-aggregate-associated SOC compared with F_1, F_2, or F_3 treated plots in that layer.

Labile organic carbon (LOC) fractions and related microbial community in soils are considered to be early and sensitive indicators of soil quality changes. The tillage treatments significantly influenced soil aggregate stability and OC distribution. Higher MWD and GMD were observed in plowing every 2 years (2TS), plowing every 4 years (4TS) and no plowing (NTS) as compared to plowing every year without residue (T). With increasing soil depth, the amount of macro-aggregates and MWD and GMD values were increased, while the proportions of micro-aggregates and the silt+ clay fraction were declined. The OC concentrations in different aggregate fractions at all soil depths followed the order of macro-aggregates>micro-aggregates>silt+ clay fraction. In the 0-5 cm soil layer, concentrations of macro-aggregate-associated OC in 2TS, 4TS and NTS were 14, 56 and 83% higher than for T, whereas T had the greatest concentration of OC associated with the silt+ clay fraction in the 10-20 cm layer. Total organic C increased significantly with the integrated use of fertilisers and organic sources (from 13 to 16.03 g kg^{-1}) compared with unfertilized control (11.5 g kg^{-1}) or sole fertiliser (NPKZn; 12.17 g kg^{-1}) treatment at 0–7.5 cm soil depth. Averaged across soil depths, labile fractions like microbial biomass C (MBC) and permanganate-oxidisable C (PmOC) were generally higher in treatments that received farmyard manure (FYM), sulfitation pressmud (SPM) or green gram residue (GR) along with NPK fertiliser, ranging from 192 to 276 mg kg^{-1} and from 0.60 to 0.75 g kg^{-1} respectively compared with NPKZn and NPK + cereal residue (CR) treatments, in which MBC and PmOC ranged from 118 to 170 mg kg^{-1} and from 0.43 to 0.57 g kg^{-1} respectively. 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.

Keywords: tillage and fertilization, rice-wheat system, soil organic carbon (SOC), labile carbon fractions

Introduction
Soils on Earth contain approximately 2,344 Gt organic carbons (C), which is three times more C than in the atmosphere, and soil is often regarded as the second largest organic C pool after the ocean (Stockmann *et al*., 2013) [37].

The labile fractions of carbon are susceptible to short-term turnover. Because LOC has a much shorter turnover time and greater turnover rate than more stable organic carbon in soils, it responds more quickly to changes in management practices. The strong biological activity of LOC fractions means that they play a crucial role in carbon cycling, and they may be regarded as early and sensitive indicators of soil organic C (SOC) changes (Banger *et al*., 2010) [1].

Fertilization and organic matter input to soil through management practices such as balanced fertilization (NPK application) and integrated nutrient management through NPK + FYM or PM application increase the SOC content (Bhattacharyya *et al*., 2011) [3] and enhance soil aggregation (Naresh *et al*., 2015). Farmyard manure largely consists of coarse particles of organic materials that produces transient binding agents and increases microbial activity in soils upon decomposition (Gulde *et al*., 2008) [14]. Poultry manure consists of fine as well as coarse particles of organic materials that also improve soil aggregation. Hence, animal manure application has a positive impact on aggregation that may lead to a greater physically protected SOC and thus is a potential technique for increased SOC stabilization and C sequestration. Thus, it is very imperative to better understand conservation tillage and manure addition effects on the process of C stabilization.

Labile organic carbon is easily mineralized, and it is directly available for microbial activity. It originates from the decomposition of plant litter, root exudates, hydrolysis of soil organic matter, microbes, and their metabolic products (Liu *et al*., 2006) [20]. Dissolved organic carbon (DOC) refers to organic carbon in the soil solution, which is directly involved in soil biochemical process (Jin *et al*., 2020) [18]. Particulate organic carbon (POC) is determined by particle size. It consists of un-decomposed or semi-decomposed microbial biomass, plants, and root residues (Bongiorno *et al*., 2019) [4]. Permanganate oxidizable carbon (POXC) and microbial biomass carbon (MBC) are important carbon fractions that regulate key processes such as nutrient cycling and its availability, soil aggregation, and soil carbon accrual (Culman *et al*., 2012) [7]. Labile organic carbon fractions include various components, characterized by short turnovers; hence, they are considered to be more sensitive indicators of agricultural managements, as compared to SOC (Nandan *et al*., 2019) [27]. Soil aggregates are basic units of soil structure. Aggregate-protected soil organic matter is an important platform for organic carbon stabilization (Okolo *et al*., 2020) [29]. It is reported that macro-aggregates (>0.25 mm) make a larger contribution to SOC accumulation than micro-aggregates (Six *et al*., 2000) [34].

In the present review study, we hypothesized that long-term application of crop straw would increase soil organic matter (SOM) quality by increasing LOC fractions and by stimulating related microbial community activities secreted by microorganisms. We sought to document specific changes in LOC pools, the potential activities of soil microbial community related to conservation tillage, and the relationships among LOC fractions and microbial community activities. The objectives of this study were to: (1) investigate the effects of continuous organic and organic plus inorganic fertilizers (INM) management on total SOC and labile fractions of SOC; (2) examine the effects of organic plus inorganic fertilizers on potential microbial community activities related to conservation tillage; (3) the relationships among LOC fractions and potential microbial community activities; and (4) explore the carbon pool management index (CPMI) as an early indicator of changes in SOM quality.

Soil Organic Carbon Distribution

Shen *et al*. (2021) [33] reported that the content of SOC was higher in micro-aggregates than in macro-aggregates under all tillage treatments. Furthermore, there was a trend that SOC content substantially increased with the decrease in aggregate particle sizes in RT, SS, and NT treatments. However, in DP treatment there was no statistical difference in the organic carbon contents among four sizes of macro-aggregates. Compared to RT treatment, NT treatment showed significantly higher organic carbon content in >5 mm in 2–1 mm and <0.25 mm aggregates. Organic carbon content in DP treatment was higher than RT in >5 mm aggregates, while it was lower in 1–0.25 mm and, <0.25 mm aggregates. Besides, SS treatment also had lower organic carbon content than RT treatment in 1–0.25 mm and <0.25mm aggregates (Fig.1a).

Guo *et al*. (2019) [15] revealed that fertilizer applications significantly increased the amount of TOC, POC, and MOC compared to the CK when only a depth of 0–5 cm was considered (Fig.1b). Significant accumulation of TOC, POC, and MOC at a depth of 0–15 cm occurred in accordance with their concentration (Fig.1b). On average, the mean TOC, POC, and MOC contents in the 0–40 cm layer were 14.8–51.9%, 48.9–146.9%, and 3.9–23.3% higher, respectively, after long-term mineral or organic fertilization compared to those in the CK soil. MOC accounted for about 51.5–88.2% of TOC at a depth of 0–40 cm and, therefore, represented the majority of the soil organic carbon, while POC has a minor TOC proportion 11.8–48.5%.

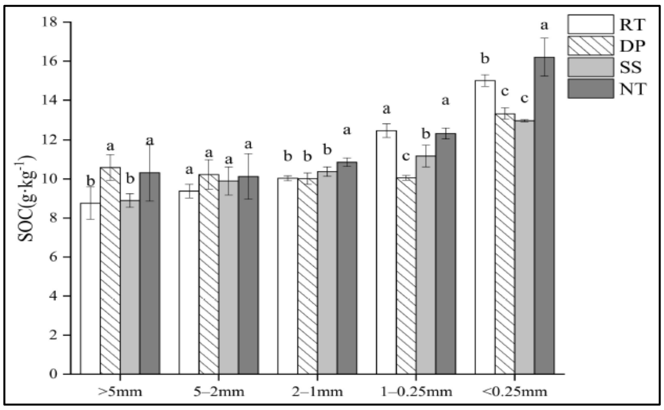

Fig 1a: Effects of tillage on SOC content in aggregates. Different filling types refer to different treatments. RT: rotary tillage, DP: deep ploughing, SS: subsoiling, NT: no tillage [Source: Shen *et al*., 2021] [33].

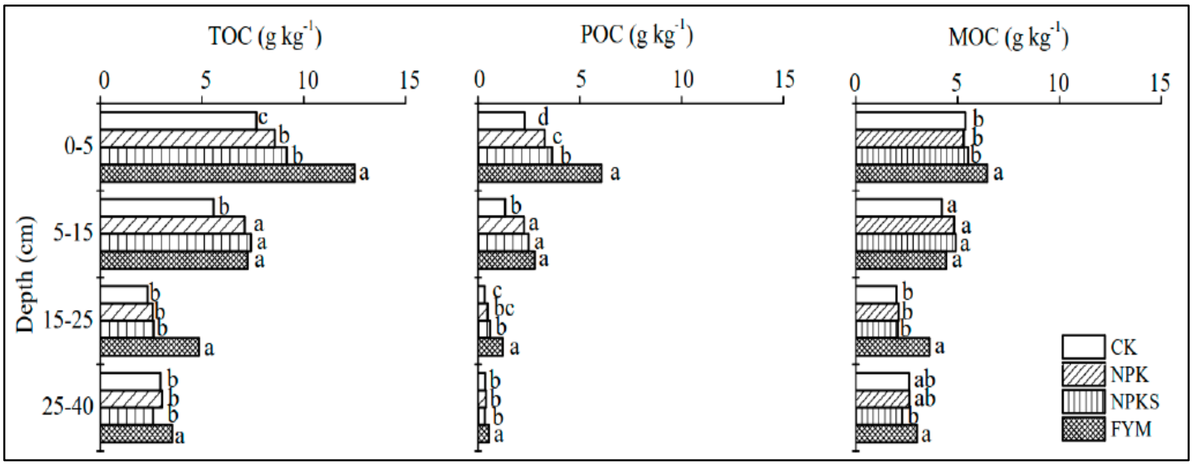

Fig 1b: Effects of fertilizer system on soil organic carbon content [Source: Guo *et al*., 2019] [15].

Choudhary *et al*. (2014) [6] revealed that compared to conventional tillage, water stable macro-aggregates in conservation 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). In surface soil, the maximum (19.2%) and minimum (8.9%) proportion of total aggregated carbon was retained with >2 mm and 0.1–0.05 mm size fractions, respectively. DSR combined with zero tillage in wheat along with residue retention (T6) had the highest capability to hold the organic carbon in surface (11.57 g kg^{-1} soil aggregates) with the highest stratification ratio of SOC (1.5). Moreover, it could show the highest carbon preservation capacity (CPC) of coarse macro and meso-aggregates. A considerable proportion of the total SOC was found to be captured by the macro-aggregates (>2–0.25 mm) under both surface (67.1%) and sub-surface layers (66.7%) leaving rest amount in micro-aggregates and 'silt + clay' sized particles.

Naresh *et al*. (2017) [28] indicates that SOC generally accumulates with increasing rate of N fertilizer application. The average N fertilizer rate to achieve maximum SOC sequestration (0.28 Mg C ha^{-1} yr^{-1}) was 171 kg $Nha^{-1}yr^{-1}$ well within the range of values often reported to maximize cereal crop yields. However, when considering the C costs of N fertilizer (i.e. manufacturing, distribution and application), the optimum N fertilizer rate was 107-120 $kgha^{-1}yr^{-1}$ based on C costs of 0.98 [0.86 + 0.08 + 0.04] to 1.23 kg C kg^{-1} for production, application, and liming components, respectively. Zibilsk *et al*. (2002) reported that the No-till resulted in significantly greater soil organic C in the top 4 cm of soil, where the organic C concentration was 58% greater than in the top 4 cm of the plow-till treatment. In the 4–8 cm depth, organic C was 15% greater than the plow-till control [Fig.2a]. The relatively low amount of readily oxidizable C (ROC) in all tillage treatments suggests that much of the soil organic C gained is humic in nature which would be expected to improve C sequestration in this soil [Fig.2b].

