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Conservation tillage practices improve soil organic carbon pools, aggregation, aggregate associated carbon and productivity in cereal based systems of North West India: A review

RK Naresh, Vivek, M Sharath Chandra and Yogesh Kumar

Abstract
Tillage intensive cropping practices have deteriorated soil physical quality and decreased soil organic carbon (SOC) levels in cereal–growing areas of North West India. Consequently, crop productivity has declined over the years demonstrating the need for sustainable alternative Tillage significantly reduced the proportion of macro-aggregate fractions (>2.00 mm) and thus aggregate stability was reduced by 35% compared with (ridge with no tillage) RNT, indicating that tillage practices led to soil structural change for this subtropical soil. The highest SOC was in the 1.00 – 0.25 mm fraction (35.7 and 30.4 mgkg-1for RNT and CT, respectively), while the lowest SOC was in micro-aggregate (<0.025 mm) and silt +clay (<0.053mm) fractions (19.5 and 15.7mgkg^{-1} for RNT and CT, respectively). Labile C fractions: particulate organic C (POC), microbial biomass C (MBC) and dissolved organic C (DOC) were all significantly higher in NT and ST than in CT in the upper 15 cm. Higher SOC content of 19.44 gkg^{-1} of soil was found in zero tilled residue retained plots followed by 18.53 g kg^{-1} in permanently raised bed with residue retained plots. Whereas, the lowest level of SOC content of 15.86 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots. Zero–till crop establishment treatments increased very–labile C faction (C*frac*$_1$) by 21% followed by labile fraction (C*frac*$_2$) (16%), non–labile fraction (C*frac*$_4$) (13%) and less–labile fraction (C*frac*$_3$) (7%). Notably, higher passive C–pool in conservation tillage practices over CTTPR–CT suggests that conservation tillage could stabilize the recalcitrant form of carbon that persists longer in the soil. Meantime, zero–till crop establishment treatments had higher water stable macro–aggregates, macro–aggregates: micro–aggregates ratio and aggregate carbon content over CTTPR–CT. DSR combined with zero tillage in wheat along with residue retention (T_6) had the highest capability to hold the organic carbon in surface (11.57 g kg^{-1}soil with the highest stratification ratio of SOC (1.5). 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. However, macro- and water-stable aggregates increased to a large extent (26 and 11%, respectively) in full CA and to a lesser extent in partial CA, mostly due to increase in coarse macro-aggregate (2–8 mm) contents in the 0–10 and 10–20-cm depth soil layers. The CA increased OC associated with all size fractions of aggregates in the surface soil layer (0–10 cm), but a higher amount of C was associated with macro-aggregates, indicating relative stabilization of OC in the soil under CA. However, adoption of conservation tillage practices involving zero-tillage, crop establishment, residue management in cereal based system can significantly improve the systems productivity by improving SOC pools and soil aggregate associated carbon. Therefore, conservation tillage in cereal based system can help directly in building–up of soil organic carbon, labile organic carbon fractions and improve the fertility status of soil and production sustainability.

Keywords: Carbon fractions, soil aggregation, aggregate-associated C, productivity

Introduction
Soil organic carbon (SOC) plays a key role in forming and stabilizing soil structure, enhancing soil physical properties, and nutrient recycling (Beare *et al*., 1994) [6]. Soil aggregate, the basic unit of soil structure, mediates many physical and chemical processes in soils (Albalasmeh *et al*., 2013; Gupta and Germida,2014; Trivedi *et al*., 2015; Cates *et al*., 2016) [1, 26, 56, 13] such as soil compaction, soil nutrient recycling, soil erosion, root penetration, and crop yield Bronick and Lal, 2005) [10]. SOC influenced aggregate stability and soil structure (Durigan *et al*., 2017) [19]. The stability of organic carbon in different size aggregates is different. Organic carbon in the micro-aggregates is less susceptible to change than it is in the macro-aggregates (Cambardella and Elliott, 1993) [11].

The soil organic matters of different cropping systems differed based on the quantity and quality of the crop residue coverage and the environment, affecting the organic carbon contents of the soil and the aggregate stability (Novara *et al*., 2015) [42]. The cropping systems mainly create conditions for the decomposition and transformation of soil organic matter by changing the distribution of soil organic carbon and the active habitat of microorganisms, thereby causing changes in soil aggregates (Qi *et al*., 2011) [49].

Soil tillage is among the important factors affecting soil properties and crop yield. Among the crop production factors, tillage contributes up-to 20% [Khurshid *et al*., 2006] [31] and affects the sustainable use of soil resources through its influence on soil properties [Lal and Stewart, 2013] [35]. Reducing tillage positively influences several aspects of the soils whereas excessive and unnecessary tillage operations give rise to opposite phenomena that are harmful to soil. Therefore, currently there is a significant interest and emphasis on the shift from extreme tillage to conservation and no-tillage methods for the purpose of controlling erosion processes. During multiple tillage operations, SOM is redistributed within the soil profile and minor changes in it may affect the formation and stability of soil aggregates. Particulate organic matter (POM) accumulates at soil surface upon crop residues retention under CA and when POM starts decomposing, formation of aggregates in soil occurs (Torres-Sallan *et al*., 2017) [58]. An important objective of sustainable use of soil resources is, therefore, to increase the pool of soil organic C. However, the understanding of the mechanisms of SOM protection in aggregates and the management conditions that favours this process needs to be improved. The objectives of the review study were: (i) to assess the impact of conservation tillage based crop establishment practices and crop residue retention in cereal–based production system on soil aggregate size fraction and aggregate–associated C content; (ii) to know the C–stabilization rate in different tillage based crop establishment practices in sub-tropical cereal–based cropping systems, and (iii) to assess the effect of residue retention, and tillage based crop establishment practices on soil organic carbon pools and soil residual fertility.

