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Soil aggregation and aggregate associated organic carbon fractions and microbial activities as affected by tillage and straw management in a rice-wheat rotation: A review

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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 topsoil achieved maximum SOC stocks after about 10 years of NT. Increasing the quantity of C input could enhance soil C sequestration or reduce the rate of soil C loss, depending largely on the local soil and climate conditions. SOC can be best preserved by crop rotations with conservation tillage practices such as no or reduced tillage, and with additions of residues, chemical fertilizers and manure SOC change was significantly influenced by the crop residue retention rate and the edaphic variable of initial SOC content.

Keywords: Tillage management, aggregates, aggregate associated c and n, water soluble c, mineralizable c

1. Introduction
Soil organic carbon (C) has profound effects on soil physical, chemical and biological properties (Haynes, (2005) [29]. Maintenance of soil organic C (SOC) in cropland is important, not only for improvement of agricultural productivity but also for reduction in C emission (Ranjan *et al*., 2012). However, short- and medium-term changes of SOC are difficult to detect because of its high temporal and spatial variability (Blair *et al*., 1995) [10]. On the contrary, soil labile organic C fractions (i.e., microbial biomass C (MBC), dissolved organic C (DOC), and easily oxidizable C (EOC)) that turn over quickly can respond to soil disturbance more rapidly than total organic C (TOC) (Ghani *et al*., 2003) [23]. Therefore, these fractions have been suggested as early sensitive indicators of the effects of land use change on soil quality (Rudrappa *et al*., 2006) [50].

Agricultural practices such as tillage methods are conventionally used for loosening soils to grow crops. But long-term soil disturbance by tillage is believed to be one of the major factors reducing SOC in agriculture (Baker *et al*., 2007) [5]. Frequent tillage may destroy soil organic matter (SOM) (Hernanz *et al*., 2002) [30] and speed up the movement of SOM to deep soil layers (Shan *et al*., 2005) [52]. As a consequence, agricultural practices that reduce soil degradation are essential to improve soil quality and agricultural sustainability. Crop residue plays an important role in SOC sequestration, increasing crop yield, improving soil organic matter, and reducing the greenhouse gas (e.g). [10–13]. As an important agricultural practice, straw return is often implemented with tillage in the production process. Although numerous studies have indicated that tillage methods combined with straw return had a significant effect On labile SOC fractions, the results varied under different soil/climate conditions. For example, both no Tillage and shallow tillage with residue cover had significantly higher

SOC than conventional tillage without residue cover in western Uttar Pradesh (Naresh *et al*., 2018) [45]. Rajan *et al* (2012) showed that in Chitwan Valley of Nepal, no-tillage with crop residue application at upper soil depth had distinctly higher SOC sequestration than conventional tillage with crop residue. The effects of tillage on soil labile organic C vary with regional climate [16], soil condition (e.g.) [17–20], residue management practice, and crop rotation (e.g.) [21, 22]. Therefore, the investigation on soil aggregation and aggregate associated organic carbon fractions and microbial activities soil labile organic for specific soil, climate, and cropping system is necessary to improve the soil quality.

Choudhary *et al*. (2014) 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 [Fig. 1a].

Johnson *et al*. (2013) [36] also found that the intensive tillage at the Chisel field showed <20% of the soil covered for all stover treatments, including full return, where all residues were returned; whereas, NT_{2005} and NT_{1995} had at least 45% of the soil covered even in low return. In NT_{2005}, significant increases in aggregates <1 mm and significant decreases in aggregates 5–9 mm were measured in low return compared to full return [Fig. 1b]. Low Return had 15% and 60% more aggregates in the 0–0.5 and 0.5–1 mm classes, respectively, compared to full return, but full return had 14% more 5–9 mm aggregates compared to low return, with moderate return intermediate. In Chisel and NT_{1995}, although means of aggregate distribution displayed a similar trend to the NT_{2005}, no statistically significant increase in the frequency of aggregates <1 mm was detected [Fig. 1b]. A similar shift, in dry aggregate size distribution toward fewer large aggregates and more small aggregates and a decline in wet aggregate stability was reported after four Stover removal cycles in a corn-soybean rotation (Hammerbeck *et al*., 2012) [28].

Bijay Singh, (2018) reported that the residual soil inorganic N produced due to application of fertilizer N beyond the optimum level may enhance mineralization of SOC by eliminating N limitation on microbial growth or by adversely affecting soil aggregation, which makes previously protected SOM more susceptible to decay. Excessive N fertilization may also decrease the C: N ratio of crop residues and enhance their decomposition rate. There may be multiple processes controlling the SOC response to N fertilization, but the extent of increased C inputs vis-à-vis SOC mineralization depends on the N sufficiency level [Fig. 2a). Green *et al*. (1995) [24] also observed that annual additions of more N than needed to maximize yields of crop could cause losses of SOM and suggested that reducing unnecessary fertilization could help conserve SOM. Naresh *et al*. (2017) [44] indicates that SOC generally accumulates with increasing rate of N fertilizer application [Fig. 2b).The average N fertilizer rate to achieve maximum SOC sequestration (0.28 Mg $Cha^{-1}yr^{-1}$) was 171 kg $Nha^{-1}yr^{-1}$ (Franzluebbers, 2005) [21] 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 Ckg^{-1} for production, application, and liming components, respectively.

Under NT, the recurrent crop residue deposition on soil surface resulted in higher TOC contents in the 0–0.05 m layer in relation to CT treatment. The soil C content follows the order: $R_2 > R_1 > R_0$, showing that the diversification of cropping systems increased the difference in TOC among treatments. In the 0.05–0.10 and 0.10–0.20 m layers, the differences in C content between treatments decreased to zero in the 0.20–0.30 m layer [Fig. 2c).

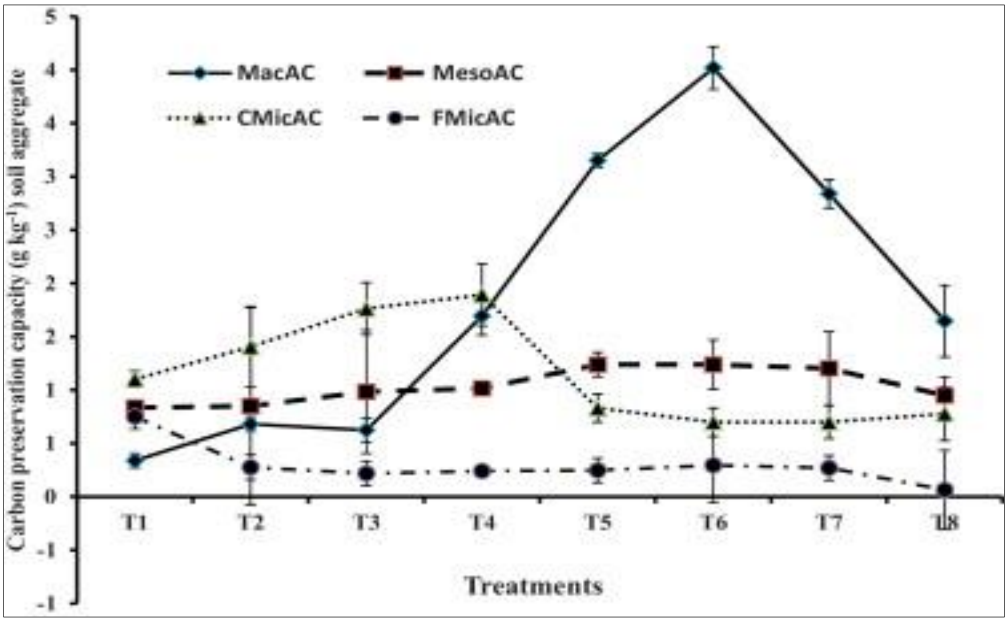


Fig 1(a): Tillage and residue management effects on soil aggregation and organic carbon dynamics in rice–wheat cropping system

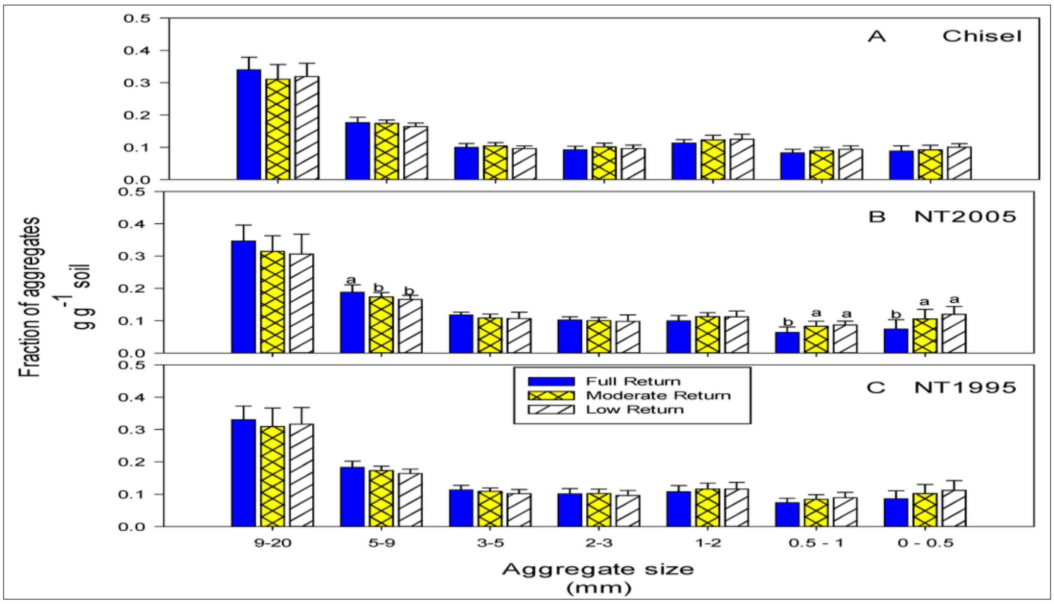


Fig 1(b): Dry aggregate size distribution as affected by stover return rates

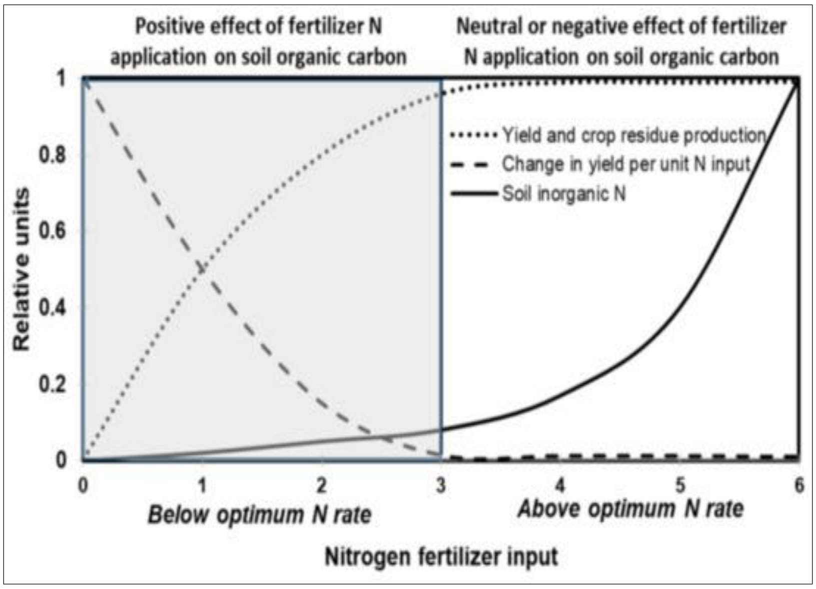


Fig 2(a): Effects of fertilizer application to crops on SOC

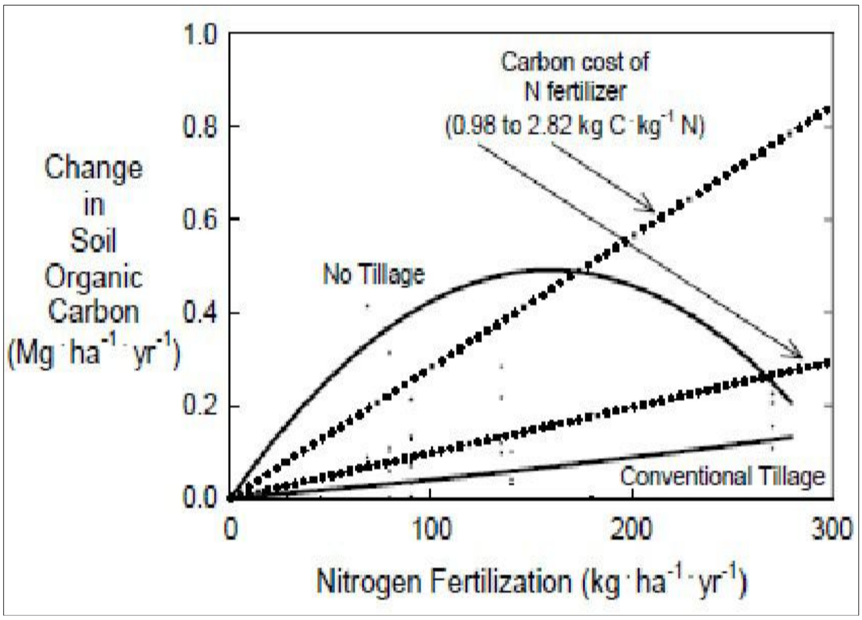


Fig 2 (b): Average change in soil organic C as affected by N fertilizer rate

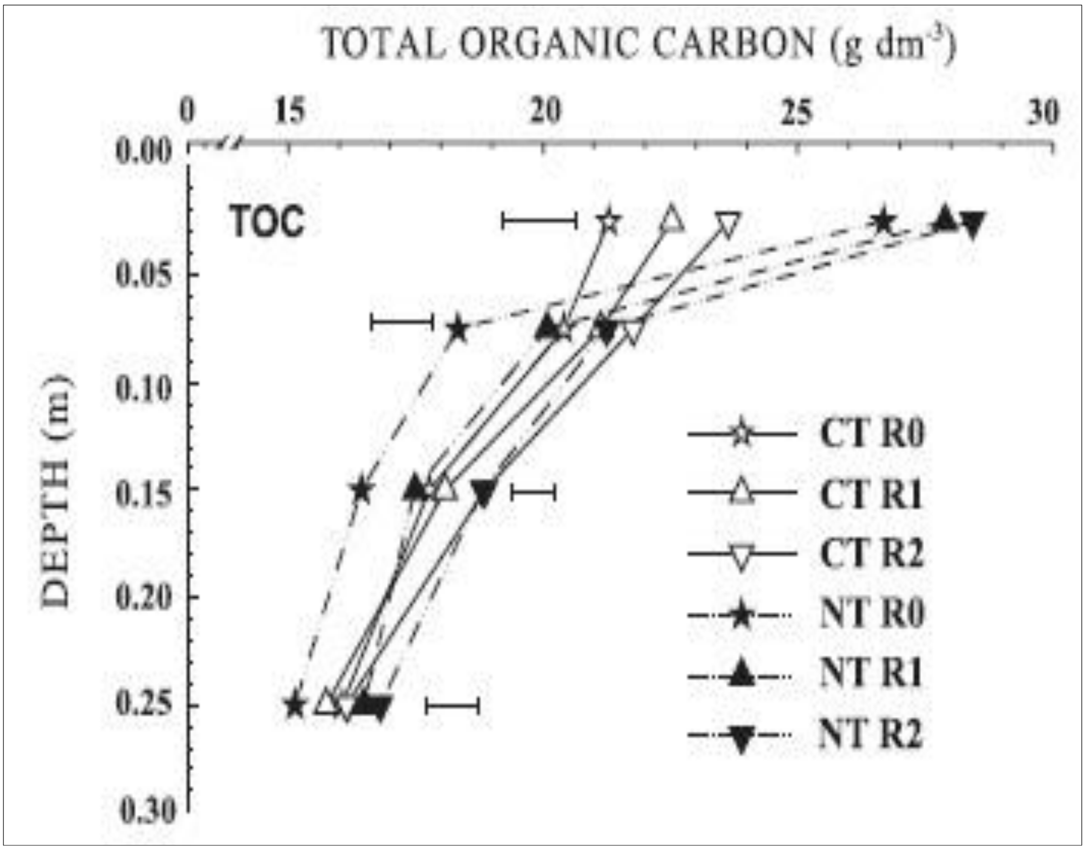


Fig 2 (c): Contents of total organic carbon (TOC) under conventional tillage (CT) and no tillage (NT) systems

Dutta and Gokhale, (2017) [20] observed that the reduced tillage in the conservation plot resulted in higher soil moisture content, due to plant debris accumulated on the top layer of the soil. Water infiltration increased in conservation plot, which can be attributed to minimum tillage practice [Fig. 3a]. Particle density or specific gravity of soil which refers to the density of the solid particles collectively was found to be higher and bulk density was significantly lower in conservation plot. The average bulk density was found to be 0.69 gcm^{-3} in conservation plot while in conventional plot it was1.17gcm^{-3}. The per cent pore space or porosity was found to be higher in conservation plot in the range of 50.11+8.40%–88.87+3.59%. This is because decreased soil disturbance leads to lesser soil compaction, which increases pore-space [Fig.3a]. Tillage practices and cropping pattern can influence bulk density and the change is more evident near the surface of the soil (Williams & Gollany, 2006). The SOC was found to be higher in conservation plot and it ranged from 3.17+0.01kgm^{-2} to as high as 20.42+0.56 kgm^{-2} during heading stage [Fig. 3b], which can be attributed to the increased accumulation of organic matter in the top soil due to minimum disturbance (minimum tillage).The reduced disturbance prevents the exposure of soil particles to microbial attack, hence reducing the loss of organic matter [Fig.3b]. A significantly higher amount of SOC was seen in heading stage, which may be because of more amount of surface water present due to heavy rainfall at that particular time [Fig. 3b]. In conventional plot, less SOC was seen (2.08+0.01kgm^{-2} –7.92+ 0.12kgm^{-2}). Here, due to continuous tillage practices, the soil aggregates were disrupted, exposing the SOM and increasing the soils decay rate. This happens because of the increase of temperature and aeration of soil, leading to an increase in microbial activity and subsequent release of previously stored organic matter in soil (Balesdent, Chenu & Balabane, 2000) [4].

Zhu *et al*. (2014) [69] 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 [Fig. 4a]. Soil TOC and labile organic C fractions generally decreased with an increase in soil depth under all treatments. The reason could be attributed to the tillage method. Tillage increases the effect of drying–rewetting and freezing-thawing on soil, which increases macro-aggregate susceptibility to disruption (Beare *et al*., 1994) [6], and accelerates the labile organic C mineralization and SOM degradation, thus increasing the loss of EOC. The difference in soil condition after plowing tillage or rotary tillage affects the rate of straw decomposition, thereby resulting in a difference in the soil nutrient accumulation (Li and Zhang, 1999). Wang *et al*. (2015) [63] concluded that the concentrations of total soil organic carbon (SOC), light fraction organic carbon (LFOC), dissolved organic carbon (DOC), and microbial biomass carbon (MBC) were significantly higher in the straw application plots than in the controls by 7.1–128.6% for both the early and late paddy season [Fig. 4b]. In general, significant and positive correlations were observed between SOC, DOC, LFOC, MBC and labile organic carbon (LOC) in the treatment and control plots for both early and late paddy [Fig. 4b]. Bhattacharyya *et al*. (2015) observed that soil bulk density under MBR + DSR-ZTW + RR-ZTMB and DSR + BM-ZTW + RR treated plots significantly decreased in the 5–15 cm layer compared to TPR-CTW plots [Fig.4c].

