Modeling of Soil Organic Carbon Concentration and Stability Variation in Top and Deep Soils with varied Aggregate Size under Climate Change of Sub-tropical India: A Review

Kancheti Mrunalini[1], R.K.Naresh[2], N.C.Mahajan[3], K.S. Krishna Prasad[4], Lingutla Sirisha[5], Sudhir Kumar[6], S.P.Singh[7], Shipra Yadav[8], Jai Ram Chaudhary[9], Richa Tiwari[10]

[1]Department of Agronomy; Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
[2,4,8,10]Department of Agronomy; Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, U.P., India
[3]Institute of Agricultural Sciences, Department of Agronomy, Banaras Hindu University, Varanasi, U. P., India
[6]Department of Agronomy; Bihar Agricultural University, Sabour, Bihar
[5]Division of Plant Physiology, Indian Agriculture Research Institute, New Delhi, India
[7]KVK, Shamli, Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, U.P., India
[9]Indian Institute of Farming System Research (IIFSR), Modipuram-Meerut, U.P., India

Abstract— *The effects of tillage on soil organic carbon (SOC) and nutrient content of soil aggregates can vary spatially and temporally, and for different soil types and cropping systems. Surface soil (0–15 cm) was fractionated into aggregate sizes (>4.76 mm, 4.76–2.00 mm, 2.00–1.00 mm, 1.00–0.25 mm, 0.25–0.053 mm, <0.053 mm) under two tillage regimes. The percentage of soil OC mineralized (SOC_{min}, % SOC) was in general higher in larger aggregates than in smaller aggregates. 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. Soil organic C decreased with increasing soil depth but was greater under tree than others and was mainly concentrated in the topsoil layer (0–20 cm). In comparison to topsoil, deep soil aggregates generally exhibited a lower C_{min}, and higher SOC_{min}. The highest SOC was in the 1.00–0.25 mm fraction, while the lowest SOC was in micro-aggregate (<0.025 mm) and silt + clay (<0.053 mm) fractions and CT, respectively. Tillage did not influence the patterns in SOC across aggregates but did change the aggregate-size distribution, indicating that tillage affected soil fertility primarily by changing soil structure. The percentage of soil OC mineralized (SOC_{min}, % SOC) was in general higher in larger aggregates than in smaller aggregates. Meanwhile, SOC_{min} was greater in coniferous forests (CF) than in broad-leaved forests (BF) at topsoil and deep soil aggregates. In comparison to topsoil, deep soil aggregates generally exhibited a lower C_{min}, and higher SOC_{min}. The sum of macro-aggregate contributing rates for clay-humus stability of soil organic C (SOC) was significantly superior to that of the micro-aggregates. Water-stable aggregates increased by 34.5% in the CA with residue retention treatment, effectively improving the soil structure. Furthermore, 0.25–1.00 and 1–2mm aggregates had the highest SOC microbial biomass storage and responded rapidly to the various tillage treatments. Greater proportion of micro-aggregates within macro-aggregates in the plots under NT–NT compared with CT–CT was also observed in the surface layer only. Plots under NT–NT had about 10% higher coarse (250–2000 μm) intra-aggregate particulate organic matter-C (iPOM–C) within >2000 μm sand free aggregates in the 0- to 5-cm soil layer compared with CT–CT plots. The fine (53–250 μm) iPOM–C within the 250- to 2000-μm aggregates was also higher in the continuous NT plots compared with CT within both >2000 and 250 to 2000 μm sand free aggregate size classes in that soil layer.*

Keywords— ***Aggregates sizes, aggregate stability, soil depth, macro-aggregates, micro-aggregates, fractionation, particulate organic carbon.***

I. INTRODUCTION

Soil organic carbon (SOC) is the largest constituent of the Earth's terrestrial carbon pool (Stockmann et al., 2013), and slight C losses from the soil may lead to considerable changes in atmospheric CO_2 concentration (Wang et al., 2002), which would affect the magnitude of future climate change (Davidson, and Janssens, 2006). Increasing anthropogenic disturbances especially, on land use/cover change is the major cause of soil quality deterioration in the world (Haynes, 2005). Soil organic carbon (SOC) has recently gained prominence in assessment of soil quality since it compound affects chemical, physical and biological aspects of the soil. Though described by some as the least most understood component of the soil because of its dynamism, (Lehmann and Kleber, 2015) SOC has been linked to its potential role in carbon sequestration through proper management of land use and cover types (Yang et al., 2012). Land use and cover types influence C fluxes in an ecosystem; through litter quality, deposition and turnover rate. Although SOC is an indicator of soil quality, conceptualization of soil fractions can be used to detect even slight changes in management and regulate degradation (Blair et al., 1995).

As CO_2 exchange between soil carbon and atmospheric CO_2 varies strongly along climate gradients (Wang et al., 2010) focus on whether there are enhanced response patterns in SOC stability along increasing latitudinal or altitudinal gradients. Numerous studies have implicated temperature as a primary controller of SOC stability by altering the quality and quantity of litter input into soil and soil physico-chemical characteristics (Bird et al., 2002; Garten et al., 2006). SOC stability was found to increase with increasing mean annual temperature (MAT) based on chemical sequential fractionation analysis Hilli et al., 2008). However, the components and stability of SOC were not always consistently related to variations on MAT (Djukic et al., 2210). Radiocarbon dating and ^{13}C enrichment differentiation for soils indicated that SOC stability along latitudinal and altitudinal gradients was negatively related to MAT (Garten, 2011). Therefore, in addition to temperature affecting SOC stability, other factors must also contribute to SOC stability.

II. MATERIAL AND METHODS

Dameni et al. (2010) revealed that the distribution of aggregates at the top soil layers (0–10 and 10–20 cm) among the different size classes was significantly influenced by land-use type. Small macro-aggregates (250–2000 μm) represented 15 to 38% and were found to be the dominant aggregates in all land-use types and all soil depths [Fig.1a]. Other size fractions constituted a smaller amount of soil weight, varying from 7% to 22% across land use and soil depths. However, the slaked treatment, large macro-aggregates (>2000 μm) had the smallest amount of soil and represented 1 to 3.5% of the total aggregates collected. In other size classes, the percentages of aggregates collected from different land uses were significantly different and followed the order of <53 μm ≈ 53–250 μm < 250–2000 μm. The distribution of micro-aggregates (53–250 μm) and the mineral fraction (<53 μm) represented 7 to 19% of the total weight of aggregates [Fig.1a]. For the rewetted treatment, the amount of large macro-aggregates (>2000 μm) was consistently greater than the amount collected from the slaked pre-treatment. The percentage of soil collected followed the order of >2000 μm ≈ 53–250 μm < (<53 μm) <250–2000 μm.

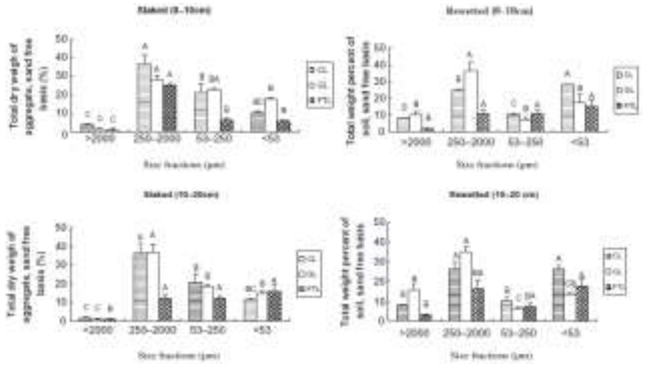

FIG. 1(a): Aggregate size distribution for slaked and rewetted pre-treatments, at the top soil layers (0–10 and 10–20 cm) of cropland (CL), forage field (GL), and fruit tree land (FTL) [Source: Dameni et al., 2010].

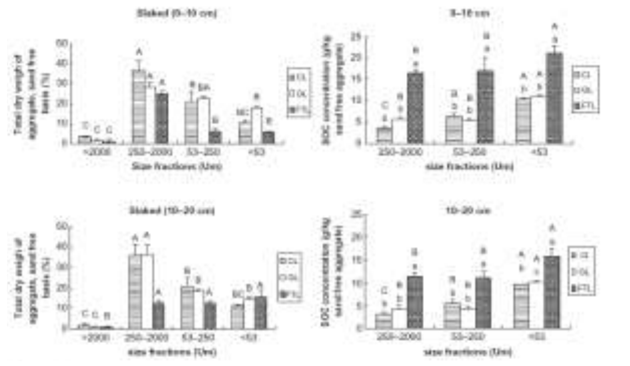

FIG. 1(b): Sand-corrected slaked aggregate organic C concentration at the top soil layers (0–10 and 10–20 cm) of cropland (CL), forage field (GL), and fruit tree land (FTL) [Source: Dameni et al., 2010].

Dameni et al. (2010) also found that the distribution of the SOC contents in aggregate-size fractions at depths of 0–10 and 10–20 cm within the profile under various land-use types [Fig.1b] indicated a significant effect of land use and soil depth on the SOC stock. Within each size class, aggregate C concentration in the FTL soil was significantly greater than in the CL and GL. For each system, differences generally narrowed with increasing soil depth. For FTL soil, a marked decrease in SOC stock from the first to the second layer was noted. In general, the measured SOC stock across land use types was greater in the topsoil (0–10 cm) than in lower depths. Multiple comparisons of means revealed that at the depth of 0–10 cm, the concentration of SOC in different land-use types followed the order FTL > GL≈ CL for all aggregate-size fractions [Fig.1b].

Fang et al. (2015) also found that the mass of soil aggregates of >5 mm diameter was the greatest followed by 2–5 mm, 0.5–1mm, 0.25–0.5 mm, and <0.25 mm, and that of 1–2 mm aggregates was the lowest [Fig.2a]. Moreover, smaller aggregates had a higher OC concentration (0.5–1 mm, 0.25–0.5 mm and <0.25 mm) than larger aggregates (>5 mm, 2–5 mm and 1–2 mm) in CF topsoil, and OC concentration decreased with increasing aggregate size in BF topsoil. In contrast, the OC concentration varied very little between aggregate size classes at deep soils in both forests [Fig 2b]. The C_{min} during the first 15 days was the highest in aggregates of 1–2 mm and <0.25 mm, followed by >5 mm and 2–5 mm, and the lowest in aggregates of 0.5–1 mm and 0.25–0.5 mm in CF topsoil [Fig.2b]. Similarly in BF topsoil, the C_{min} during the first 15 days was higher in <0.25 mm aggregates than in other aggregates, and did not differ significantly between the six aggregate categories at deeper soil depths in either vegetation type [Fig.2b].

In CF topsoil, the C_{min} measured over 43 and 71 days were generally higher in aggregates of 1–2 mm and <0.25 mm than in other aggregates, but such patterns were not observed in deep soil. In BF topsoil, the C_{min} measured over 43 and 71 days were generally higher in aggregates of >5 mm and <0.25 mm than in other aggregates, and higher in larger aggregates (>5 mm, 2–5 mm and 1–2 mm) than in smaller aggregates (0.5–1 mm, 0.25–0.5 mm and <0.25 mm) in deep soils [Fig. 2b].