Size distribution of mechanical stability aggregates

Al-Kaisi and Yin, (2005) revealed that macro-aggregate stability as a function of time shows a different trend for the same tillage systems over time. However, stable micro and macro-aggregate ranged as follows: greater in NT, ST, and CP compared with MP and DR. Ghimire *et al.* (2012) [23] revealed that 9.89% greater SOC in 0–50 cm soil profile under no-tillage than under conventional tillage in a rice-wheat system. The significant fraction of SOC under no-tillage was accumulated in surface soil with 28.3% greater SOC content in 0–5 cm depth of no-tillage system than that in the conventional tillage system. Quintero and Comer ford, (2013) [48] indicated that reduced tillage increased the soil C concentration and average C content in the whole profile (≈117 cm depth) by 50 and 33% (1636 $tCha^{-1}$ vs. 1224 t Cha^{-1}), respectively, as compared to conventional farming practices. Carbon content increased 177% in the subsoil (A2 horizon, 78 - 117 cm depth, from 215 to 596 tha^{-1}) although most of the soil C was in the A1 horizon (between 0 - 78 cm average thickness, 1097 tha^{-1}). These increases show that reduced tillage enhances C stores in Andisols which are already high in organic matter. In addition, C in aggregates represented more than 80% of the total organic matter and it was positively affected by conservation practices. The C increase was preferential in the smaller macro-aggregates (<2 mm). The aggregate dispersion energy curves further suggested that C increase was occurring in micro-aggregates within the smaller macro-aggregate fraction.

Xin *et al*. (2015) [61] revealed that the tillage treatments significantly influenced soil aggregate stability and OC distribution. Higher MWD and GMD were observed in 2TS, 4TS and NTS as compared to 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. Accordingly, the average proportions of micro-aggregates and the silt +clay fraction were reduced by 15 and 23%, respectively. In the 5–10 cm depth, the mass proportions of macro-aggregates of 2TS, 4TS and NTS were increased by 12, 11 and 13%, respectively, but there were no significant differences between T and TS. In the 10–20 cm depth, the proportions of macro-aggregates in 4TS and NTS were increased by 8% compared to 4T and NT. Across all soil depths, 2TS, 4TS and NTS had greater proportions of macro-aggregates than T, and this trend was declined with soil depth. In the 0–5 cm layer, compared with T, values of MWD under 4T and NT were increased by 41 and 68%, respectively. Values of MWD under NT in the 5–10 and 10–20 cm depths were increased by 41 and 28% as compared to that under T. The highest GMD value appeared in NTS, while the lowest appeared in T across all soil depths. Additionally, residue retention had pronounced positive effects on MWD and GMD. The average MWD values among crop residue treatments were 30, 15 and 14% higher than the corresponding treatments without crop residues in the 0–5, 5–10, and 10–20 cm depths. 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. Soil OC concentrations under 4TS and NTS were significantly higher than that of T in the 0–10 cm layer. Residue retention promoted formation of macro-aggregates, increased macro-aggregate-associated OC concentrations and thus increased total soil OC stock. In the 0–5, 5–10 and 10–20 cm depths, treatments with crop residues had higher macro-aggregate-associated OC concentrations compared to treatments without residues. In the 0–5 cm depth, comparing with that of T, macro-aggregate- associated OC concentrations under 2TS, 4TS and NTS were increased by 14, 56 and 83%, respectively. The greatest increase of micro-aggregate-associated OC concentration among treatments with residue retention was in the 0–5 cm, where OC under 4TS and NTS were 34 and 11% higher compared to that of 4T and NT, respectively. However, in the 10–20 cm, residue retention reduced OC concentration by 42% in the silt + clay fraction.

Zhou *et al*. (2020) [68] also found that the lowest aggregate content was found in the $MSA_{<0.106\ mm}$, accounting for about 2%. The highest proportions in $MSA_{>5\ mm}$, $MSA_{2\text{-}5\ mm}$, and $MSA_{1\text{-}2\ mm}$ were obtained in FS (50.2%), FC (24.8%), and FC (14.6%) treatments, respectively. Meanwhile, we were surprised to find that SC treatment documented the highest proportion in the $MSA_{0.5\text{-}1\ mm}$ (17.4%), $MSA_{0.25\text{-}0.5\ mm}$ (6.5%), $MSA_{0.106\text{-}0.25\ mm}$ (2.9%), and $MSA_{<0.106\ mm}$ (2.3%). On the other hand, the lowest proportions in the MSA > 5 mm and $MSA_{2-5\ mm}$ were identified in FC treatment (34.7%) and CC treatment (18.5%), respectively. While, the FS treatment had the lowest proportions in the $MSA_{1-2\ mm}$ (11%), $MSA_{0.5-1\ mm}$ (11.8%), $MSA_{0.25-0.5\ mm}$ (1.9%), $MSA_{0.106-0.25\ mm}$ (0.8%), and $MSA_{<0.106\ mm}$ (1.2%). Six *et al*.(2000) believed that macro-aggregates were the best structures in the soil, and the higher the content, the better agglomeration and stability of soil aggregates.