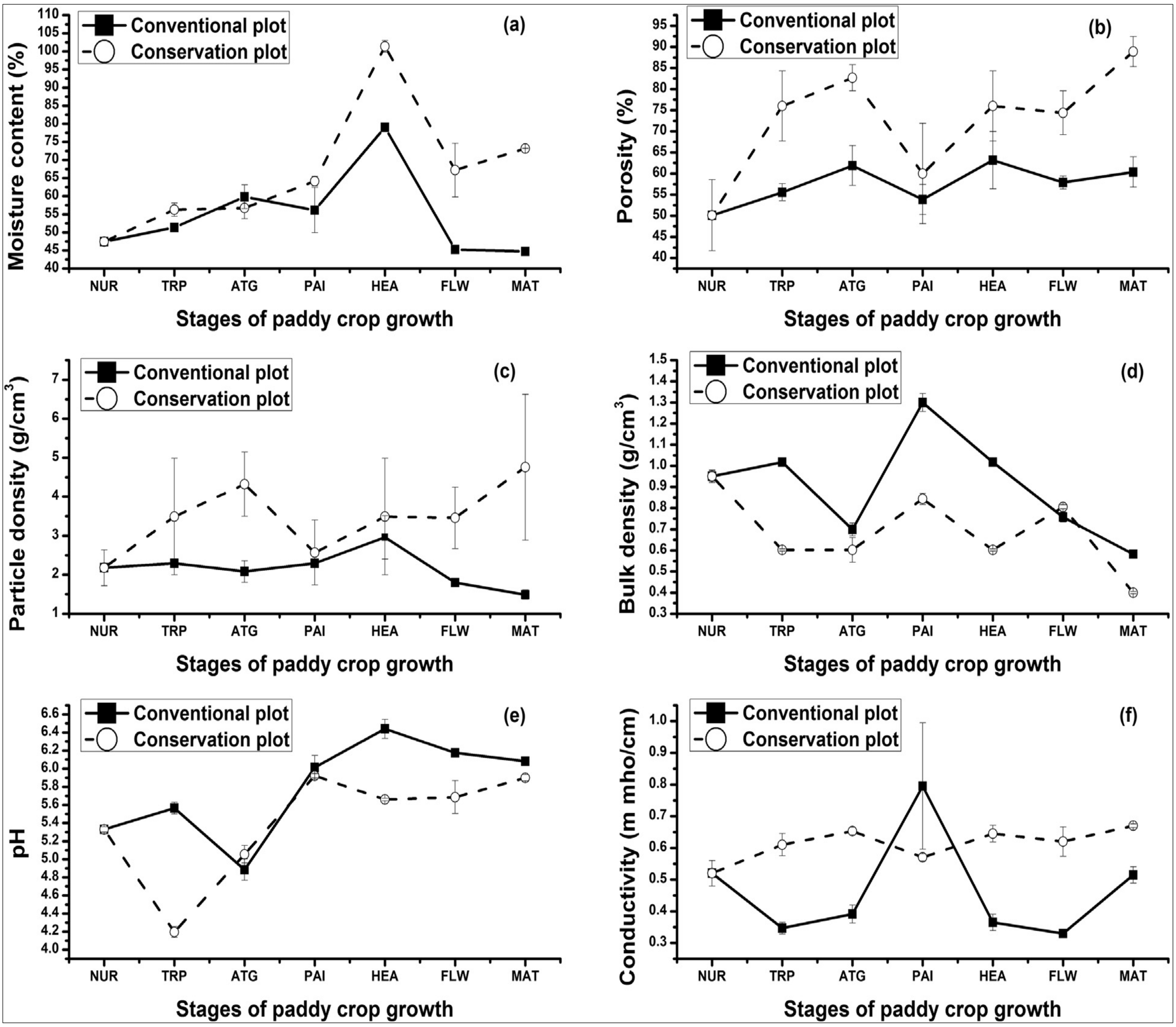


Fig 3 (a): Variation of the soil parameters (a) moisture content (b) porosity (c) particle density (d) bulk density (e) pH (f) conductivity during the various stages of paddy crop growth

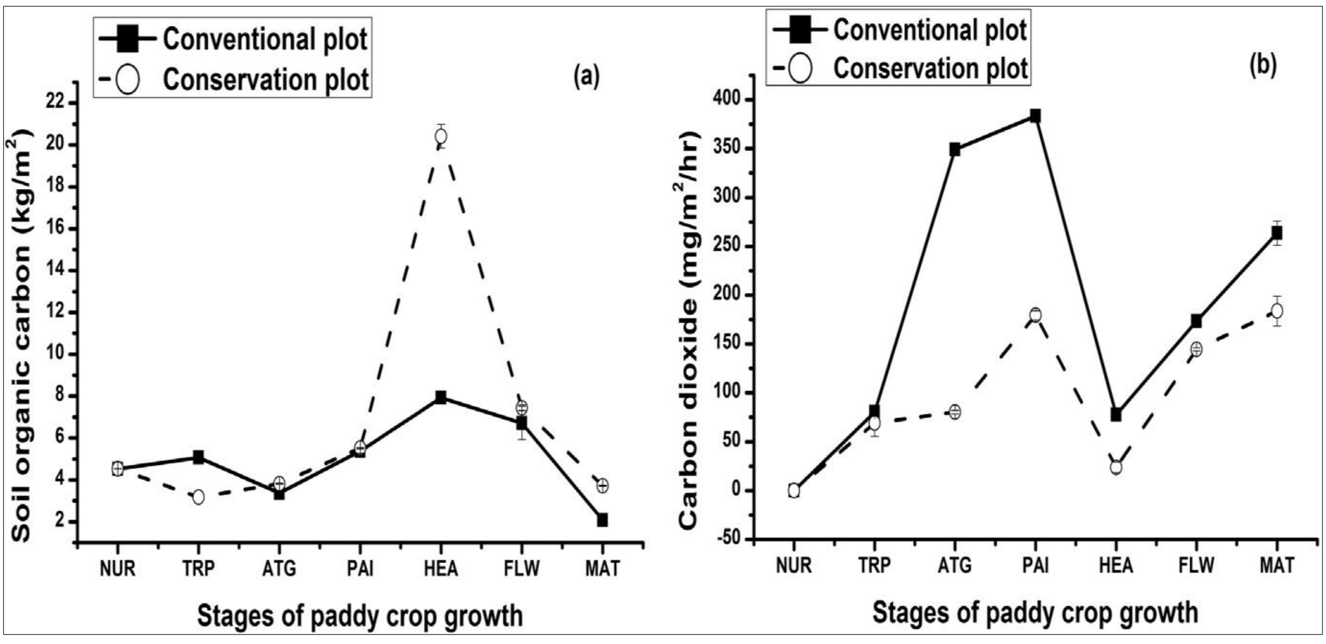


Fig 3 (b): Variation of (a) soil organic carbon and (b) carbon dioxide observed in the conventional and conserved plots, during the various stages of paddy crop growth

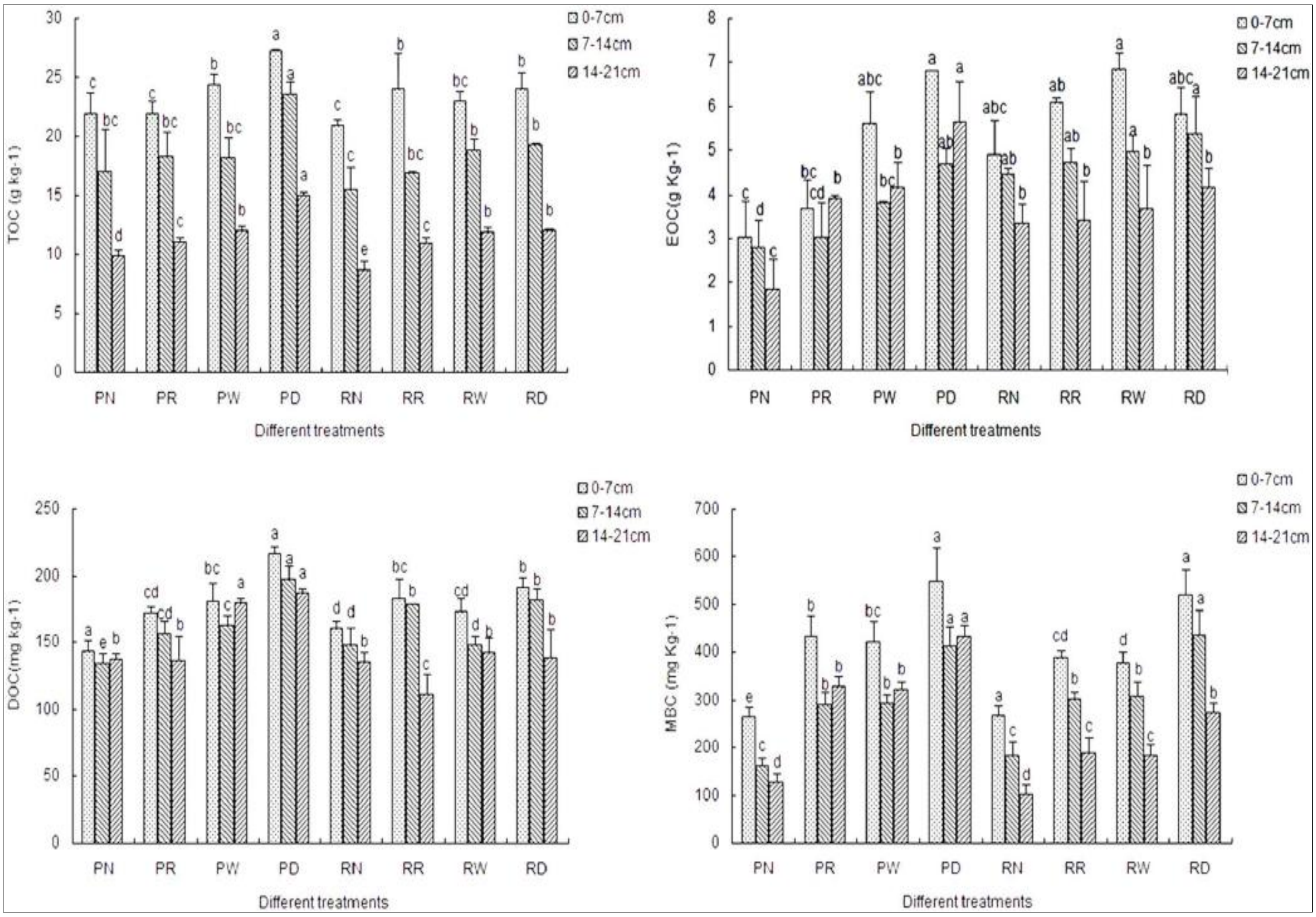


Fig. 4 (a): Effects of eight treatments on soil TOC, EOC, DOC and MBC contents at three depths

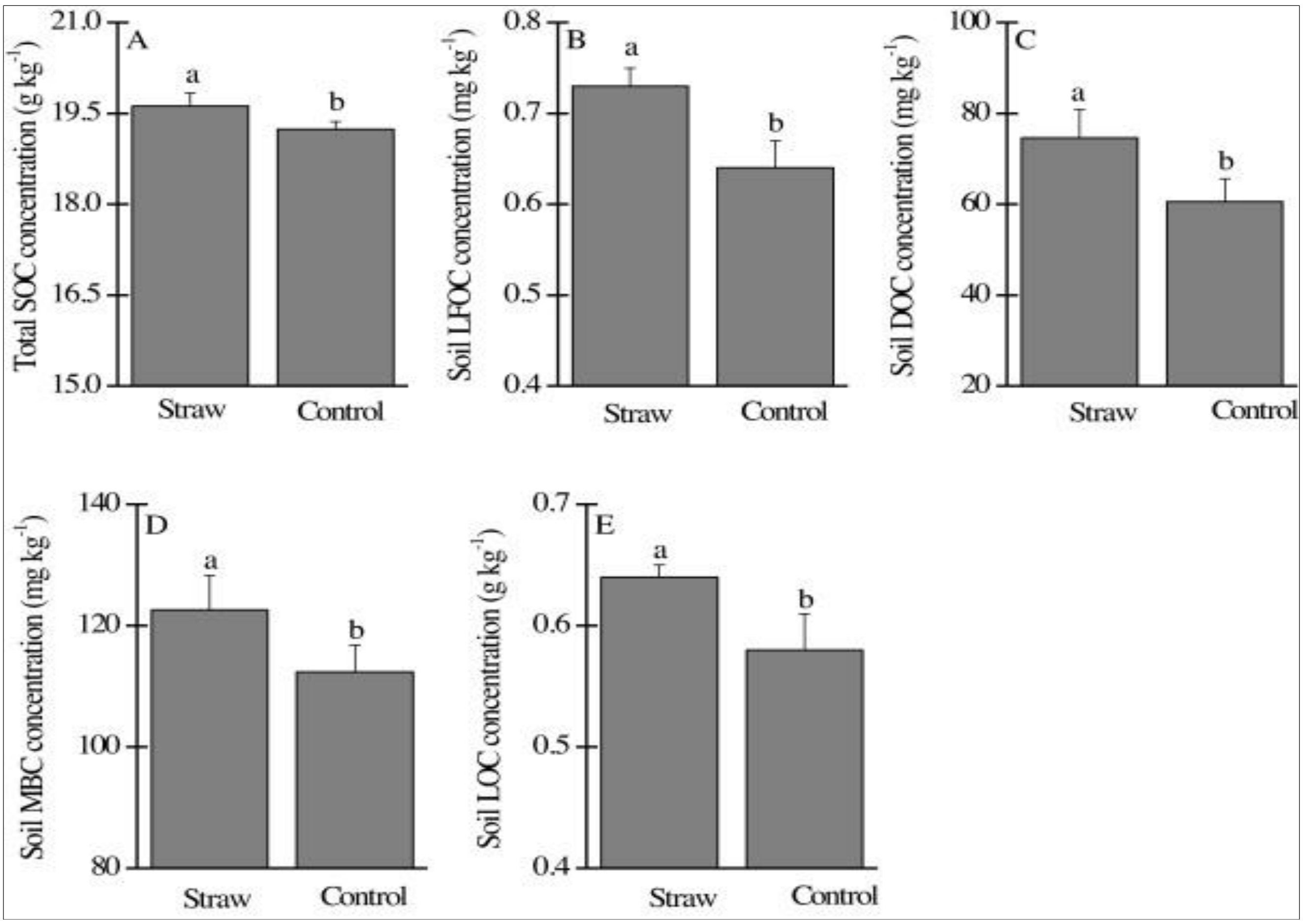


Fig. 4 (b): Effects of rice straw incorporation on active soil organic carbon pools

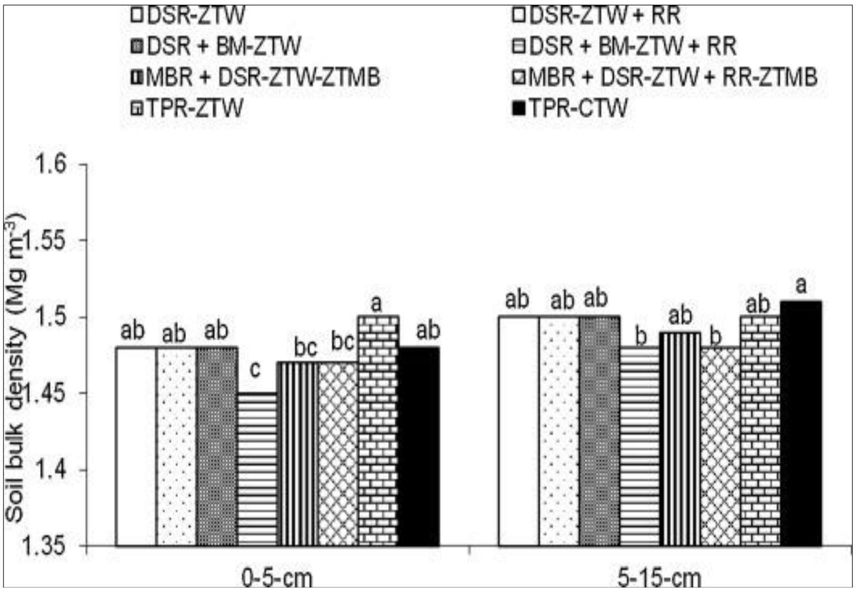


Fig. 4c: Effect of tillage residue practices on soil organic carbon accumulation in rice-wheat rotation

Six *et al*. (1998) concluded that the concentration of free LF C was not affected by tillage, but was on average 45% less in the cultivated systems than NV. Proportions of crop-derived C in macro-aggregates were similar in NT and CT, but were three times greater in micro-aggregates from NT than micro-aggregates from CT. Moreover, the rate of macro-aggregates in CT compared with NT leads to a slower rate of micro-aggregate formation within macro-aggregates and less stabilization of new SOM in free micro-aggregates under CT [Fig. 5a]. Zhao *et al*. (2018) [68] reported that the SOC content of each aggregate class in the 0–20 cm layer was significantly higher than that in the 20–40 cm layer [Fig. 5b]. Increases in the SOC content of aggregate fractions were highest in MRWR, followed by MR, and finally WR [Fig. 5b]. Crop-derived organic particles or colloids can combine with mineral matter, binding micro-aggregates into macro-aggregates. Fresh straw incorporation provides substrate for microorganisms, and straw input can alter the distribution of SOC and increase the SOC content of aggregates, especially in macro-aggregates (Guan *et al*., 2015).

Mazumdar *et al*. (2015) also found that the Concentration of C was higher in macro-aggregates as compared to micro-aggregates. Irrespective of treatments, C concentration was highest in 1-2 mm followed by 0.5-1mm size of macro-aggregates and the concentration decreased as the aggregates became smaller in size [Fig. 6a]. Incorporation of organic manures induces decomposition of organic matter where roots hyphae and polysaccharides bind mineral particles into micro-aggregates and then these micro-aggregates bind to form C rich macro=aggregates [Fig.6a]. Zhao *et al*. (2018) [68] revealed that the straw return treatments, particularly MR-WR, increased the proportions of mSOM and fine iPOM within small macro-aggregates and micro-aggregates, especially in the 0–20 cm layer [Fig. 6b]. The carbon content of iPOM was much lower at 20–40 cm than at 0–20 cm [Fig. 6b].

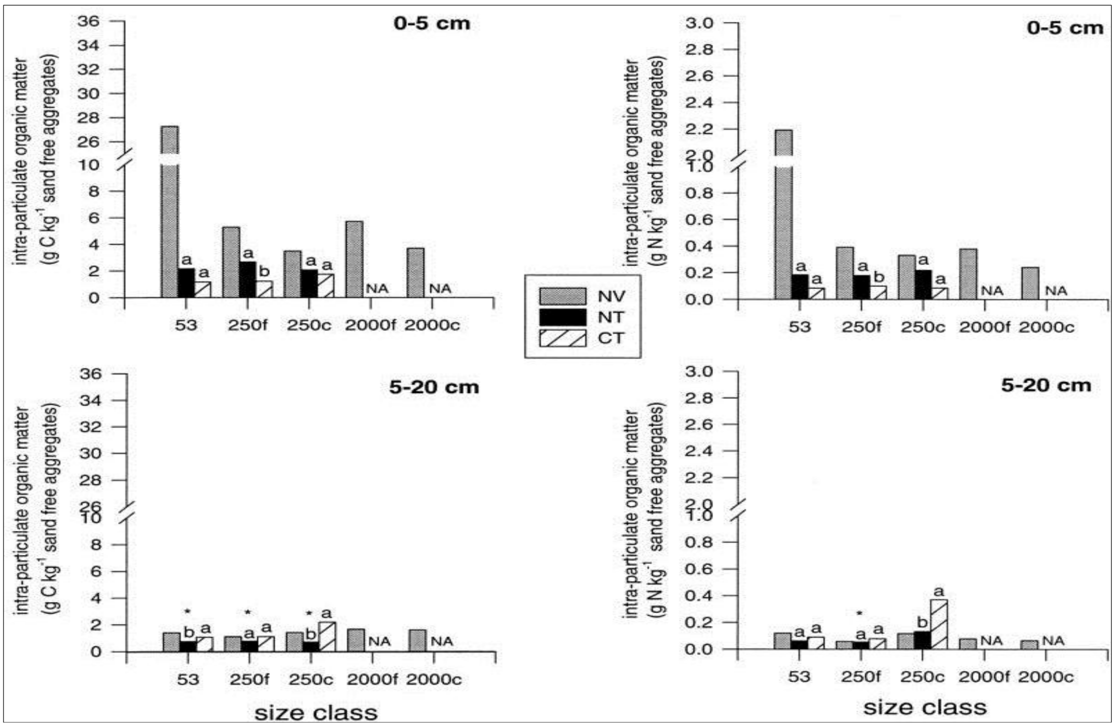


Fig. 5 (a): Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems

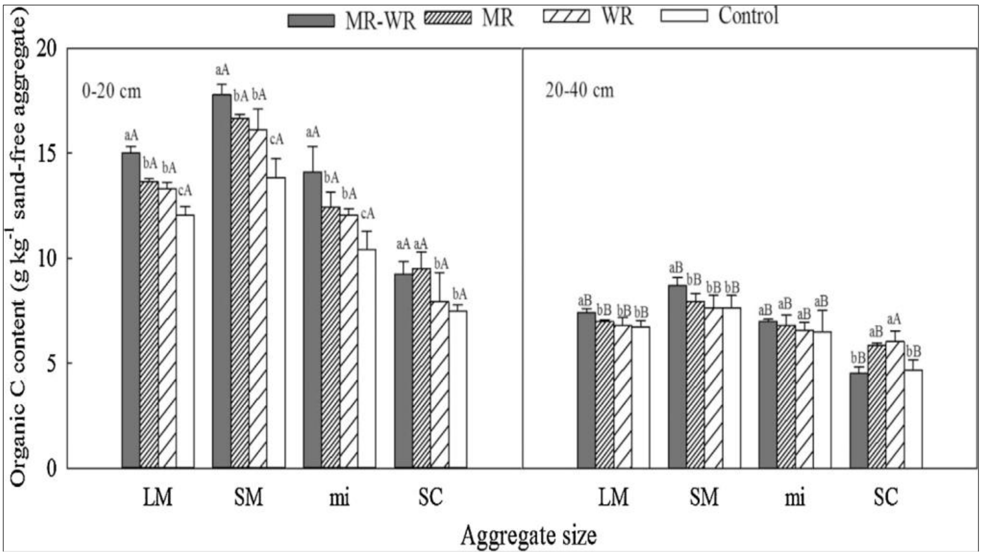


Fig 5 (b): Organic C content (g kg^{-1} aggregate) of aggregates: LM, SM, mi, and SC in the 0–20 cm and 20–40 cm soil layers under MR-WR, MR, WR, and Control.