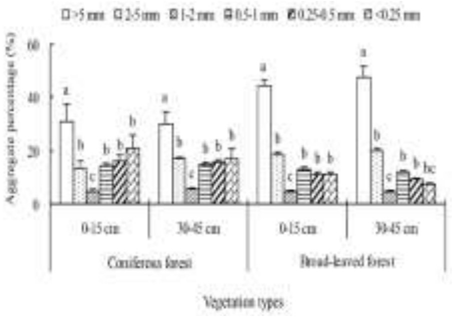

FIG. 2(a): The components of soil aggregate fractions of two depths in two restored plantations [Source: Fang et al., 2015]

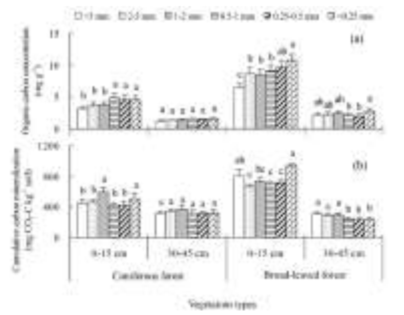

FIG. 2(b): The organic carbon concentration and mineralization of aggregate soil within 71 days at various soil depths in two restored plantations [Source: Fang et al., 2015]

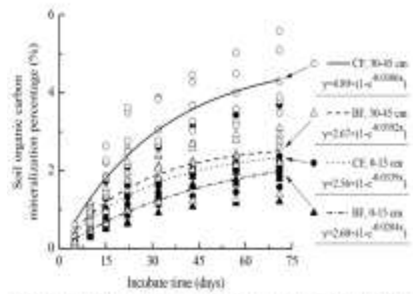

FIG. 2(c): The weighted mean of soil organic carbon mineralized percentage in various aggregates vary with incubation days in two soil depths under two restored plantations [Source: Fang et al., 2015]

Fang et al. (2015) revealed that in CF topsoil, the SOC_{min} was significantly higher in aggregates of 1–2 mm than that in aggregates of 0.5–1 mm and 0.25–0.5 mm, while the highest value of OC mineralization percentage was found in aggregates of >5mm in BF topsoil. Likewise, the soil OC mineralized potential (C0), mineralization constant (k) and decomposition days of half mineralizable carbon ($t_{0.5}$) varied with aggregate size, vegetation type and soil depth. The C_0 was higher in CF than in BF soil aggregates at both depths, while the $t_{0.5}$ in BF topsoil aggregates exceeded those in topsoil aggregates of CF. In CF, the

C_0 and $t_{0.5}$ were higher in deep soil aggregates than in topsoil aggregates, however, the $t_{0.5}$ was lower in deep soil aggregates than in topsoil aggregates in BF [Fig.2c].

Generally, physical protection is one of the important mechanisms to carbon stability. Compared with BF, CF had smaller soil aggregates and fewer larger soil aggregates, and the MWD was lower in CF than that in BF deep soils, which means the stability of the soil OC was better in CF Martens, (2000). However, the value of SOC_{min} was significantly higher in CF than in BF and there was no difference of C_{min} in deep soil of CF and BF [Fig. 2b]. Soil organic matters were the adhesive in the formation of soil aggregates [6], which mainly came from root exudates and decomposition of microbes on plant residue Rumpel and Koegel-Knabner, (2011).Soil aggregates might not be a major factor controlling OC stability when soil OC concentration was both low both in CF and BF at the early stages of vegetation restoration. Thus SOC_{min} was not lower in CF with relatively higher percentage of smaller soil aggregates than in BF.

Blume et al. (2002) reported that microbial activity in deep soil was similar to that measured in topsoil when normalized to biomass size. Therefore, it would not be surprised that deep soil had a higher SOC_{min} in view of lower OC concentration compared with topsoil [Fig.3a]. Taylor et al. [61] considered that deep soil was metabolically active and contained substantial numbers of microorganisms despite the low biomass contents, which was consistent with the finding that deep soils had a higher value of C_{mic}/C_{org} quotient (ratio of microbial biomass carbon to OC) Agnelli et al. (2004).

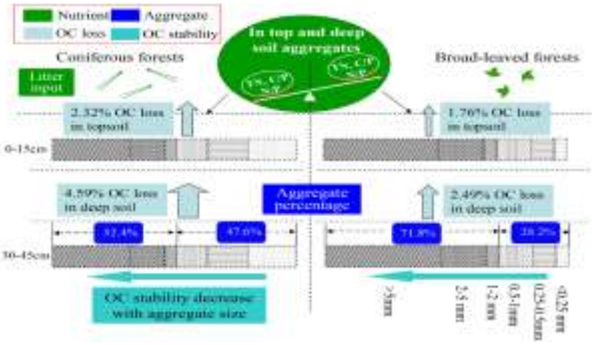

FIG. 3(a): A stylized illustration of the mechanical framework shows the difference of OC stability influenced by nutrient concentration and aggregate composition in two restored plantations [Source: Fang et al., 2015].

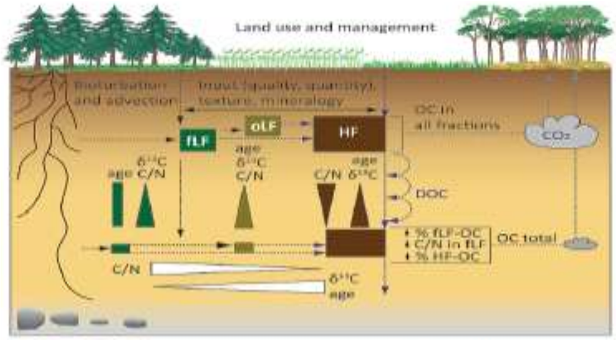

FIG. 3(b): Characteristics of density fractions in topsoil and subsoil layers and their relation to soil respiration (fLF: free light fraction, oLF: occluded light fraction, HF: heavy fraction, OC: OC concentration) [Source: Schrumpf et al., 2013]

Schrumpf et al. (2013) also found that the density fractionation separates total soil OC into fractions of different OC-to-TN ratios and HF-OC was in a more advanced decomposition stage than LF-OC, and that more microbial derived OC contributed to HF-OC. This is in line with smaller OC-to-TN-ratios [Fig.3b].

Wang et al. (2014) observed that at both the depositional and the eroding site, the HF represented the most important part of the total SOC at all depths, constituting >80% of SOC [Fig.4a]. The contribution of the HF to SOC was slightly lower at the depositional site than at the eroding site at all depths, indicating the larger contribution of fLF and oLF to SOC at the depositional site. The relative contribution of fLF and oLF to SOC decreased with depth at both sites. No free and occluded light fractions were present at 160-200 cm depth at the eroding site. Gu *et al*. (2016) [revealed that SOC concentration in all treatments decreased with soil depth. The significant differences of SOC among treatments were solely at depths of 0-40 cm, where soil physicochemical properties changed. Further changes would have occurred following activity by microorganisms. Average SOC content at depths of 0-40cm in ST and GT were 6.26 g kg^{-1} and 6.59 gKg^{-1} respectively, significantly higher than that of 5.44 g kg^{-1} in CK [Fig.4b]. The use of ST and GT increased SOC by 15.15% and 21.14% respectively. In the course of the growing season, SOC concentrations in all treatments presented substantial changes with seasons. The maximum SOC was recorded in the dry and cold season, and the minimum in the warm and wet season. Gu *et al*. (2016) also found that compared to the control without cover (CK), ST and GT treatments increased the contents of SOC,LOC, DOC, POC and EOC by 14.73%, 16.5%, 22.5%, 41.5% and 21%, respectively, in the 0-40 cm soil layer, and by 17%, 14%, 19%, and 30%, respectively, in the 0-100 cm soil layer [Fig.4c].

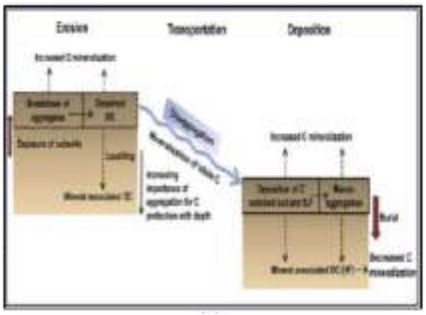

FIG 4(a): Conceptual model of the interplay between physical and chemical stabilization of soil organic carbon during erosion and deposition [Source: Wang *et al*., 2014]

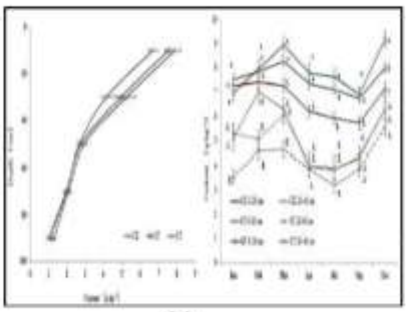

FIG 4(b): Changes of soil total organic carbon [Source: Gu *et al*., 2016]

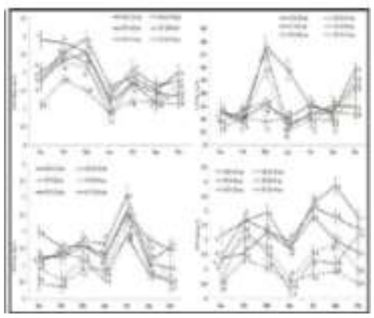

FIG 4(c): Dynamic changes of carbon fractions [Source: Gu *et al*., 2016]

Zibilsk et al. (2002) reported that the No-till resulted in significantly greater soil organic C in the top 4 cm of soil, where the organic C concentration was 58% greater than in the top 4 cm of the plow-till treatment. In the 4–8 cm depth, organic C was

15% greater than the plow-till control [Fig.5a]. The differences were relatively modest, but consistent with organic C gains observed in hot climates where conservation tillage has been adopted. Higher concentrations of total soil N occurred in the same treatments; however a significant reduction in N was detected below 12 cm in the ridge-till treatment [Fig.5b]. The relatively low amount of readily oxidizable C (ROC) in all tillage treatments suggests that much of the soil organic C gained is humic in nature which would be expected to improve C sequestration in this soil [Fig.5c].

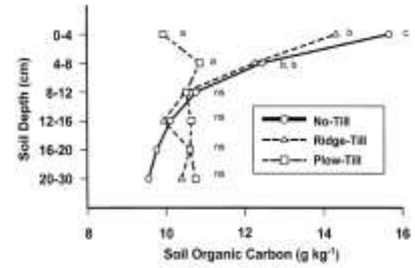

FIG. 5(a): Soil organic carbon by depth after 9 years of no-till, ridge-till or plow-till treatment [Source: Zibilsk et al., 2002]

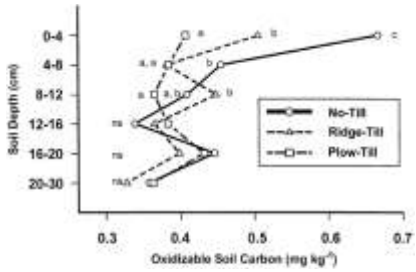

FIG. 5(b): Readily oxidizable soil carbon by depth after 9 years of no-till, ridge-till or plow-till treatment [Source: Zibilsk et al., 2002]

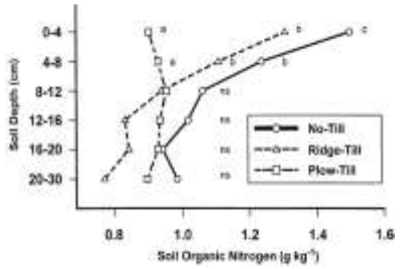

FIG 5(c): Total soil nitrogen by depth after 9 years of no-till, ridge-till or plow-till treatment [Source: Zibilsk et al., 2002]

Huggins et al. (2014) revealed that in addition to less C inputs than CC, SS accelerated rates of SOC decomposition. Tillage effects on SOC were greatest in CC where CP had 26% and NT 20% more SOC than MP, whereas SOC in SS was similar across tillage treatments [Fig.6a]. Up to 33% of the greater SOC under CC for CP and NT, compared with MP, occurred below tillage operating depths. Jacinthe and Lal, (2009) concluded that the rates of C sequestration were estimated from the temporal trend in the recent SOC pool (0– 40 cm in NR (23.2 Mg C ha^{-1}), 9-yr MP (32.9 Mg C ha^{-1}) and 13-yr MP (33 Mg C ha^{-1}), and ranged between 0.8 and 0.25 Mg C ha^{-1} yr^{-1} during the first and second decades of restoration. Despite a similar amount of crop residue returned (2.8 Mg C ha^{-1} yr^{-1}), recent SOC under 13-yr NT (36.8 Mg C ha^{-1}) exceeded that under 13-yr MP by 3.8 Mg C ha^{-1} [Fig.6b]. Murugan et al. (2013) revealed that the GRT and NT treatments increased the stocks of SOC (+7 %) and microbial biomass C (+20 %) in comparison with the MBT treatment. The differences between the GRT and NT were small, but there were more positive effects for the GRT treatment in most cases (Fig.6c].

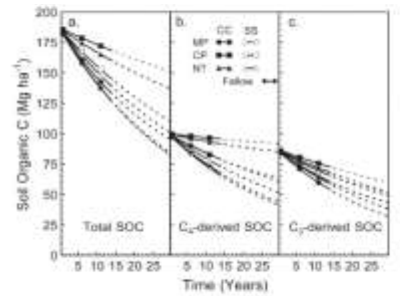

FIG. 6(a): Thirty year simulation of tillage and crop sequence effects on total soil organic C, C_4 derived SOC and C_3–derived SOC [Source: Huggins et al., 2014].