Size distribution of water-stable aggregates

Wagner *et al*. (2007) [59] also found that in the surface soil, the mean yields of water-stable macro-aggregates were significantly higher under MT and NT than under CT treatment. Significant differences below 5 cm were only found in 25-40 cm soil depth under NT. The carbon content of the micro-aggregates within macro-aggregates was higher under reduced tillage treatments, indicating increased macro-aggregate turnover under CT. However, in contrast, in 5-25 and 25-40 cm soil depth no negative effect by CT was found on yields of macro-aggregates and carbon contents within macro-aggregates assume that the soil mixing and litter incorporation in higher soil depths by CT might lead to a flush of microbial activity, producing binding agents as nucleation sites for macro-aggregates, probably counteracting the physical impact of tillage.

Aulakh *et al*. (2013) [4] showed total WSA after 2 years of the experiment in 0 - 5 cm soil layer of CT system, T_2 and T_4 treatments increased total WSA from 71% in control (T_1) to79 and 81% without CR, and to 82 (T_6) and 83% (T_8) with CR. The corresponding increase of total WSA under CA system was 75% in control (T9) to 81 (T10) and 82% (T12) without CR and 83 (T_{14}) and 85% (T_{16}) in with CR. Chu *et al*. (2016) revealed that cropping system increased the stocks of OC and N in total soils at mean rates of 13.2 g OC m^{-2} yr^{-1} and 0.8 g N m^{-2} yr^{-1} at the 0–20 cm depth and of 2.4 g OC m^{-2} yr^{-1} and 0.4 g N m^{-2} yr^{-1} at the 20–40 cm depth. The stocks of OC and N in this system increased by 45 and 36%, respectively, (with recovery rates of 31.1 OC m^{-2} yr^{-1} and 2.4 g N m^{-2} yr^{-1}) at the 0–20 cm depth and by 5 and 6%, (with recovery rates of 3.0 OC m^{-2} yr^{-1} and 0.03 g N m^{-2} yr^{-1}) at the 20–40 cm depth. 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.

Zhang-liu *et al*. (2013) [63] showed that NT and RT treatments significantly increased the proportion of macro-aggregate fractions (>2000μm and 250-2000 μm) compared with the MP-R and MP+R treatments. For the 0-5cm depth, the total amount of macro-aggregate fractions (>250μm) was increased by 65% in NT and 32% in RT relative to the MP+R. Averaged across all depths, the macro- aggregate fraction followed the order of NT (0.39) > RT (0.30) > MP+R (0.25)=MP–R (0.24). Accordingly, the proportion of micro-aggregate fraction (53-250 μm) was increased with the intensity of soil disturbance. In the 0-5 and 5-10cm depths, NT and RT had significantly higher total soil C concentration than that of MP−Rand MP+R in all aggregate size fractions. However, in the10-20cm depth, conservation tillage system reduced total C concentration in the macro-aggregate fraction (>250μm) but not in the micro-aggregate and silt + clay fractions. The greatest change in aggregate C appeared in the large macro-aggregate fractions where aggregate-associated C concentration decreased with depth. In the 0-5cm depth, the >2000μm fraction had the largest C concentration under NT, whereas the <53μm fraction had the lowest C concentration under the MP−R treatment. Similar trend was also observed in the >2000μm and 25-2000μm fractions (23 vs.24 $gCkg^{-1}$ aggregates) in the 5-10cm depth. The large macro-aggregate (>2000μm) had relatively lower C concentration than that in the >250-2000μm fraction in the 10-20cm depth. Averaged across soil depths, all aggregate size fractions had 6-9% higher total soil C concentration in NT and RT than in MP−R and MP+R, except for the 53-250 μm fraction. Again mould-board plough showed slightly higher soil C concentration than the conservation tillage systems in the 53-250μm fraction.

Bartlova *et al*. (2015) [5] observed that the different values of WSA were found according to different methods of tillage, both in topsoil (0–0.30 m) and subsoil (0.30–0.60 m). In contrast to the other two tillage methods, the ploughing variant showed a statistically provable reduction in WSA. The same results were obtained by Hůla *et al*. (2010) [27] who found that, after three years, the ploughing variant showed worsened soil structure in comparison to reduced tillage. Cultivation of land leads to changes in the chemistry of carbon intake in soils. These changes in chemical composition are generally apparent in organic material inside aggregates, whereas changes in organic material linked to clay particles are only slight.