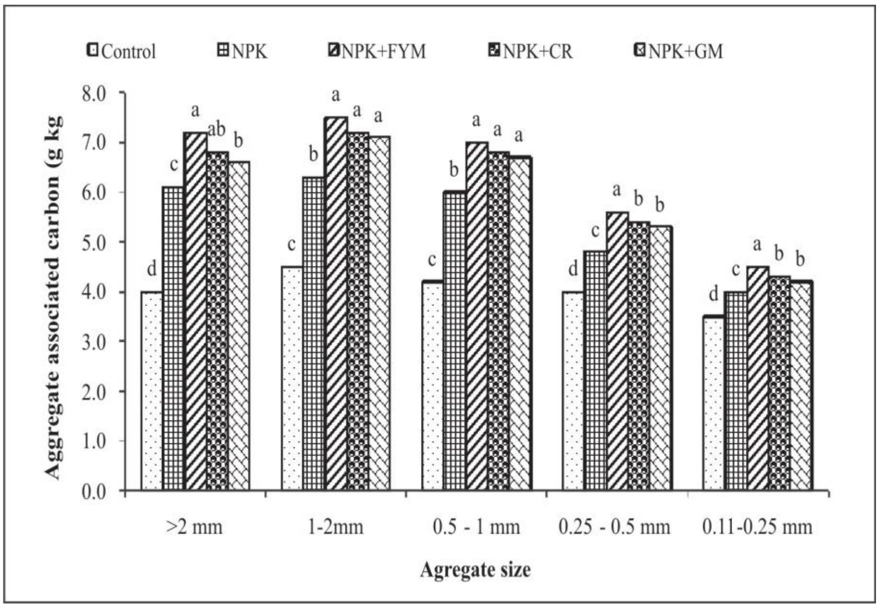


Fig 6 (a): Effects of long term integrated nutrient management practices on aggregate associated carbon in the soil

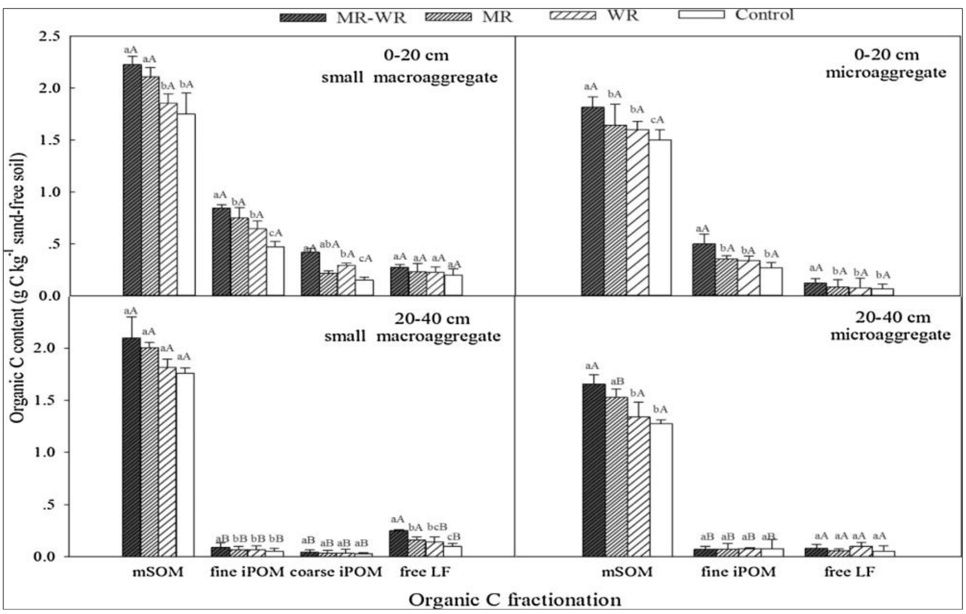


Fig 6 (b): Organic C content (g kg^{-1} soil) of the SOC fractions: coarse iPOM, fine iPOM, mSOM, and free LF of small macro-aggregates and micro-aggregates in the 0–20 cm and 20–40 cm soil layers under MR-WR, MR, and WR

Chen *et al*. (2009) [13] also found that the portion of 0.25–2 mm aggregates, mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates from ST and NT treatments were larger than from CT at both 0–15- and 15–30-cm soil depths [Fig.7a]. Naresh *et al*. (2018) [45] also found that the sandy loam nature of soils in the western Uttar Pradesh might hinder the formation of large stable macro-aggregates. The aggregate-size distribution and stability are important indicators of soil physical quality (e.g. soil structure, aggregation and degradation) (Shrestha *et al*., 2007) [54]. Tillage reduced the proportion of 2–0.25 mm aggregates in comparison with the conservation tillage treatments and there was a corresponding increase in the proportion of micro-aggregates (0.25–0.05 mm and/ or <0.05 mm fraction). Zibilske and Bradford (2007) [70] showed that plow tillage had significantly lower MWDs than no-tillage and ridge tillage at both 0–5- and 10–15-cm depths in a Higalgo sandly clay loam soil. The content of large macro-aggregates (>2 mm) was very low [Fig. 7b]. Small macro-aggregates (2 0.25 mm) represented the greatest portions in all treatments at both 0–15 and 15– 30 cm. At 0–15 cm, CT contained significantly less small macro-aggregates (2–0.25 mm) than ST or NT, which were not different from each other [Fig. 7b]. At 15–30 cm, ST and NT contained higher amounts of small macro-aggregates than CT; the difference was only significant between CT and NT [Fig.7b]. However, the <0.05 mm fraction was dominated by C. Naresh *et al*. (2017) [44] concluded that the macro-aggregates are less stable than micro-aggregates, and therefore more susceptible to the disruption forces of tillage.

The influence of tillage on aggregate C and Nt content is shown in [Fig.7c]. At 0–15 cm, tillage effect was confined to the 2–0.25 mm size fraction, in which the conservation tillage treatments contained significantly higher SOC contents than CT, ST had significantly higher Nt contents than CT, and NT tended to have higher Nt contents than CT [Fig. 7c]. No significant differences were detected in SOC and Nt contents in the 0.25– 0.05 mm and <0.05 mm classes among all treatments [Fig. 7c]. The highest SOC and Nt contents were found in the 2–0.25 size fraction. Data from the 15- to 30-cm samples show generally diminished effect of tillage treatments [Fig.7c]. Soil organic C and Nt contents in the aggregate-size fractions generally decreased with increase in soil depth for all treatments [Fig.7c]. Chen *et al*. (2009) [26] reported that reduced tillage (RT) contained 7.3% more SOC and 7.9% more N stocks than plough tillage (PT) in the 0–20-cm depth, respectively, and estimated that RT accumulate an average 0.32 Mg C ha^{-1} yr^{-1} and 0.033 Mg N ha^{-1} yr^{-1} more than PT over an average period of 11 years, respectively.

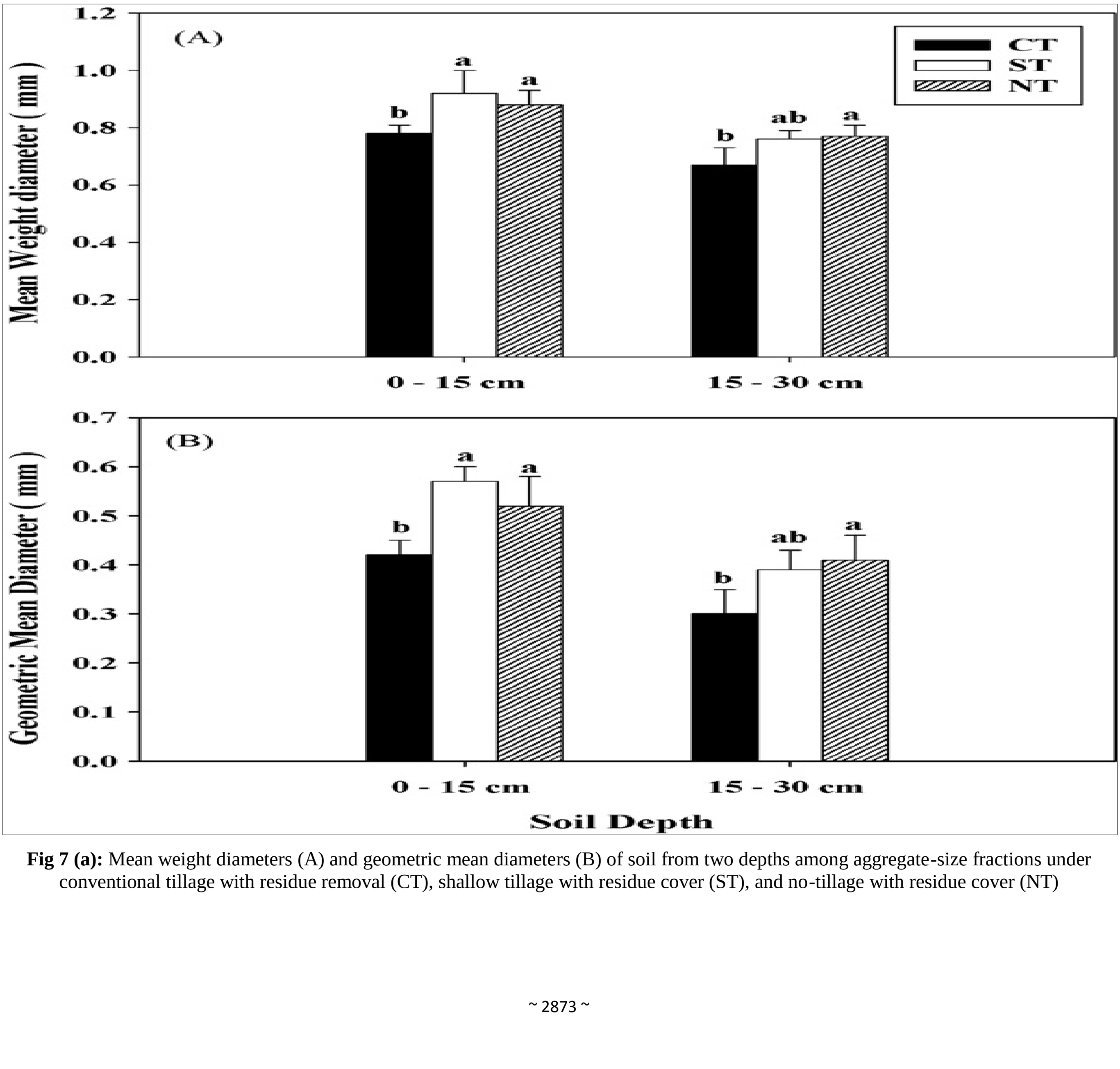


Fig 7 (a): Mean weight diameters (A) and geometric mean diameters (B) of soil from two depths among aggregate-size fractions under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT)

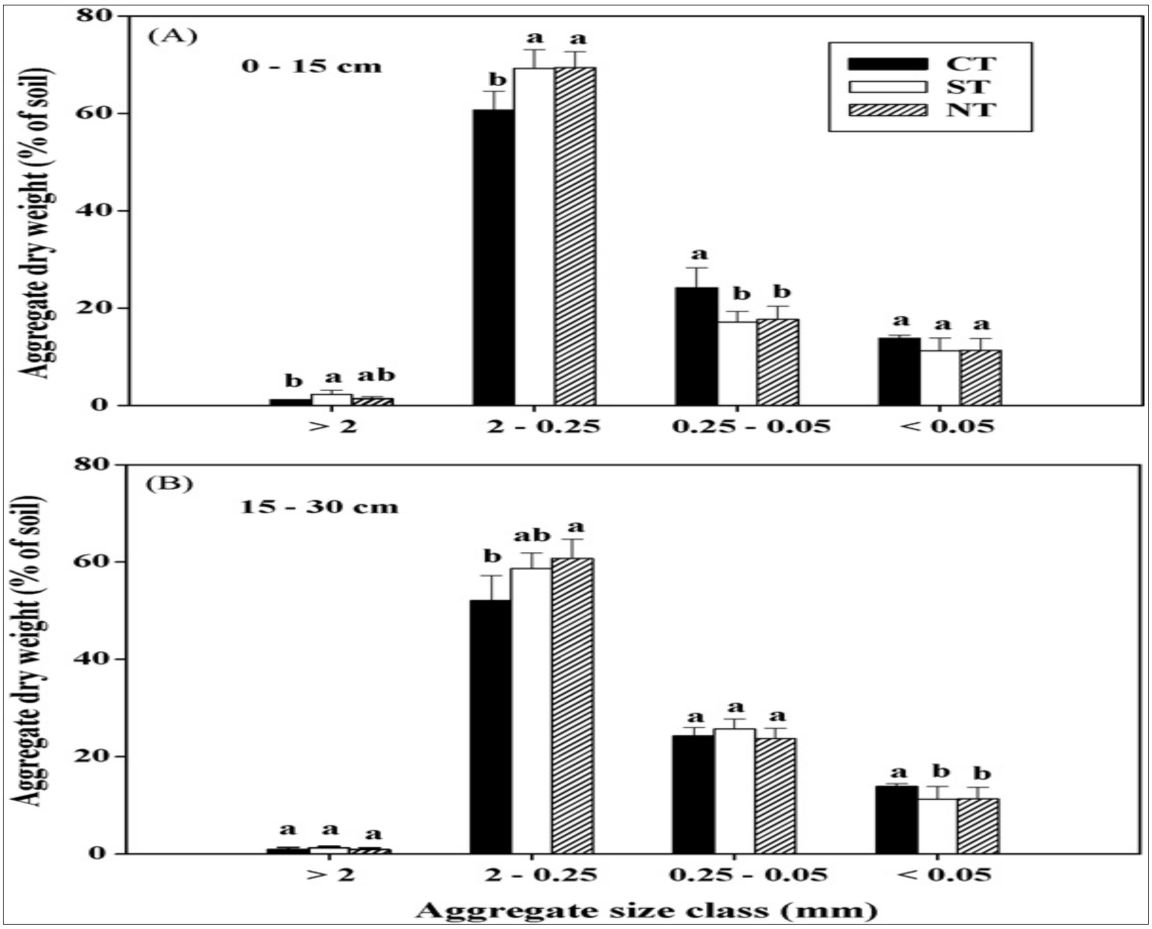


Fig 7 (b): Aggregate-size distribution as determined by wet sieving for (a) the 0–15-cm and (b) the 15–30-cm layers under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT)

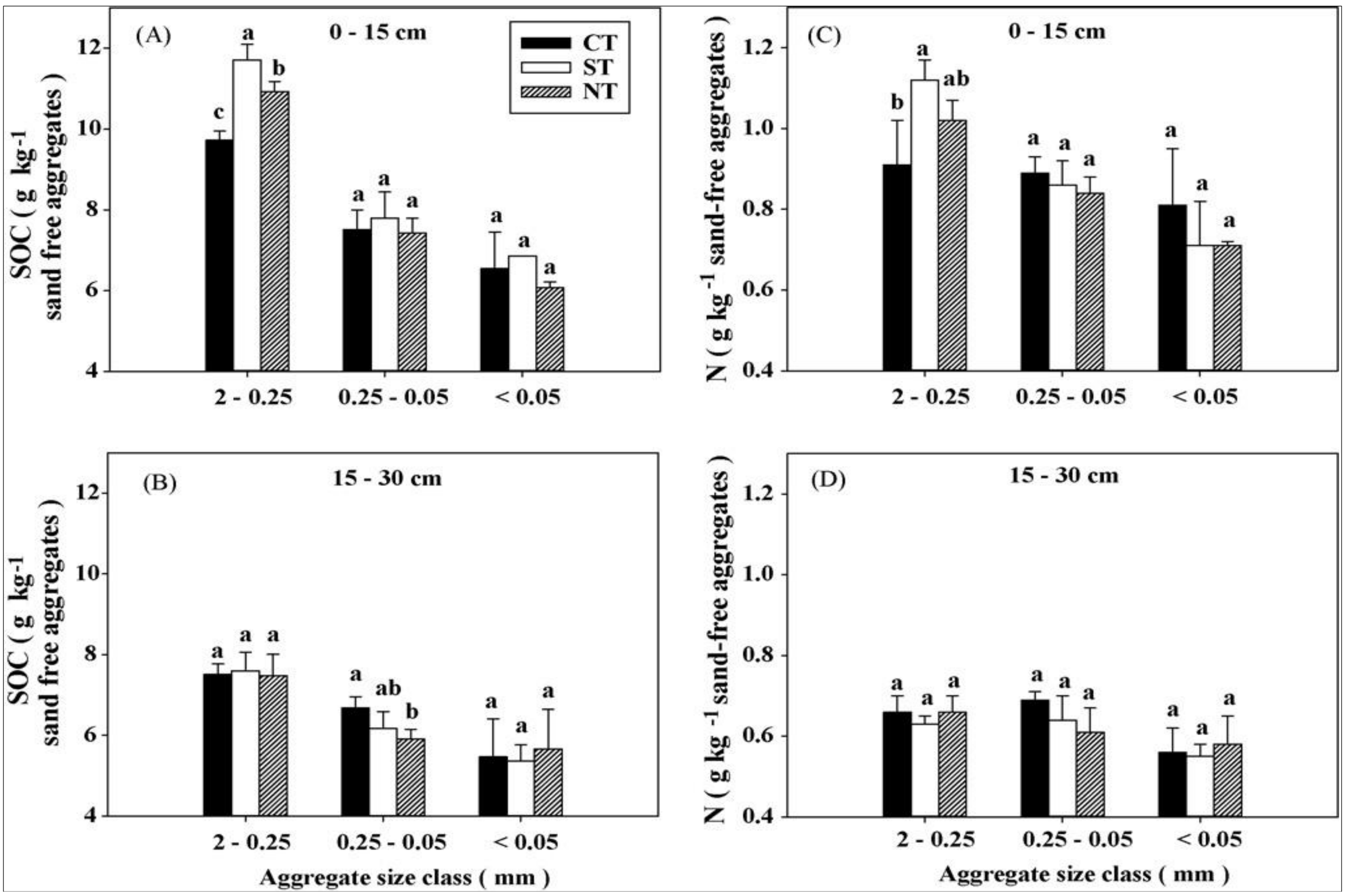


Fig 7 (c): Soil organic carbon (SOC) and nitrogen content (g kg^{-1}) of sand-free aggregates from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT**)**

Bhattacharyya *et al*. (2010) [8] observed that fertilization had little effect on aggregation in sizes below S3 in all soil depths. It had no effect on S5 and S7 in the 0–15 and 15–30 cm [Fig.8a] and on S4, S5, S6 and S7 in the 30–45 cm soil layers [Fig.8a]. Addition of FYM increased the percentages of large sized aggregates (2–4.75 and 1–2 mm) in all soil layers. Proportion of aggregates [2 mm (S1) was nearly 41% higher under NPK? FYM treated plots than that observed under NPK in the 0–15 cm soil layer [Fig.8a]. The application of FYM increased porosity, thereby reducing soil bulk density in all depths. Sharma *et al*. (1995) [53] reported reduction in soil bulk density with organic matter additions. Soil bulk density decreased with FYM application due to greater SOC content and increase in root biomass produced that resulted in better soil aeration and improved soil structure. Type of mineral fertilization had no effect on SOC storage in smaller fractions (S6 and S7) in all soil layers. Plots with NPK had higher SOC storage over NK in the 0–15 and 15–30 cm soil depths, except for S5–S7 [Fig.8b]. Addition of FYM with mineral fertilizers (NPK? FYM) significantly increased SOC storage over NPK for S1–S7 in the 0–15 cm, S1 to S5 in the 15–30 cm, and S1–S4 in the 30– 45 cm [Fig. 8b] soil depths. In all soil layers, plots under NPK? FYM exhibited the highest SOC storage in S5. Across treatments, mean SOC associated with S5 fraction was nearly 39% of the total aggregate associated-C in the 0–45 cm depth interval [Fig.8b]. Majumder *et al*. (2007) [41] also observed that cultivation with balanced fertilization caused net enrichment of the total SOC content of a sub-tropical alluvial soil. Plots with NPK? FYM had higher SOC sequestration than NPK treated plots, which is a result of increased yields of roots and plant residues, and the direct application of organic matter through FYM. Zhu *et al*. (2014) [69] revealed that the 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 [Fig.8c]. Compared to conventional tillage (CT), no-tillage and reduced tillage could significantly improve the SOC content in cropland. Frequent tillage under CT easily exacerbate C-rich macro-aggregates in soils broken down due to the increase of tillage intensity, then forming a large number of small aggregates with relatively low organic carbon content and free organic matter particles. Free organic matter particles have poor stability and are easy to degradation, thereby causing the loss of SOC (Yang *et al*., 2003) [64]. Liu *et al*. (2009) [23] have found that SOM content under plowing and rotary tillage at deeper soil both were higher than that of the upper soil. The reason might be that rotary tillage and plowing tillage mixed crop straw into the deeper soil layer, making SOM well distributed at different depths (Gao *et al*., 2000) [23].