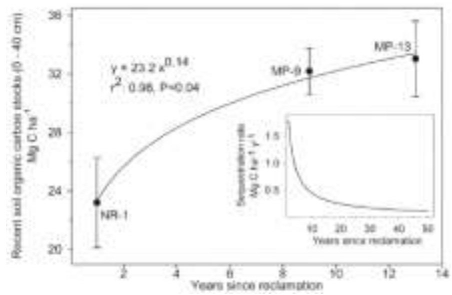

FIG. 6(b): Temporal evolution of recent organic carbon (SOC) pools in mineland reclaimed to agricultural land-use under conventional tillage [Source: Jacinthe and Lal, 2009]

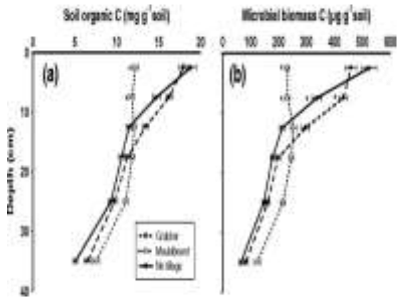

FIG. 6(c): Influence of different tillage intensities on soil microbial biomass at different depths (Source: Murugan et al., 2013]

Naresh et al. (2017) reported that the T_3 treatment resulted in significantly increased 66.1%, 50.9%, 38.3% and 32% LFOC, PON, LFON and POC, over T_7 treatment and WSC 39.6% in surface soil and 37.4% in subsurface soil [Table 1].LFOC were also significantly higher following the treatments including organic amendment than following applications solely of chemical fertilizers, except that the F_5, F_6 and F_7 treatments resulted in similar LFOC contents. Application solely of chemical fertilizers had no significant effects on LFOC compared with unfertilized control plots. Nevertheless, application of F_5 or F_6 significantly increased contents of POC relative to F_1 (by 49.6% and 63.4%, respectively). Rajan et al. (2012) concluded that FYM can increase the root biomass and microbial biomass debris which is the main source of POC. It is suggested that the greater biochemical recalcitrance of root litter. Puget et al. (1995) might have also increased the POC contents in soil depending upon the root biomass produced. The continuous replacement of organic manure on the soil creates a favorable environment for the cycling of C and formation of macro-aggregates. Furthermore, POC acts as a cementing agent to stabilize macro-aggregates and protect intra-aggregate C in the form of POC Six et al., (2002).

TABLE 1
EFFECT OF 15 YEARS OF APPLICATION OF TREATMENTS ON CONTENTS OF VARIOUS LABILE FRACTIONS OF CARBON IN SOIL [NARESH ET AL., 2017]

Treatments	0-5 cm layer					5-15 cm layer				
	WSC ($mgkg^{-1}$)	POC ($mgkg^{-1}$)	PON ($mgkg^{-1}$)	LFOC ($mgkg^{-1}$)	LFON ($mgkg^{-1}$)	WSC ($mgkg^{-1}$)	POC ($mgkg^{-1}$)	PON ($mgkg^{-1}$)	LFOC ($mgkg^{-1}$)	LFON ($mgkg^{-1}$)
Tillage crop residue practices										
T_1	23.9^{d}	638^{d}	67.2^{d}	81.3^{d}	9.1^{d}	15.7^{d}	535^{e}	54.7^{e}	65.1^{d}	7.8^{d}
T_2	25.9^{c}	898^{bc}	88.6^{cd}	107.8^{bc}	11.8^{c}	17.8^{cd}	674^{cd}	74.5^{cd}	94.1^{bc}	9.1^{c}
T_3	27.8^{ab}	1105^{ab}	106.7^{ab}	155.2^{a}	13.3^{ab}	19.6^{bc}	785^{bc}	91.8^{ab}	132.6^{a}	10.9^{ab}
T_4	22.7^{d}	779^{cd}	77.9^{d}	95.7^{c}	9.8^{d}	17.6^{cd}	609de	69.1^{de}	87.6^{c}	8.3^{cd}
T_5	26.4^{bc}	1033^{b}	97.4^{bc}	128.8^{b}	12.6^{bc}	20.3^{ab}	842^{ab}	87.3^{bc}	102.0^{b}	10.4^{b}
T_6	29.2^{a}	1357^{a}	117.5^{a}	177.8^{a}	14.2^{a}	22.6^{a}	974^{a}	106.1^{a}	141.2^{a}	11.8^{a}
T_7	17.2^{e}	620^{d}	22.5^{e}	52.7^{e}	8.2^{d}	13.2^{e}	485^{e}	18.8^{f}	49.8^{e}	6.8^{e}
Nutrient Management Practices										
F_1	21.9^{e}	631^{d}	24.7^{e}	89.2^{c}	6.8^{d}	15.1^{e}	585	17.3^{e}	47.0^{f}	5.9^{e}
F_2	29.2^{cd}	869^{c}	92.5^{c}	96.4^{c}	9.5^{c}	20.2^{cd}	789	73.5^{cd}	85.9^{d}	8.9^{c}
F_3	29.8^{c}	956^{bc}	96.8^{c}	108.1^{bc}	10.5^{bc}	21.9^{bc}	813	79.4^{c}	96.9^{cd}	9.6^{bc}
F_4	28.4^{d}	788^{cd}	72.9^{d}	91.3^{c}	7.9^{d}	18.8^{d}	728	59.4^{d}	66.7^{e}	7.2^{d}
F_5	32.5^{a}	1381^{a}	130.8^{a}	183.9^{a}	13.8^{a}	26.4^{a}	1032a	112.1^{a}	152.9^{a}	12.4^{a}
F_6	31.6^{ab}	1156^{ab}	114.2^{ab}	160.5^{a}	12.6^{ab}	23.6^{ab}	905ab	96.7^{ab}	139.7^{a}	11.9^{a}
F_7	30.9^{b}	1102^{b}	103.9^{bc}	123.5^{b}	11.5^{b}	22.7^{b}	826b	88.3^{bc}	103.2^{bc}	10.1^{b}

Values in a column followed by the same letter are not significantly different ($P < 0.05$).

WSC = water soluble C, POC = particulate organic C, PON = particulate organic N, LFOC = light fraction organic C, and LFON = light fraction organic N.

Xiao et al. (2016) showed that the SOC concentrations were significantly higher in macro-aggregates than micro-aggregates; the MBC and C_{mic}: C_{org} ratios were highest in small macro-aggregates. Therefore, small macro-aggregates might have more active C dynamics [Fig.7a]. In agricultural ecosystems, decreases in SOC are mainly induced by frequent soil disturbance (e.g. tillage, fertilization, and weed control) and crop removal (Kocyigit and Demirci, 2012). MBC in aggregates and bulk soil in other land uses decreased compared with that in enclosure land [Fig.7b]. Further, the maize field had the lowest MBC. Moreover, the MBC in small micro-aggregates of prescribed-burning land (1850.62 mg kg^{-1}) was significantly higher than that of enclosure land (1219.90 mg kg^{-1}). The pasture and maize fields had much lower MBC in micro-aggregates (623.36 $mgkg^{-1}$ and 514.30 $mgkg^{-1}$, respectively). However, the MBC in large macro-aggregates did not differ significantly among all land uses. In the three aggregates, MBC was the highest in small macro-aggregates, followed by large macro-aggregates and micro-aggregates [Fig.7b]. The C_{mic}: C_{org} ratios ranged between 1.71% and 3.44% [Fig.7b]. Compared to enclosure land, the ratios in other land uses increased in aggregates and bulk soil. The highest C_{mic}: C_{org} ratio (3.44%) was observed in small macro-aggregates. This is mainly because the large radius of large aggregates could limit the O_2 concentration and gas diffusion required by microbes (Gupta and Germida, 2015; Jiang et al., 2011). Thus, large macro-aggregates might diminish the impacts of land uses and facilitate the maintenance of a stable microbial biomass.

Dou et al. (2008) reported that SMBC was 5 to 8%, mineralized C was 2%, POM C was 14 to 31%, hydrolyzable C was 53 to 71%, and DOC was 1 to 2% of SOC. No-till significantly increased SMBC in the 0- to 30-cm depth, especially in the surface 0 to 5 cm [Fig.7c]. Under NT, SMBC at 0 to 5 cm was 25, 33, and 22% greater for CW, SWS, and WS, respectively, than under CT, but was 20 and 8% lower for CW and WS, respectively, than under CT at the 5- to 15-cm depth. At the 15- to 30-cm depth, no consistent effect of tillage was observed [Fig7c].

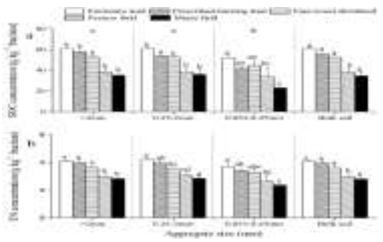

Fig. 7(a): Soil organic carbon (SOC) (a) and total nitrogen (TN) (b) concentrations in the three sizes of soil aggregates and in bulk soil of different land uses [Source: Xiao et al., 2016]

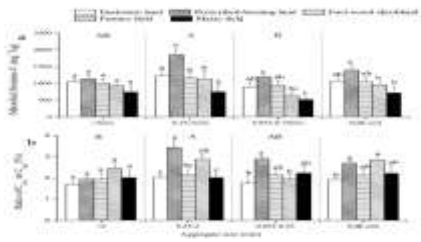

Fig.7 (b): Microbial biomass carbon (MBC) (a) and the C_{mic}: C_{org} ratios (b) of the three sizes of soil aggregates and bulk soil of different land uses [Source: Xiao et al., 2016]

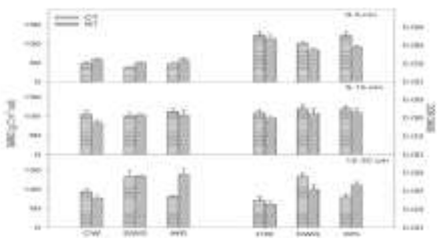

Fig. 7(c): Soil microbial biomass C (SMBC) and its proportion of soil organic C (SOC) as affected by cropping sequence and tillage at 0- to 5-, 5- to 15-, and 15- to 30-cm depths [Source:Dou et al., 2008]

Kumar et al. (2018) also found that the ZTR (zero till with residue retention) (T_1) and RTR (Reduced till with residue retention) (T_3) showed significantly higher BC, WSOC, SOC and OC content of 24.5%, 21.9%,19.37 and 18.34 gkg^{-1}, respectively [Table 2] as compared to the other treatments. Irrespective of residue retention, wheat sown in zero till plots enhanced 22.7%, 15.7%, 36.9% and 28.8% of BC, WSOC, SOC and OC, respectively, in surface soil as compared to conventional tillage [Table 2]. Simultaneously, residue retention in zero tillage caused an increment of 22.3%, 14.0%, 24.1% and 19.4% in BC, WSOC, SOC and OC, respectively over the treatments with no residue management. Similar increasing trends of conservation practices on different forms of carbon under sub-surface (15–30 cm) soil were observed however, the magnitude was relatively lower [Table 2]. Zhu *et al*., (2011) compared to conventional tillage (CT) and zero-tillage (ZT) 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 Song *et al*., (2011).