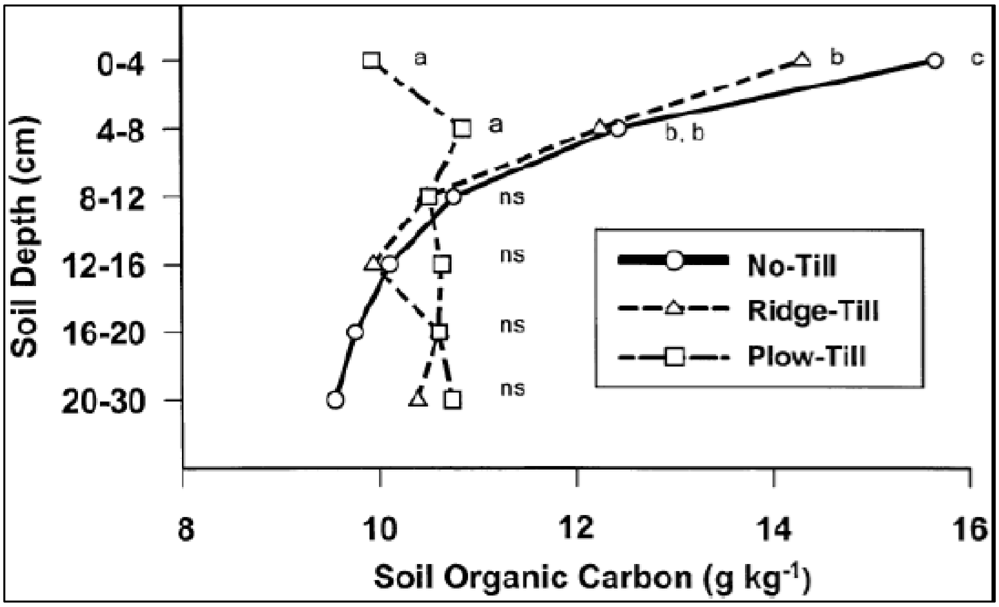

Fig 2(a): Soil organic carbon by depth after 9 years of no-till, ridge-till or plow-till treatment [Source: Zibilsk *et al*., 2002]

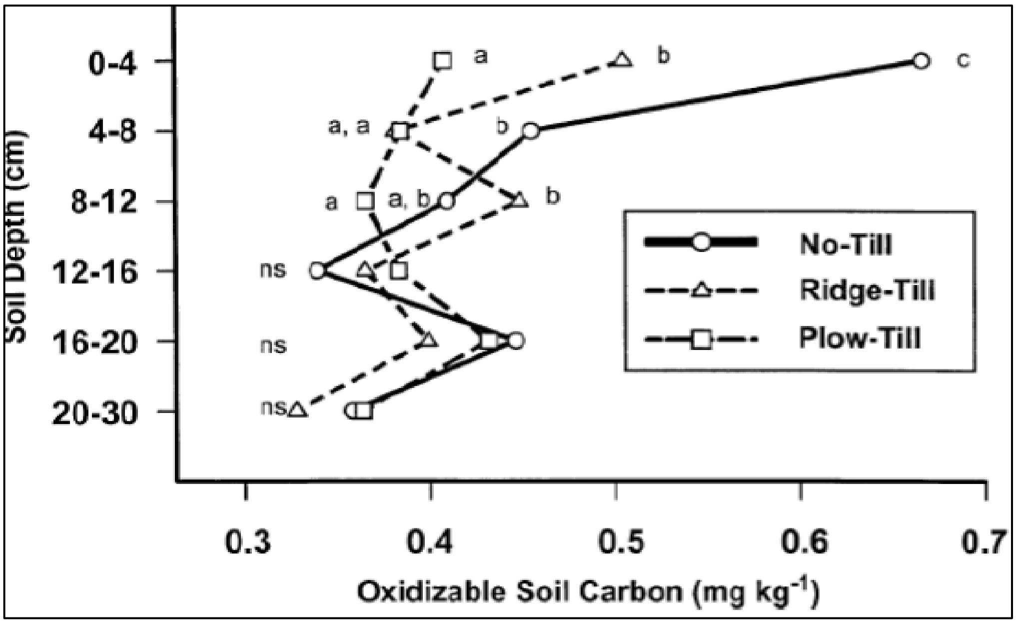

Fig 2(b): Readily oxidizable soil carbon by depth after 9 years of no-till, ridge-till or plow-till treatment [Source: Zibilsk *et al*., 2002]

Jacinthe and Lal, (2009) [17] concluded that the rates of C sequestration were estimated from the temporal trend in the recent SOC pool (0– 40 cm in NR (23.2 Mg C ha^{-1}), 9-yr MP (32.9 Mg C ha^{-1}) and 13-yr MP (33 Mg C ha^{-1}), and ranged between 0.8 and 0.25 Mg C ha^{-1} yr^{-1} during the first and second decades of restoration. Despite a similar amount of crop residue returned (2.8 Mg C ha^{-1} yr^{-1}), recent SOC under 13-yr NT (36.8 Mg C ha^{-1}) exceeded that under 13-yr MP by 3.8 Mg C ha^{-1}.

Huggins *et al*. (2014) revealed that tillage by crop sequence interactions occurred as treatments with MP and SS as well as fallow averaged 135 Mg SOC ha^{-1} (0- to 45-cm depth), while CP treatments with corn (CC and CS) and NT with CC averaged 164 Mg SOC ha^{-1}. Crop sequence effects on SOC (0- to 45-cm depth) occurred when tillage was reduced with CP and NT averaging 15% greater SOC in CC than SS. Depth distributions of SOC provide further data on interactive effects of tillage and differences in crop C inputs associated with crop sequence. Under reduced tillage (CP and NT), the SOC in CC was significantly greater than in SS at all depths with the exception of the 15- to 30-cm depth in NT. In addition to less C inputs than CC, SS accelerated rates of SOC decomposition. Tillage effects on SOC were greatest in CC where CP had 26% and NT 20% more SOC than MP, whereas SOC in SS was similar across tillage treatments. Up to 33% of the greater SOC under CC for CP and NT, compared with MP, occurred below tillage operating depths. Substantial losses of SOC were estimated (1.6 Mg SOC ha^{-1} yr^{-1}) despite lowering SOC decay rates with reduced tillage and high levels of C inputs with CC.

Miao *et al*. (2018) [26] also found that the content of soil microbial biomass C (SMBC) and soil soluble organic C (SSOC) decreased with soil depth (Fig. 3a). The SMBC content at the 0–60 cm depth under the SM and RF treatments was significantly higher than that of the FA soil. SMBC content did not significantly differ among the soil samples subjected to the CC, SM, and RF treatments, with the exception of the 0–20 cm depth. The SSOC content of soil samples subjected to the CC, SM, and RF treatments was greater than that of the FA soil. The N fertilization rates showed no distinct effect on the content of SMBC or SSOC at the 0–60 cm soil depth.

Figure 3a showed that about 50% of SOC stock was accumulated in the upper 40 cm depth. At the 0–20 cm depth, SOC stock increased by 3.4%, 13.3%, and 10.1%, respectively, in the soil samples subjected to the CC, SM, and RF treatments, in comparison to that of the FA soil. Similar to the SOC stock, the SIC stock at the 0–40 cm depth accounted for 75.9%–78.8% of total SIC stock (Fig. 3b). Average SIC stock significantly increased by 7.6%–9.9% at the 0–20 cm depth, 19.1%–24.6% at the 20–40 cm depth, and 38.2%–39.6% at the 40–60 cm depth at the soil samples subjected to the CC, SM, and RF treatments, respectively, in comparison to that of the FA soil.

The SOC stocks at the 0–100 cm depth subjected to different N application rates were in the following decreasing order: N120 (86.3 Mg/hm^2)>N0 (85.3 Mg/hm^2)>N240 (84.3 Mg/hm2) (Fig. 3c). On the contrary, SIC stock decreased as the rate of N addition increased (Fig. 3d). At the 0–100 cm depth, SOC stocks ranged from 83.7 to 85.8 Mg/hm^2, and did not significantly differ among the fallow and the tested cultivation treatments. SIC stocks ranged from 58.8 to 70.0 Mg/hm^2 among the soil samples. SIC stock was significantly increased by 18.7% in the soil samples subjected to the crop cultivation treatments in comparison to that of the FA soil (Fig. 4a).

N fertilization rates did not affect SOC, SIC, or total carbon (TC) stock for the entire 0–100 cm soil depth (Fig. 4b). SOC content accounted for 54.3%–59.0% of TC within the 0–100 cm soil depth, whereas SIC content accounted for 41.0%–45.7%.

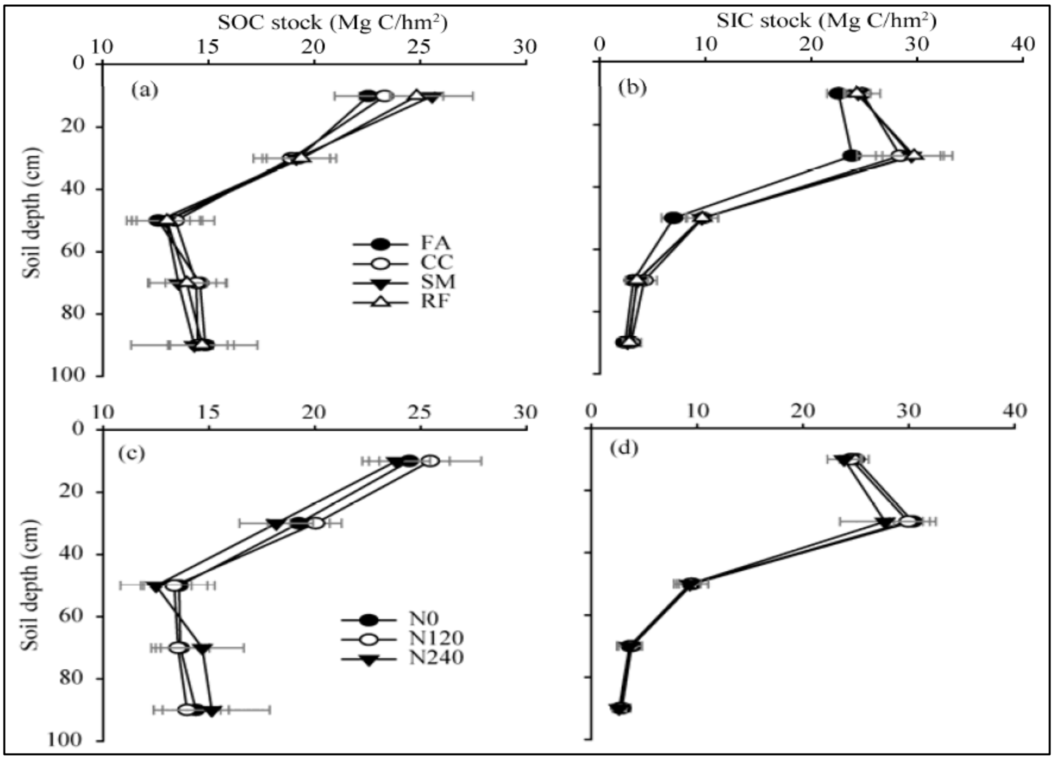

Fig 3a: Stocks of soil organic carbon (SOC) and soil inorganic carbon (SIC) under different cultivation practices (a, b) and N fertilization rates (c, d). FA, fallow; CC, conventional cultivation; SM, straw mulch; RF, plastic film-mulched ridge and straw-mulched furrow; N0, 0 kg N/hm^2; N120, 120 kg N/hm^2; N240, 240 kg N/hm^2 [Source: Miao *et al*., 2018] [26]