Chen *et al*. (2016) [23] reported that the SOC concentration decreased with soil depth [Fig. 9a]. In both 0–10 and 10–20 cm, the SOC concentration in the RP treatment was significantly greater than that in the other four treatments, yet no significant differences were found among the other four. In 20–30 cm, there were in general no significant differences among all the rotation systems. For POC, the concentration in the RW treatment was significantly lower than that in the RF, RO, and RP treatments, being 22.6%, 26.0% and 22.7% at 0–10 cm respectively, and 12.0%, 17.0%, and 12.4% at 10–20 cm, respectively. The concentrations of DOC in the RP treatment were significantly greater than in the other treatments irrespective of the soil depth. By contrast, the DOC concentration in the RF treatment was significantly lower than those in the rotations with plant growth and the decreases in DOC ranged from 46% to 140.0% at 0–10 cm and 36.9% to 80.9% at 10– 20 cm soil depths. The concentrations of HWC in the RP and RG rotation systems were significantly higher than those in the RO, RW, and RF rotation systems at the 0–10 cm and 10–20 cm depths. The MBC concentration in RO and RW was significantly decreased compared with RP, RG and RF at the 0–10 cm and 10– 20 cm depths. In addition, the values in RG and RP were significantly greater than in the other rotation treatments at the 0–10 cm and 10–20 cm depths. However, no significant differences among the rotations were found at the depth of 20–30 cm [Fig. 9a]. The contents of DOC, HWC, MBC, and $KMnO_4$-C in the RP treatment were comparatively higher than in the other treatments. The improved labile SOC fractions might partly explain the improvement of soil properties. For example, dissolved carbohydrates, which are very important bonding agents for soil aggregates (Haynes and Beare, 1996) [6], accounted for about 45–60% of C in HWC and 3–20% of C in DOC.

Tripathi *et al*. (2014) [59] 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 [Fig. 9b]. Application of FYM alone or in combination with inorganic fertilizers significantly improved the formation of macro and meso-aggregates compared to unfertilized control at both sampling depths. The incorporation of FYM alone increased the occurrence of macro-aggregates (5–2 mm) by 165.33% whereas meso-aggregates increased by 130.68% in 2–1 mm fraction, by 282.83% in 1–0.5 mm fraction over unfertilized control in 0–15 cm soil layer. The proportion of micro-aggregates (0.25–0.1 mm and 0.1–0.053 mm) was less in FYM + inorganic fertilized plots than the plots applied with inorganic fertilizer alone. The application of FYM decreased the micro-aggregate fraction of 0.25– 0.1 mm by 0.35 to 9.94% and micro-aggregate fraction of 0.1–0.053 by 0.4–30.63% compared to unfertilized control in the surface soil. The increase in the proportion of water stable macro-aggregates (>2 mm) by FYM + inorganic fertilizer application could be attributed to the input of additional organic residues and available C to the soils and increase in ECe as compared with inorganic fertilizer application alone and unfertilized control [Fig.9b].

Zou *et al*. (2014) [45] revealed that the soil DOC ranged from 297.83–351.97 g kg^{-1} for S_{400}, 223.08–243.88 g kg^{-1} for S_{800}, 220–254.34 g kg^{-1} for S_{1200} and 311.83–321.43 g kg^{-1} for S_{1600}. Straw return to deep soil significantly decreased the soil DOC. The straw return treatments had significantly lower soil DOC than the CK at each soil depth, except for the S_{400} treatment at depths of 0–10 cm and 20–40 cm. The soil DOC contents were not significantly different between the soil layers in each treatment. Regarding the vertical distribution of soil DOC, the soil DOC decreased with increasing soil depth in all treatments [Fig 9c]. In addition, the soil DOC content had a relatively strong impact on the migration of heavy metals and the adsorption of inorganic ions (Moore *et al*., 1992) [43]. The soil DOC content was lower in the straw return treatments than in the CK. This result potentially occurred because the crops absorbed DOC during their growth and development or because the DOC was temporarily accumulated in or transformed to other substances. Otherwise, the decrease in DOC could be associated with microbial use (Moore *et al*., 1992) [43]. The DOC content influenced the migration of soil organic and inorganic components and their transformations and degradation. In addition, the environmental changes in soil chemistry should also be considered.

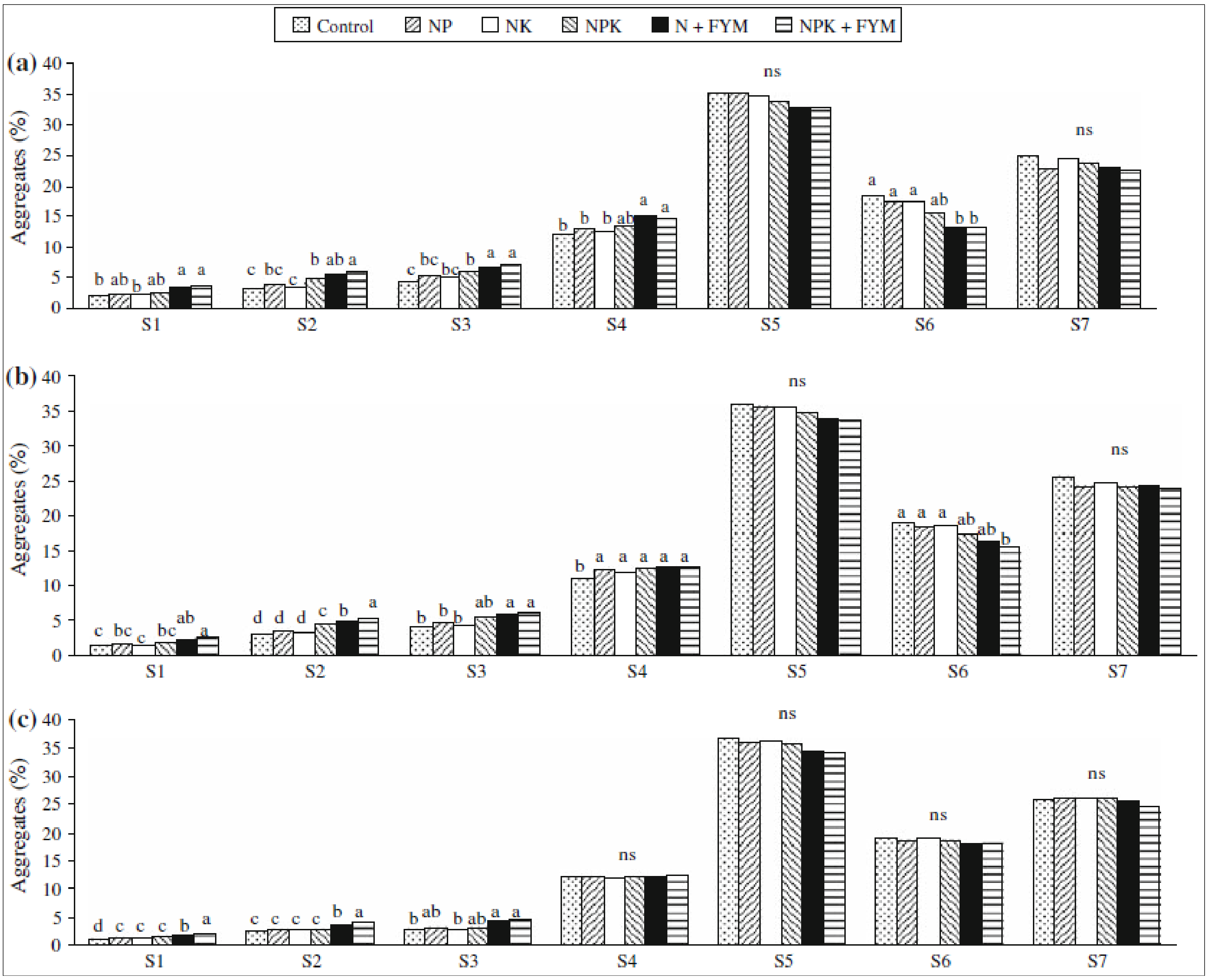
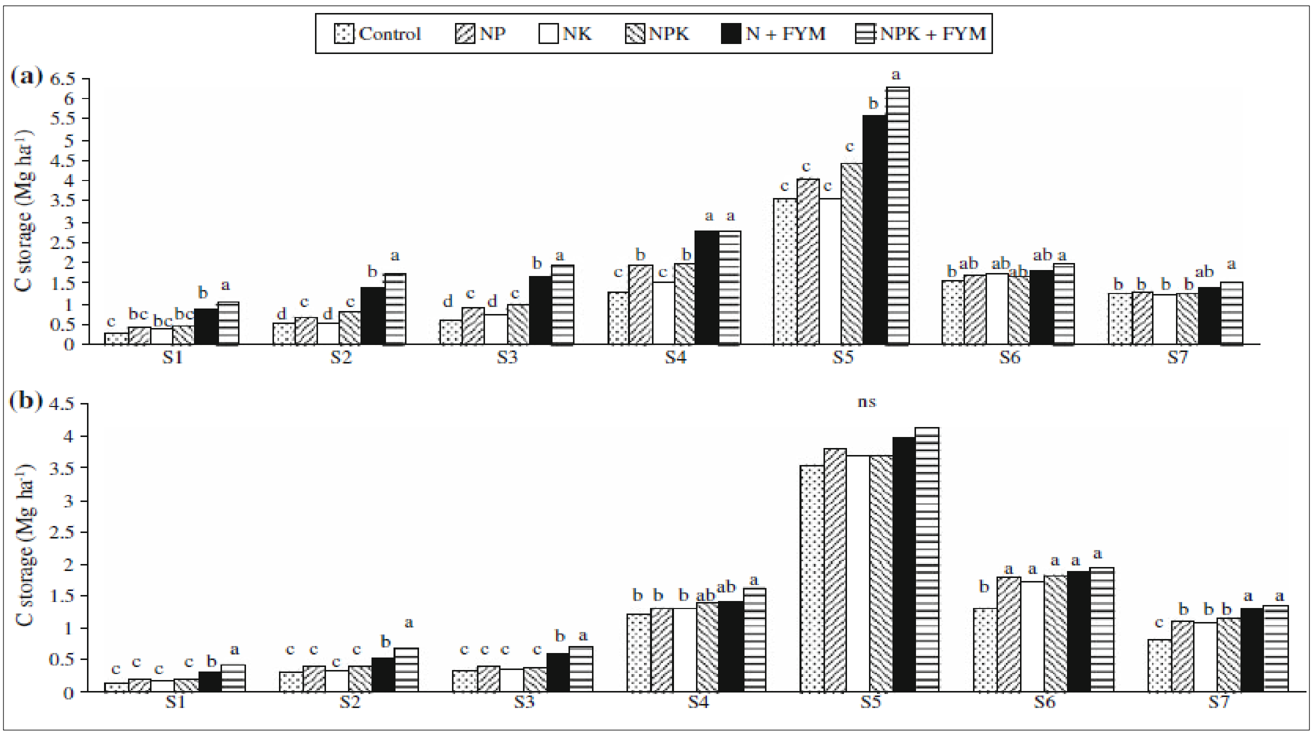


Fig 8 (a): Effect of fertilization on the percentages of seven different aggregate-size fractions at a 0–15, b 15–30 and c 30–45 cm soil depths



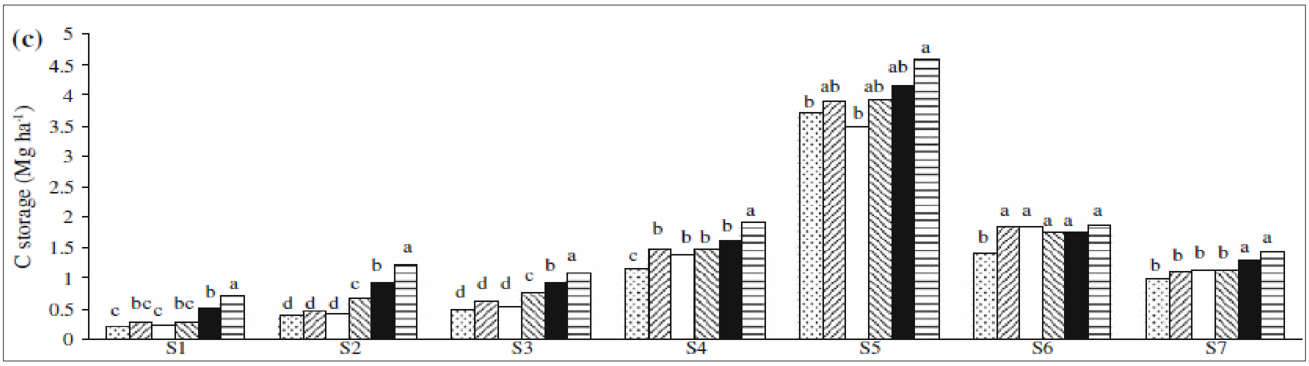


Fig 8 (b): Effect of fertilization on total soil organic C content of seven different sized aggregates at a 0–15, b 15–30 and c 30–45 cm soil depths

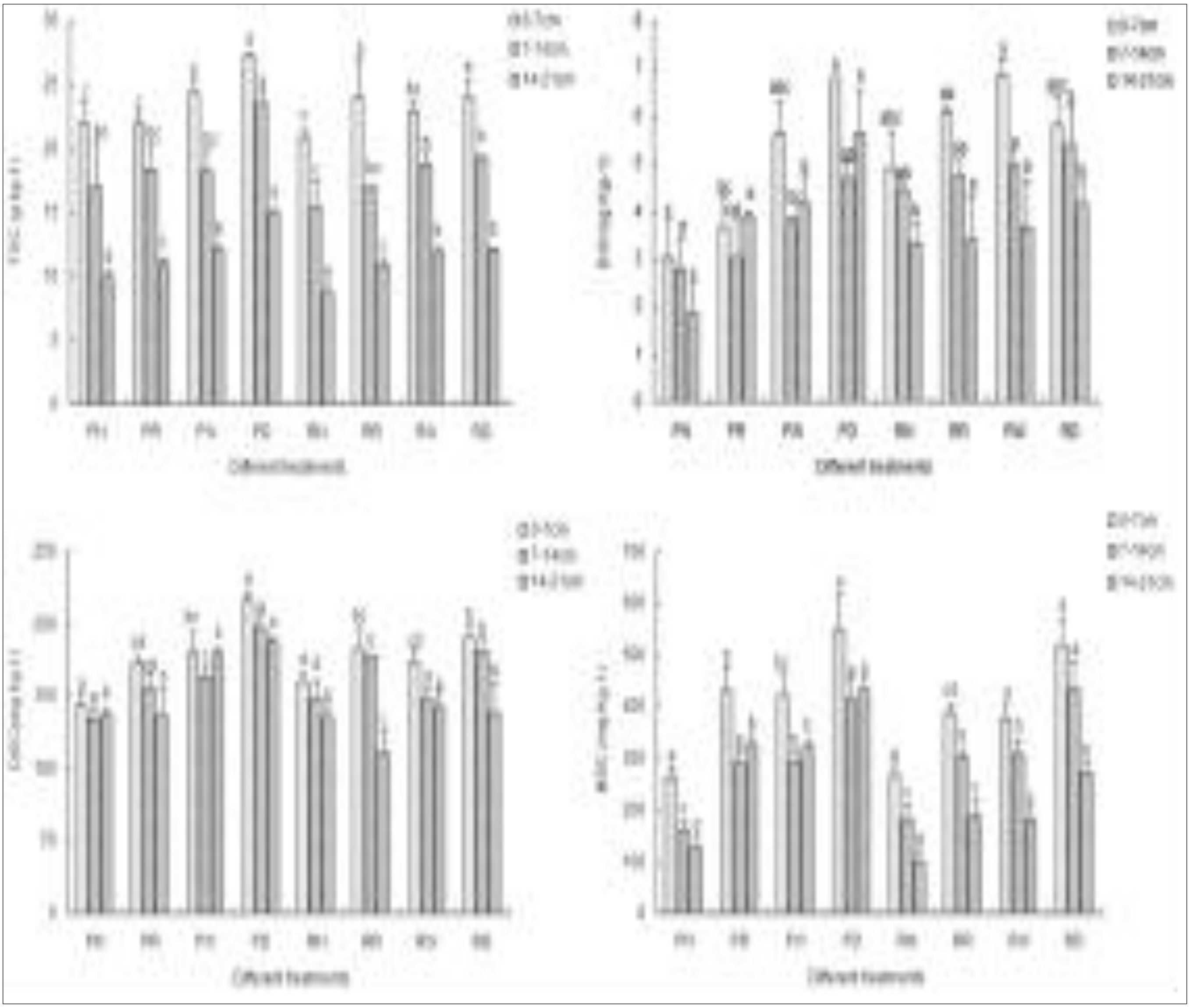


Fig 8 (c): Effects of eight treatments on soil TOC, EOC, DOC and MBC contents at three depths

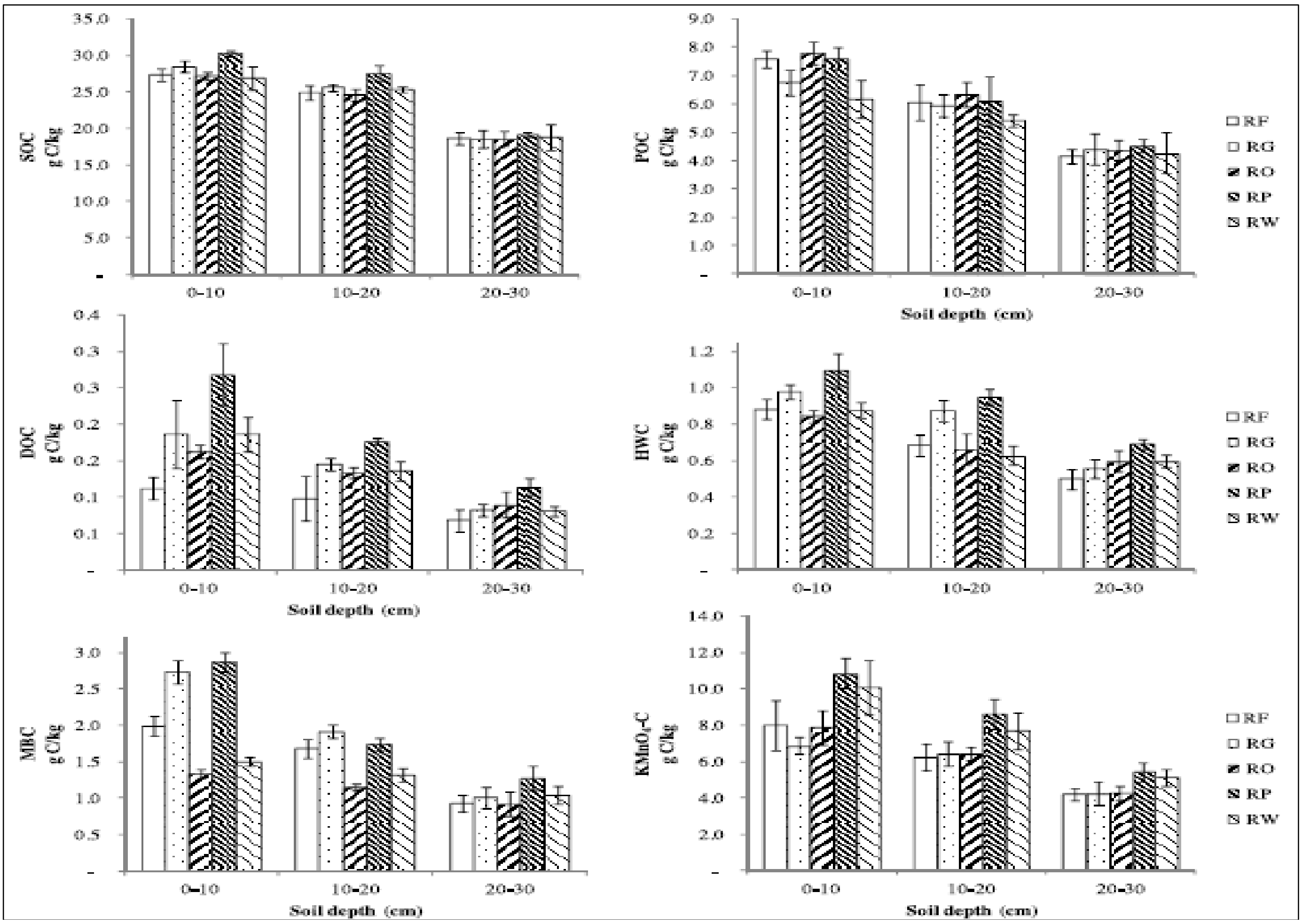


Fig 9 (a): Fractions of labile soil organic carbon (g C kg^{-1} soil): microbial biomass C (MBC), dissolved organic C (DOC), hot-water extractable C (HWC), permanganate-oxidizable C ($KMnO_4$-C), and particulate organic C (POC), as affected by rotation treatments at soil depths of 0–10,10–20, and 20–30 cm.