Song *et al*. (2016) [55] reported that compared to conventional tillage, the percentages of >2mm macro aggregates and water-stable macro-aggregates in rice-wheat double- conservation tillage were increased 17.22% and 36.38% in the 0– 15 cm soil layer and 28.93% and 66.34% in the 15–30 cm soil layer. In surface soil (0–15cm), the maximum proportion of total aggregated carbon was retained with 0.25–0.106mm aggregates, and rice-wheat double-conservation tillage had the greatest ability to hold the organic carbon (33.64g kg^{-1}). Dhaliwal *et al*. (2018) [17] revealed that the mean SOC concentration decreased with the size of the dry stable aggregates (DSA) and water stable aggregates (WSA). In DSA, the mean SOC concentration was 58.06 and 24.2% higher in large and small macro-aggregates than in micro-aggregates respectively; in WSA it was 295.6 and 226.08% higher in large and small macro-aggregates than in micro-aggregates respectively in surface soil layer. The mean SOC concentration in surface soil was higher in DSA (0.79%) and WSA (0.63%) as compared to bulk soil (0.52%).

Zheng *et al*. (2018) [67] 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. The carbon content of iPOM was much lower at 20–40 cm than at 0–20 cm. Zhou *et al*. (2020) [68] reported that the highest proportions in the $WSA_{>5\ mm}$, $WSA_{2-5\ mm}$, $WSA_{1-2\ mm}$ and $WSA_{0.5-1\ mm}$ were obtained in SC (4.3%), FS (7.6%), FC (9.3%), and CS (20.7%) treatments. However, the lowest proportion in the $WSA_{>5\ mm}$ was the FC treatment (0.3%), and The lowest proportions in $WSA_{2-5\ mm}$, $WSA_{1-2\ mm}$ and $WSA_{0.5-1\ mm}$ were all found in CC treatment with 3.9%, 2.9%, and 8.9%, respectively. We were surprised to note that the CC treatment documented the highest proportion in the $WSA_{0.25-0.5\ mm}$ (20.6%), $WSA_{0.106-0.25\ mm}$ (30.5%), and $WSA_{<0.106\ mm}$ (31.2%). On the other hand, the lowest proportions in the $WSA_{0.25-0.5\ mm}$, $WSA_{0.106-0.25\ mm}$, and $WSA_{<0.106\ mm}$ were identified in CS (13.9%), FS (18.7%), and CS (22.1%) treatments, respectively. The SC treatment had the highest

SOC concentration in the $WSA_{1-2\ mm}$ with 23.38 g kg^{-1}. The highest SOC concentrations in the $WSA_{>5\ mm}$, $WSA_{0.5-1\ mm}$, and $WSA_{<0.106\ mm}$ were obtained by the CS treatment with 24.02 g kg^{-1}, 23.61 g kg^{-1}, and 15.60 g kg^{-1}, respectively. Meanwhile, the highest SOC concentrations in the $WSA_{2-5\ mm}$, $WSA_{0.25-0.5\ mm}$, and $WSA_{0.106-0.25\ mm}$, WSAs were obtained in the FS treatment with 22.13 g kg^{-1}, 21.33 g kg^{-1}, and 20.58 g kg^{-1}, respectively.

Carbon fractions and C–stabilization

Naresh *et al*. (2017) [53] revealed that WSC was found to be 3.74% higher in surface soil than in sub-surface soil. In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to conventional tillage, PRB and ZT coupled with 6tha^{-1} CR increased 39.6% WSC in surface soil and 37.4% in sub surface soil. Among all the treatments, T_6 had significantly higher (20.15%) proportion of WSC than the other treatments compared. Plots under ZT had about 32% higher POC than CT plots (620 mg kg^{-1} bulk soil) in the surface soil layer. In 0 - 5 cm soil layer of tillage system, T_1, and T_4 treatments increased POC content from 620 mgkg^{-1} in CT (T_7) to 638 and 779 mgkg^{-1} without residue retention and to 898, 1105, 1033 and 1357 mgkg^{-1} in ZT and PRB with residue retention (T_2, T_3, T_5, and T_6), respectively. In subsurface layer (5-15 cm), similar increasing trends were observed; however, the magnitude was relatively lower. It is evident that the POC contents in both surface and sub-surface soil were significantly higher in plots receiving 50% RDN as CF+50% RDN as FYM (F_5) treated plots compared to 50% RDN as CF+50% RDN as GM/SPM (F_6) fertilizer and unfertilized control (F_1) plots. The values of LFOC in surface soil were 81.3, 95.7, 107.8, 155.2, 128.8, 177.8 and 52.7 mgkg^{-1} in ZT and PRB without residue retention, ZT and PRB with 4 and 6 tha^{-1} residue retention and conventional tillage (CT) treatments. In 5- 15 cm layer, the increasing trends in LFOC content due to use of tillage practices and residue retention were similar to those observed in 0-5cm layer, however, the magnitude was relatively lower. Significant increase in LFOC in surface soil (0–5 cm) was maintained in plots receiving 50% RDN as CF+50% RDN as FYM (F_5) and integrated use of 50% RDN as CF+50% RDN as GM/SPM (F_6) fertilizer over 1/3rd N as CF+1/3rd N as FYM+1/3rd N as GM/SPM (F_7) over unfertilized control plots (F_1). In general, the impact of applied fertilizer, organic sources and residue retention in improving WSC, POC, PON, LFOC and LFON content was significant in 0 - 5 cm soil layer and was substantially higher than in 5 - 15 cm soil layer under both ZT and PRB and CT system.