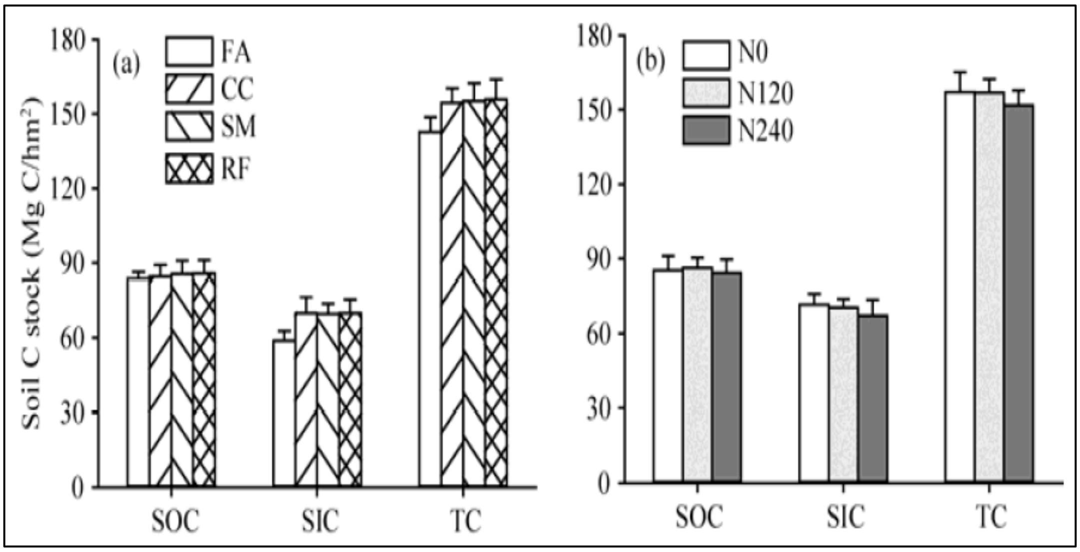

Fig 3b: Stocks of soil organic C (SOC), soil inorganic C (SIC), and total C (TC=SOC+SIC) for the entire 0–100 cm soil depth under different cultivation practices (a) and N fertilization rates (b). FA, fallow; CC, conventional cultivation; SM, straw mulch; RF, plastic film-mulched ridge and straw-mulched furrow; N0, 0 kg N/hm^2; N120,120 kg N/hm^2; N240, 240 kg N/hm^2 [Source: Miao *et al*., 2018] [26]

Manjaiah and Singh (2001) [24] 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 (Lorenz *et al*., 2005) [22]. Applying straw with N and P fertilizer (NP+S) had the highest total C input yet decreased SOC concentration over the FYM with NP fertilizer treatment. As NP+FYM treatment significantly increased SOC concentration, this suggests that animal manure is more effective in building soil C than straw, possibly due to the presence of more humified and recalcitrant C forms in animal manure as compared to the straw. For the inorganic fertilizer treatment, the optimum application of inorganic fertilizer NP treatment showed a higher SOC concentration over the application of inorganic fertilizer N treatment at all the sampling depths. The optimum fertilization results in better plant growth including the root biomass which could have added to the SOC particularly as indicated in the lower layers.

Gami *et al*. (2009) [13] 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. 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, 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 40 cm.

Labile Organic Carbon Fractions Distribution

Shen *et al*. (2021) [33] observed that DOC and POXC content increased with the decrease in aggregate particle sizes in all treatments. Compared with RT treatment, DP and NT treatments showed significantly higher DOC content in large size macro-aggregates. However, significant lower DOC values were found in micro-aggregates in DP treatment. It was 1–0.25 mm macro-aggregates that showed the highest POC content in RT, DP, and SS treatments, while it was 5–2 mm in NT treatment. DP, SS, and NT treatments showed lower POC content in small size macro-aggregates and micro-aggregates (Fig.4a). Only NT treatment showed significantly higher POC in large macro-aggregates. Compared with RT treatment, SS and NT treatments contained lower MBC content in all particle sizes aggregates. In DP treatment, there were higher values of MBC content in 5–2mm and 2–1mm aggregates, while lower values of that in 1–0.25 mm and <0.25 mm aggregates than RT. Regarding POXC content, DP treatment showed significantly higher POXC content in all aggregate sizes. While the values in SS treatment were significantly lower (Fig.4a). NT treatment showed higher POXC in macro-aggregates but lower values in micro-aggregates than RT.

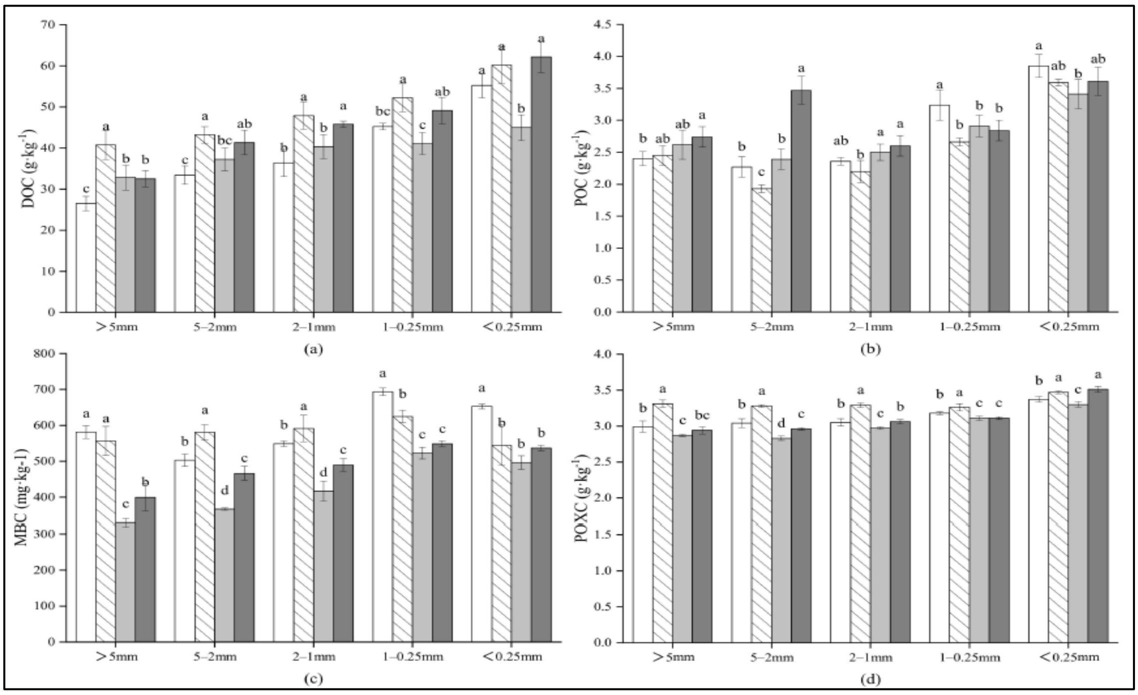

Fig 4a: Effects of tillage on DOC, POC, MBC, and POXC content in aggregates. Shown is the data for: (**a**) DOC content in aggregates; (**b**) POC content in aggregates; (**c**) MBC content in aggregates; (**d**) POXC content in aggregates [Source: Shen *et al*., 2021] [33]

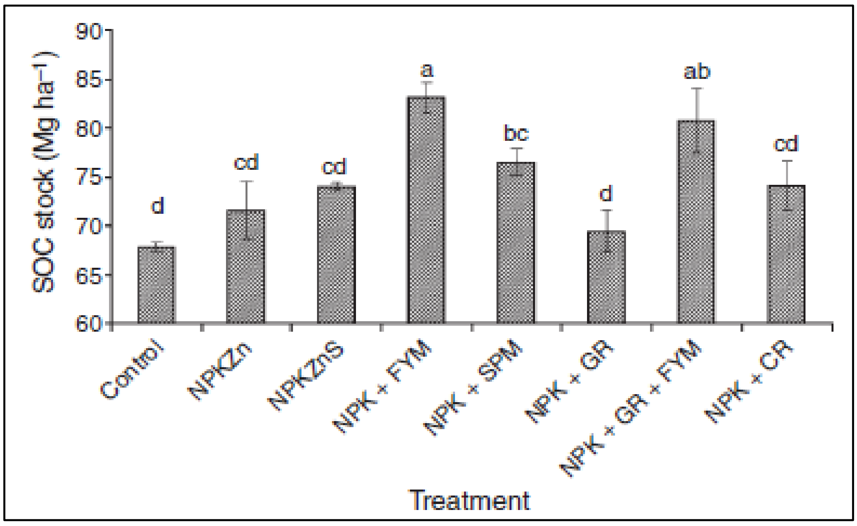

Fig 4b: Effects of long-term fertilization and manuring on soil organic carbon (SOC) stock (0–60 cm soil depth) in the rice–wheat system [Das *et al*., 2016] [8]

Das *et al*. (2016) [8] observed that the SOC stock of the 0–60 cm profile ranged from 67.9 to 83.1Mgha^{-1} under different nutrient management options (Fig. 4b). Unfertilized control had the lowest SOC stock, which was statistically at par with sole fertilizer treatments or two IPNS treatments (NPK +GR and NPK + CR). The SOC stock under NPK+ SPM treatment was significantly greater compared with control, and increased further in the NPK +FYM and NPK +GR +FYM treatments. A significant decline in WBC with increasing soil depth was apparent, because the WBC at the 15–30 cm soil depth was less than half that at the 0–7.5 cm depth. Highest WBC was recorded under the NPK +GR +FYM treatment, followed by the NPK + FYM and NPK+ CR or NPK + SPM treatments. Application of fertilizers alone also increased WBC significantly over that in the unfertilized control, although IPNS was generally superior to sole fertilizer use. Compared with uncultivated soil, WBC decreased by 14–26% at different soil depths under unfertilized control conditions. Conversely, RWS with conjoint use of fertilizers and manure increased WBC in topsoil (0–7.5 cm) over the years, ranging from 24% under the NPK+GR treatment to as high as 58% under the NPK +GR +FYM treatment. The corresponding magnitude of the increase in WBC at the 7.5–15 cm depth over uncultivated soil ranged between 10% and 31%. The increases in WBC under sole fertilizer treatments (i.e. NPKZn or NPKZnS) were relatively small. The greater improvement in WBC with FYM than with SPM observed in the present study was due to the fact that SPM is not as rich a source of C as FYM (Mandal *et al*., 2013).

Dong *et al*. (2009) [10] suggested that intensive tillage may result in less immobilization of soil carbon by microorganisms. Six *et al*. (2000) [34] suggested that the development of POC is an important mechanism by which organic carbon was stored in no tillage soil. Firstly, soil particles combine plant residues into macro-aggregates. Then the POC and organic binding agents are polymerized into micro-aggregates to be protected. Xiao *et al*. (2019) [40] reported that tillage disturbance increases microbial metabolic activity and increased MBC content. This may be caused by the releasing of POC in macro-aggregates. Zhong and Zeng, (2019) [41] also found that NT treatment might show higher MBC content after long-term conservation tillage because of its minimum disturbance to microbial habitats.

Das *et al*. (2016) [8] reported that among the OOC fractions (Table 1), 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 C_{VL} increased significantly under IPNS treatments, with particularly high values (2.51 g kg^{-1}) the highest C_{VL} 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 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. *Labile C* averaged across treatments, C_L was highest at the 0–7.5 cm depth (2.81gkg^{-1}), followed by the 7.5–15 and 15–30 cm soil depths (2.13 and 1.11 g kg^{-1} respectively; Table 1). Similarly, across soil depths, the lowest C_L content was seen in the unfertilized control treatment (1.40 g kg^{-1}), whereas the highest was seen in the NPK+GR +FYM treatment (2.46 g kg^{-1}). The C_L content under the NPK+ FYM treatment (2.32 g kg^{-1}) was statistically on par with that in the NPK +GR +FYM treatment. Changes in C_L under different treatments compared with uncultivated soil followed a pattern similar to that seen for C_{VL} content.

Less-labile C like C_{VL} or CL, the C_{LL} content also decreased sharply with increasing soil depth (Table 1). However, the effects of treatment on C_{LL} differed from those on C_{VL} and C_L, because C_{LL} was highest under the NPK+ CR treatment, followed by the NPKZn treatment (1.16 and 1.09 g kg^{-1} respectively). The C_{LL} content under IPNS treatments involving GR, FYM or SPM was invariably lower (0.51–0.70 g kg^{-1}) than that under NPK +CR or sole fertilizer treatments. Compared with the adjacent uncultivated soil (Table 1), the C_{LL} content was highest under the NPK + CR followed by the NPKZn treatment, with increases of 145% and 110% respectively at the 0–7.5 cm depth, and 60% and 46% respectively at the 7.5–15 cm depth. However, at the 15–30 cm depth, C_{LL} invariably decreased in all treatments and the reduction over uncultivated soil was in the range 15–66%. *Non-labile C* the C_{NL} content at the 0–7.5, 7.5–15 and 15–30 cm soil depths varied, with values in the range 7.23– 10.07, 6.73–8.63 and 4.30–6.40 gkg^{-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}).