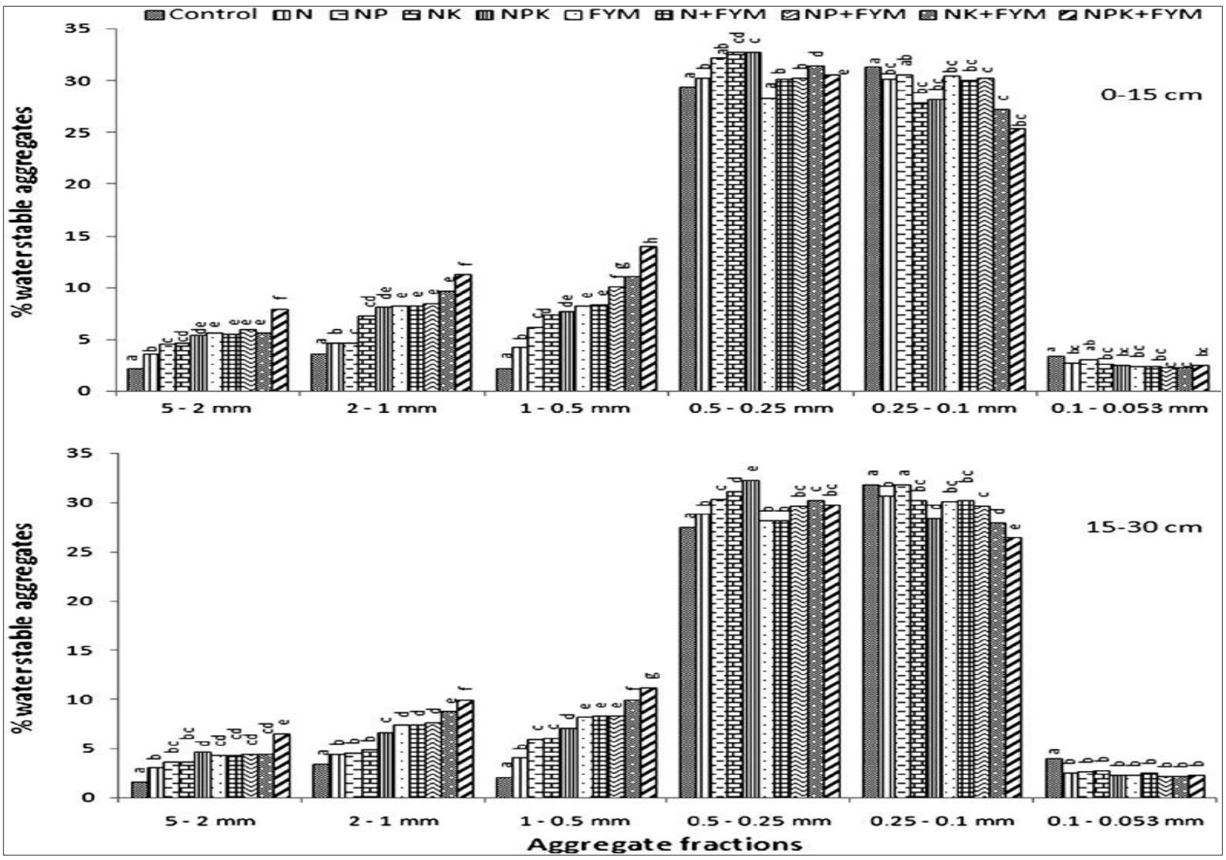


Fig 9 (b)

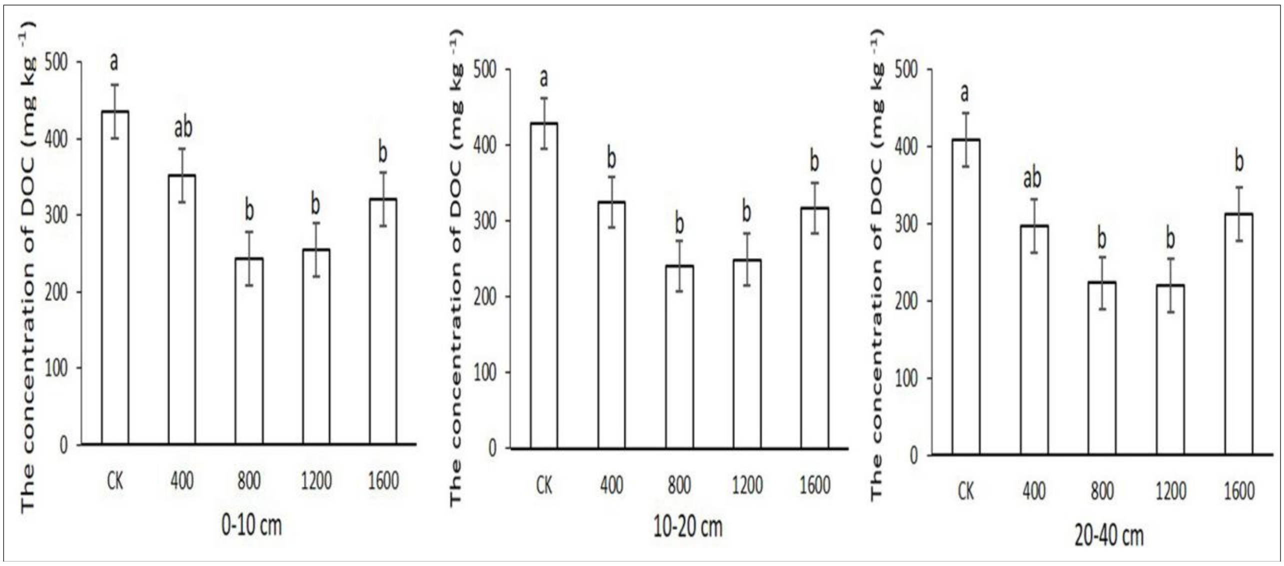


Fig. 9 (c): Effects of returning straw to the deep soil on soil dissolved organic carbon (DOC) at the three soil depths

The soil EOC content ranged from 7.98–11.23 g kg^{-1} for S_{400}, 8.80–13.47 g kg^{-1} for S_{800}, 7.92–10.02 g kg^{-1} for S_{1200} and 7.58–9.42 g kg^{-1} for S_{1600}. The EOC contents in the S800 treatment were the highest, and the EOC contents in the CK were the lowest at each soil depth. Some appreciable differences were observed between the straw return in the different treatments, which decreased in the following order: S_{800} > S_{400} > S_{1200} > S_{1600} > CK [Fig 10a]. The deep soil (depth of 20–40 cm) had the lowest EOC content compared with the other two depths. In the control treatment, the soil EOC decreased as the soil depth increased from 0–10 cm to 10–20 cm. In the straw return treatments, the soil EOC was higher at 10–20 cm than at 0–10 cm [Fig. 10a]. Soil EOC may reflect the effectiveness of organic C for indicating soil quality, which was more sensitive than other indicators in farmland soil (Jiang *et al*., 2006). The EOC content was higher at 0–20 cm than at 20–40 cm because of increased microbial activity, and the soil permeability was improved after straw was returned to the 0-40-cm soil layer. The EOC content was the highest in S_{800}, which could suggest that the application of 800 $kgha^{-1}$ straw was the most effective for improving soil microbial activity and the soil EOC content. The soil LFOC in the different straw return treatments ranged from 223.12–280.37 mg kg^{-1} for S_{400}, 235.67–300.32 mg kg^{-1} for S_{800}, 233.78–301.32 mg kg^{-1} for S_{1200}, and 218.44–268.77 mg kg^{-1} for S_{1600}. The ranges of soil LFOC in all treatments decreased as follows: S_{1200} > S_{800} > S_{400}, CK>S_{1600} at 0–10 cm, S_{800}, S_{1200} > CK, S_{400} > S_{1600} at 10–20 cm, and S_{800}, S_{1200} > S_{400} > S_{1600} > CK at 20–40 cm [Fig 10b].

Gu *et al*. (2016) [23] bserved that the soil under mulching treatments ST and GT had significantly higher LOC, DOC, POC and EOC concentrations in the surface 0±40 cm layer than those with no mulching treatment [Fig.10c], probably attributable to the inputs of straw, root and its sections. Concentrations of labile C fractions in all treatments tended to decrease with soil depth [Fig. 10c]. Liu *et al*. (2012) [40], this could have been due to the fact that concentrations of total carbon and labile C fractions in all treatments showed seasonal dynamic change. LOC is a short-term repository of soil nutrients and its main constituent is freestate carbon (Post and Kwon, 2000) [47].

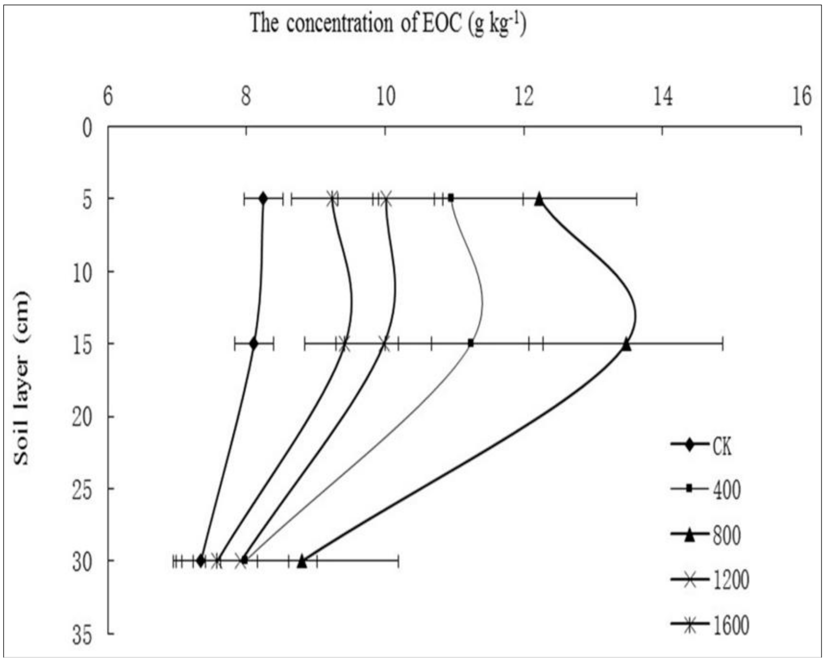


Fig 10 (a): Effects of straw return to deep soil on the easily oxidized organic carbon (EOC) contents at three soil depths

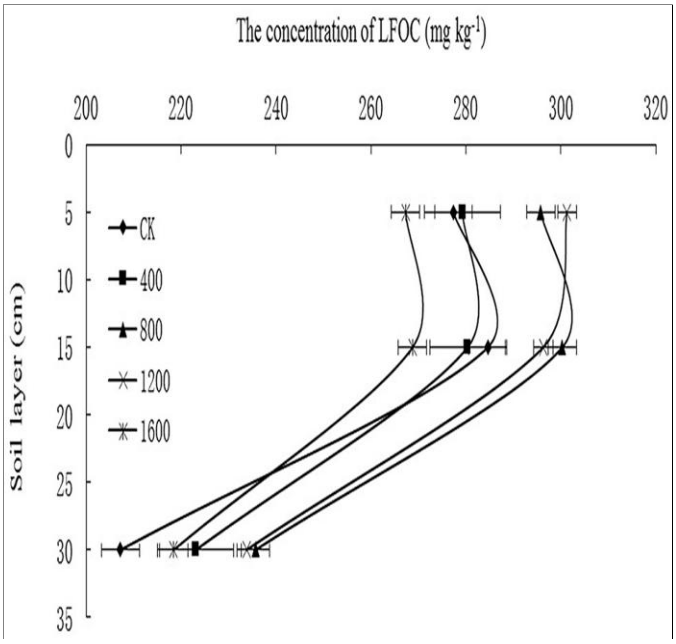


Fig 10 (b): Effects of returning straw to deep soil on the soil light fraction organic carbon (LFOC) at three soil depths

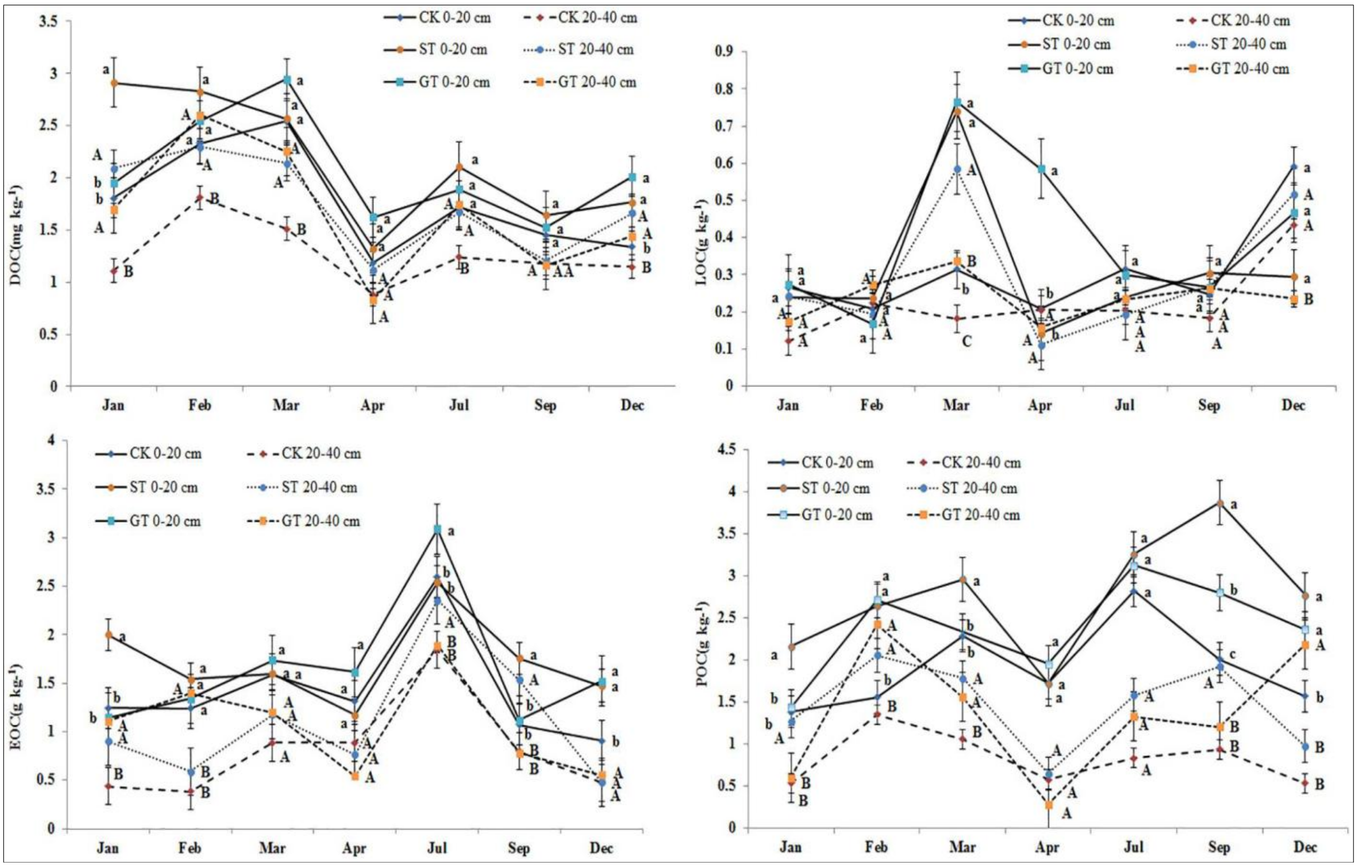


Fig 10 (c): Dynamic changes of carbon fractions

Naresh *et al*. (2017) [44] reported that the WSC was found to be 5.48% higher in surface soil than in sub-surface soil [Table 1]. 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} (F5) 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 1]. 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} F5) 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 1].

Table 1: 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 [Naresh *et al*., 2017].

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, $_c$POM = coarse particulate organic carbon, $_f$POM = fine particulate organic carbon

Ben-Hur Costa de Campos *et al*. (2011) concluded that NT, the recurrent crop residue deposition on soil surface resulted in higher TOC contents in the 0–0.05 m layer in relation to CT treatment [Fig. 11a]. In the 0.05–0.10 and 0.10–0.20 m layers, the differences in C content between treatments decreased to zero in the 0.20–0.30 m layer [Fig. 11a]. Desrochers, Johan, (2017) [18] also found that the coarse silt-clay C contents were greater than fine silt-clay C contents. Averaged across irrigation and tillage treatments, the coarse silt-clay-associated C content was 48% greater in the no-burn-high- (814 g m^{-2}) compared to the burn-high-residue combination (551 g m^{-2}), while that in the burn-low- and no-burn-low-residue combinations were intermittent and did not differ (716 and 647 g m^{-2}), respectively, [Fig.11b]. Similarly, averaged across irrigation and burn treatments, the fine silt-clay-associated N content was 39% greater in the NT-high- (36.7 g m^{-2}) than in the NT-low-residue (26.4 g m^{-2}) and 59% greater than in the combined average of the CT-high- and CT-low-residue combinations (22.9 and 23.2 g m^{-2}, respectively), [Fig. 11b]. The burn-low-residue-level, irrigation-low-residue, NT-irrigation combinations decreased the total aggregated soil fraction by 1.9, 1.9 and 1.1%, respectively, compared to their respective remaining three treatment combinations. This reduction in the aggregated fraction was likely due to the combined effects of the burning, residue-level, and tillage interactions resulting in low plant biomass accumulation, optimized conditions for microbial degradation and disruption of aggregates without providing adequate soil-residue contact for microbial production of aggregate-binding exudates. The burn-low-residue combination decreased the aggregated soil fraction compared to the other three burn-residue-level combinations, though the coarse silt-clay-associated C content was greatest under the no-burn-high- compared to the no-burn-low-residue combination, while the burn-low- and high-residue combinations were intermediate and did not differ. Comparatively, the fine silt-clay C content and coarse and fine silt-clay N contents did not differ among burn residue-level combinations. The high-residue-burn interaction resulted in a complete burn of aboveground residue resulting in a cumulative reduction in non-aggregated coarse C content, compared to the remaining residue-level-burn combinations [Fig. 11b].