Nandan *et al*. (2019) [37] reported that tillage based crop establishment practices and residue management treatments strongly influenced TOC and soil C–fractions, C–pools, and C–management indices. Residue retention treatment increased $Cfrac_1$, $Cfrac_2$, $Cfrac_3$, $Cfrac_4$, and TOC by 18, 24, 5, 10, and 12%, respectively, over residue removal treatment. Conservation tillage treatments (NPTPR–ZT, ZTTPR–ZT and ZTDSR–ZT) had 13–21%, 12–16%, 5–7%, 9–13%, and 9–14% higher ($p < 0.05$) $Cfrac_1$, $Cfrac_2$, $Cfrac_3$, $Cfrac_4$, and TOC, respectively, over CTTPR–CT. ZTDSR–ZT and ZTTPR–ZT treatments increased active C–pool, LI and CMI over CTTPR–CT. Irrespective of the cropping system, ZTDSR–ZT or ZTTPR–ZT with crop residue retention had 29–30% higher TOC over conventional CTTPR–CT without residue retention. Stabilization of added carbon in soil was the highest in ZTDSR–ZT and reduced progressively to the order of ZTDSR–ZT > ZTTPR–ZT ≥ NPTPR–ZT > CTTPR–CT. The increased TOC in zero–tillage/reduced tillage is possibly because of minimum mechanical disturbance of soil and restricted of soil carbon oxidation. Intensive tillage practices accelerate soil organic matter (SOM) mineralization (Elder and Lal, 2008) [21]. Very–labile C–fraction ($Cfrac_1$) and labile C–fraction ($Cfrac_2$) are highly prone to oxidation processes (Nath *et al*., 2017a) [43].

Soil aggregates and aggregate associated C

Jiang *et al*. (2010) [30] revealed that tillage significantly reduced the proportion of macro-aggregate fractions (>2.00 mm) and thus aggregate stability was reduced by 35% compared with RNT, indicating that tillage practices led to soil structural change for this subtropical soil. The highest SOC was in the 1.00–0.25mm fraction (35.7 and 30.4mg/kg for RNT and CT, respectively), while the lowest SOC was in micro-aggregate (<0.025mm) and silt + clay (<0.053mm) fractions (19.5 and 15.7mg/kg for RNT and CT, respectively). Zhu *et al*. (2014) observed that the contents of soil TOC and labile organic C fractions, where PD generally had the highest contents of TOC, DOC, MBC and EOC at the three soil depths. Crop straw return treatments (PR, PW, PD, RR, RW, RD) had consistently higher amount of TOC and labile organic C fractions at the three soil depths than without crop straw return treatments (PN, RN). Moreover, PN had significantly lower TOC, DOC, MBC and EOC at 0–7 cm and 7–14 cm, and RN had the lowest TOC and MBC at 14–21 cm compared to other treatments.

Bhattacharyya *et al*. (2015) [7] 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. Mazumdar *et al*. (2015) [36] 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. 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. Kumar *et al*. (2015) [34] also found that the plots under conservation agriculture practices had nearly 17 and 14% higher of microbial biomass carbon (MBC), total organic carbon (TOC) and organic C fractions (that is, water soluble organic C, easily oxidizable organic C, particulate organic C, humus C and black C) content as compared with conventional tillage.

Ou *et al*. (2016) reported that the tillage systems obviously affected the distribution of soil aggregates with different sizes. 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 was11.5-20.5%lower in MP+S than in MP-S for all the soil layers. Dutta and Gokhale, (2017) [20] observed that 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.

Naresh *et al*. (2017) [53] also observed that macro-aggregates are less stable than micro-aggregates and more susceptible to the disruptive forces of tillage, and > 2 mm size macro-aggregates showed the lowest percentage distribution across depths. This might be attributed to the mechanical disruption of macro-aggregates with frequent tillage operations and reduced aggregate stability. The proportion of the micro-aggregates in all treatments was small and they had the lowest OC content. However, micro-aggregates formation and the micro-aggregates within the macro-aggregates can play an important role in C storage and stabilization in the long term. Zhao *et al*. (2018) [66] 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. Increases in the SOC content of aggregate fractions were highest in MRWR, followed by MR, and finally WR. Crop-derived organic particles or colloids can combine with mineral matter, binding micro-aggregates into macro-aggregates.

Tiwari *et al*. (2018) [57] also found that POC reduction was mainly driven by a decrease in fine POC in topsoil, while DOC was mainly reduced in subsoil. Fine POC, LFOC and microbial biomass can be 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 F1 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}.

Nandan *et al*. (2019) [37] observed that residue retention treatment increased the content of coarse macro–aggregate and meso–aggregate over residue removal treatment. The ZT based crop establishment treatments (ZTTPR–ZT and ZTDSR–ZT) had higher content of coarse macro–aggregate and meso–aggregate over CTTPR–CT. The ZT based treatments ZTTPR–ZT, ZTDSR–ZT, and NTTPR–ZT increased WSMacA by 16, 15, and 9%, respectively over CTTPR–CT. C–stabilization is strongly associated with aggregate size composition (Andruschkewitsch *et al*., 2014b) [2]. Intensive tillage practices cause physical disruption of macro–aggregates and expose SOM to microbial decomposition (Zotarelli *et al*., 2007) [70]. Besides this, the release of polysaccharide compounds during the decomposition of crop residue acts as a cementing agent and has a crucial role in macro–aggregate formation (Choudhury *et al*., 2014) [12].