Table 1: Oxidisable organic C fractions under long-term fertilization (NPK, NPKZn, NPKZnS) and manure treatments in an Inceptisol of Modipuram, India [Source: Das *et al*., 2016) [8]

Soil Depth (cm)	Control	NPKZn	NPKZnS	NPK+FYM	NPK+SPM	NPK+GR	NPK+GR+FYM	NPK+CR	Mean
CVL(gkg^{-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.sd.(P<0.05):T=0.10;D=0.06;T x D =0.17									
C_L(gkg^{-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;TxD=0.31									
C_{LL}(gkg^{-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.sd(P<0.05):T=0.06;D=0.04;TxD=0.10									
CNL(gkg^{-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.sd(P,0.05): T=0.47; D+0.29:T x 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

Bhardwaj *et al*. (2019) [2] reported that Oxidizable C was the maximum in FYM followed by GM and crop residue (WS, RS) treatments in the surface 0.15 m soil (Fig 5a). At the lower depths (0.15–0.30 m), there was no significant difference in the oxidizable C for any management. At both depths O and F accumulated least oxidizable C. VLc (very labile C) and LLc (less labile C) fractions constituted a major part of soil organic C, for all managements. All integrated nutrient management (INM) accumulated a similar amount of VLc fraction for all measured depths. GM accumulated the maximum Lc fraction at the surface 0–0.15 m. The LLc fraction was maximum in FYM which was followed by all other integrated nutrient managements. Management O had least LLc fraction in surface 0.15 m. There was no difference in NLc fraction for any of the treatments, for any measured depth.

There was 46 to 65% decrease in oxidizable C, from the surface (0–0.15 m) to lower layer (0.15–0.30 m). Change in soil C content was directly related to the C input to the soil (Fig. 5a). In general, the most increases were in the VLc and the LLc fractions of soil C in all management. With an increase in C input, the most significant increase was noticed in the Lc (labile C) and the LLc (less labile C) fractions. Management FYM had maximum contributions to the LLc and the VLc fractions while GM had a maximum contribution to Lc. Non-labile (NLc) C fraction changed little with increased total C input to the soil in different treatments.

Moreover, significantly higher carbon sequestration potential (CSP) was noted for FYM, GM and WS management, for shallower depths (0–0.15 m) (Fig. 5b). For lower depths (0.15– 0.30 m), there were no significant differences amongst management. Different managements and C inputs led to significant variation in bulk density only for surface 0.15 m soil. LE and GM had the least bulk density at this depth while there were no significant differences at 0.15–0.30 m. Consequent of C inputs and bulk density changes; soil C stock was maximum in FYM, GM, and WS for 0.15 m. For all depths, O had the least organic C stock. Drinkwater *et al.* (1998) [12] had similar observations wherein manure and legume-based systems had higher storage of soil carbon and nitrogen despite no quantitative differences in C inputs. The qualitative differences (C: N ratio, decomposability) contributed to differences in soil organic C stocks, thus Farmyard manure (FYM) based management involving the input of highly decomposed organic matter, with more stable C components, not only resulted in higher total C stock but also most of it was in less labile fraction (LLc). Legume-based managements (GM, LE) also had higher organic C stock at all depths. This disproves the conventional notion that biomass quality in agricultural systems may not play a significant role in C storage in soil.

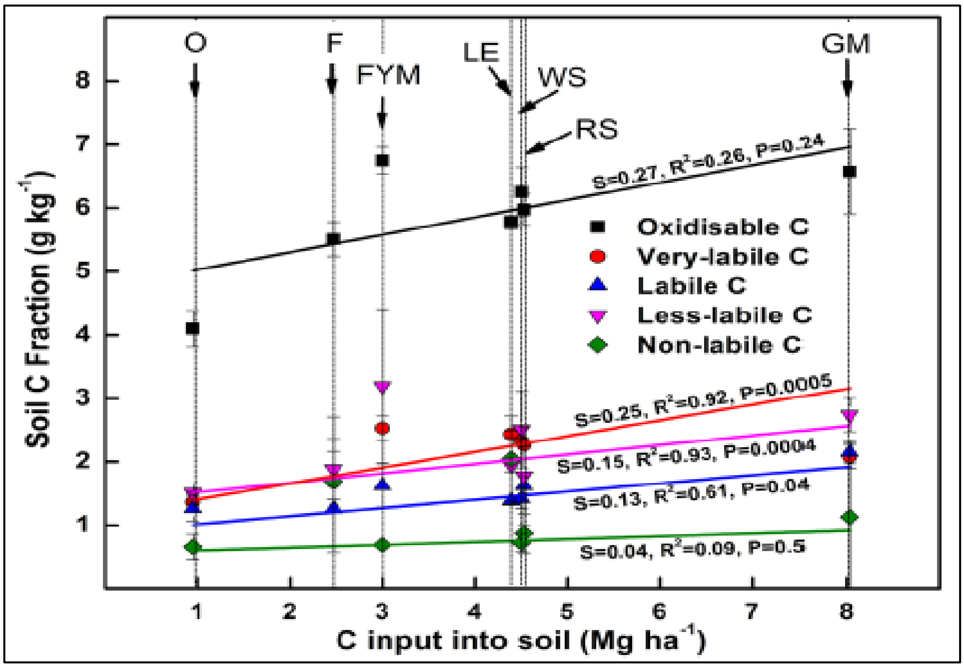

Fig 5a: Relationship between carbon (C) input into the soil and soil C fractions under different nutrient management. O = no fertilizer, F = 100% inorganic fertilizers, LE = opportunity legume crop (*Vigna radiata*), GM = green manuring, FYM = farmyard manure, WS = wheat stubble, RS = rice stubble [Source: Bhardwaj *et al*., 2019] [2]

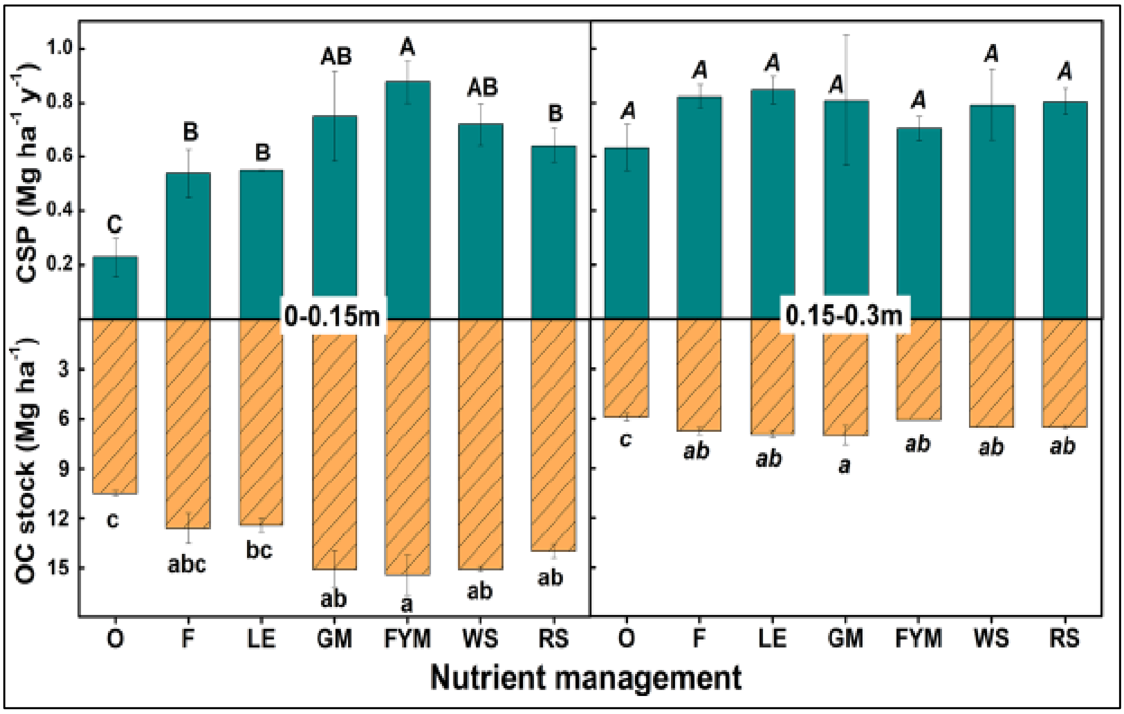

Fig 5b: Carbon (C) sequestration potential (CSP) and soil C stock under different nutrient management after 10 years of initiation (2005–2015). O = no fertilizer, F = 100% inorganic fertilizers, LE = opportunity legume crop (*Vigna radiata*), GM = green manuring, FYM = farmyard manure, WS = wheat stubble, RS = rice stubble, OC = organic carbon, CSP = carbon sequestration potential [Source: Bhardwaj *et al*., 2019] [2]

Pant *et al*. (2020) [30] reported that particulate organic carbon was found stratified along with soil depths (Fig. 6 (a, b)). A higher POC was found in surface soil decreasing with depth after harvest of both crops. Maximum POC content was obtained in soil at all depths where 100% NPK was applied along with FYM followed by 150% NPK. At 0–15 cm, POC content under 100% NPK+FYM and 150% NPK treatments over control were 551% and 405% higher after rice harvest and 445% and 210% higher after wheat harvest, respectively. Continuous application of NPK with FYM in rice-wheat system resulted in significantly higher POC over control at 0–15 cm soil depth. Purakayastha *et al*. (2008) [32] concluded that FYM can increase the root biomass and microbial biomass debris which is the main source of POC. In 15–30, 30–45 and 45–60 cm soil layers also had the maximum POC in the same treatment significantly higher with other treatments. There was greater accumulation of POC due to supplementation of FYM with NPK (Nayak *et al*. 2012). Manure, NPK, and Manure + NPK fertilizations increased the POC content and its contribution to TOC compared with control treatment (Wang *et al*., 2015) [39].

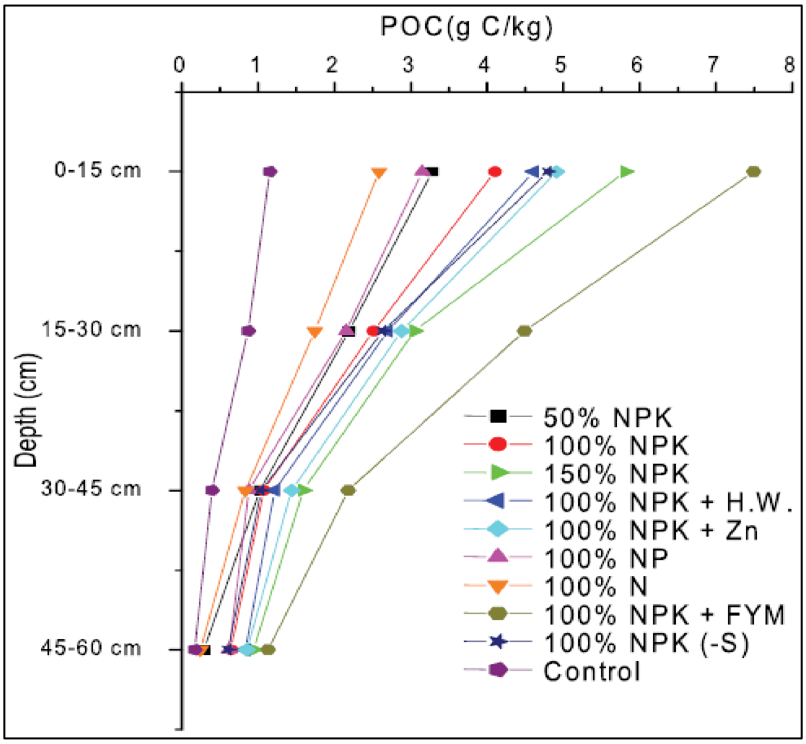

Fig 6a: Effect of different nutrient management practices on particulate organic carbon (g kg^{-1} soil) after rice crop [Source: Pant *et al.*, 2020] [30]