The greater aggregated soil fraction and total microbial and total bacterial biomass observed under the CT-irrigated compared to NT-irrigated treatment combination supports the notion that a greater microbial biomass increases aggregation through the production of microbial exudates. However, the NT-irrigated combination has a greater fine LF C content compared to the three remaining tillage-irrigation combinations, suggesting the combined effects of tillage and irrigation may alter the near-surface soil microclimate to benefit fine LF C accumulation [Fig. 11c]. Bacterial biomass content, averaged across burn and residue level treatments, total microbial biomass content was 15 and 42% greater [Fig.11c], in the CT-irrigated (3134 kg ha^{-1}) than in the NT-non-irrigated (2720 kg ha^{-1}) and NT-irrigated combinations (2212 kg ha^{-1}), respectively [Fig. 11c]. Total microbial biomass was also 23% greater in the NT-non-irrigated (2752 kg ha^{-1}) than in the NT-irrigated combinations (2212 kg ha^{-1}), while total microbial biomass in the CT-non-irrigated (2851 kg ha^{-1}) did not differ from the CT-irrigated or NT-non-irrigated combinations, but was 29% greater than in the NT-irrigated combination [Fig. 11c]. The greater microbial and bacterial biomass content associated with the CT- compared to the NT-irrigated and non-irrigated combination in addition to the greater CT compared to NT-residue-level combinations partially supports the positive association between microbial biomass and the macro-aggregate fraction.

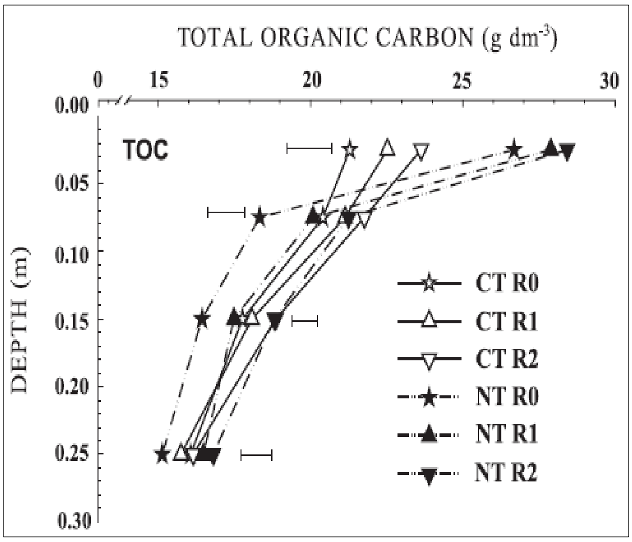


Fig 11 (a): Contents of total organic carbon (TOC) in subtropical oxisol under conventional tillage (CT) and no tillage (NT) systems

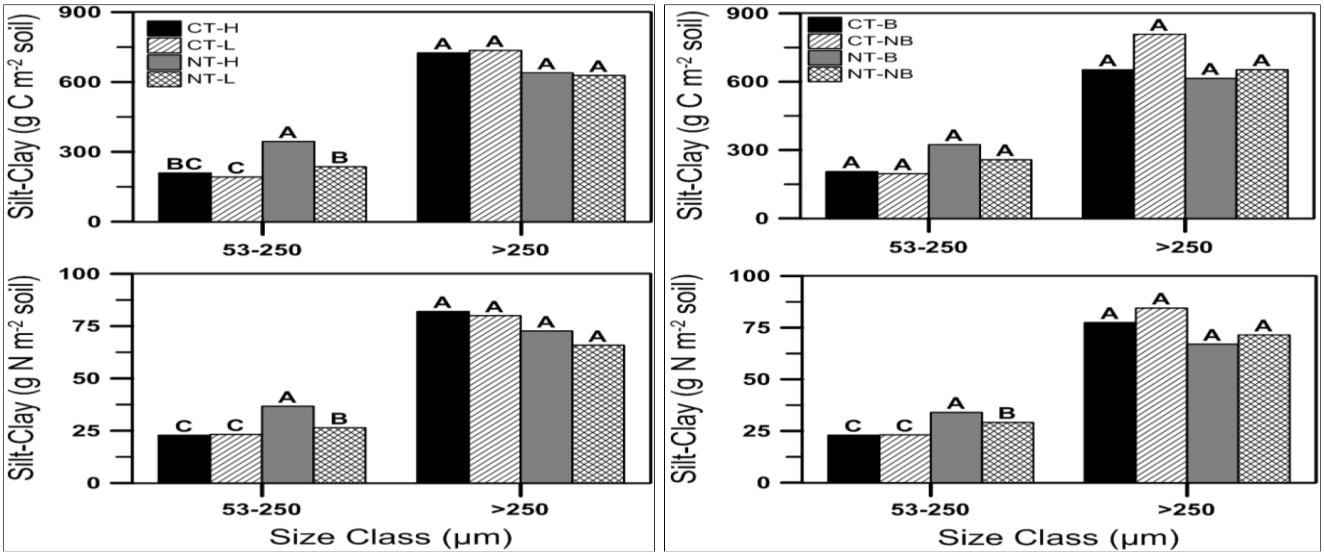


Fig 11 (b): Tillage [conventional tillage (CT) and no-tillage (NT)-residue-level high (H) and low (L)/ burn (burn) (B) and no burn (NB) treatment effects on silt-clay fraction C and N contents

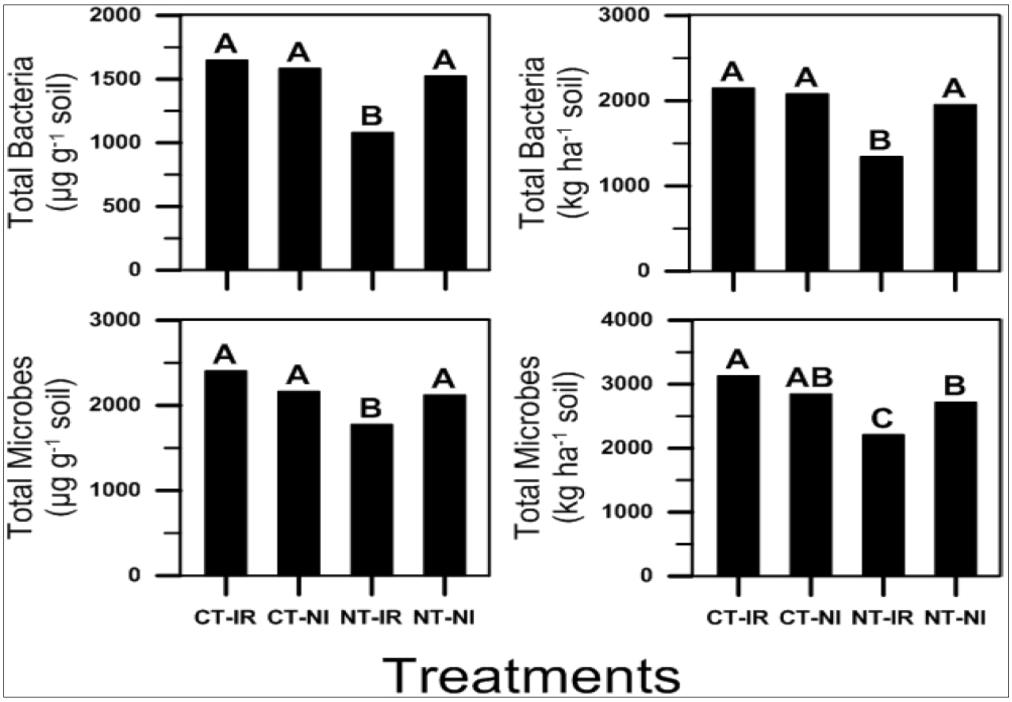


Fig 11(c): Tillage [conventional tillage (CT) and no-tillage (NT)] treatment effects on total bacterial and total microbial biomass concentrations

Naresh *et al*. (2018) [45] reported that conservation tillage practices significantly influenced the total soil carbon (TC), Total inorganic carbon (TIC), total soil organic carbon (SOC) and oxidizable organic carbon (OC) content of the surface (0–15 cm) soil [Table 2]. Wide raised beds transplanted rice and zero till wheat with 100% (T9) or with 50% residue management (T8) showed significantly higher TC, SOC content of 11.93 and 10.73 g kg-1, respectively in T9 and 10.98 and 9.38 g kg-1, respectively in T_8 [Table 2] as compared to the other treatments. Irrespective of residue incorporation/retention, wide raised beds with zero till wheat enhanced 53.6%, 33.3%, 38.7% and 41.9% of TC, TIC, SOC and OC, respectively, in surface soil as compared to conventional tillage with transplanted rice cultivation. Simultaneously, residue retention caused an increment of 6.4%, 7.4%, 8.7% and 10.6% in TC, TIC, SOC and OC, respectively over the treatments without residue management. There was no significant effect of conservation practices on different forms of carbon under sub-surface (15–30 cm) soil Table 2). Stewart *et al*. (2008) [57] stated that the C sequestration capacity of a soil is determined mainly by the protection of C in the aggregates. Soil C stocks change with tillage and management practices (Srinivasarao *et al*., 2012) [56].

Table 2: Effect of tillage and residue management practices on distribution of different forms of carbon in soil [Naresh *et al*., 2018]

Treatments	TC ($g\ kg^{-1}$)		TIC ($g\ kg^{-1}$)		SOC ($g\ kg^{-1}$)		OC ($g\ kg^{-1}$)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
T_1	8.42ef ± 0.01	7.81d± 0.01	0.45bc± 0.05	0.30c±0.03	6.67de±0.02	8.36c±0.02	5.43de±0.03	5.32d±0.01
T_2	8.95de± 0.01	8.57bc± 0.01	0.60abc±0.06	0.45bc±0.05	7.89bc±0.01	8.50c±0.02	7.56abc±0.04	5.47cd±0.01
T_3	10.03bc± 0.10	8.91ab± 0.05	0.60abc±0.06	0.60b±0.06	8.73ab±0.10	9.27b±0.01	7.78ab±0.03	6.00bc ±0.01
T_4	8.24ef± 0.11	7.36d±0.01	0.34c±0.03	0.26c±0.03	5.79e± 0.02	7.13d±0.03	4.61e±0.01	4.09e±0.01
T_5	8.36ef±0.01	7.63d±0.01	0.41bc±0.03	0.30c±0.03	6.13de±0.02	7.67d±0.08	5.14de±0.03	4.24e±0.01
T_6	9.49cd± 0.04	8.22cd±0.07	0.60abc±0.06	0.60b ±0.06	7.05cd±0.01	9.05cd±0.01	6.77bcd±0.01	5.51cd±0.09
T_7	8.63de±0.02	8.10cd ±0.02	0.60abc± 0.06	0.45bc±0.05	6.79de±0.09	8.62c± 0.04	5.58cde±0.10	5.58cd±0.03
T_8	10.98ab± 0.03	9.24a± 0.01	0.75ab ±0.08	0.60b±0.06	9.38a±0.06	9.31ab±0.02	7.59abc±0.08	6.37b±0.03
T_9	11.93a± 0.05	10.40a± 0.01	0.90a±0.09	0.80a±0.09	10.73a±0.02	9.94a±0.01	8.41a±0.07	7.38a±0.04
T_{10}	6.39f ±0.01	6.12e± 0.06	0.30c±0.03	0.22c±0.03	4.16e±0.02	6.82d±0.03	3.53e±0.01	3.07e±0.01

TC=Total carbon; TIC=Total inorganic carbon; SOC=Total soil organic carbon; OC= Oxidizable organic carbon Different small letters within the same column show the significant difference at P = 0.05 according to Duncan Multiple Range Test for separation of mean.

Ou *et al*. (2016) [58] reported that the tillage systems obviously affected the distribution of soil aggregates with different sizes [Fig. 12a]. The proportion of the >2 mm aggregate fraction in NT+S was 7.1 % higher than that in NT-S in the 0.00-0.05 m layer. There was no significant difference in the total amount of all the aggregate fractions between NT+S and NT-S in both the 0.05-0.20 and 0.20-0.30 m layers. NT+S and NT-S showed higher proportions of >2 mm aggregate and lower proportions of <0.053 mm aggregate compared to the MP system for the 0.00-0.20 m layer. The proportion of >0.25 mm macro-aggregate was significantly higher in MP+S than in MP-S in most cases, but the proportion of <0.053 mm aggregate was 11.5-20.5 % lower in MP+S than in MP-S for all the soil layers [Fig. 12a]. reported that the NT system did affect the SOC stock distribution in the soil profile but not the total quantity. Tillage regimes obviously influenced soil aggregation distribution in the soil profile. In the upper 0.00-0.05 and 0.05-0.20 m layers, the NT system improved the formation level of the >2 mm aggregate but reduced the formation level of <0.053 mm aggregates, compared to the MP system, suggesting that mechanical operation reduced large-macro-aggregate formation and disrupted soil macro-aggregates into individual particles (Huang *et al*., 2010 and Jiang *et al*., 2011) [8]. The aggregate-associated SOC concentration in different soil layers was influenced by tillage systems [Fig. 12b]. In the 0.00-0.05 m layer, SOC concentration in macro-aggregates showed the order of NT+S>MP+S = NT-S>MP-S, whereas the NT system was superior to the MP system. However, the NT system significantly reduced the SOC concentration in the 2.00-0.25 mm fraction in the 0.05-0.20 m layer. A similar trend was observed in the 0.25-0.053 mm fraction in the 0.20-0.30 m layer. Across all the soil layers, there was no difference in the <0.053 mm fraction between NT-S and MP-S, as well as between NT+S and MP+S, indicating that the NT system did not affect the SOC concentration in the silt + clay fraction. In average across the soil layers, the SOC concentration in the macro-aggregate was increased by 13.5 % in MP+S, 4.4 % in NT-S and 19.3 % in NT+S, and those in the micro-aggregate (<0.25 mm) were increased by 6.1 % in MP+S and 7.0 % in NT+S compared to MP-S. For all the soil layers, the SOC concentration in all the aggregate size classes was increased with straw incorporation, by 20.0, 3.8 and 5.7 % under the MP system, and 20.2, 6.3 and 8.8 % under the NT system [Fig. 12b]. The higher proportion of >2 mm aggregates and lower proportion of <0.053 mm aggregates under NT systems might be the result of the higher soil hydrophobicity, low intensity of wetting and drying cycles, higher soil C concentration or the physical and chemical characteristics of large macro-aggregates making them more resistant to breaking up (Vogelmann *et al*., 2013) [60].

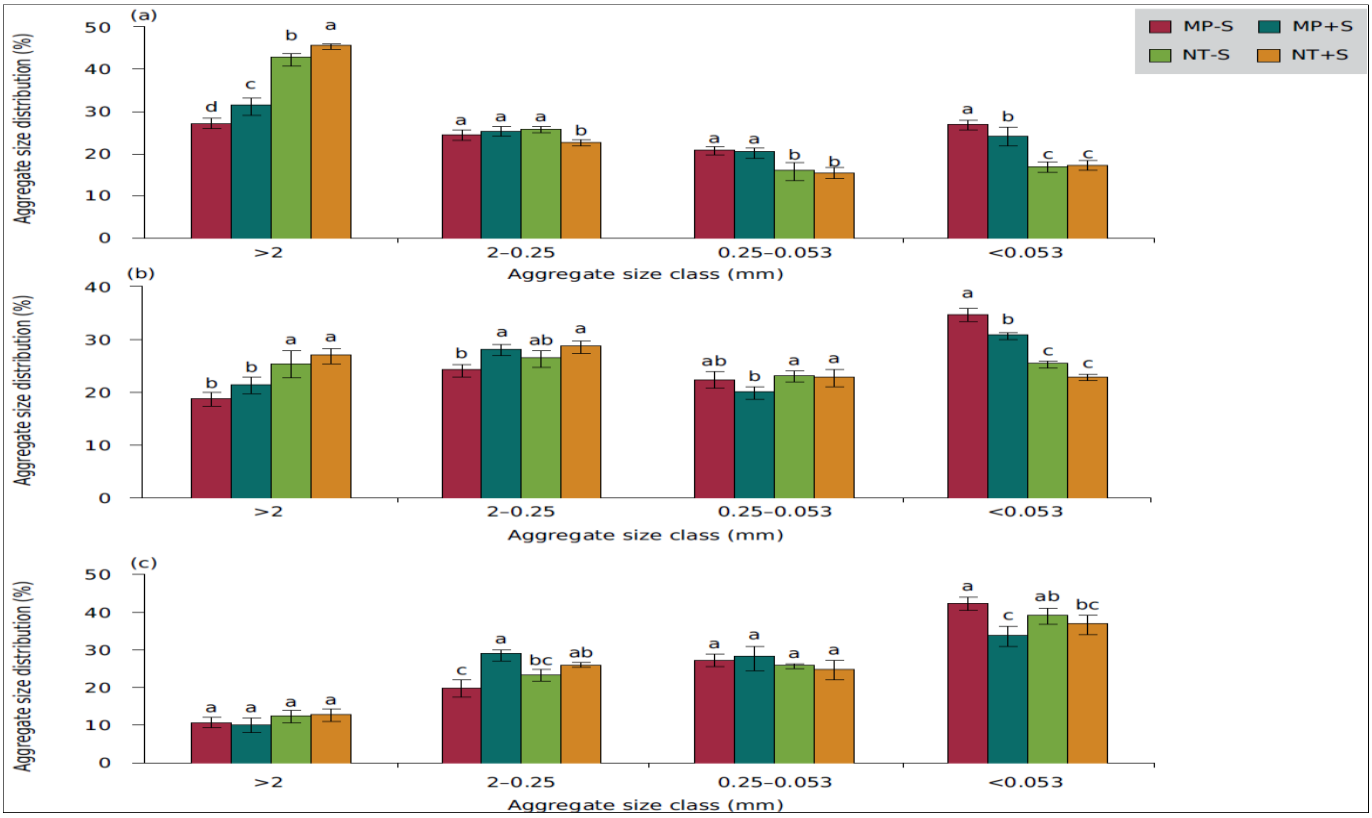


Fig 12 (a): Distribution (%) of water-stable aggregates with different sizes in different soil layers as influenced by tillage treatments. (a) 0.00-0.05 m; (b) 0.05-0.20 m; (c) 0.20-0.30 m. MP-S: moldboard plow without straw; MP+S: moldboard plow with straw; NT-S: no-tillage without straw; NT+S: no-tillage with straw.