Fractions of SOM Pools

Soil organic matter (SOM) plays an important role in maintaining the productivity of tropical soils because it provides energy and substrates, and promotes the biological diversity that helps to maintain soil quality and ecosystem functionality. SOM directly influences soil quality, due to its effect on soil properties (Wendling *et al*., 2010) [60]. Once soil is cultivated for agricultural production, especially in the tropics and the semi-arid regions, SOM is rapidly decomposed due to modifications in conditions such as aeration, temperature, and water content (Ashagrie *et al*., 2007) [3]. This can affect many soil functions that are either directly or indirectly related to SOM, due to its capacity to retain waterandnutrients.Although the breakdownrate of SOM canbefasterin thetropics,regular inputs of organic amendments can promote a build-up of SOM (Follett,2001) [22].

Mandal *et al*. (2012) reported that the SOC stock was highest within 0–15-cm soil and gradually decreased with increase in depth in each land use systems. In 0–15 cm depth, highest SOC stock (16.80 Mg ha^{-1}) was estimated in rice–fallow system. In 15–30 cm, it ranged from 8.74 in rice–rice system to 16.08 Mg ha^{-1} in mango orchard. In the 30–45-cm soil depth, the SOC stock ranged from 6.41 in rice–potato to 15.71 Mg ha^{-1} in rice–fallow system. The total SOC stock within the 0–60-cm soil profile ranged from 33.68 to 59.10 Mg ha^{-1} among rice-based systems, highest being in soils under rice–fallow system and the lowest for rice–rice system

Proportions of labile C and N pools in SOM showed variation among treatments, with significant differences observed for POXC/SOC, C_{min}/SOC, and POM-N/TN. POXC/SOC was lower under GP than under cultivated treatments. C_{min}/SOC was significantly lower under FP than under DT/CT and SP treatments, while GP and NT had intermediate levels of C_{min}/SOC. POM-N/TN was higher under NT and DT/CT treatments compared to plow-tillage treatments and GP. In general, POM-C/SOC and MBC/SOC were lower, while N-pools in TN were higher under GP than under cultivated treatments, although such differences were not statistically significant ($P > 0.05$). On average, SOC had 22.8% POM-C, 3.6% POXC, 0.9% WEOC, 2.9% MBC, and 3.3% C_{min}. Similarly, TN constituted about 17.1% PON, 1.9% TDN, and 4.9% MBN, and 1.1% KEN.

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

Jat *et al*. (2019) [29] showed that the SOC was increased by 69.7%, 40.7% and 9.0% under CSA-based scenarios; Sc4, Sc3 and Sc2, respectively compared to Sc1 (16.2 Mg C ha^{-1}) at 0–15 cm soil depth. In surface soil layer, active and passive pool carbon (18.6 and 10.2 Mg C ha^{-1}) was higher by 90% and 59%, with Sc4 compared to Sc1 (9.8 Mg C ha^{-1} and 6.4 Mg C ha^{-1}), respectively. However, Sc4 (12.4 Mg C ha^{-1}) and Sc3 (10.6 Mg C ha^{-1}) recorded highest very labile C (C_{VL}) which was about 82% and 56% higher compared with Sc1 (6.8 Mg C ha^{-1}). Sc4 conserved significantly higher C_L (110%), C_{LL} (39%) and C_{NL} (71%) at surface soil layer compared with Sc1. Highest active pool (C_{AP}) (72%) and passive pool (C_{PP}) carbon (47%) as per cent of SOC were recorded with Sc3 and Sc2, respectively at 0–15 cm soil depth. Sc3 showed higher C_{VL} (45–47%) and C_L (23–25%) carbon content as per cent of SOC compared to other scenarios. Highest C_{LL} (18%) and C_{NL} (29%) carbon were associated with Sc2 at 0–15 cm soil depth. At 15–30 cm depth, SOC concentration was about 8% higher in Sc2 (12.5 Mg C ha^{-1}) where crop residues were incorporated into the soil during puddling operation compared with Sc3 and Sc4 where residues were retained on soil surface. Sc2 also showed highest C_{AP} (8.6 Mg C ha^{-1}), C_{PP} (3.9 Mg C ha^{-1}) and C_{VL} (7.6 Mg C ha^{-1}) than the other scenarios at 15–30 cm soil depth. Luo *et al*. (2010) [67] reported that conversion from CT to ZT facilitated redistribution of C in the soil profile significantly, but did not increase the total SOC stock.