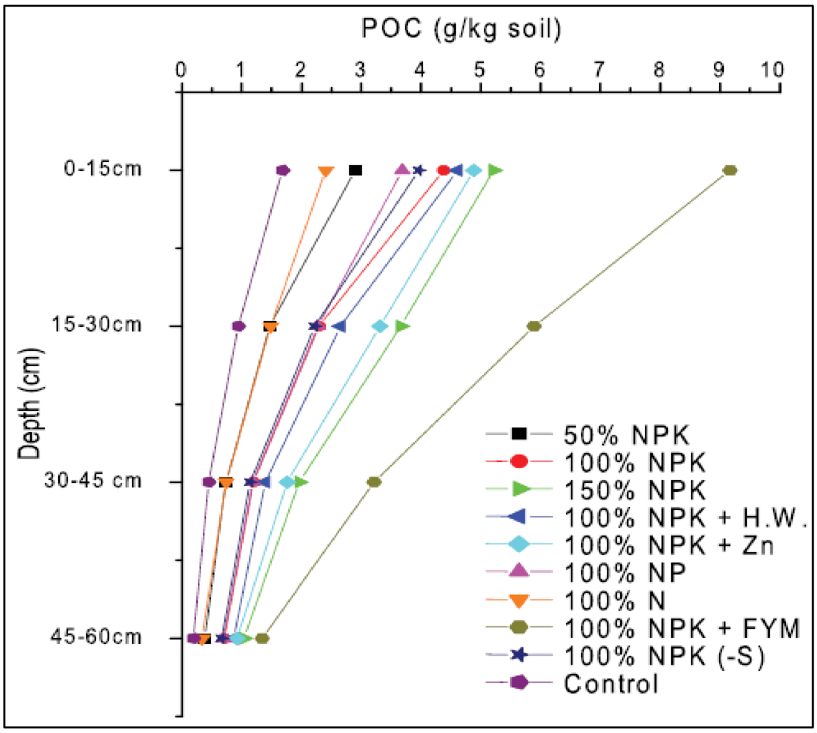

Fig 6b: Effect of different nutrient management practices on particulate organic carbon (g kg^{-1} soil) after wheat crop [Source: Pant *et al.*, 2020] [30]

Pant *et al*. (2020) [30] also found that the surface soil obtained more aggregated C than sub-surface soil after harvest of both the crops (Fig. 7 (a, b)). The maximum aggregate carbon concentration in soil at all depths was obtained under 100% NPK was applied along with FYM followed by 150% NPK treatment. The percent increase in both the treatments was observed to be 161.6% and 111.7% after rice harvest and 136.7% and 93.45% after wheat harvest in comparison to control, respectively. However, there was subsequent decrease in aggregate carbon concentration with increase in depth. In the treatment 100% NPK with FYM at 0–15 cm depth recorded 683% increment over 45–60 cm after rice harvest whereas at the same depth, it was about 612% increase over 45–60 cm after wheat harvest. Soil with 100% NPK + FYM significantly increased water stable aggregates organic carbon contents as compared to the other treatments. The microbial action on FYM resulted in the formation of organo-mineral complexes leading to aggregation of soil particles, which further influenced soil C storage and dynamics (Brar *et al*., 2013) [5].

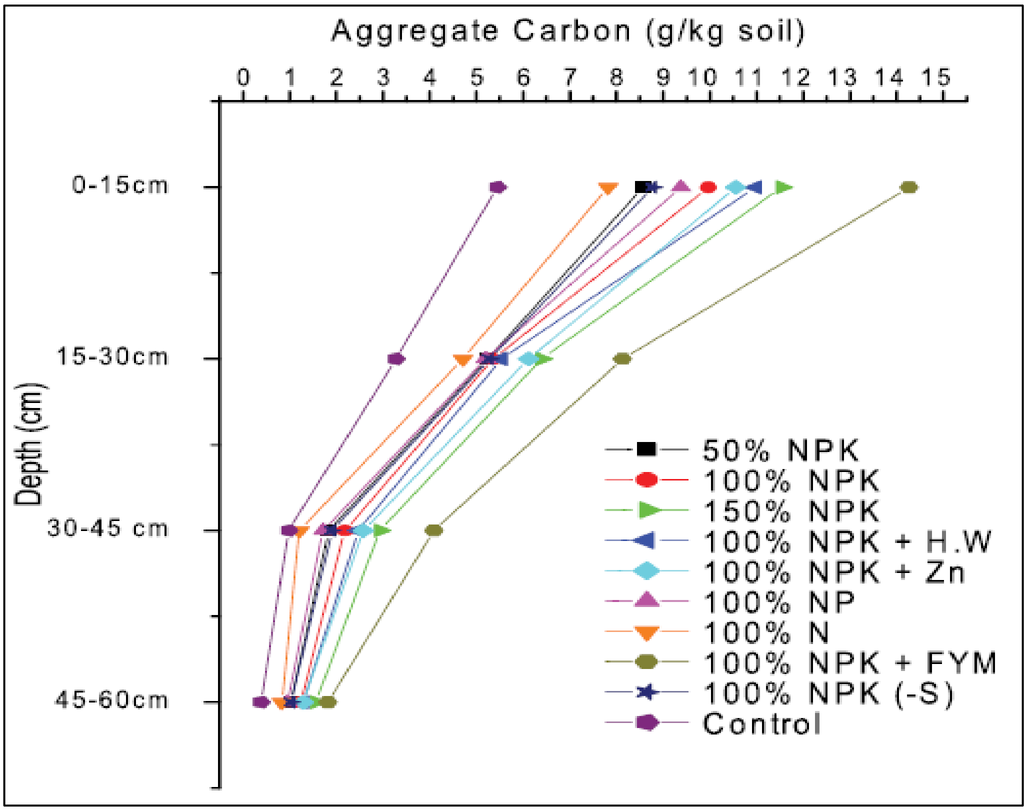

Fig 7a: Effect of organic and inorganic fertilizers on aggregate carbon (g kg^{-1} soil) after rice crop [Source: Pant *et al.*, 2020] [30]

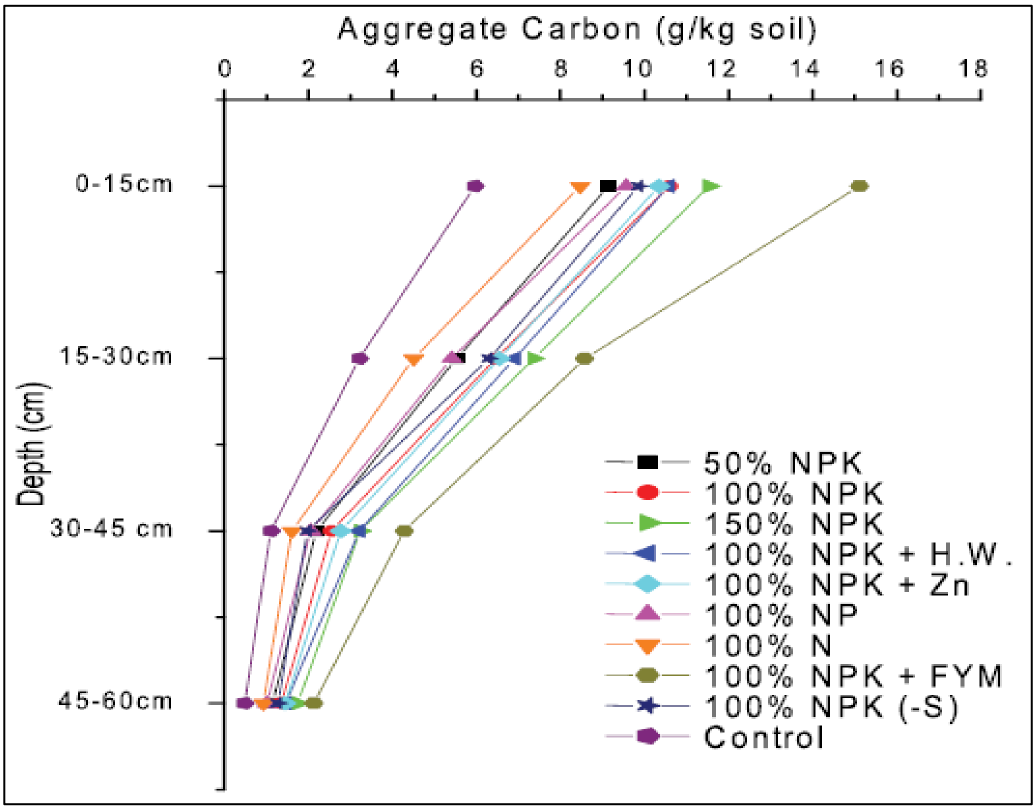

Fig 7b: Effect of organic and inorganic fertilizers on aggregate carbon (g kg^{-1} soil) after wheat [Source: Pant *et al.*, 2020] [30]

Soil microbial biomass carbon

SMB is defined as the small (0-4%) living component of soil organic matter excluding macro-fauna and plant roots (Dalal, 1998) [9]. Soil microbial biomass carbon (Cmic) have been used as indicators of changes in soil organic matter status that will occur in response to alterations in land use, cropping system, tillage practice and soil pollution (Sparling *et al.*, 1992) [36].

Ma *et al.* (2016) [23] reported that the proportion of SMBC to TOC ranged from 1.02 to 4.49, indicating that TOC is relatively low, or due to sampling for the summer after spring harvest, when soil temperature is high, the microbial activity is relatively strong. The SMBC at all depths (0–90 cm) with a sharp decline in depth increased perhaps due to a higher microbial biomass and organic matter content. SMBC was significantly higher in PRB in the surface soil layer (0–10 cm) than in TT and FB, which showed that no-till and accumulation of crop residues enriches the topsoil with microbial biomass. Microbial biomass concentrations are controlled by the level of SOM and oxygen status.

Tripathi *et al*. (2014) [38] observed that the significant positive correlations were observed between TOC and organic C fractions (POC and SMBC), illustrating a close relationship between TOC and POC and TOC and SMBC and that SOC is a major determinant of POC and SMBC. The microbial biomass carbon includes living microbial bodies (bacteria, fungi, soil fauna and algae) (Divya *et al*., 2014); it is more sensitive to soil disturbance than TOC. The proportion of SMBC to TOC is evaluation of carbon availability indexes for agriculture soil, which is usually 0.5–4.6% (Marumoto and Domsch, 1982).

Liu *et al*. (2016) [21, 23] also found that the averaged across soil depths (0–25 cm depth), MBC of the grassland (1624.1 mg kg^{-1}) and forestland (839.1 mg kg^{-1}) were 6.9 and 3.6 times more, respectively than those for arable land use (245.9 and 226.2 mg kg^{-1} for no tillage (NT) and plow tillage (PT), respectively. Similarly, the MBN concentration was 4.1 and 2.5 times more in grassland (78.0 mg kg^{-1}) and forest (50.0 $mgkg^{-1}$) than in arable land (20.0 and 18.0 mg kg^{-1} for NT and PT, respectively, in the 0–25 cm soil layer. The higher MBC and MBN concentrations under NT than that of PT could be attributed to several factors including higher moisture content, more soil aggregation, higher SOC and TN concentration, and minimum disturbance, which provide a steady source of SOC and TN to support microbial community near the soil surface.