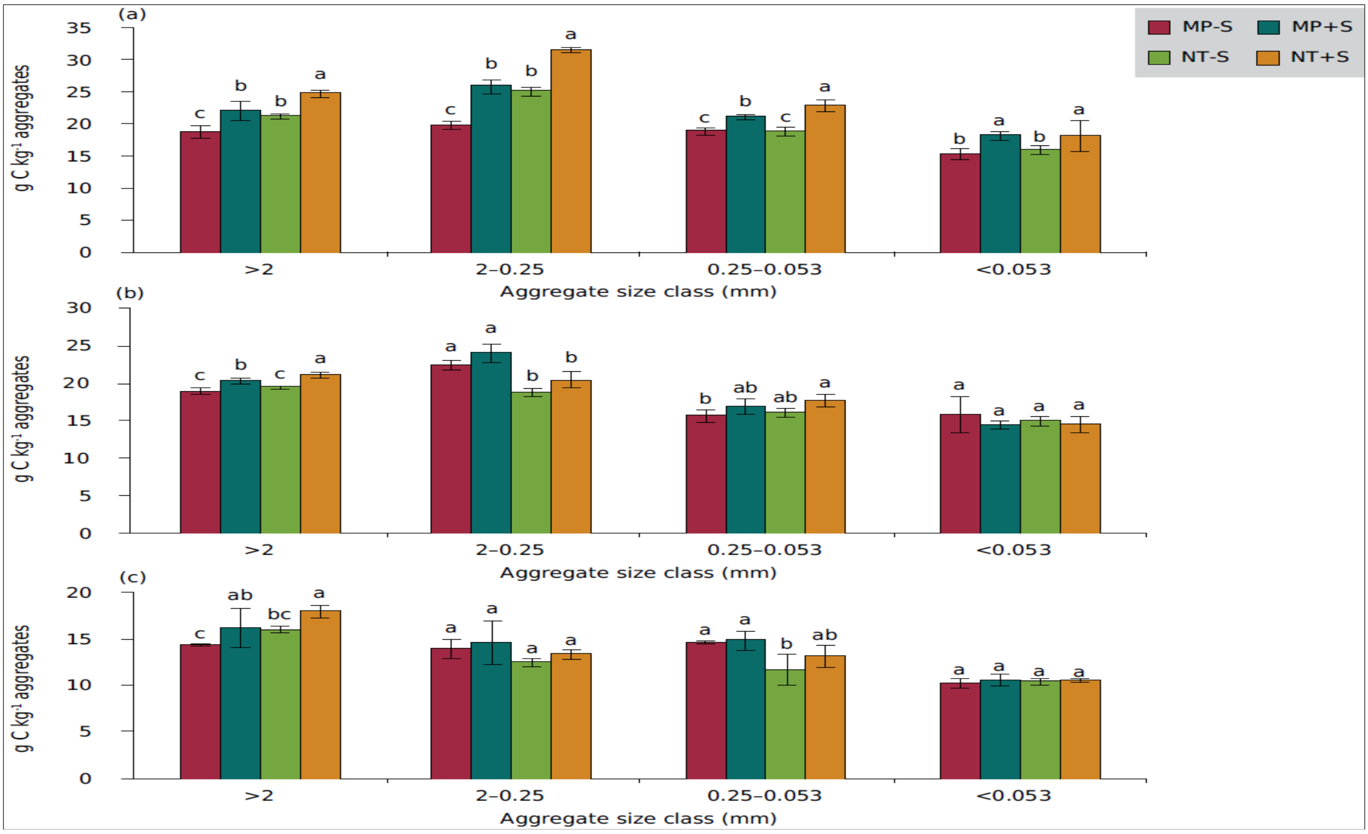


Fig 12(b): Aggregate-associated SOC concentration in different layer intervals as influenced by tillage treatments. (a) 0.00-0.05 m; (b) 0.05-0.20 m; (c) 0.20-0.30 m. MP-S: moldboard plow without straw; MP+S: moldboard plow with straw; NT-S: no-tillage without straw; NT+S: no-tillage with straw.

Guo *et al.* (2016) also found that compared with CT treatments, NT treatments did not affect SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly increased the SOC concentration of bulk soil in the 0−5 cm soil layer [Table 3]. In comparison with NS treatments, S treatments had not significant effects on SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly enhanced the SOC concentration of bulk soil in the 0−5 cm soil layer [Table 3]. In the 0−5 cm soil layer, NT treatments significantly increased SOC concentration by 5.8%, 6.8%, and 7.9% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate, respectively, compared with CT treatments [Table 3]. NT treatments significantly increased MBC of bulk soil, >0.25 mm and <0.25 mm aggregates by 11.2%, 11.5% and 20.0%, respectively, compared with CT treatments. DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under NT treatments were 15.5%, 29.5%, and 14.1% higher than those under CT treatments, respectively. In comparison with NS treatments, S treatments significantly increased SOC concentrations of bulk soil by 12.8%, >0.25 mm aggregate by 11.3%, and <0.25 mm aggregate by 14.1%. In addition, MBC of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under S treatments were 29.8%, 30.2%, and 24.1% higher than those of NS treatments, respectively. S treatments exhibited 25.0%, 37.5%, and 23.2% higher DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate compared with NS treatments, respectively. In the 0−5 cm soil layer, there were significant interactions of tillage and straw returning on SOC concentration of >0.25 mm and <0.25 mm aggregates, MBC of bulk soil and <0.25 mm aggregate, and DOC concentration of >0.25 mm aggregate [Table 3]. This increase in SOC concentration can be attributed to a combination of less soil disturbance and more residues returned to the soil surface under conservation tillage (Dikgwatlhe *et al*., 2014) [15].

Table 3: Changes in SOC fractions within aggregates under different tillage and residue treatments [Guo *et al*., 2016].

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

Different letters in a line denote significant differences among treatments.

CTNS, conventional intensive tillage with straw removal; CTS, conventional intensive tillage with straw returning; NTNS, no-tillage with straw removal; tillage; NTS, no-tillage with straw returning. SOC, soil organic C; MBC, microbial biomass C; DOC, dissolved organic C

Ramesh and Chandrasekaran, (2004) [49] also concluded that the notwithstanding to the fact that traditional rice–rice cropping system (A1) also conserved SOC content (0.29 and 1.69 % higher than initial during 2000–2001 and 2000–2002, respectively) the magnitude was less. This might be possibly due to the land submergence for a longer period resulting in anaerobiosis, led to slower decomposition and build-up of SOC [Fig.13a]. In fact the GM effect was much marked with continued application. This increase in SOC [Fig.13b] through sequestration had two positive effects – enhancement of soil quality and regulatory capacity of the soil. These formed the basis for sustainable management of soil resources. Influence of organics on SOC dynamics [Fig.13c] may be ascribed to the fact that PM owing to its higher organic matter content could have increased moisture-holding capacity of the soil and resulted in considerable residual carbon, leading to higher SOM and its fractions [Fig.13c].

Wang *et al*. (2017) [63] observed that compared with the CK, the manuring significantly increased the portion of large macro-aggregates (>2 mm) by 2.4% and reduced the portion of micro-aggregates (<0.25 mm) by 5.9% [Fig14a] and SOC contents of two macro-aggregate classes (9.1% for >2 mm, and 12.4% for 0.25–1 mm) and of the bulk soil (15.2%) [Fig.14a]. Under both the CK and manuring treatments, the percentage of different aggregate classes decreased in following order: large macro-aggregates (>2 mm)> moderate macro-aggregates (1–2 mm) > small macro-aggregates (0.25–1 mm) > micro-aggregates (<0.25 mm) [Fig.14a]. Under both the CK and manuring treatments, all macro-aggregates had higher SOC contents than the micro-aggregates [Fig.14a]. Therefore, manuring and aggregate size both had significant effects on SOC contents, However, manuring significantly increased the TN contents of the large macro-aggregates (7.1% for >2 mm) and the bulk soil (10.3%), but not for the micro-aggregates [Fig.14a]. Manuring-brought SOC were likely fixed, adsorbed or immobilized during macro-aggregate formation. Compared with micro-aggregates, macro-aggregates occlude more particulate organic C and have higher SOC saturation level (Yu *et al*., 2012). This could be explained by the following three lines of reasoning. Firstly, manure-derived carbon at current input level is unlikely to reach micro-aggregates because of the priority of C localization in macro-aggregates. The second possibility is that the turnover of micro-aggregates (destruction + formation) was too slow to incorporate significant amounts of C from manuring. Thirdly, the SOC in micro-aggregates was at a relatively stable level prior to the present.

Manuring significantly increased the total microbial, bacterial, fungal, and AMF PLFAs of all macro-aggregate classes and the bulk soil but not of the micro-aggregates [Fig.14b]. Under the CK groups, the macro-aggregates had similar total microbial and bacterial PLFAs and F/B-PLFAs ratios, but had higher fungal (>2mm) and AMF (1–2mm) PLFAs compared with the micro-aggregates. However, under the manuring groups, the macro-aggregates (>2 and 1–2 mm) had higher contents of the total microbial, bacterial, fungal, and AMF PLFAs and F/B-PLFAs ratio than the micro-aggregates [Fig.14b]. Manuring and aggregate size had significant effects on microbial PLFAs. The recoveries of total, bacterial, fungal, and AMF PLFAs were 103.6±10.7%, 103.4±12.1%, 96.1±6.4%, and 106.6 ±7.1%, respectively, in isolating aggregate classes [Fig.14b]. Three reasons may explain the similar contents of bacterial PLFAs between the micro-aggregates and macro-aggregates. Firstly, bacteria in the micro-aggregates have equal (or even better) access to water, nutrients and oxygen, compared with those in the macro-aggregates. Secondly, bacteria predominantly reside in smaller pores within micro-aggregates (Ding and Han, 2014). Finally, the micro-aggregates and macro- aggregates had similar TN content. In the manuring groups, macro-aggregates had higher bacterial PLFAs compared with the micro-aggregates. This difference may be resulted from the higher C availability in macro-aggregates (Chen *et al*., 2015). With manure amendment, most chemical properties and microbial parameters changed in macro-aggregates, especially in >2 mm macro-aggregates, but not in micro-aggregates [Fig.14c]. The 1st and 2nd principal components (PC1 and PC2) explained 87.3% and 8.9% of total variance, respectively [Fig.14c]. The result suggests that SOC, microbial biomass and enzyme activities in the macro-aggregates are more sensitive to manure amendment than those in the micro-aggregates.

Deng *et al*. (2016) [17] revealed that soil OC stocks and OC sequestration in the surface 20 cm of soils were significantly increased along with the vegetation restoration since land-use change [Fig.15a]. Among the different restoration stages, the rates showed non-significant differences [Fig.15a], but the values were higher in the early stage (< 30 year) of vegetation restoration than the latter [Fig.15a]. This is probably because: (1) vegetation restoration facilitated SOC accumulation from biomass input (Tang *et al*., 2010) [58]. Vegetation biomass resulting from aboveground leaf litter and belowground roots is the main source of organic matter input into the soil (Zhao *et al*., 2015) [68] (2) vegetation restoration probably contributed to the formation of stable soil aggregates (An *et al*., 2010) [26], thus facilitating physical protection of SOC within aggregates (Blanco-Canqui and Lal, 2004) [26]; and (3) the lower SOC concentrations of farmland under conventional tillage may be due to OC loss resulting from soil erosion, higher organic matter decomposition associated with aggregate disruption and/or OC input reduction caused by continuous removal of crop residues (Saha *et al*., 2014) [51]. The rates of soil OC sequestrations increased in the early 30 years, and then slightly decreased along with vegetation restoration, but the trend was not significant over the restoration age [Fig. 15b]. Among the different restoration stages, the rates showed non-significant differences [Fig.15b], but the values were higher in the early stage (< 30 year) of vegetation restoration than the latter [Fig.15b]. An *et al*. (2009) [26] found that soil nutrients and microbial properties all increased very quickly in the earlier vegetation restoration stage lasting as long as 23 years, and were stable without significant fluctuation in later years. Soil microorganisms increase following the availability of increased organic inputs from vegetation (Jangid *et al*., 2011) [34]. Soil nutrients and organic matter probably increase following increases in soil microbes and may explain the observed changes in soil carbon sequestration rates. The proportions of old soil OC decreased, while the proportions of new soil C increased significantly with time since land-use change [Fig.15c]. This indicated that time since land-use change was an important factor determining the proportions of new and old OC in soils (Zhang *et al*., 2015) [61].

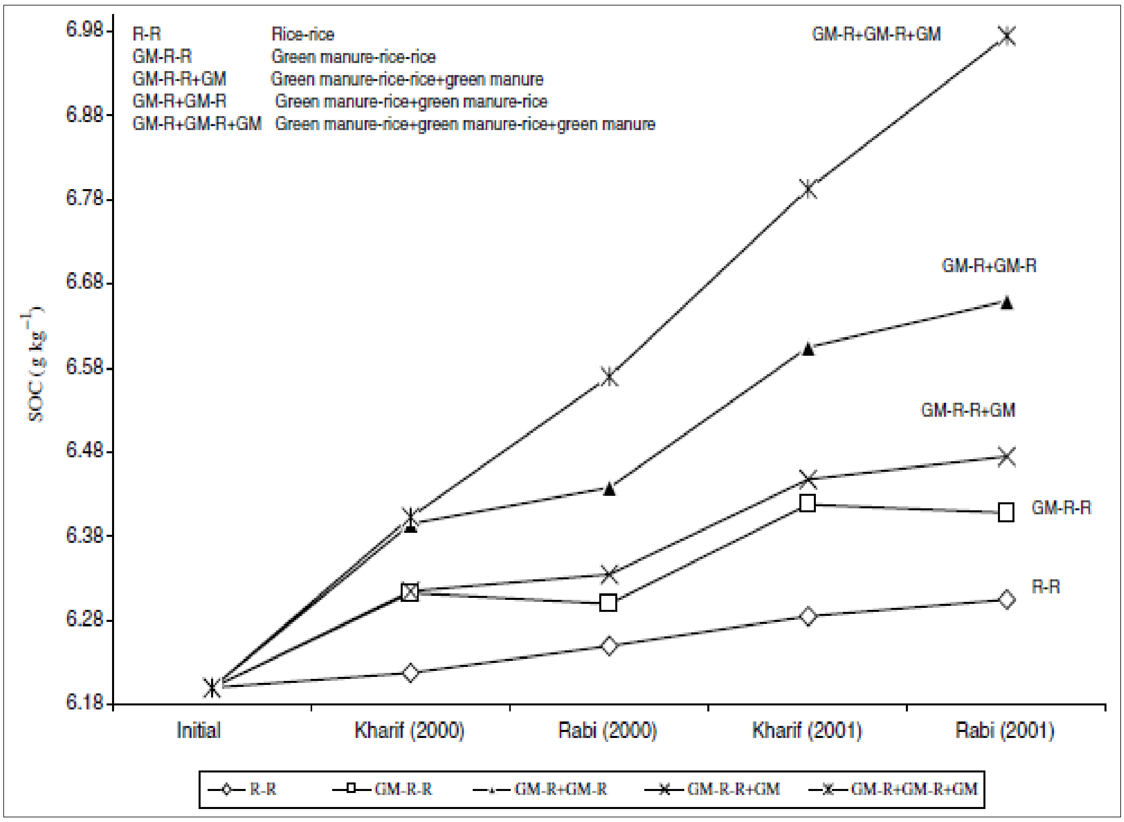


Fig 13(a): Effect of season and crops on soil organic carbon dynamics

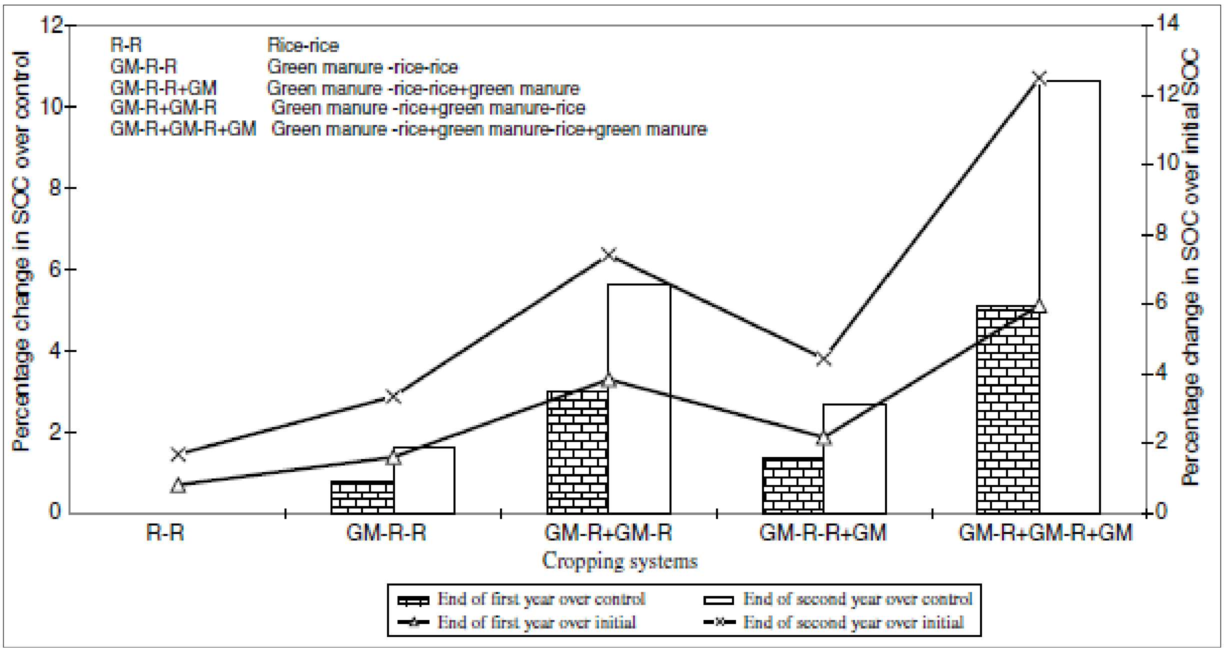


Fig 13(b): Effect of cropping systems on soil organic carbon change compared with initial and final content

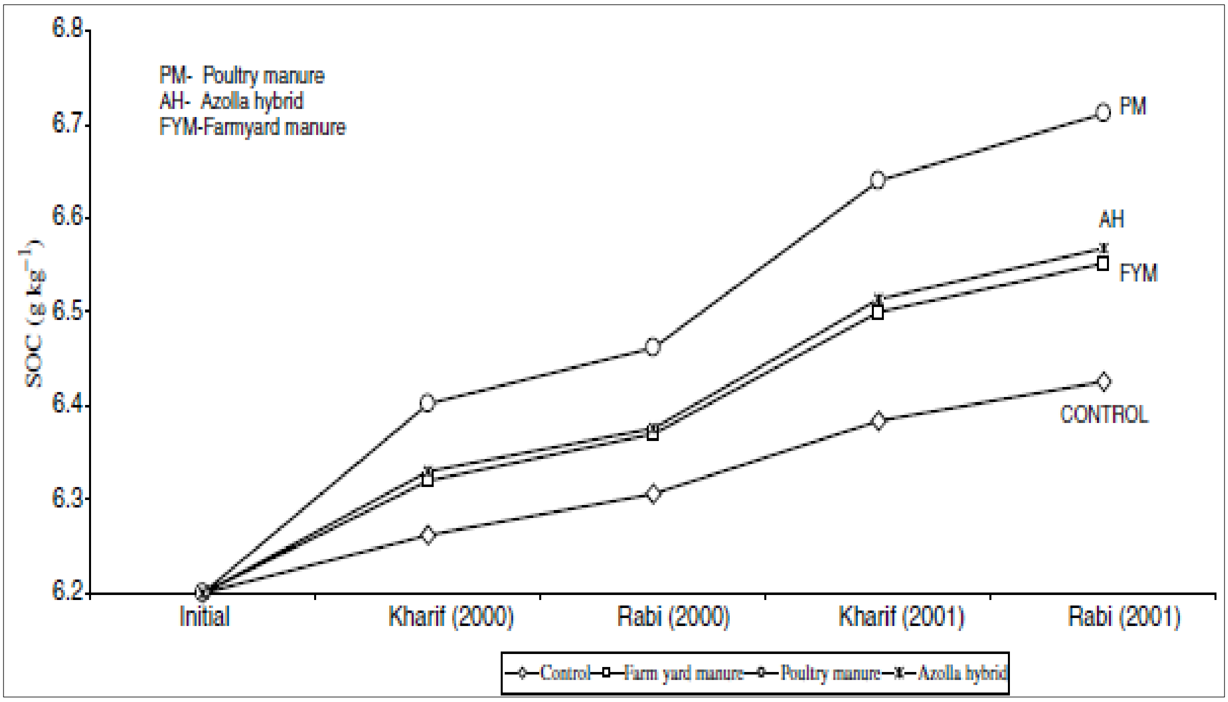
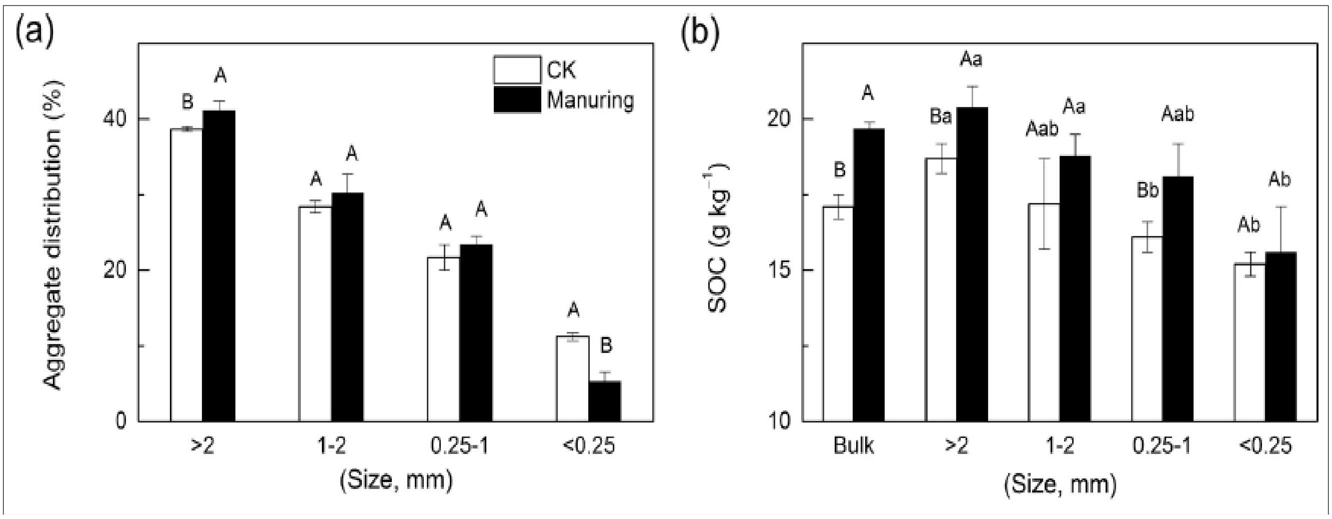