TABLE 2
EFFECT OF TILLAGE AND NITROGEN MANAGEMENT ON DISTRIBUTION OF DIFFERENT FORMS OF CARBON IN SOIL [KUMAR ET AL., 2018]

Treatments	WSOC (gkg^{-1})		SOC (gkg^{-1})		OC ($g\ kg^{-1}$)		BC (gkg^{-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
Tillage Practices								
T_1 ZTR	28.8	26.2	23.1	19.3	9.61	9.13	4.69	4.28
T_2 ZTWR	25.3	24.6	18.4	14.8	7.87	7.21	3.76	3.19
T_3 RTR	27.0	25.9	22.4	18.2	8.68	8.17	4.13	3.87
T_4 RTWR	23.7	21.8	18.1	14.2	7.66	7.07	3.12	2.96
T_5 CTR	26.1	24.4	21.8	17.4	8.49	7.96	3.82	3.48
T_6 CT	21.8	20.9	16.1	13.1	6.21	5.64	2.89	2.63
Nitrogen Management								
F_0 Control	21.1	14.9	16.1	13.1	6.13	5.48	1.58	1.07
F_1 80 kg N ha^{-1}	28.3	21.2	17.8	14.7	6.46	6.16	2.46	1.75
F_2 120 kg N ha^{-1}	29.5	22.1	19.1	16.1	7.25	6.71	3.26	2.18
F_3 160 kg N ha^{-1}	30.2	23.1	20.8	18.2	7.75	7.28	3.82	2.66
F_4 200 kg N ha^{-1}	31.1	25.4	21.3	18.7	7.93	7.48	4.15	3.42

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.
WSOC= Water soluble organic carbon, SOC =Total soil organic carbon, OC =Oxidizable organic carbon, BC =Black carbon

Kumar et al. (2018) revealed that at the 0–15 and 15-30 cm, POC, PON, LFOC and LFON content under ZT and RT with residue retention was greater than under without residue and conventional sown plots, respectively. The decrease in the disruption of soil macro-aggregates under ZT plots permitted a greater accumulation of SOC between and within the aggregates. Thus, less soil disturbance is the major cause of higher POC in the ZT and RT plots compared with the CT plots in the 0-15cm and 15-30 cm soil layers [Table 3]. This phenomenon might lead to micro-aggregate formation within macro-aggregates formed around fine intra-aggregate POC and to a long-term stabilization of SOC occluded within these micro-aggregates. The sequestration rate of POC, PON, LFOC and LFON in all the treatments followed the order 200 kg Nha^{-1}(F_4) > 160 kg Nha^{-1} (F_3) > 120 kg Nha^{-1}(F_2) >800 kg Nha^{-1} (F_1) > control (unfertilized) (F_0) [Table 3]. Chen et al., (2009) also found that single effect of residue application was not significant but its significance became apparent after its interaction with tillage system.

TABLE 3
EFFECT OF DIFFERENT TREATMENTS ON CONTENTS OF VARIOUS LABILE FRACTIONS OF CARBON IN SOIL [KUMAR ET AL., 2018]

Treatments	POC ($mgkg^{-1}$)		PON ($mgkg^{-1}$)		LFOC ($mgkg^{-1}$)		LFON ($mgkg^{-1}$)	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
Tillage Practices								
T_1 ZTR	1342.8	967.9	119.5	108.1	194.7	154.8	14.8	12.3
T_2 ZTWR	981.1	667.4	94.6	86.5	120.5	104.7	11.8	10.3
T_3 RTR	1230.2	836.9	109.7	97.8	170.9	144.9	13.7	11.6
T_4 RTWR	869.4	604.4	82.6	76.6	107.1	97.3	9.7	8.6
T_5 CTR	1099.1	779.4	98.4	89.3	143.8	115.9	12.8	10.9
T_6 CT	617.5	481.8	69.2	57.6	90.8	73.6	9.6	7.9
Nitrogen Management								
F_0 Control	709.7	658.6	31.7	26.3	123.9	104.3	6.4	5.8
F_1 80 kg N ha^{-1}	860.7	785.6	68.4	56.2	132.8	116.1	7.6	6.9
F_2 120 kg N ha^{-1}	952.2	808.9	89.5	78.5	150.6	127.6	9.7	8.6
F_3 160 kg N ha^{-1}	1099.5	823.8	96.8	83.4	168.5	145.7	10.2	9.8
F_4 200 kg N ha^{-1}	1153.1	898.4	103.9	97.3	176.2	152.9	11.7	10.6

Values in a column followed by the same letter are not significantly different ($P < 0.05$).
POC = particulate organic carbon, PON = particulate organic nitrogen, LFOC = labile fraction organic carbon, and LFON = labile fraction organic nitrogen.

Zheng et al. (2018) observed that the SOC storage in macro-aggregates under different treatments significantly decreased with soil depth [Table 4]. However, no significant variation was observed in the micro-aggregate associated C storage with depth. SOC storage increased with aggregate size from 1±2 to > 2mm and decreased with a decrease in aggregate size. The SOC storage in macro-aggregates of all sizes from 0-30cm depth was higher in the ST treatment than in other treatments. From 30-60cm, trends were less clear. SOC storage in micro-aggregates showed the opposite trend, with significantly higher levels in the CT treatment from 0-30cm, and no significant differences between treatments below this depth. Soil aggregates have three major effects on soil (Kladivko, 2001). They regulate and maintain water, fertilizer, gas, and heat in the soil, affect the types and activity of the soil enzymes, and also maintain and stabilize the loose arable layer (Ismail et al., 1994). Almost 90% of SOC exists in the form of aggregates in the topsoil. Protection and maintenance of the macro-aggregate stability and ratio are of great importance in the sustainability of soil fertility (Nimmo and Perkins, 2002). In addition, the contributing rate of SOC in differently sized aggregates decreased, consistent with the trend of soil aggregate-associated C storage and SOC with increasing soil depth.

Naresh et al. (2016) also found significantly higher POC content was probably also due to higher biomass C. Results on PON content after 3-year showed that in 0-5 cm soil layer of CT system, T_1, and T_5 treatments increased PON content from 35.8 mgkg^{-1} in CT (T_9) to 47.3 and 67.7 mg·kg^{-1} without CR, and to 78.3, 92.4 and 103.8 mgkg^{-1} with CR @ 2, 4and 6 tha^{-1}, respectively. The corresponding increase of PON content under CA system was from 35.9 mgkg^{-1} in CT system to 49 and 69.6 mgkg^{-1} without CR and 79.3, 93.0 and 104.3mgkg^{-1} with CR @ 2, 4 and 6 tha^{-1}, respectively. Small improvement in PON content was observed after 4 years of the experiment. Singh et al. (2014) found that carbon stock of 18.75, 19.84 and 23.83Mg ha^{-1} in the surface 0.4 m soil depth observed under CT was increased to 22.32, 26.73 and 33.07Mg ha^{-1} in 15 years of ZT in sandy loam, loam and clay loam soil. This increase was highest in clay loam (38.8%) followed by loam (34.7%) and sandy loam (19.0%) soil. The carbon sequestration rate was found to be 0.24, 0.46 and 0.62 Mg ha^{-1} yr^{-1}in sandy loam, loam and clay loam soil under ZT over CT. Thus, fine textured soils have more potential for storing carbon and ZT practice enhances carbon sequestration rate in soils by providing better conditions in terms of moisture and temperature for higher biomass production and reduced oxidation (Gonzalez-Sanchez et al., 2012). Gupta Choudhury et al. (2014) revealed that the residue incorporation or retention 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),which depicted that residue management could improve 2.1-fold higher water stable aggregates as compared to the other treatments without residue incorporation/retention. Bhattacharya et al. (2013) reported that tillage-induced changes in POM C were distinguishable only in the 0- to 5-cm soil layer; the differences were insignificant in the 5- to 15-cm soil layer. Plots under ZT had about 14% higher POM C than CT plots (3.61 g kg$^{–1}$ bulk soil) in the surface soil layer.

TABLE 4
DISTRIBUTION OF SOIL ORGANIC CARBON STORAGE IN WATER-STABLE AGGREGATES IN DIFFERENT SOIL LAYERS AND TILLAGE TREATMENTS [ZHENG ET AL., 2018]

Depth (cm)	Treatments	Macro-aggregate (t ha^{-1})				Micro-aggregate (t ha^{-1})			
		> 2 mm	2-1 mm	1-0.25 mm	Sum	0.25-0.053 mm	0.053-0.002 mm	< 0.002 mm	Sum
0-10	ST	2.65±0.74a*	5.87±0.34a	7.75±0.23a	16.28±0.85a	1.38±0.11c	0.26±0.02c	0.26±0.08b	1.90±0.08c
	NT	1.40±0.07b	5.82±0.36a	7.78±0.40a	15.00±0.11a	1.26±0.10c	0.23±0.02c	0.25±0.04b	1.75±0.08c
	MP	0.35±0.01b	3.98±0.29b	5.91±0.43b	10.24±0.17b	2.44±0.06b	0.73±0.05b	0.69±0.07a	3.86±0.08b
	CT	0.44±0.04b	4.43±0.22b	6.11±0.54b	10.99±0.37b	2.88±0.08a	1.96±0.23a	0.44±0.14ab	5.28±0.20a
10-20	ST	2.43±0.03a	6.85±0.19a	9.14±0.16ab	18.42±0.29a	0.61±0.01ab	1.54±0.10c	0.72±0.01ab	2.86±0.11b
	NT	1.62±0.02b	5.04±0.25b	8.49±0.10b	15.15±0.22b	0.49±0.10b	1.40±0.03c	0.67±0.14b	2.56±0.27b
	MP	0.59±0.03d	4.02±0.31c	7.67±0.31c	12.28±0.16c	0.82±0.01a	3.27±0.06b	0.97±0.02ab	5.05±0.07a
	CT	1.35±0.09c	4.69±0.09bc	9.42±0.19a	15.46±0.36b	0.73±0.11ab	3.56±0.08a	1.05±0.17a	5.35±0.23a
20-30	ST	3.06±0.10a	6.77±0.51a	9.92±0.17a	19.75±0.47a	1.70±0.56a	0.96±0.28b	0.21±0.11c	2.87±0.44b
	NT	1.41±0.03b	6.32±0.47a	8.30±0.10ab	16.02±0.34c	1.99±0.13a	0.98±0.10b	0.54±0.11bc	3.51±0.32b
	MP	2.15±0.26b	6.52±1.23a	9.03±1.10ab	17.71±0.38b	2.03±0.22a	0.59±0.21b	0.59±0.06b	3.20±0.37b
	CT	2.09±0.46b	3.48±0.36b	7.76±0.11b	13.33±0.07d	1.88±0.07a	1.73±0.09a	2.12±0.14a	5.73±0.06a
30-40	ST	1.92±0.03a	5.74±0.61a	7.01±0.57a	14.67±0.09a	1.29±0.26a	0.68±0.24a	0.33±0.04a	2.31±0.10a
	NT	1.06±0.25ab	4.00±0.54a	4.43±0.15b	9.50±0.34b	1.27±0.15a	0.93±0.34a	0.26±0.10a	2.45±0.27a
	MP	1.12±0.45ab	4.71±0.42a	7.72±0.57a	13.56±0.23a	1.20±0.06a	0.56±0.14a	0.31±0.12a	2.07±0.12a
	CT	0.60±0.14b	2.87±1.53a	5.83±1.19ab	9.30±1.01b	2.00±0.58a	0.95±0.26a	0.10±0.02a	3.05±0.86a
40-50	ST	0.66±0.23ab	3.29±0.90a	4.60±0.55a	8.55±0.39a	0.79±0.35a	0.48±0.18a	0.26±0.06a	1.53±0.58a
	NT	0.23±0.07b	1.66±0.24a	4.02±0.36ab	5.90±0.23c	1.09±0.26a	0.16±0.04a	0.21±0.06a	1.46±0.35a
	MP	0.87±0.24a	2.97±0.60a	3.35±0.26b	7.18±0.27b	0.93±0.16a	0.25±0.19a	0.34±0.07a	1.53±0.26a
	CT	0.55±0.19ab	1.71±0.20a	4.85±0.04a	7.11±0.33b	1.35±0.29a	0.33±0.11a	0.15±0.06a	1.83±0.27a
50-60	ST	0.23±0.15a	1.99±0.21a	3.48±0.31a	5.69±0.05a	0.80±0.04b	0.22±0.04b	0.33±0.06a	1.34±0.12b
	NT	0.34±0.07a	1.06±0.06b	3.50±0.17a	4.90±0.06b	1.33±0.08a	0.19±0.04b	0.17±0.03a	1.69±0.10b
	MP	0.31±0.11a	2.21±0.25a	3.20±0.35ab	5.72±0.14a	1.29±0.03a	0.20±0.06b	0.23±0.07a	1.71±0.15b
	CT	0.15±0.03a	1.83±0.10a	2.38±0.06b	4.36±0.05c	1.21±0.02a	0.96±0.06a	0.26±0.04a	2.44±0.12a

* Data are represented as means ± S.D., and data with the same letters within each column indicate no significant difference at $P = 0.05$ level.