Naresh *et al*. (2017) [28] reported that the WSC was found to be 5.48% higher in surface soil than in sub-surface soil [Table 2]. In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to CT, FIRB and ZT coupled with $6tha^{-1}$ CR increased 35.6% WSC in surface soil and 33.1% in sub surface soil. Among all the treatments, T_6 had significantly higher (19.73%) proportion of WSC than the other treatments compared. Irrespective of tillage practices, residue retention resulted in 22.56% and 25.61% higher WSC as compared to the non-residue treatments in surface and sub-surface soil, respectively. The microbial biomass carbon (MBC) is an important component of the SOM that regulates the transformation and storage of nutrients. The soil MBC regulates all SOM transformations and is considered to be the chief component of the active SOM pool. It is evident that the MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 100% RDN as CF+ VC @ $5tha^{-1}$ (F_5) and 75% RDN as CF+ VC @ $5tha^{-1}$ (F_4) treated plots compared to 100% RDN as CF (F_2) fertilizer and unfertilized control plots [Table 2]. The values of MBC in surface soil varied from 116.8 $mgkg^{-1}$ in unfertilized control plot to 424.1 $mgkg^{-1}$ in integrated nutrient use of 100% RDN as CF+ VC @ $5tha^{-1}$ plots, respectively; while it varied from 106.6 $mgkg^{-1}$ (control) to 324.9 mgkg−1 (100% RDN as CF+ VC @ $5tha^{-1}$ F_5) in sub-surface (15-30 cm) soil layer. The values of MBC increased by 72.5 and 58.4% under 100% RDN as CF+ VC @ $5tha^{-1}$ (F_5) and 75% RDN as CF+ VC @ $5tha^{-1}$ (F_4) treatment in surface soil over control. The values of LFC in surface soil (0-15 cm) were 81.3, 95.7, 107.8, 128.8, 155.2, 177.8 and 52.7 $mgkg^{-1}$ in ZT and FIRB without residue retention, ZT and FIRB with 4 & 6 tha^{-1} residue retention and CT treatments, respectively [Table 2].

Table 2: Concentrations of different soil organic matter carbon fractions fPOM and cPOM at different soil depths as affected by tillage and nutrient management to the continuous RW cropping system [Source: Naresh *et al*., 2017] [28].

Treatments	0-15 cm layer					15-30 cm layer				
	WSC ($mgkg^{-1}$)	MBC ($mgkg^{-1}$)	LFC ($mgkg^{-1}$)	$_f$POM (g Ckg^{-1})	$_c$POM (g Ckg^{-1})	WSC ($mgkg^{-1}$)	MBC ($mgkg^{-1}$)	LFC ($mgkg^{-1}$)	$_f$POM (g Ckg^{-1})	$_c$POM (g Ckg^{-1})
Tillage crop residue practices										
T_1	16.9^{d}	311.4^{c}	81.3^{d}	0.44^{d}	0.92^{cd}	15.7^{d}	193.9^{cd}	65.1^{d}	0.32^{cd}	0.58^{bc}
T_2	18.9^{c}	345.2^{bc}	107.8^{bc}	0.62^{bcd}	1.82^{bc}	17.8^{cd}	219.8^{c}	94.1^{bc}	0.55^{de}	1.31^{bcd}
T_3	20.8^{ab}	481.7^{a}	155.2^{a}	0.88^{ab}	2.54^{a}	19.6^{bc}	294.8^{ab}	132.6^{a}	0.83^{c}	1.93^{a}
T_4	18.7^{d}	306.5^{c}	95.7^{c}	0.53^{cd}	1.03^{d}	17.6^{cd}	187.5^{cd}	87.6^{c}	0.35^{bc}	0.94^{ab}
T_5	21.4^{bc}	398.6^{b}	128.8^{b}	0.86^{bc}	2.21^{ab}	20.3^{ab}	240.9^{bc}	102.9^{b}	0.72a	1.64^{a}
T_6	23.2^{a}	535.8^{a}	177.8^{a}	1.30^{a}	2.38^{ab}	21.6^{a}	361.8^{a}	141.2^{a}	1.19^{e}	1.89^{cd}
T_7	14.2^{e}	266.7^{c}	52.7^{e}	0.38^{d}	0.94^{d}	13.8^{e}	145.9^{d}	49.8^{e}	0.26^{f}	0.61^{d}
Fertilizer Management Practices										
F_1	21.9^{e}	116.8^{c}	89.2^{c}	0.41^{d}	$0. 64^{d}$	15.1^{e}	106.6^{d}	47.9^{f}	0.28	0.48^{d}
F_2	28.4^{d}	189.2^{c}	123.5^{bc}	0.60^{cd}	0.93^{d}	18.8^{d}	166.8^{cd}	66.7^{e}	0.45	0.59
F_3	29.2^{cd}	239.9^{bc}	146.4^{c}	0.71^{cd}	1.52^{cd}	20.2^{cd}	196.8^{bc}	85.9^{d}	0.52	0.74^{cd}
F_4	29.8^{c}	280.7b	160.5^{b}	1.33^{ab}	2.81^{ab}	21.9^{bc}	219.9^{bc}	103.2^{bc}	0.72	1.64^{ab}
F_5	32.5^{a}	424.1^{a}	183.9^{a}	1.89^{a}	3.78^{a}	26.4^{a}	324.9^{a}	152.9^{a}	0.92	2.34^{a}
F_6	28.9	210.3	133.2^{c}	0.66	1.19	19.8	178.2	76.4	0.51	0.63

****** Different letters within columns are significantly different at P=0.05 according to Duncan Multiple Range Test (DMRT) for separation of means. WSC = water soluble carbon, MBC = microbial biomass carbon, LFC = labile fraction carbon, cPOM = coarse particulate organic carbon, fPOM = fine particulate organic carbon

Pant *et al*. (2020) [30] observed that the integrated approach of nutrient management showed positive impact on soil microbial biomass carbon and received more biomass carbon in surface layers with subsequent decrease at each increase in depth (Fig. 8 (a, b)). The lowest SMBC concentration was obtained under control and highest with 100% NPK+FYM. The surface and subsurface soil obtained more SMBC after wheat harvest as compared to rice harvest. There were 24.38%, 29.67% and 23.10%, 28.05% increase in SMBC under treatment 100% NPK+FYM in comparison to 100% NPK+ Zn and 150% NPK after harvest of rice and wheat crops, respectively, at 0–15 cm layer. Balanced fertilization with 100% NPK with FYM increased MBC content in soil over 100% N and 100% NP treatments, respectively. Microbial biomass is a key component of soils since it defines the functional component of the micro biota primarily responsible for decompositions, soil organic matter turn over and nutrient transformations (Smith and Paul 1990) [35]. The increase in SMBC with the addition of FYM could be attributed to an availability of substrates for the microorganisms. The soil MBC represents about 1–5% of total soil organic carbon, can provide an effective early warning of the improvement or deterioration of soil quality as a result of different management practices (Powlson, 1994) [31].

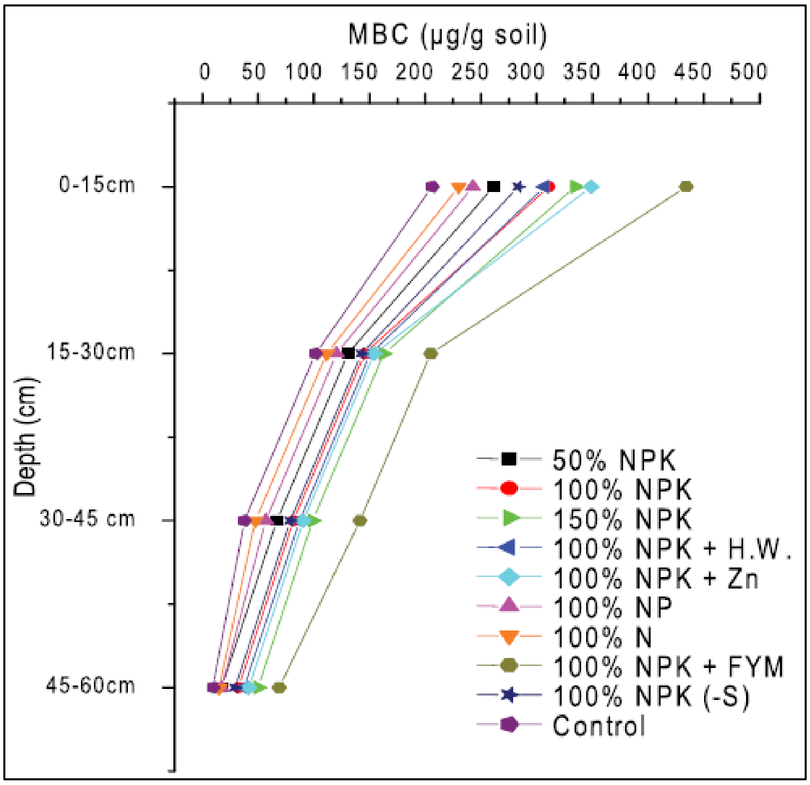

Fig 8b: Effect of nutrient management practices on soil microbial biomass carbon (µg g^{-1} soil) after wheat crop [Source: Pant *et al*., 2020] [30]

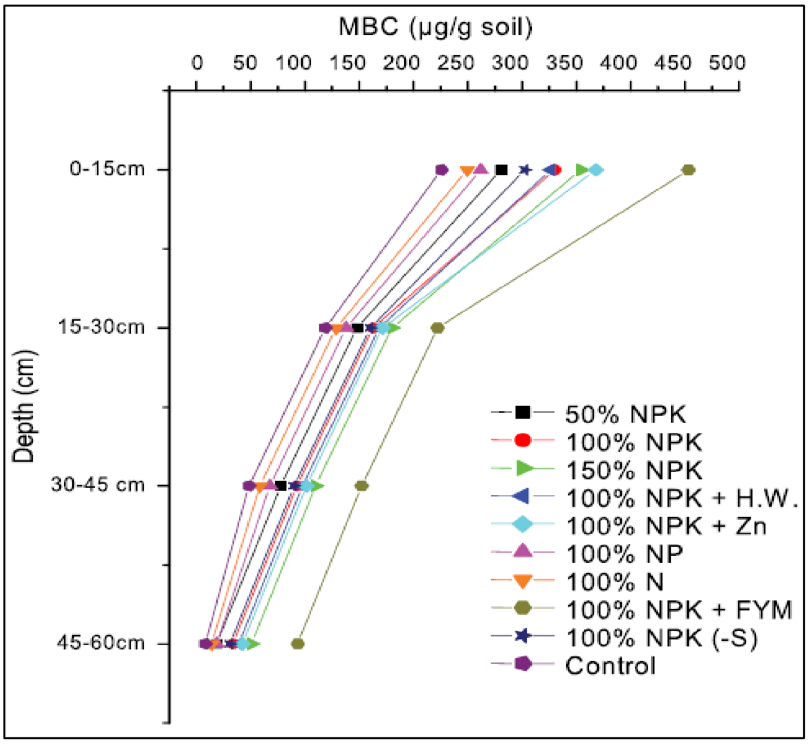

Fig. 8a: Effect of nutrient management practices on soil microbial biomass carbon (µg g^{-1} soil) after rice crop [Source: Pant *et al*., 2020] [30]

Miao *et al*. (2018) [26] reported that the contents of SMBC and SSOC decreased with soil depth [Fig.8a]. The SMBC content at the 0–60 cm depth under the SM and RF treatments was significantly higher than that of the FA soil. The SSOC

content of soil samples subjected to the CC, SM, and RF treatments was greater than that of the FA soil. The N fertilization rates showed no distinct effect on the content of SMBC or SSOC at the 0–60 cm soil depth [Fig.9a].
Kushwaha *et al*. (2000) [19] observed that the highest levels of soil MBC and MBN (368±503 and 38.2±59.7μg g^{-1}, respectively) were obtained in minimum tillage residue retained (MT+R) treatment and lowest levels (214±264 and 20.3±27.1μg g^{-1}, respectively) in conventional tillage residue removed (CT-R, control) treatment. Along with residue retention tillage reduction from conventional to zero increased the levels of MBC and MBN (36±82 and 29±104% over control, respectively [Fig.9b]. This increase (28% in of C and 33% N) was maximum in MT+R and minimum (10% for C and N both) in minimum tillage residue removed (MT-R) treatment. In all treatments concentrations of N in microbial biomass were greater at seedling stage, thereafter these concentrations decreased drastically (21±38%) at grain-forming stage of both crops. In residue removed treatments, N-mineralization rates were maximum during the seedling stage of crops and then decreased through the crop maturity [Fig.9b]