Fig 13(c): Effect of organics/bio-species on soil organic carbon in different seasons



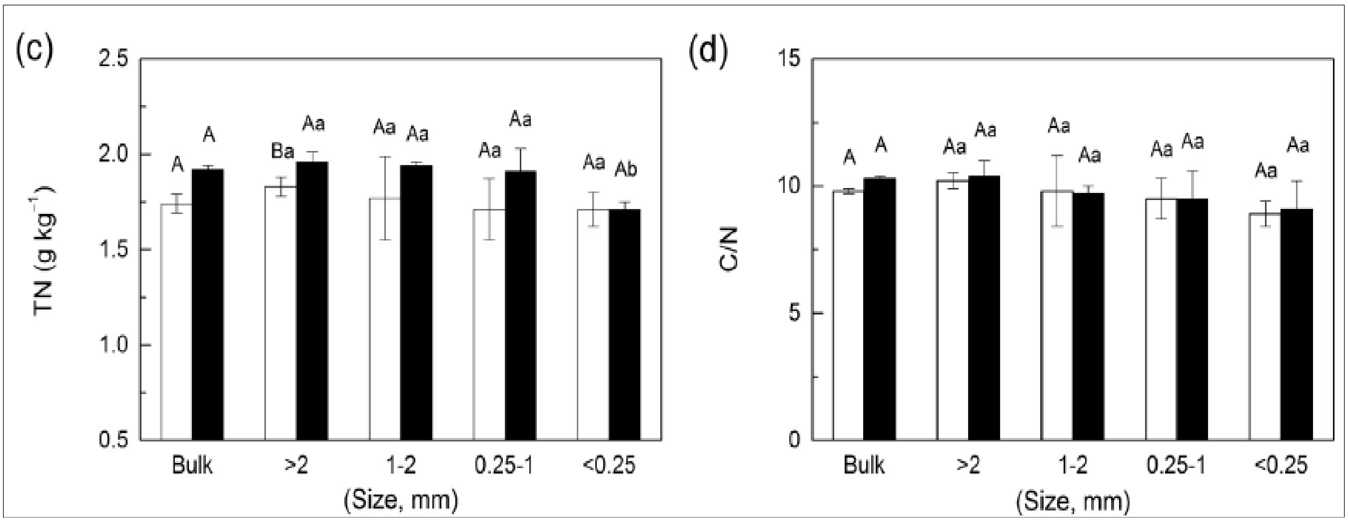


Fig 14 (a): Soil aggregate classes and their characteristics in SOC, TN and C/N (dry weight basis) of the control (CK) and manuring treatments

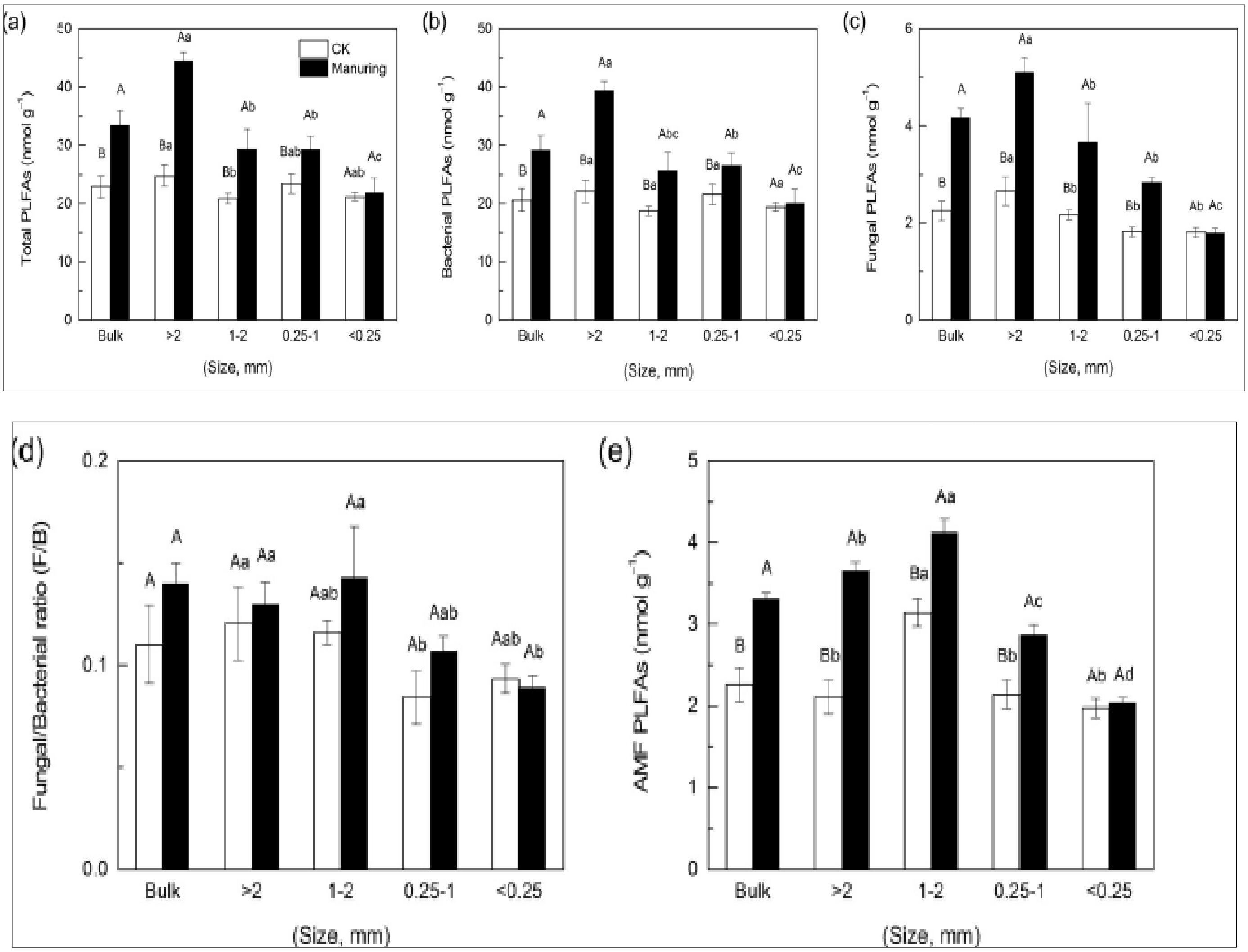


Fig 14(b): Microbial total, bacterial, fungal, arbuscular mycorrhizal fungi (AMF) PLFAs, fungal/ bacterial-PLFAs ratio (F/B)

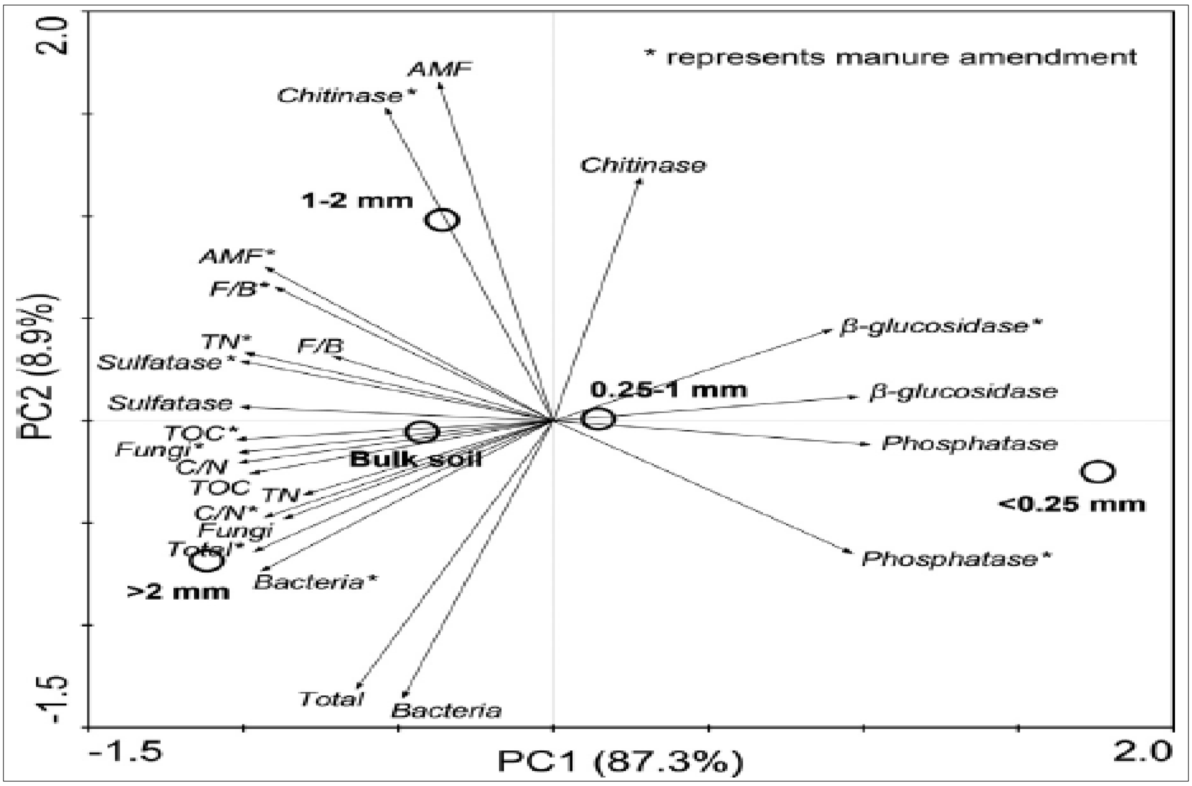


Fig 14 (c): Principal components analysis (PCA) of soil properties and microbial parameters in aggregate size classes

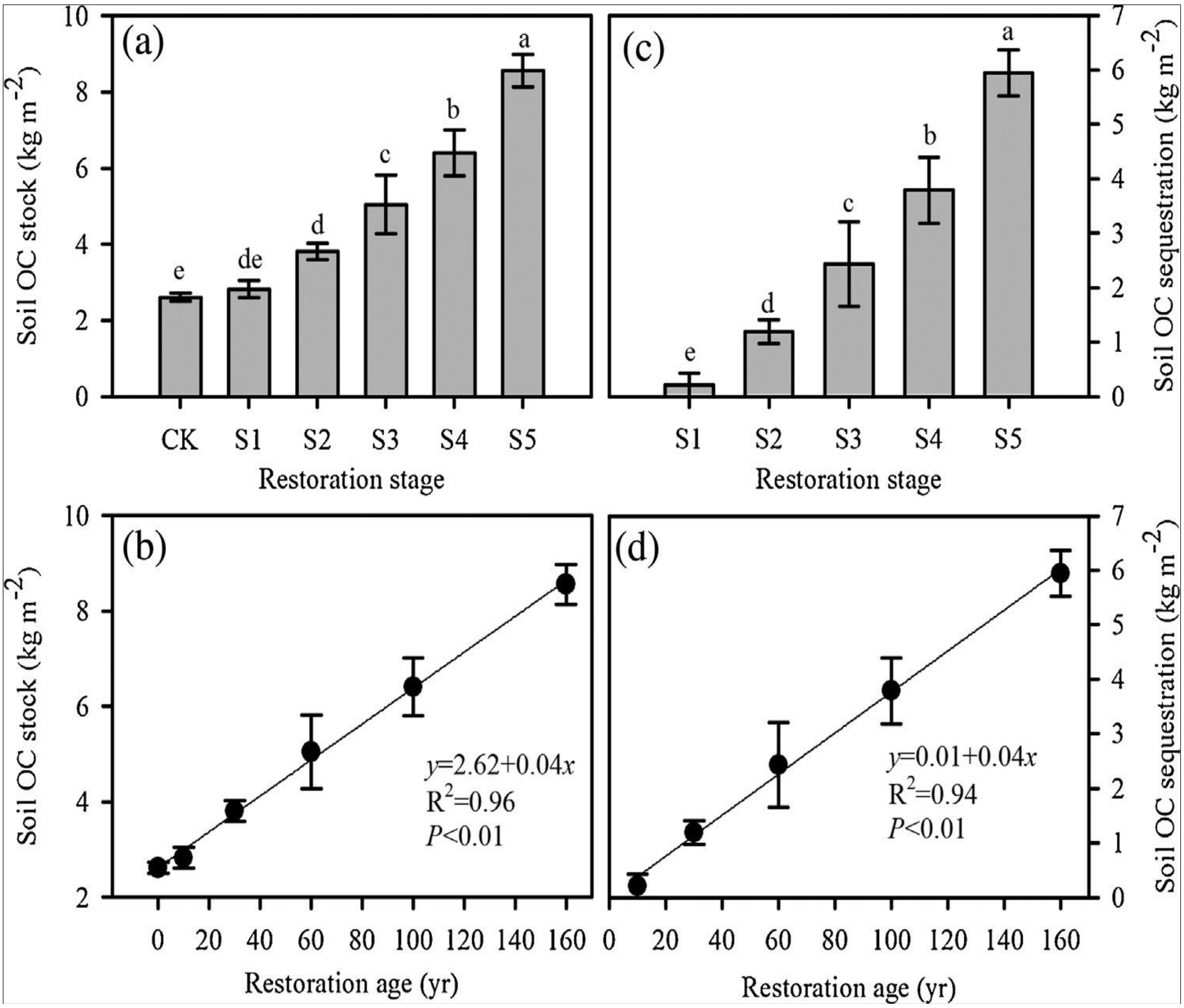


Fig 15 (a): Soil OC stocks (a) and sequestrations (c) in each restoration stage, and soil OC stocks (b) and sequestrations (d) changes over the time since land-use change

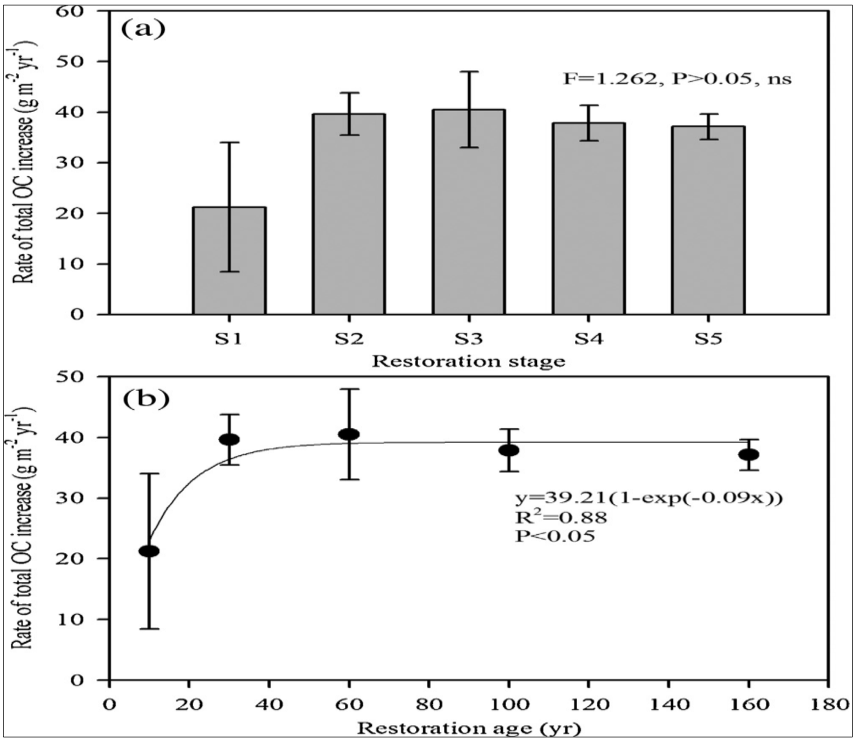


Fig 15 (b): Rates of total soil OC stocks increase in each restoration stage (a) and changes over time (b) since land-use change

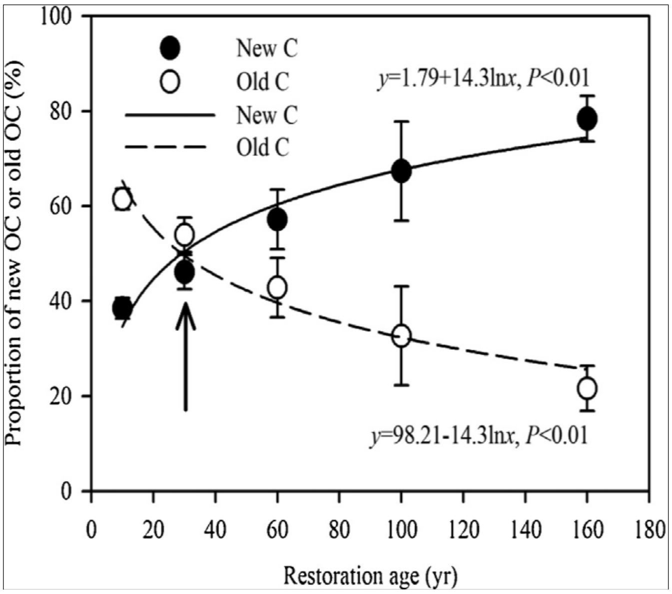


Fig 15 (C): Changes in the proportions of new and old soil OC in soils with time since land-use change

Conclusions

Across the management practices evaluated in the review study, tillage had the greatest effect on SOC and its various fractions (CPOM-C, and C_{min}) in the surface (0–15 cm) soil with positive results observed with conservation tillage practices compared with conventional tillage. SOC concentration in surface soil (0–15 cm) and SOC storage of the profile (0–30 cm) were slightly increased by the long term fertilizer treatments, but they were sharply increased by the manure and straw amendment (VC, 50%RDF+ VC @ 5tha^{-1} and 100% RDF+ VC @ 5tha^{-1}). Compared with returning half and twice the amount of straw, returning the total amount showed higher CPMI increments and rice yields, suggesting that it will result in more soil ecological benefits. SOC, microbial biomasses and enzyme activities in the macro-aggregates are more sensitive to manure amendment than in the micro-aggregates. Manure amendment benefited soil structure, increased C sequestration, microbial activities, and most likely soil fertility. No tillage can increase soil aggregations, improve soil properties, and favourably influence SOC accretion. Effects of crop residue addition are often observed when they are integrated with reduced tillage systems or with improved nutrient management. The rate of new soil OC increase ranged from 110.18 to 28.17 g m^{-2} yr^{-1} in the early (~10 year) and later stages (~160 year), respectively. It took about 30 years for the amount of new soil OC to reach the same level as old OC in 0–20 cm of soil after farmland conversion. This suggests that organic matter in soils under rice-wheat systems could be easily lost through decomposition if the existing land use is altered. Computation of CMI showed that compared to rice–wheat systems provide better options for C rehabilitation in soils. Most of the soil C pools, except water-soluble C, were correlated though the amount extracted by different methods varied considerably, suggesting that each method enumerated a different fraction of TOC. The C: N ratio and the proportion of intensities of oxygen-containing carbonyl and carboxyl functional groups to aliphatic methyl and methylene functional groups increased in the light fractions of the amended soils, suggesting incorporation and retention of amendment. The inclusion of amendment C and N to physically-protected pools suggests that short-term or single management events may have a long-lasting impact on ecosystem C and N dynamics.

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