Naresh et al. (2015a) also found 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 to 15 cm) soil. Wide raised beds transplanted rice and zero till wheat with 100% (T_9) or with 50% residue retention (T_8) showed significantly higher TC,SOC content of 11.93 and10.73 g kg^{-1} in T_9 and 10.98 and 9.38 gkg^{-1}, respectively in T_8 as compared to the other treatments. Irrespective of residue incorporation/ retention, wide raised beds with zero till wheat enhanced 40.5, 34.5, 36.7 and 34.6% of TIC, TC, SOC and OC in surface soil as compared to CT with transplanted rice cultivation. Aulakh *et al*. (2013) showed that PMN content after 2 years of the experiment in 0-5 cm soil layer of CT system, T_2, T_3 and T_4 treatments increased PMN content from 2.7 $mgkg^{-1}$ $7d^{-1}$ in control (T_1) to 2.9, 3.9 and 5.1 $mgkg^{-1}$ $7d^{-1}$ without CR, and to 6.9, 8.4 and 9.7 mg kg^{-1} $7d^{-1}$ with CR (T_6, T_7 and T_8), respectively. The corresponding increase of PMN content under CA system was from 3.6 $mgkg^{-1}$ $7d^{-1}$ in control to 3.9, 5.1 and 6.5 $mgkg^{-1}$ $7d^{-1}$ without CR and to 8.9, 10.3 and 12.1 $mgkg^{-1}$ $7d^{-1}$ with CR. PMN, a measure of the soil capacity to supply mineral N, constitutes an important measure of the soil health due to its strong relationship with the capability of soil to supply N for crop growth.

Ou et al. (2016) reported that the tillage systems obviously affected the distribution of soil aggregates with different sizes [Fig.8a]. 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. 8a]. Du et al. (2013) 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). The aggregate-associated SOC concentration in different soil layers was influenced by tillage systems [Fig.8b]. 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. 8b]. 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).

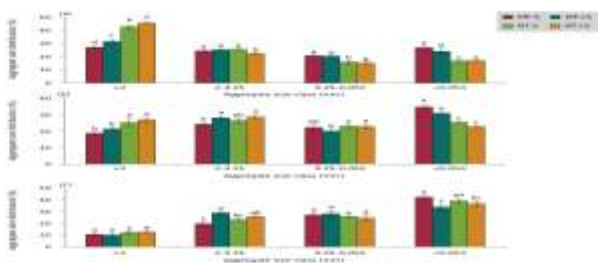

FIG.8 (a): Distribution (%) of water-stable aggregates with different sizes in different soil layers as influenced by tillage treatments. (a) 0.00-0.05 m; (b) 0.05-0.20 m; (c) 0.20-0.30 m. MP-S: moldboard plow without straw; MP+S: moldboard plow with straw; NT-S: no-tillage without straw; NT+S: no-tillage with straw [Source: Ou et al., 2016].

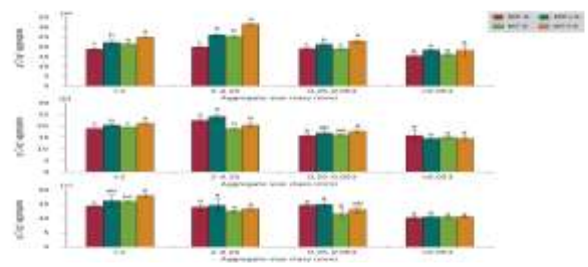

FIG.8 (b): Aggregate-associated SOC concentration in different layer intervals as influenced by tillage treatments. (a) 0.00-0.05 m; (b) 0.05-0.20 m; (c) 0.20-0.30 m. MP-S: moldboard plow without straw; MP+S: moldboard plow with straw; NT-S: no-tillage without straw; NT+S: no-tillage with straw.

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 5]. 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 5]. 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 [Table5]. 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 5]. 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).

TABLE 5
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

Naresh et al. (2018) reported that the SOC pool was the highest in the100 per cent RDF + VC (56.8 Mg C ha^{-1}), and it was on par with 50 per cent RDF +VC (52.8 Mg C ha^{-1})>75 per cent RDF +VC (51.4 Mg C ha^{-1})>VC (49.4Mg C ha^{-1}) >RDF (39.3 Mg C ha^{-1})> control (35.9 Mg C ha^{-1}) treatments. A higher percentage of C build-up was observed in 100 per cent RDF + VC treatment (43.6 per cent) followed by 50 per cent RDF+VC treatment (40.7 per cent), which was reflected in the profile SOC concentration of respective treatments. The SOC build-up rate also followed a similar trend as C build-up. The C budgeting shows that 36.8 per cent of the C applied as VC was stabilized. With the exception of the control and sole application of RDF through chemical fertilizer, the magnitude of SOC sequestration in other treatments was 7.9–9.6 Mg ha^{-1}. Higher SOC sequestration was observed with the application of vermicompost along with 100, 75 and 50 per cent recommended rate of RDF. Cultivation of a crop without using any organic and/or inorganic fertilizer inputs (control) caused a net depletion of SOC pool by 12.0 Mg C ha^{-1}. Though application of VC decreased the bulk density of the soil particularly at surface and subsurface layer due to higher SOC and increased root biomass it improves the SOC concentration significantly and ultimately increased SOC stock of the profile. SOC concentrations and stocks increased considerably with organic manure incorporation rates, which are possibly attributed to a larger proportion of recalcitrant organic compounds in manure (Liu *et al*., 2014). Vermi-compost manure application can result in an increase in lignin and lignin-like products, which are major components of the resistant C pool in the soil (Lima *et al*., 2009). Crop production was also enhanced by the manure inputs, which lead to higher total C inputs from rhizodeposition, root biomass and stubble return [Table 6]. The prevailing low levels of SOC concentrations are attributed to soil-mining practices – a little or no crop residues returned to the soil, excessive tillage, unbalanced fertilizer use and severe soil degradation. Ploughing for seedbed preparation disturbs the soil, adversely affects the distribution and stability of aggregates, exacerbates the oxidation of SOM and depletes the SOC pool (Kong *et al*., 2005).

TABLE 6
PROFILE ORGANIC C (OC), C BUILD-UP, C BUILD-UP RATE, C SEQUESTERED, C: N RATIO AND WET AGGREGATE STABILITY (WAS)IN THE SOIL PROFILE AS AFFECTED BY 7 YR OF TILLAGE CROP RESIDUE AND NUTRIENT MANAGEMENT PRACTICES [SOURCE: NARESH ET AL., 2018]

Treatments	Profile OC Mg ha^{-1}	C build-up %	C build-up rate Mg C ha^{-1} y^{-1}	C Sequestrated Mg C ha^{-1}	C:N Ratio	WAS (%)
Tillage crop residue practices						
T_1	43.5±3.1^{d}	27.9±0.7^{c}	1.06±0.08^{e}	6.7±0.2^{d}	14.5^{ab}	93.4^{c}
T_2	51.7±2.5^{c}	34.2±1.8^{b}	1.36±0.07^{cd}	8.2±0.1^{c}	12.7^{b}	92.9^{c}
T_3	69.4±3.3^{a}	36.6±0.6^{b}	1.46±0.09^{b}	8.6±0.8^{bc}	9.43^{c}	95.7^{ab}
T_4	63.3±2.8^{b}	31.8±0.6^{bc}	1.33±0.04^{d}	7.6±0.8^{b}	13.5^{ab}	94.5^{bc}
T_5	72.9±3.7^{a}	41.0±2.2^{a}	1.63±0.09^{a}	9.2±0.2^{ab}	12.3^{b}	96.9^{a}
T_6	73.0±3.6^{a}	41.2±2.3^{a}	1.64±0.10^{a}	9.6±0.2^{a}	9.28^{c}	97.6^{a}
T_7	41.5±2.9^{d}	22.4±1.2^{c}	0.89±0.06^{f}	5.3±0.5^{e}	15.3^{a}	89.7^{d}
Fertilizer Management Practices						
F_1	35.9±1.6^{c}	-	-	-12.0±0.7^{d}	16.2^{a}	93.7^{d}
F_2	39.3±1.8^{c}	29.8±0.06^{d}	1.28±0.007^{d}	-0.61±0.8^{c}	15.3^{ab}	92.3^{bc}
F_3	52.8±0.02^{ab}	40.7±2.4^{a}	1.82±0.006^{a}	9.3±0.8^{a}	14.5^{bc}	90.1^{b}
F_4	51.4±2.1^{ab}	37.3±0.06^{b}	1.73±0.021^{b}	8.5±0.5^{b}	13.7^{c}	89.9^{b}
F_5	56.8±1.9^{c}	43.6±0.09^{a}	1.88±0.001^{a}	9.6±0.7^{a}	8.99^{e}	87.4^{a}
F_6	49.4±2.3^{b}	34.2±1.8^{c}	1.46±0.07^{c}	7.9±0.3^{c}	10.8^{d}	91.1^{bc}

Zhao et al. (2014) concluded that the contents of SOC, TN, POC and LOC responded differently as the change of soil depth [Fig.9a]. In all land use types, contents of SOC, TN, POC and LOC in top soil (0–10 cm) were 3.26–7.86 g.kg^{-1} 0.39–0.72 g.kg^{-1}, 0.65–1.31 g.kg^{-1} and 0.76–1.07 g.kg^{-1}, respectively, which were significantly higher than other soil layers. The contents of SOC, TN, POC and LOC decreased significantly in soil depth of 10–40 cm while the decreases trended to be flatter in subsoil (40–100 cm). Additionally, the differences in contents of SOC, TN, POC and LOC in deep subsoil (100–200 cm) were negligible. Vegetation can greatly influence soil quality, C and N cycling, and regional socioeconomic development (Fu et al., 2010). It is also reported that converting cropland into land with perennial vegetation would increase the SOC content (Groenendijk et al., 2002).

Duval et al. (2016) reported that the concentration of labile soil organic carbon (POC_c and POC_f) did not reflect any differences between the cover crops and Ct in 2008 at 0–20 cm [Fig.9b]. The 3 years of C-input by cover crops were insufficient to affect the most dynamic and labile fractions of SOM, despite C-input differences among treatments. As from 2009, SOC increase by the cover crops was mainly due to higher POC_c concentration [Fig.9b]. In 2009 and 2011, the cover crops significantly enhanced POC_c levels compared with Ct. Differences among cover crops were also found. In general, gramineous species showed higher POC_c concentration than V. This difference among species may have been caused by the higher quality of the legume contribution (lower C: N), which stimulated residue decomposition and thus had a direct influence on POC_c. Regarding the Ct treatment, POC_c increased in the W, O and O + V treatments by 66 and 95% in 2009 - 2011, respectively, whereas in the V treatment, POC_c rose by 33 and 49% for the same periods [Fig.9b]. These results suggest that cover crops of gramineous species would enhance accumulation of more recalcitrant materials on the soil surface, thus promoting SOM increase. Also, larger residue amounts with a high concentration of soluble compounds and a low C: N ratio (vetch + soybean residues) would fuel microbial activity, stimulate decomposition and have a negative effect on organic fractions (Scherer-Lorenzen, 2008).

Chen et al. (2009) also found that the amount of large macro-aggregates was extremely low and made up of almost all rocks, therefore SOC and Nt content was not determined in large macro-aggregates. The influence of tillage on aggregate C and Nt content is shown in [Fig.9c]. 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.9c]. 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.9c].

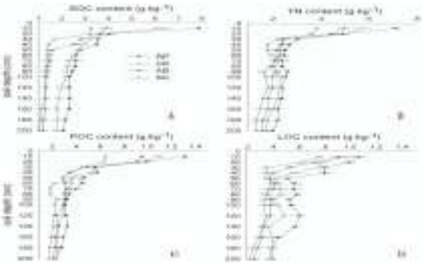

FIG. 9(a): Distribution of soil organic carbon (SOC, A), total nitrogen (TN, B), particulate organic carbon (POC, C), and labile organic carbon (LOC, D) contents of different land used types in soil depth of 0–200 cm [Source: Zhao et al., 2014].

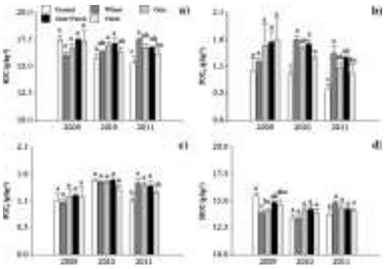

FIG. 9(b): Total organic carbon (SOC) (a), coarse particulate organic carbon (POCc) (b), fine particulate organic carbon (POCf) (c) and mineral-associated organic carbon (MOC) (d) as affected by cover crops at 0–20 cm depth [Source: Duval et al., 2016] .