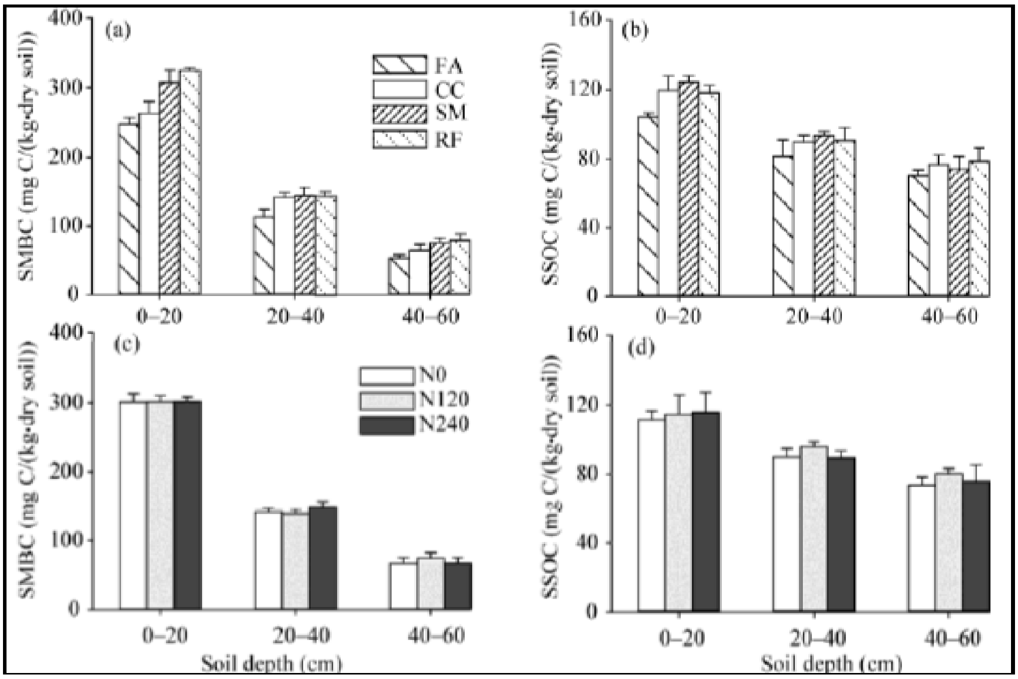

Fig 9a: Soil microbial biomass C (SMBC) and soil soluble organic C (SSOC) contents under different cultivation practices (a, b) and N fertilization rates (c, d). FA, fallow; CC, conventional cultivation; SM, straw mulch; RF, plastic film-mulched ridge and straw-mulched furrow; N0, 0 kg N/hm^2; N120, 120 kg N/hm2; N240, 240 kg N/hm^2 [Source: Miao *et al*., 2018] [26]

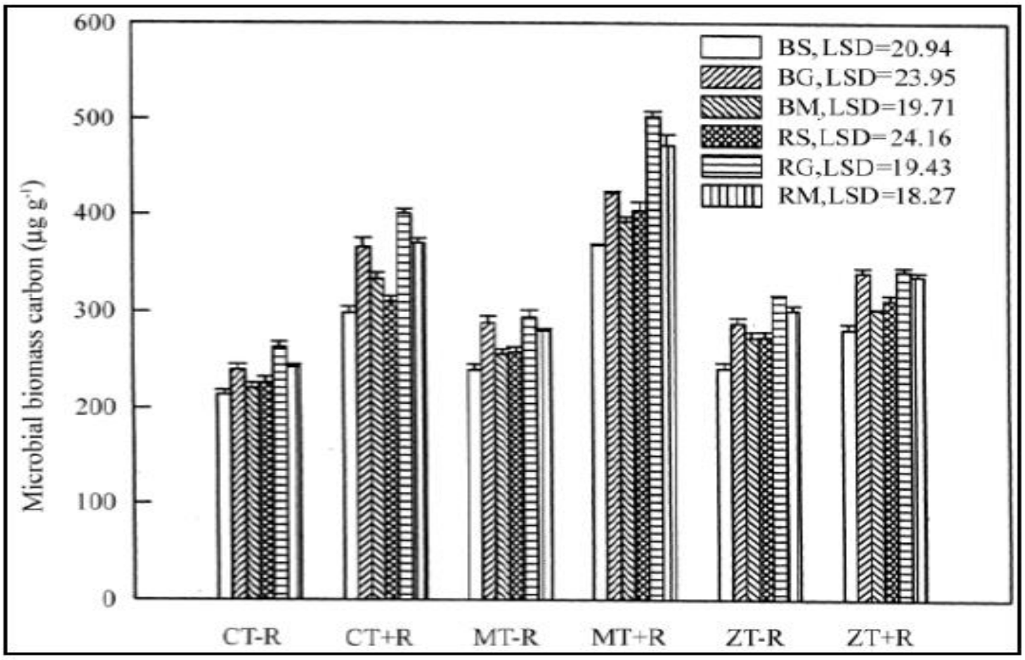

Fig 9b: Responses of soil microbial biomass carbon (μg g^{-1}) to different tillage and residue manipulation treatments during barley and rice crop periods in a dry-land agro-ecosystem; code: BS, barley seedling stage; BG, barley grain-forming stage; BM, barley maturity stage; RS, rice seedling stage; RG, rice grain-forming stage; RM, rice maturity stage [Source: Kushwaha *et al*., 2000] [19]

Liang *et al*. (2011) observed that in the 0–10 cm soil layer, SMBC and SMBN in the three fertilized treatments were higher than in the unfertilized treatment on all sampling dates, while microbial biomass C and N in the 0−10 cm soil layers were the highest at grain filling. In the same soil layer, soil-soluble organic C generally decreased in the order MNPK > SNPK > NPK > CK, while soluble organic N was the highest in the MNPK followed by the SNPK treatment. There was no significant difference in soluble organic N in the NPK and CK treatments throughout most of the maize growing season. Changes in soluble organic N occurred along the growing season and were more significant than those for soluble organic C. Soluble organic N was the highest at grain filling and the lowest at harvest. Overall, microbial biomass and soluble organic N in the surface soil were generally the highest at grain filling when maize growth was most vigorous [Fig.10a].

Dou *et al*. (2008) [11] reported that SMBC was 5 to 8%, mineralized C was 2%, POM C was 14 to 31%, hydrolyzable C was 53 to 71%, and DOC was 1 to 2% of SOC. No-till significantly increased SMBC in the 0- to 30-cm depth, especially in the surface 0 to 5 cm [Fig.10b]. Under NT, SMBC at 0 to 5 cm was 25, 33, and 22% greater for CW, SWS, and WS, respectively, than under CT, but was 20 and 8% lower for CW and WS, respectively, than under CT at the 5- to 15-cm depth. At the 15- to 30-cm depth, no consistent effect of tillage was observed [Fig.10b]. Enhanced cropping intensity increased SMBC only under NT, where SMBC was 31 and 36% greater for SWS and WS than CW at 0 to 30 cm.

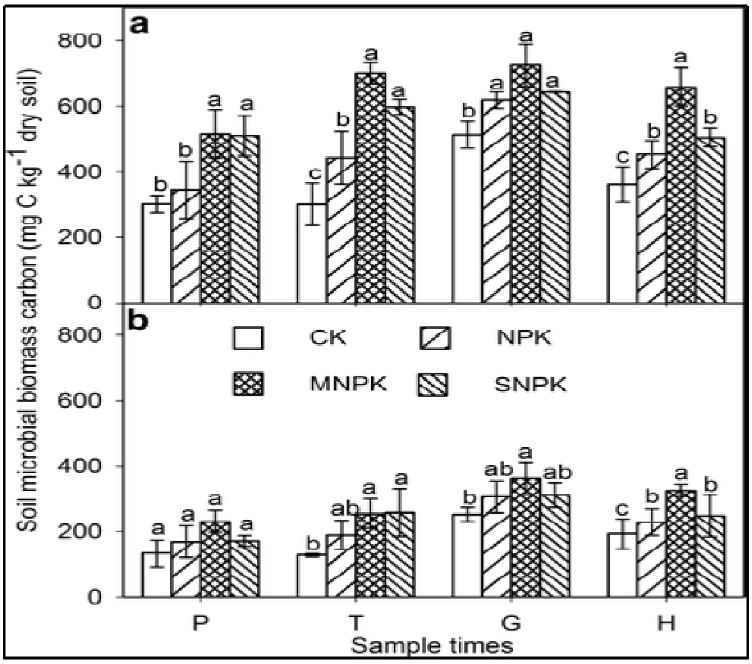

Fig 10a: Effects of fertilization on soil microbial biomass C and N and soluble organic C and N [Source: Liang *et al*., 2011]

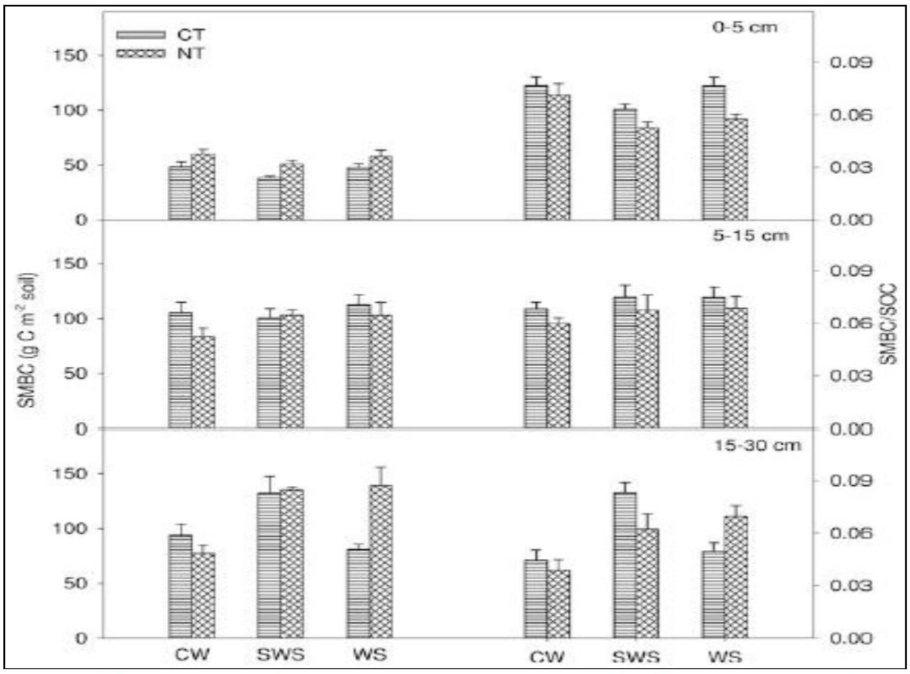

Fig 10b: Soil microbial biomass C (SMBC) and its proportion of soil organic C (SOC) as affected by cropping sequence and tillage at 0- to 5-, 5- to 15-, and 15- to 30-cm depths [Source: Dou *et al*., 2008] [11]

Conclusion

The sequential accumulation of different organic fractions in soil at different depths was the resultant effect of different sources of nutrients applied through inorganic and organic sources alone or in combinations. Carbon fractions acquired in different amount was more pronounced at 0–15 cm depth than within subsurface region. Treatment NPK with FYM witnessed 158% and 144% increased concentration of TOC at all depths after the harvest of rice and wheat, respectively. However, wheat harvested field acquired more TOC concentration at all depth than in rice harvested plots. The application of FYM, addition of crop residues, root biomass, root exudates and plant biomass itself sequestered more soil organic carbon over the years in surface layers than in subsurface layers after both crop harvests. This impacted to conserve all active and passive carbon fractions *viz*. aggregated carbon, water-soluble carbon (WSC), soil microbial biomass nitrogen, soil microbial biomass carbon more at the surface region. Hence, 100% NPK + 15 t ha^{-1} FYM was found to be most promising treatment amongst in conserving different carbon fractions in rice and wheat cropping systems. 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. At the same time, on average the estimate of soil C storage to 60 cm 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.