Carbon restoration in soil profile

Pandey *et al*. (2014) [45] revealed that no-tillage before sowing of rice and wheat could increase SOC by 0.59 Mg C ha^{-1} yr^{-1}. The rate of SOC sequestration due to reduced- or no-tillage management in rice-based systems in South Asia varied from 0- to 2114 kg ha^{-1} yr^{-1}. Xue *et al*. (2015) [62] found that over time, CT system generally exhibit a significant decline in SOC concentration due to destruction of the soil structure, exposing SOM protected within soil aggregates to microbial organisms. Thus, the adoption of no-till system can minimize the loss of SOC leading to higher or similar concentration compared to CT. Conforti *et al*. (2016) [16] observed that the maximum value (214.5 Mg ha^{-1}) of SOC stock was observed in the A horizons accounting for about 30% of the estimated total SOC stock along soil profile. The significant lowest values were recorded in the organic horizon, which stored approximately 2% of total SOC stock. Vertical distribution of SOC stock highlighted that even though there was less variability in SOC stock across A-Bw horizons, a significant decrease with depth was observed towards BC and especially Cr layers. The results revealed that the sampling thickness of 20 cm for Cr layers can be considered reliable because of the above quoted decreasing trend of SOC stock in depth. This behaviour is consistent with the evidence that N96% of SOC was stored in the overlying soil horizons. In addition, a similar decreasing trend of the weathering degree of the parent rock down-profile suggests a possible corresponding decrease in the storage capacity of SOC Naresh *et al*. (2018) [41] reported that as compared to the RDF treatment also, the NPK+FYM treatment had higher SOC concentration in all the TCE. The highest increase in SOC in the NPK+FYM treatment was observed in F_6 with TCE T_6. In comparison with the control, the mean rate of SOC build-up during the 18 years of cropping was the highest in F_6 with T_6 (50.63%) and the lowest in $F_1$with T_7 (9.79%). It was estimated that 30 per cent of applied C through FYM was stabilized, and the rest (70 per cent) was lost through oxidation. Kuhn *et al*. (2016) also found that the benefit of NT compared to CT on the changes of SOC stocks varied across different soil depths. In topsoil layers (above 20 cm), NT in general had greater SOC stocks than CT but the benefit tended to decline with soil depths, and even turned to be negative in soil layers deeper than 20cm. In addition, in each soil layer, except for the top 5 cm, the total SOC stocks generally declined with the number of years after NT adoption.

Storage of SOC

Soil organic matter (SOM) is the organic matter component of soil, consisting of plant and animal detritus at various stages of decomposition, cells and tissues of soil microbes, and substances that soil microbes synthesize. SOM provides numerous benefits to the physical and chemical properties of soil and its capacity to provide regulatory ecosystem services Brady and Weil, 1999) [9]. SOM is especially critical for soil functions and quality (Beare *et al*., 1994) [6]. SOM also acts as a major sink and source of soil carbon (C). Although the C content of SOM varies considerably (Périé and Ouimet, 2008; Jain *et al*., 1997) [47]. SOM is ordinarily estimated to contain 58% C, and "soil organic carbon" (SOC) is often used as a synonym for SOM, with measured SOC content often serving as a proxy for SOM. Soil represents one of the largest C sinks on Earth and is significant in the global carbon cycle. Therefore, SOM/SOC dynamics and the capacity of soils to provide the ecosystem service of carbon sequestration through SOM management have received considerable attention recently.

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. Du *et al*. (2013) and Conceicao *et al*. (2015) [15] reported that the NT system resulted in stratification of SOC, while the MP system resulted in a more homogeneous distribution in the 0.00-0.20 m layer. When considering the whole 0.00-0.30 m layer, however, the differences in SOC stock were not significant between NT-S and MP-S as well as between NT+S and MP+S. This indicates that the NT system did affect the SOC stock distribution in the soil profile but not the total quantity.

Guo *et al*. (2016) [25] reported that NT treatments significantly increased SOC concentration of bulk soil, >0.25 aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer by 5.8%, 6.8% and 7.9% relative to CT treatments, respectively. S treatments had higher SOC concentration of bulk soil (12.9%), >0.25 mm aggregate (11.3%), and <0.25 mm aggregate (14.1%) than NS treatments. Compared with CT treatments, NT treatments increased MBC by 11.2%, 11.5%, and 20%, and dissolved organic carbon (DOC) concentration by 15.5%, 29.5%, and 14.1% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively. Compared with NS treatments, S treatments significantly increased MBC by 29.8%, 30.2%, and 24.1%, and DOC concentration by 23.2%, 25.0%, and 37.5% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate in the 0−5 cm soil layer, respectively.

Sapkota *et al*. (2017) [51] observed that the variation in the SOC concentration between different treatments was highest in the top 0.15 m of soil, with values generally declining with depth. On average, ZTDSR-ZTW+R and PBDSR-PBW+R had 86, 32 and 13% higher SOC concentrations than CTR-CTW at 0–0.05, 0.05–0.15 and 0.15–0.3 m soil depths, respectively, but 5% less than that of CTR-CTW at the lowest soil depth. ZTDSR-ZTW had 50 and 26% higher SOC concentrations than CTR-CTW at 0–0.05 and 0.05–0.15 m soil depths, but 5 and 10% lower concentrations than CTR-CTW at 0.15–0.3 and 0.3–0.6 m soil depths, respectively. The increase in SOC concentration at 0.15 m soil depth in ZT systems compared with the other treatments could be due to (i) surface retention of crop residues (or stubbles in the case of no residue), (ii) higher plant biomass production (Naresh *et al*., 2018) [41] leading to large amounts of root residues left in the system and (iii) a lower rate of organic matter decomposition due to minimum soil disturbance. Sharma *et al*. (2019) [52] also found that total soil organic content increased by 6.5–12.5% and 3.1–12.9% in different soil layers up to 0–60 cm depth in ZTDSR followed by ZTW + R over

PTR followed by CTW − R practices, respectively. The corresponding increase of the oxidizable C was 4.2–28.2% and 8.2–8.5%, respectively.