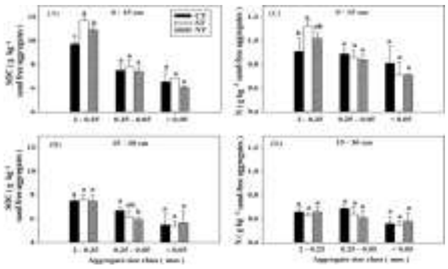

FIG. 9(c): Soil organic carbon (SOC) and nitrogen content (g kg1) of sand-free aggregates from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT) [Chen et al., 2009].

Krishna et al. (2018) reported that the total organic carbon (TOC) allocated into different pools in order of very labile > less labile > non labile >labile, constituting about 41.4, 20.6, 19.3 and 18.7%, respectively. In comparison with control, system receiving farmyard manure (FYM-10 Mg ha^{-1} season-^{1}) alone showed greater C build up (40.5%) followed by 100% NPK+FYM (120:60:40 kg N, P, K ha^{-1}+ 5 Mg FYM ha^{-1}season^{-1}) (16.2%). In fact, a net depletion of carbon stock was observed with 50% NPK (-1.2 Mg ha^{-1}) and control (-1.8 Mg ha^{-1}) treatments. Only 28.9% of C applied through FYM was stabilized as SOC. A minimal input of 2.34 Mg C ha^{-1} y^{-1} is needed to maintain SOC level [Table 7]. The magnitude of carbon pools extracted under a gradient of oxidizing conditions was as follows: C_{VL} >C_{LL} > C_{NL} > C_{L} constituting about 41.4, 20.6, and 19.3 and 18.7%, respectively, of the TOC [Table 7]. However, the contribution of VL, L and LL pools to SOC was 51.2, 23.1 and 25.5%, respectively. While active pool (C_{VL} + C_{L}) constituted about 60.1%, passive pool (C_{LL} + C_{NL}) represented 39.9% of the TOC. Among the treatments, 100% NPK+FYM (44.4%) maintained a proportionately higher amount of soil C in passive pools. With an increase in the dose of fertilization, on average, C allocation into passive pool was increased (33.0, 35.3, 40.7% and 39.3% of TOC under control, 50% NPK, 100% NPK and 150% NPK treatments, respectively).

TABLE 7
OXIDISABLE ORGANIC CARBON FRACTIONS (VERY LABILE, LABILE, LESS LABILE AND NON-LABILE) IN SOILS (G KG-1) AT DIFFERENT LAYERS (CM) [KRISHNA ET AL., 2018]

Treatment	Very labile C				Labile C			
	0-15	15-30	30-45	Total	0-15	15-30	30-45	Total
Control	3.6±0.5^{c}	1.4±0.3^{b}	1.3±0.2^{a}	6.3±0.4^{b}	2.4±0.3^{a}	1. 0±0.2^{a}	0.8±0.4^{a}	4.2±0.6^{a}
50% NPK	4.6±0.3^{bc}	2.1±0.7^{ab}	1.5±0.1^{a}	8.1±0.9^{a}	1.7±0.4^{ab}	0.9±0.5^{a}	0.7±0.2^{a}	3.3±0.7^{a}
100% NPK	4.4±0.3^{bc}	2.3±0.2^{a}	1.4±0.5^{a}	8.0±0.7^{a}	1.8±0.4^{ab}	0.8±0.5^{a}	0.6±0.3^{a}	3.2±0.8^{a}
150% NPK	5.0±0.2^{ab}	2.6±0.2^{a}	1.5±0.1^{a}	9.0±0.3^{a}	1.2±0.3^{b}	0.7±0.2^{a}	0.9±0.2^{a}	2.8±0.4^{a}
100% NPK+FYM	4.8±0.2^{ab}	2.0±0.2^{ab}	1.3±0.3^{a}	8.1±0.2^{a}	1.9±0.3^{ab}	0.7±0.2^{a}	0.7±0.3^{a}	3.4±0.2^{a}
FYM	5.9±1.3^{a}	2.2±0.2^{a}	1.4±0.3^{a}	9.5±1.6^{a}	2.5±0.9^{a}	0.7±0.3^{a}	0.7±0.2^{a}	3.9±0.9^{a}
Fallow	4.2±0.7^{bc}	1.5±0.5^{b}	0.7±0.3^{b}	6.3±0.8^{b}	2.2±1.0^{ab}	1.0±0.3^{a}	1.0±0.4^{a}	4.1±1.1^{a}
	Less labile C				Non labile C			
Control	1.5±0.3^{c}	0.6±0.4^{c}	0.4±0.0^{c}	2.6±0.7^{d}	1.2±0.5^{b}	1.2±0.3^{a}	0.2±0.2^{b}	2.6±0.5^{b}
50% NPK	1.8±0.1^{c}	0.4±0.1^{c}	0.5±0.2^{c}	2.7±0.1^{cd}	1.2±0.9^{b}	1.7±0.8^{a}	0.7±0.4^{ab}	3.5±1.8^{ab}
100% NPK	2.5±0.3^{ab}	0.8±0.1^{bc}	1.1±0.2^{ab}	4.4±0.1^{b}	1.3±0.6^{b}	1.5±0.6^{a}	0.5±0.2^{ab}	3.3±1.0^{ab}
150% NPK	2.6±0.2^{a}	0.9±0.1^{bc}	0.4±0.2^{c}	3.9±0.1^{b}	1.4±0.3^{b}	1.5±0.2^{a}	0.8±0.1^{a}	3.7±0.3^{ab}
100% NPK+FYM	2.7±0.6^{a}	1.5±0.2^{a}	1.4±0.1^{a}	5.6±0.7^{a}	2.0±0.8^{b}	1.3±0.1^{a}	0.3±0.3^{ab}	3.5±0.7^{ab}
FYM	1.9±0.7^{bc}	1.7±0.2^{a}	1.0±0.2^{b}	4.5±0.7^{ab}	3.7±1.3^{a}	1.0±0.2^{a}	0.5±0.5^{ab}	5.1±1.9^{a}
Fallow	1.5±0.3^{c}	1.3±0.7^{ab}	0.9±0.4^{b}	3.8±1.2^{bc}	2.1±0.2^{b}	1.4±0.7^{a}	0.4±0.2^{ab}	3.9±0.9^{ab}

*values in the same column followed by different letters are significantly different at $P<0.001$ according to Duncan's Multiple Range Test (DMRT) for separation of means. ± indicates the standard deviation values.

Nath et al. (2015) revealed that the TOC content for all the treatments was high in surface soil (0-10 cm) than in subsurface soil (10- 30 cm). TOC in surface and sub-surface soil was in the order organic > organic + inorganic > VM >inorganic > control and organic > organic +inorganic > inorganic > VM > control respectively [Table 8]. Build-up of higher amount of TOC in surface soil over sub-surface soil is attributed to accumulation of organic matter from root biomass and left over crop residues in the former that decreased with soil depth. Addition of root biomass and root exudates results in such variation in soil depths (Kaur et al., 2008). Application of organic manure alone or in combination with inorganic fertilizer considerably increased TOC in 0-10 cm soil depth than control plot [Table 8]. A higher percentage of C build-up was observed in 100 per cent RDF + VC treatment (43.6 per cent) followed by 50 per cent RDF+VC treatment (40.7 per cent), which was reflected in the profile SOC concentration of respective treatments [Table 8]. The SOC build-up rate also followed a similar trend as C build-up. The C budgeting shows that 36.8 per cent of the C applied as VC was stabilized. Higher SOC sequestration was observed with the application of vermin-compost along with 100, 75 and 50 per cent recommended rate of RDF. Cultivation of a crop without using any organic and/or inorganic fertilizer inputs (control) caused a net depletion of SOC pool by 12.0 Mg C ha^{-1}.Maintaining the SOC pool above the critical level is necessary to sustain agronomic productivity and to minimize environmental degradation (Lal, 2010c). However, maintaining or improving the SOC pool in light-textured soils of arid and semi-arid regions is a major challenge (Srinivasarao *et al*., 2012).

TABLE 8
SOIL ORGANIC CARBON (SOC) POOLS UNDER DIFFERENT MANAGEMENT REGIMES IN SURFACE SOIL (0-10 CM) AND SUBSURFACE (10-30 CM) PADDY GROWING SOILS [NATH ET AL., 2015]

Treatments	Sub fractionation of organic carbon (%)						
	Very labile (C_{VL})	Labile (C_L)	Less labile (C_{LL})	Non-labile (C_{NL})	TOC (%)	Active pool (C_{AP})	Passive pool (C_{PP})
0-10 cm							
Control	0.28 (22%)	0.04 (3%)	0.10 (8%)	0.88 (67%)	1.30^a	25%	75%
VM	0.33 (24%)	0.10 (7%)	0.17 (12%)	0.76 (57%)	1.36^b	31%	69%
Inorganic	0.30 (23%)	0.10 (8%)	0.14 (11%)	0.79 (59%)	1.33^a	30%	70%
Organic	0.36 (25%)	0.13 (9%)	0.12 (8%)	0.85 (59%)	1.46^{ab}	34%	66%
Organic+Inorganic	0.37 (26%)	0.14 (10%)	0.05 (4%)	0.87 (60%)	1.43^{ab}	36%	64%
10-30 cm							
Control	0.13 (19%)	0.06 (9%)	0.16 (23%)	0.35 (50%)	0.70^a	27%	73%
VM	0.15 (19%)	0.10 (13%)	0.15 (20%)	0.40 (49%)	0.80^b	31%	69%
Inorganic	0.13 (16%)	0.11 (14%)	0.17 (21%)	0.40 (49%)	0.81^b	30%	70%
Organic	0.14 (19%)	0.09 (12%)	0.10 (14%)	0.41 (55%)	0.74^{ab}	31%	69%
Organic+Inorganic	0.16 (19%)	0.09 (11%)	0.15 (18%)	0.45 (53%)	0.85^b	29%	71%
0-30 cm							
Control	0.21 (21%)	0.05 (5%)	0.13 (13%)	0.61 (61%)	1.0^a	26%	74%
VM	0.24 (22%)	0.10 (9%)	0.16 (15%)	0.58 (54%)	1.08^b	31%	69%
Inorganic	0.22 (20%)	0.11 (10%)	0.16 (14%)	0.60 (56%)	1.07^b	30%	70%
Organic	0.25 (23%)	0.11 (10%)	0.11 (10%)	0.63 (57%)	1.24^{ab}	33%	67%
Organic+Inorganic	0.27 (23%)	0.12 (10%)	0.10 (9%)	0.66 (58%)	1.14^{ab}	33%	67%

Parentheses show percent of TOC; different letters superscripted refers to significant differences between the treatments at 5% level of significance. [Control: without any organic and inorganic fertilizer; VM: village management (partially decomposed cow dung applied @ 70-80 Mg ha^{-1}); Inorganic (NPK) fertilizer (130-100-60 was used in the form of urea, single superphosphate and muriate of potash); Organic manure (phosphate solubilizing biofertilizer and azobacter bio-fertilizer applied in two steps: seedlings dip and soil application; Organic+Inorganic: both organic and inorganic fertilizer applied together].

Application of high fertilizer N rate in high C: N residue amended soils lowers the C: N ratio of the residue which avoids net immobilization but enhances the mineralization process (Pathak *et al*., 2006). This N remained in the soil after harvest and helped to maintain inorganic N concentrations in soil. The WAS under ZT without residue retention (93.4%) significantly increased by 4%compared to CT system (89.7%). A similar trend was observed under fertilizer management practices where control (91.7%) significantly increased WAS by 2.3% compare to 100% VC (93.9%). The 50%RDF +50%VC and 75%RDF +25%VC decreased WAS by 4% compared to under 100% RDF system [Table 8]. The study reported that mechanical tillage increased the breakdown of soil macro-aggregates and that CT disrupted soil macro-aggregates into micro-aggregates or individual particles. In addition, soil under CT system distributed aggregates during the plowing event by bringing protected aggregates to the soil surface**.**

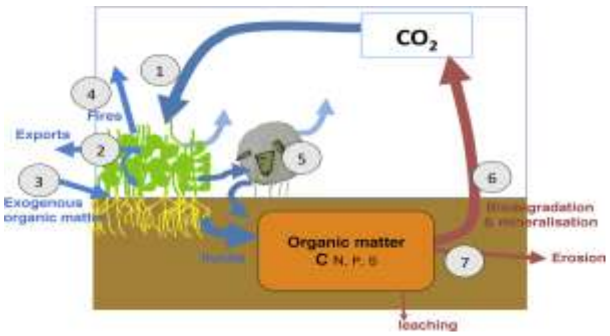

FIG. 10(a): Levers associated with agricultural practices that may influence SOC stocks.