Across the management practices tillage had the greatest effect on SOC and its various fractions and in the surface (0–15 cm) soil of tillage implementation, with positive results observed with conservation tillage practices compared with conventional tillage. SOC stocks and those of the labile fractions decreased in topsoil and subsoil below 20 cm following land conversion. The LOC fractions to SOC ratios also decreased, indicating a reduction in C quality as a consequence of land use change. Reduced LOC fraction stocks in subsoil could partially be explained by the decrease in fine root biomass in subsoil, with consequences for SOC stock. However, not all labile fractions could be useful early indicators of SOC alterations due to land use change. In fact, only fPOC, LFOC, and MBC in topsoil, and LFOC and DOC in subsoil were highly sensitive to land use change in subtropical climatic conditions of North West IGP. There was a significant reduction in SMBC content with depth in all treatments. SMBC in the PRB treatment increased by 19.8%, 26.2%, 10.3%, 27.7%, 10% and 9% at 0–5, 5–10, 10–20, 20–40, 40–60 and 60–90 cm depths, respectively, when compared with the TT treatment. The mean SMBC of the PRB treatment was 14% higher than that in the TT treatment.

The distribution pattern of soil microbial biomass associated with aggregates was likely governed by the size of aggregates, whereas the tillage effect was not significant at the aggregate-size scale. Tillage regimes that contribute to greater soil aggregation also will improve soil microbial activity to aid in crop production. Heterogeneous distribution of OC and microbial biomass may lead to “hot-spots” of aggregation, and suggests that microorganisms associated with 1.0–2.0 mm aggregates are the most biologically active in the ecosystem. Conventional tillage (CT) significantly reduces macro-aggregates to smaller ones, thus aggregate stability was reduced by 35% compared with conservation system (CS), further indicating that tillage practices led to soil structural damage. The concentrations of SOC and other nutrients are also significantly higher under CS than CT, implying that CS may be an ideal enhancer of soil productivity in this sub-tropical ecosystem through improving soil structure which leads to the protection of SOM and nutrients, and the maintenance of higher nutrient content. 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.

References

1. Banger K, Toor G, Biswas A, Sidhu S, Sudhir K. Soil organic carbon fractions after 16 years of applications of fertilizers and organic manure in a Typic Rhodalfs in semi-arid tropics. Nutr. Cycl. Agroecosyst. 2010;86:391-399.
2. Bhardwaj AK, Rajwar D, Mandal UK, Ahmed S, *et al*. Impact of carbon inputs on soil carbon fractionation, sequestration and biological responses under major nutrient management practices for rice-wheat cropping systems. Sci Rep 2019;9:9114. https://doi.org/10.1038/s41598-019-45534-z
3. Bhattacharyya R, Kundu S, Srivastva AK, Gupta HS, Prakash V, Bhatt JC. Long term fertilization effects on soil organic carbon pools in a sandy loam soil of the Indian Himalayas. Plant Soil 2011;341:109Y124.
4. Bongiorno G, Bunemann EK, Oguejiofor CU, Meier J, Gort G, Comans R, *et al*. Sensitivity of Labile Carbon Fractions to Tillage and Organic Matter Management and Their Potential as Comprehensive Soil Quality Indicators across Pedoclimatic Conditions in Europe. Ecol. Indic. 2019;99:38-50.
5. Brar BS, Singh K, Dheri GS, Kumar B. Carbon sequestration and soil carbon pools in a rice–wheat cropping system: Effect of long-term use of inorganic fertilizers and organic manure. Soil Tillage Res. 2013;128:30-36.
6. Choudhury S, Gupta Sivastava S, Ranbir Singh, Chaudhari SK, Sharma DK, Singh SK. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. Soil Tillage Res. 2014;136:67-83.
7. Culman SW, Snapp SS, Freeman MA, Schipanski ME, Beniston J, Lal R, Drinkwater LE, *et al*. Permanganate Oxidizable Carbon Reflects a Processed Soil Fraction That Is Sensitive to Management. Soil Sci. Soc. Am. J. 2012;76:494-504.
8. Das D, Dwivedi BS, Singh VK, Datta SP, Meena MC, Chakraborty D *et al*. Long-term effects of fertilizers and organic sources on soil organic carbon fractions under a rice–wheat system in the Indo-Gangetic Plains of north-west India, Soil Research, 2016.

http://dx.doi.org/10.1071/SR16097
9. Dalal RC. Soil microbial biomass-What do the numbers really mean? Aust J Exp Agri. 1998;38:645-665.
10. Dong WX, Hu CS, Chen SY, Zhang YM. Tillage and Residue Management Effects on Soil Carbon and CO_2 Emission in a Wheat-Corn Double-Cropping System. Nutr. Cycl. Agroecosyst. 2009;83:27-37.
11. Dou F, Wright AL, Hons FM. Sensitivity of labile soil organic carbon to tillage in wheat-based cropping systems. Soil Sci Soc Am J. 2008;72:1445-1453.
12. Drinkwater LE, Wagoner P, Sarantonio M. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature. 1998;396:262-265.
13. Gami SK, Lauren JG, Duxbury JM. Soil organic carbon and nitrogen stocks in Nepal long-term soil fertility experiments. Soil Tillage Res. 2009;106:95-103.
14. Gulde S, Chung H, Amelung W, Chang C, Six J. Soil carbon saturation controls labile and stable carbon pool dynamics. Soil Sci. Soc. Am. J. 2008;72:605Y612
15. Guo Z, Zhang L, Wei Yang, Li Hua, Cai C. Aggregate Stability under Long-Term Fertilization Practices: The Case of Eroded Ultisols of South-Central China. Sustainability 2019;11:1169; doi:10.3390/su11041169
16. Huggins DR, Allmaras RR, Clapp CE, Lamb JA, Randall GW. Corn-Soybean Sequence and Tillage Effects on Soil Carbon Dynamics and Storage. Soil Sci. Soc. Am. J. 2014;71(1):145-154.
17. Jacinthe PA, Lal R. Tillage Effects on Carbon Sequestration and Microbial Biomass in Reclaimed Farmland Soils of Southwestern Indiana. Soil Sci. Soc. Am. J. 2009;73:605-613.
18. Jin XX, Gall AR, Saeed MF, Li SY, Filley T, Wang JK. Plastic Film Mulching and Nitrogen Fertilization Enhance the Conversion of Newly-Added Maize Straw to Water-Soluble Organic Carbon. Soil Tillage Res. 2020;197:104527.
19. Kushwaha CP, Tripathi SK, Singh KP. Variations in soil microbial biomass and N availability due to residue and tillage management in a dry-land rice agro-ecosystem. Soil Tillage Res. 2000;56:153-166.
20. Liu M, Yu WT, Jiang ZS, Ma Q. A Research Review on Soil Active Organic Carbon. Chin. J Ecol. 2006;11:1412-1417
21. Liu M, David Ussiri AN, Lal R. Soil Organic Carbon and Nitrogen Fractions under Different Land Uses and Tillage Practices. Comm Soil Sci Plant Anal. 2016;47(12):1528-1541.
22. Lorenz K, Lal R. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. Adv Agron. 2005;88:35-66.
23. Ma Z, Chen J, Lyu X, Liu Li-li, Siddique KHM. Distribution of soil carbon and grain yield of spring wheat under a permanent raised bed planting system in an arid area of northwest China. Soil Tillage Res. 2016;163:274-281.
24. Mahajan M, Singh D. Soil organic matter and biological properties after 26 years of maize–wheat–cowpea cropping as affected by manure and fertilization in a Cambisol in semiarid region of India. Agric Ecosyst Environ. 2001;86:155-162
25. Mandal N, Dwivedi BS, Meena MC, Singh D, Datta SP, Tomar RK, *et al*. x Effect of induced defoliation in pigeonpea, farmyard manure and sulphitation pressmud on soil organic carbon fractions, mineral nitrogen and crop yields in a pigeonpea–wheat cropping system. Field Crops Research. 2001;154:178–187
26. Miao C, Zhujun C, Jianbin Z, Jichang H, Qianyun S. Effects of long-term cultivation practices and nitrogen fertilization rates on carbon stock in a calcareous soil on the Chinese Loess Plateau. J Arid Land. 2018;10(1):129-139.
27. Nandan R, Singh V, Singh SS, Kumar V, Hazra KK, Nath CP, Poonia S *et al.* Impact of Conservation Tillage in Rice-Based Cropping Systems on Soil Aggregation, Carbon Pools and Nutrients. Geoderma. 2019;340:104-114.
28. Naresh RK, Timsina J, Bhaskar S, Gupta RK, Singh AK, Dhaliwal SS, *et al*. Effects of Tillage, Residue and Nutrient Management on Soil Organic Carbon Dynamics and its Fractions, Soil Aggregate Stability and Soil Carbon Sequestration: A Review. EC Nutrition. 2017;2(12):53-80.
29. Okolo CC, Gebresamuel G, Zenebe A, Haile M, Eze PN. Accumulation of Organic Carbon in Various Soil Aggregate Sizes under Different Land Use Systems in a Semi-Arid Environment. Agric. Ecosyst. Environ. 2020;297:13.
30. Pant PK, Shri Ram, Pallavi Bhatt, Aakash Mishra, Veer Singh. Vertical distribution of different pools of soil organic carbon under long-term fertilizer experiment on rice-wheat sequence in mollisols of North India, Communications in Soil Science and Plant Analysis, 2020. DOI: 10.1080/00103624.2020.1859527
31. Powlson DS. The soil microbial biomass before, beyond and back. In Beyond the Biomass, ed. K. Ritz, J. Dighton, and K. E. Giller, 3–20. UK: Wiley, Chichester, 1994.
32. Purakayastha TJ, Rudrappa L, Singh D, Swarup A, Bhadraray S. Long term impact of fertilizers on soil organic carbon pools and sequestration rates in maize–wheat–cowpea cropping system. Geoderma. 2008;144:370-78.
33. Shen X, Wang L, Yang Q, Xiu W, Li G, Zhao J, Zhang G. Dynamics of Soil Organic Carbon and Labile Carbon Fractions in Soil Aggregates Affected by Different Tillage Managements. Sustainability. 2021;13:1541. https://doi.org/10.3390/su13031541
34. Six J, Elliott ET, Paustian K. Soil Macro-aggregate Turnover and Micro-aggregate Formation: A Mechanism for C Sequestration under No-Tillage Agriculture. Soil Biol. Biochem. 2000;32:2099-2103.
35. Smith JL, Paul EA. The significance of soil microbial biomass estimations. In Soil biology, ed. J. M. Bollag and G. Stotzuy., New York: Marcel Dekker. 1990;6:357.
36. Sparling GP. Ratio of microbial biomass to soil organic carbon as a sensitive indicator of changes in soil organic matter. Aust J Soil Res 1992;30:195-207.
37. Stockmann U *et al*. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 2013;164:80-99.
38. Tripathi R, Nayak AK, Bhattacharyya P, Shukla AK, Shahid M, Raja R *et al*. Soil aggregation and distribution of carbon and nitrogen in different fractions after 41 years long-term fertilizer experiment in tropical rice–rice system. Geoderma. 2014;213:280-286.
39. Wang Y, Hu N, Xu M, Li Z, Lou Y, Chen Y *et al.* 23-year manure and fertilizer application increases soil organic carbon sequestration of a rice–barley cropping

system. Biology and Fertility of Soils. 2015;51:583. doi:10.1007/s00374-015-1007-2.
40. Xiao D, Ye YY, Xiao SS, Zhang W, He XY, Liu N, *et al* Tillage Frequency Affects Microbial Metabolic Activity and Short-Term Changes in CO_2 Fluxes within 1 Week in Karst Ecosystems. J Soils Sediments, 2019;19:3453-3462.
41. Zhong S, Zeng HC. Influence of Long-Term Tillage and Residue Management on Soil Biota in Tropical Climate. J Biobased Mater Bioenergy 2019;13:576-584.
42. Zibilske LM, Bradford JM, Smart JR. Conservation tillage induced changes in organic carbon, total nitrogen and available phosphorus in a semi-arid alkaline subtropical soil. Soil Tillage Res. 2000;66(2):153-163.