Patra *et al*. (2019) [46] reported that the SOC storage at 0–10 cm soil depth was the highest under NT-MWMB (12.49 Mg ha^{-1}) followed by NT-RWMB (12.12 Mg ha^{-1}), RT-RWMB (11.52 Mg ha^{-1}) and CT-RW (8.57 Mg ha^{-1}). However, storage of SOC at 0–10 cm depth was significantly lower under CT-RW compared to other treatments. The storage of SOC at 0–25 cm depth was the highest under RT-RWMB followed by NT-RWMB, NT-MWMB and CT-RW. However, it was only significantly higher than under CT-RW. At 0–30 cm soil depth, NT-RWMB stored the highest amount of SOC (25.32 Mg ha^{-1}) and it differed significantly only from that under CT-RW (20.83 Mg ha^{-1}). However, there were no statistically significant differences among NT-MWMB, NT-RWMB and RT-RWMB and NT-MWMB, RT-RWMB and CT-RW. The increased of SOC may indicate a higher SOM sequestration and soil quality under no-till treatments than under treatments with tillage operations (Zhao *et al*. 2015) [65]. Therefore SOC could be used as an indicator of soil quality improvement under different conservation agriculture practices in IGPs of India.

Crop Productivity

Naresh *et al*. (2014) [39] also found that laser land leveling produced maximum grain yield (5.73 and 4.60 tha^{-1}) against the minimum (4.25 and 3.85 tha^{-1}) in un leveled field. Significantly higher grain yield over traditionally leveled field and unleveled field might be attributable to better development of yield components like higher productive tillers m^{-1} row length and more 1000 grain weight due to more efficient use of inputs, uniform internode length, thicker canes and uniform availability of soil moisture in the effective root zone of the crop. Naresh *et al*. (2012) [38] attributed higher grain yield in precision land leveling to more uniform "wattar" conditions that facilitated timely preparation of field and timely sowing of the crop as compared to unleveled fields. Singh *et al*. (2017) [53] revealed that grain yield under T_4FIRB andT_1ZT were at par and significantly superior over other tillage crop establishment practices. However, T_2 RT was significantly superior over remaining treatments. T_3 and T_5 were at par and lowest yield was obtained underT_5 conventional tillage. The higher grain yield in FIRB was mainly due to higher number of productive tiller's and number of grains spike-1 as compared with zero tillage. Bilalis *et al*. 2011 [8] and Naresh *et al*. (2012) [38] reported that the yield per hectare was primarily improved due to more moisture supply, less penetration resistance impedance which responsible for better root development and its beneficial effect on the per plant yield. The grain yield per plant improved with increased moisture supply mainly through improvement number of grains per spike, number of spikelet per spike and test weight.

Sagar *et al*. (2018) [50] observed that the grain yield in land configurations $B_{75–2}$, $B_{75–3}$, $B_{90–2}$ and $B_{90–3}$ was lower than that in flat planting due to low plant density, but the yield was higher in $B_{90–4}$ than flat planting. Nandan *et al*. (2019) [37] reported that the higher rice grain yield was recorded in ZTDSR–ZT treatment than other tillage based crop establishment treatments, where the rice grain yield in NPTPR–ZT and CTTPR–CT treatments were comparable. The ZT–based crop establishment practices had higher wheat and maize grain yields than CTTPR–CT. Residue retention increased productivity of all the crops, being the highest positive on maize yield (7–10%), followed by wheat (5–11%) and rice (3–8%).

Conclusion

The conservation tillage treatments effectively improved the soil structure and strengthened the stability of water-stable soil aggregates. In addition, they increased the SOC content and storage in aggregates of different sizes with comparison of MP and CT. SOC concentration in the $WSA_{0.106-0.25}$ mm, WSA_{2-5} mm, and $WSA_{0.5-1}$ mm had a dominant effect on aggregate stability as well as SOC in $WSA_{>5\ mm}$ affected SOC concentration in bulk soils. Furthermore, long-term adoption of conservation tillage methods significantly increased the content of water-stable macro-aggregates and of aggregate MWD, and increased the SOC content, ratio of, and storage in the macro-aggregates. In particular, the ST treatment increased the SOC content and enriched the newly formed C in macro-aggregates. In addition, correlation analysis suggested a significant correlation between SOC and aggregate- associated C in differently sized aggregates. The 0.25-1 and 1-2mm aggregates were the main sites of SOC storage and were also the important indices of the soil C pool saturation.

The organic carbon content under no-tillage and reduced tillage system increased compared to conventional tillage due to retention of residues and minimum disturbance in the former system. The no-tillage system showed a trend to accumulate organic carbon near the soil surface layer. Conventional tillage reduced soil organic C stocks and that of its labile fractions both in top and subsoil (20-100 cm). 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.

Rice-Wheat cropping system in western Uttar Pradesh of India has depleted a significant amount of SOC and threatened the sustainability of agriculture in the region of different textured soils. Conservation tillage practices such as reduced- and no-tillage and crop residue addition increased SOC accumulation and improved sustainability of agricultural systems. No-tillage increased soil aggregation, improved other soil properties, and favourably influenced SOC accretion. Effects of crop residue addition are often observed when it was integrated with reduced-tillage systems. This review study also revealed several challenges and research opportunities impacts of alternative tillage and crop residue management practices to improve SOC concentration and stock and enhance soil carbon pools.

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