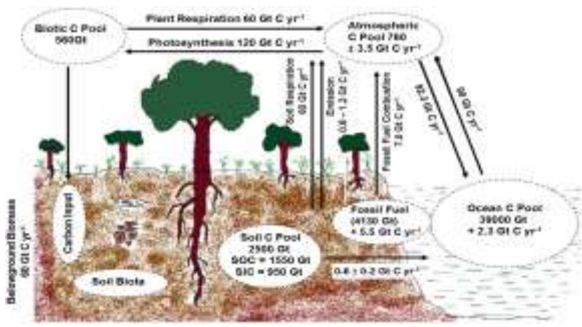

FIG. 10(b): Sources and sinks of carbon from different pools under terrestrial and aquatic ecosystems.

Several organic cropping systems, characterized by a diversified rotation including legume cover crops, exhibited similar or higher SOC stocks than their conventional counterparts, while fresh OC inputs to soil were not higher and tillage was more frequent (Autret et al., 2016) (a process not represented in [Fig. 10a]. Kallenbach et al. (2015) showed that in an organic cropping system, soil microorganisms had a higher carbon use effeciency and higher growth rates than under the reference conventional system. This should result in more microbial necromass being formed per unit of C input. Microbial necromass represents a significant fraction of soil organic matter and a major constituent of SOM stabilized in the long term (Cotrufo et al., 2013), which would explain the increased or preserved SOC stocks.

Each year, an estimated 25–40 billion tons of fertile soil are lost globally (FAO and ITPS, 2015). Hence, improving soil health through sustainable land management should be a common goal for farmers and land managers, to protect, maintain and build their most vital resource – soils. Soils are the major reservoir of C in terrestrial ecosystems, and soil C plays a dynamic role in influencing the global C cycle and climate change [Fig. 10b] while regulating soil health and productivity (**Mehra et al., 2018; Singh et al., 2018).** Soil contains C in two forms: soil organic C (SOC) and soil inorganic C (SIC), with most soils (except calcareous soils) having more SOC than SIC [Fig. 10b]. Thus far, enormous scientific progress has been attained in understanding soil functional characteristics relating to SOC stocks and C dynamics in agro-ecosystems (**Stockmann et al., 2013**).

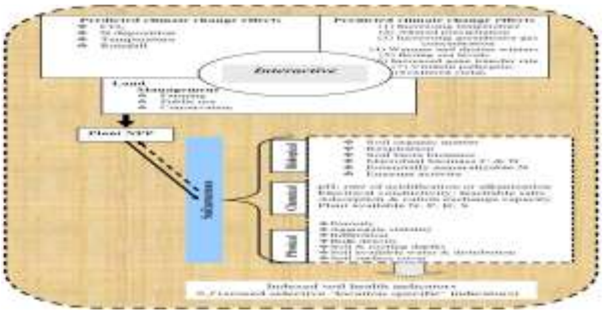

FIG. 11(a): Potential links between climate change, land use and management change, and soil health indicators (Source: Allen et al. 2011)

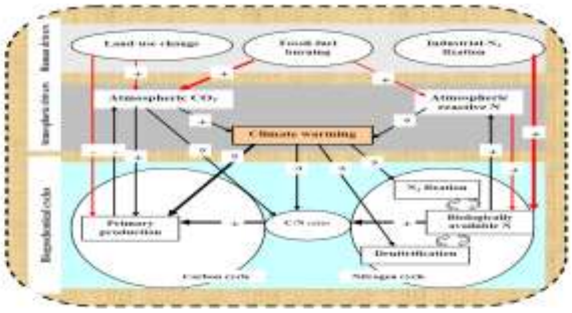

FIG.11 (b): Potential nitrogen–carbon-climate interactions (Source: Gruber and Galloway, 2008)

Allen et al. (2011) revealed that climate change scenarios considered by Intergovernmental Panel on Climate Change (IPCC) prediction include increase in atmospheric CO_2 concentration, increases in air temperature, changes in precipitation and prevalence of extreme climate events. For instance, global temperature change of 1.6–6.4 ºC by 2100, atmospheric CO_2 concentration increases by up to 550 ppm and precipitation change by at least 20% have been predicted (IPCC, 2007a). However, the predicted changes vary geographically and with future greenhouse gas (GHG) emission control. Therefore, the actual magnitude of changes of these parameters and consequences of these changes will therefore be location specific and be dependent on the extent of future success in reducing emission of GHG. Changes in precipitation are likely to be different for different parts of the world [Fig.11a].

Gruber and Galloway, (2008) also found that, soil organic matter (SOM) is essential in maintaining physical, chemical and biological functions in soil. In fact, SOM is the key indicator of soil health. It contains both living and non-living components. Living components include soil microbial biomass and living roots. Non-living SOM is a heterogeneous organic matter, variously described as labile, slow and recalcitrant SOM, light fraction (free or occluded) and heavy fraction, particulate (> 53 mm) and non-particulate SOM. It is also described by its chemical constituents such as proteins, lipids, starch, carbohydrates, hemicelluloses, celluloses, lignins, polyphenols, pectins and tannins or by humic acid, fulvic acid and humins. Soil organic carbon (SOC) constitutes about 50% of SOM and contains labile, slow and recalcitrant C pools. It could be also considered that, the influence of atmospheric N deposition, an important component of global environmental change; the rates of N deposition have increased by threefold to fivefold over the past century and may continue to increase rapidly in densely populated areas. The increasing rates of atmospheric N deposition may play a major role in modulating climate change impacts [Fig.11b].

III. CONCLUSION

In topsoil, WS macro-aggregate formation was highest (28.2 g of >250 mm aggregates per gram of C added) with the lowest residue input (2.5 g residue-C kg^{-1} soil). In the subsoil, WS macro-aggregate formation increased to 76.3 g of >250 mm aggregates per gram of C added with residue input of 5 g residue-C kg^{-1} soil and decreased thereafter. The concentration of POC, MBC and HWC were higher under topsoil (0-10 cm) as compared to subsoil (10-20 cm) in CA practices. Organic carbon concentrations in the <0.053-, 0.053- to 0.25-, 0.25- to 2.0, and >2.0-mm fractions were 14.0, 12.0, 14.4, 24.1% greater, respectively, in CA than in CF. The contents of SOC,LOC, DOC, POC and EOC by 14.73%, 16.5%, 22.5%, 41.5% and 21% in the 0-40 cm soil layer, and by 17%, 14%, 19%, and 30% in the 0-100 cm soil layer. These results suggest that over time, the MBC and MBC-derived C under the fine-sized residue treatment may constitute a significant source of stable SOC through strong physical and chemical bonding to the mineral soil matrix. Conservation management in the North West IGP is important in maintaining soil structure stability and conserving SOC from rapid decomposition with associated organic carbon fractions.

Soil microbial biomass, the active fraction of soil organic matter which plays a central role in the flow of C and N in ecosystems responds rapidly to management practices, and serves as an index of soil fertility. The practices of crop residue retention and tillage reduction provided an increased supply of C and N which was reflected in terms of increased levels of microbial biomass, N-mineralization rate in soil. Residue retention and tillage reduction both increased the proportion of organic C and total N present in soil organic matter as microbial biomass. 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. 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. The LOC fractions to SOC ratios also decreased, indicating a reduction in C quality as a consequence of tillage and residue management. Reduced LOC fraction stocks in subsoil could partially be explained by the decrease in fine root biomass in subsoil, with consequences for SOC stock.

REFERENCES

[1] Agnelli, A., Ascher, J., Corti, G., Ceccherini, M.T., Nannipieri, P., and Pietramellara, G. 2004. Distribution of microbial communities in a forest soil profile investigated by microbial biomass, soil respiration and DGGE of total and extracellular DNA. *Soil Biol Biochem* 36: 859–868.

[2] Allen, D. E., Singh, B.P., and Dalal, R.C. 2011.Soil Health Indicators under Climate Change: A Review of Current Knowledge. In: Soil Health and Climate Change (Eds. Singh, B. P.; A. L. Cowie; K. Y. Chan). Soil Biology Series, Vol. 29. Springer-Verlag Berlin Heidelberg, Chapter 2, pp: 25 – 45.

[3] Autret, Bn., Mary, B., Chenu, C., Balabane, M., Girardin, C., Bertrand, M., Grandeau, G., and Beaudoin, N. 2016. Alternative arable cropping systems: a key to increase soil organic carbon storage? Results from a 16 year field experiment. *Agric. Ecosyst. Environ.* 232: 150–164

[4] Bird, M., Santruckova, H., Lloyd, J. and Lawson, E. 2002. The isotopic composition of soil organic carbon on a north-south transect in western Canada. *Eur. J. Soil Sci.* 53: 393–403

[5] Blair GJ, Lefroy RD, Lisle L.1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Crop Pasture Sci*. 46 **(7):**1459–1466.

[6] Blume, E., Bischoff, M., Reichert, J., Moorman, T., Konopka, A., and Turco, R. 2002. Surface and subsurface microbial biomass, community structure and metabolic activity as a function of soil depth and season. *Appl Soil Ecol* 20: 171–181.

[7] Chen, H., Hou, R., Gong, Y., Li, H., Fan, M., and Kuzyakov, Y. 2009. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. *Soil Tillage Res*. 106: 85–94.

[8] Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K., and Paul, E. 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Glob Change Biol*. 19: 988–995.

[9] Dameni, H., Wang, J., and Qin, L. 2010. Soil Aggregate and Organic Carbon Stability under Different Land Uses in the North China Plain. *Commu Soil Sci Plant Anal*, 41**(9):** 1144 -1157

[10] Davidson, E.A.; Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440: 165–173.

[11] Dikgwatlhe, S.B., Chen, Z.D., Lal, R., Zhang, H.L., and Chen, F.2014. Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat–maize cropping system in the North China Plain. *Soil Tillage Res*. 144:110–118.

[12] Djukic, I., Zehetner, F., Tatzber, M. and Gerzabek, M. H. 2010. Soil organic-matter stocks and characteristics along an Alpine elevation gradient. *J. Plant Nutr. Soil Sci.* 173: 30–38.

[13] Dou, F., Wright, A.L., and Hons, F.M. 2008. Sensitivity of labile soil organic carbon to tillage in wheat-based cropping systems. *Soil Sci Soc Am J*. 72: 1445–1453.

[14] Du, Z.L., Ren, T.S., Hu, C.S., Zhang, Q.Z., and Humberto, B.C.2013. Soil aggregate stability and aggregate associated carbon under different tillage systems in the north China plain. *J Integr Agric.* 12:2114-23.

[15] Duval, M.E., Galantini, J.A., Capture, J.E., and Martinez, J.M. 2016. Winter cover crops in soybean monoculture: Effects on soil organic carbon and its fractions. *Soil Tillage Res*. 161: 95–105.

[16] Fang, X.M., Chen, F.S., Wan, S.Z., Yang, Q.P., and Shi, J.M. 2015. Topsoil and Deep Soil Organic Carbon Concentration and Stability Vary with Aggregate Size and Vegetation Type in Subtropical China. *PLoS ONE* 10**(9):** e0139380. doi:10.1371/journal.pone.0139380

[17] Fu, X.L., Shao, M.A., Wei, X.R., and Robertm, H. 2010. Soil organic carbon and total nitrogen as affected by vegetation types in Northern Loess Plateau of China, *Geoderma* 155: 31–35.

[18] Garten, C. T. 2011.Comparison of forest soil carbon dynamics at five sites along a latitudinal gradient. *Geoderma* 167-68: 30–40.

[19] Garten, C. T., Jr. and Hanson, P. J. 2006. Measured forest soil C stocks and estimated turnover times along an elevation gradient. *Geoderma*136: 342–352.

[20] Gonzalez-Sanchez, E.J., Ordonez-Fernandez, R., Carbonell- Bojollo, R., Veroz-Gonzalez, O., Gil- Ribes, J.A. 2012. Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. *Soil Tillage Res*. 122: 52–60.

[21] Groenendijk, F.M., Condron, L.M., and Rijkse, W.C. 2002. Effect of afforestation on organic carbon, nitrogen, and sulfur concentration in New Zealand hill country soils. Geoderma 108: 91–100.

[22] Gruber, N., and Galloway, J.N. 2008. An Earth-system perspective of the global nitrogen cycle. *Nature*, 451:293–296.

[23] Gu, C., Liu, Y., Mohamed, I., Zhang, R., Wang, X., Nie, X., *et al*. 2016.Dynamic Changes of Soil Surface Organic Carbon under Different Mulching Practices in Citrus Orchards on Sloping Land. *PLoS ONE*. 11**(12)**:e0168384.doi:10.1371/ journal. pone.0168384

[24] Guo, L.J., Lin, S., Liu, T.Q., Cao, C.G., and Li, C.F. 2016. Effects of Conservation Tillage on Topsoil Microbial Metabolic Characteristics and Organic Carbon within Aggregates under a Rice (Oryza sativa L.) –Wheat (Triticum aestivum L.) Cropping System in Central China. *PLoS ONE* 11**(1):** e0146145.doi:10.1371/journal.pone.0146145

[25] Gupta Choudhury, Shreyasi., Sonal Srivastava, Ranbir Singh, Chaudhari,S.K.,Sharma, D.K.,Singh, S.K. and Dipak Sarkar. 2014. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. *Soil Tillage Res*,136:76–83

[26] Gupta, V. and Germida, J. J. 2015. Soil aggregation: Influence on microbial biomass and implications for biological processes. *Soil Biol. Biochem*. 80: A3–A9.

[27] Haynes RJ. 2005. Labile organic matter fractions as central components of the quality of agricultural soils: an overview. *Adv Agron*. 85:221–268.

[28] Hilli, S., Stark, S. and Derome, J. 2008. Carbon quality and stocks in organic horizons in boreal forest soils. *Ecosystems* 11:270–282.

[29] Huang, S., Sun, Y.N., Rui, W.Y., Liu, W.R., and Zhang, W.J.2010. Long-term effect of no-tillage on soil organic carbon fractions in a continuous maize cropping system of northeast China. *Pedosphere*.20:285-92.

[30] Huggins, D.R., Allmaras, R.R., Clapp, C.E., Lamb, J.A., and Randall, G.W. 2014. Corn-Soybean Sequence and Tillage Effects on Soil Carbon Dynamics and Storage. Soil Sci. Soc. Am. J. 71**(1):** 145-154.

[31] Ismail, I., Blevins, R.L., and Frye, W.W. 1994. Long-term no-tillage effects on soil properties and continuous corn yields. *Soil Sci. Soc. Am. J*. 58:193-198.

[32] Jacinthe. P.A., and Lal, R. 2009. Tillage Effects on Carbon Sequestration and Microbial Biomass in Reclaimed Farmland Soils of South western Indian. Soil Sci. Soc. Am. J. 73: 605-613.

[33] Jiang, P.K., Xu, Q.F., Xu, Z.H., and Cao, Z.H. 2006. Seasonal changes in soil labile organic carbon pools within a Phyllostachys praecox stand under high rate fertilization and winter mulch in subtropical China. *Ecol Manage*. 236: 30–36.

[34] Jiang, X., Wright, A. L., Wang, J. and Li, Z. 2011. Long-term tillage effects on the distribution patterns of microbial biomass and activities within soil aggregates. *Catena* 87: 276–280.

[35] Kallenbach, C.M., Grandy, A.S., Frey, S.D., and Diefendorf, A.F. 2015. Microbial physiology and necromass regulate agricultural soil carbon accumulation. *Soil Biol. Biochem*. 91: 279–290.

[36] Kladivko, E.J. 2001. Tillage systems and soil ecology. Soil Tillage Res. 61:61-76.

[37] Kocyigit, R. and Demirci, S. 2012. Long-term changes of aggregate-associated and labile soil organic carbon and nitrogen after conversion from forest to grassland and cropland in northern Turkey. *Land Degrad. Develop*. 23: 475–482.

[38] Kong, A.Y.Y., Six, J., Bryatn, D.C., Denison, R.F., and van Kessel, C. 2005. The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Sci Soc Am J*. 69:1078-1085.

[39] Krishna, C. A., Majumder, S.P., Padhan, D., Badole, S., Datta,A., Mandal, B., and Gade, K.R. 2018. Carbon dynamics, potential and cost of carbon sequestration in double rice cropping system in semi-arid southern India. *J. Soil Sci Plant Nutri*,18 **(2):** 418-434

[40] Kumar,V., Naresh, R.K., Satendra Kumar, Sumit Kumar, Sunil Kumar, Vivak, Singh, S.P., and Mahajan, N.C. 2018. Tillage, crop residue, and nitrogen levels on dynamics of soil labile organic carbon fractions, productivity and grain quality of wheat crop in *Typic Ustochrept* soil. *J.Pharmacog Phytochem*. 7**(1):** 598-609.

[41] Lal, R. 2010c.Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Biosci*. 60:708-721.

[42] Lehmann J, Kleber M.2015. The contentious nature of soil organic matter. *Nature* 528:60–68.

[43] Lima, D.L., Santos, S.M., Scherer, H.W., Schneider, R.J., Duarte, A.C., Santos, E.B., et al. 2009. Effects of organic and inorganic amendments on soil organic matter properties. *Geoderma*. 150 **(1):**38-45.

[44] Liu, E.K., Teclemariam, S.G., Yan, C.R., Yu, J.M., Gu, R.S., Liu, S., et al. 2014.Long-term effects of no-tillage management practice on soil organic carbon and its fractions in the northern China. *Geoderma*. 213:379-384.

[45] Martens, D.A. 2000. Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. *Soil Biol Biochem* 32: 361–369

[46] Murugan, R.,Josef Koch, H., and Joergensen, R.G. 2013. Long-term influence of different tillage intensities on soil microbial biomass, residues and community structure at different depths. Biol. Fertility Soils, 50 (3): 487-498.

[47] Naresh, R.K., Gupta, Raj K., Gajendra Pal, Dhaliwal, S.S, Kumar, Dipender, Kumar Vineet, Arya, Vichitra Kumar, Raju, Singh, S.P., Basharullah and Singh, Onkar. 2015a.Tillage crop establishment strategies and soil fertility management: resource use efficiencies and soil carbon sequestration in a rice-wheat cropping system. *Eco. Env. & Cons*. 21:127-134

[48] Naresh, R.K., Gupta, Raj K., Singh, S.P. Dhaliwal, S.S., Ashish Dwivedi, Onkar Singh, Vikrant Singh, and Rathore, R.S. 2016.Tillage, irrigation levels and rice straw mulches effects on wheat productivity, soil aggregates and soil organic carbon dynamics after rice in sandy loam soils of subtropical climatic conditions. *J Pure Appl MicrobioI*, 10**(2):** 1061-1080.

[49] Naresh,R.K., Arvind Kumar, Bhaskar,S., Dhaliwal, S.S., Vivek, Satendra Kumar, Sunil Kumar and Gupta, R.K. 2017. Organic matter fractions and soil carbon sequestration after 15- years of integrated nutrient management and tillage systems in an annual double cropping system in northern India. *J.Pharmacog Phytochem*. 6**(6):** 670-683.

[50] Naresh, R.K., Jat, P.C., Kumar, V., Singh, S.P., and Kumar, Y. 2018. Carbon and nitrogen dynamics, carbon sequestration and energy saving in soils under different tillage, stubble mulching and fertilizer management in rice–wheat cropping system. *J.Pharmacog Phytochem*. 7**(6):** 723-740.

[51] Nath, A.J., Bhattacharyya, T., Deka, J., Das, A.K., and Ray, S.K. 2015. Management effect on soil organic carbon pools in lowland rain-fed paddy growing soil. *J. Tropical Agri*. 53 **(2):** 131-138.

[52] Nimmo, J.R., and Perkins, K.S. 2002. Aggregate stability and size distribution. In: Dane JH, Topp GC, editors. Methods of Soil Analysis: Part 4^{th} Physical Methods. Madison, Wisconsin, USA: *Soil Sci Soc Am, Inc;* pp. 317-328.

[53] Ou, H.P., Liu, X.H., Chen, Q.S., Huang, Y.F., He, M.J.,Tan, H.W., Xu, F.L., Li, Y.R., and Gu M.H. 2016. Water-Stable Aggregates and Associated Carbon in a Subtropical Rice Soil under Variable Tillage. *Rev Bras Cienc Solo*. v40:e0150145.

[54] Pathak, H., Singh, R., Bhatia, A., and Jain, N. 2006. Recycling of rice straw to improve wheat yield and soil fertility and reduce atmospheric pollution. *Paddy Water Environ*. 4:111-117

[55] Puget, P., Chenu, C., and Balesdent, J. 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. *Eur J Soil Sci*.46:449-459.

[56] Rajan, G., Keshav, R.A., Zueng-Sang, C., Shree, C.S., and Khem, R.D. 2012. Soil organic carbon sequestration as affected by tillage, crop residue, and nitrogen application in rice– wheat rotation system. *Paddy Water Environ*. 10:95-102.

[57] Rumpel, C., and Koegel-Knabner, I. 2011. Deep soil organic matter-a key but poorly understood component of terrestrial C cycle. *Plant Soil* 338: 143–158.

[58] Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., et al. 2011. Persistence of soil organic matter asan ecosystem property. *Nature*. 478:49-56.

[59] Scherer-Lorenzen, M. 2008. Functional diversity affects decomposition processes in experimental grasslands. *Funct. Ecol*. 22**(3):** 547–555.

[60] Six, J., Conant, R.T., Paul, E.A., and Paustian, K. 2002. Stabilization mechanisms of soil organic matter: Implications for C saturation of soils. Plant Soil. 241:155-176.

[61] Song, M.W., Li, A.Z., Cai, L.Q., and Zhang, R.S. 2011.Effects of different tillage methods on soil organic carbon pool. *J Agro-Enviro Sci*. 27**(2):**6222-626.

[62] Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Kumar, A.K., Kundu, S., Vittal, K.P.R., et al. 2012. Long-term effects of crop residues and fertility management on carbon sequestration and agronomic productivity of groundnut–finger millet rotation on an Alfisol in southern India, *Int J Agri Sustain*. 10**(3):**1-15

[63] Stockmann, U.; Adams, M.A.; Crawford, J.W.; Field, D.J.; Henakaarchchi, N.; Jenkins, M.; Minasny, B.; McBratney, A.B.; de Remy de Courcelles, V.; Singh, K.; et al. 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agric. Ecosyst. Environ*.164: 80–99.

[64] Vogelmann, E.S., Reichert, J.M., Prevedello, J., Awe, G.O., and Mataix-Solera, J.2013. Can occurrence of soil hydrophobicity promote the increase of aggregates stability? *Catena*, 110:24-31.

[65] Wang, G.; Qian, J.; Cheng, G.; Lai, Y. 2002. Soil organic carbon pool of grassland soils on the Qinghai-Tibetan Plateau and its global implication. *Sci. Total Environ*. 291: 207–217.

[66] Wang, W., Chen, W. L. and Wang, S. P. 2010.Forest soil respiration and its heterotrophic and autotrophic components: Global patterns and responses to temperature and precipitation. *Soil Biol. Biochem.*42:1236–1244.

[67] Wang, X., Cammeraat, E.L.H., Cerli, C., and Kalbitz, K. 2014. Soil aggregation and the stabilization of organic carbon as affected byerosion and deposition. *Soil Biol Biochem*. 72:55-65.

[68] Xiao, S.S., Zhang, W., Ye, Y., Zhao, J., and Wang, K. 2016. Soil aggregate mediates the impacts of land uses on organic carbon, total nitrogen, and microbial activity in a Karst ecosystem. *Sci Rep*. | 7:41402 | DOI: 10.1038/srep41402

[69] Yang X, Ren W, Sun B, Zhang S. 2012. Effects of contrasting soil management regimes on total and labile soil organic carbon fractions in loess soil in China. *Geoderma*.177:49–56.

[70] Zhao, F., Yang, G., Han, X., Feng, Y., and Ren, G. 2014. Stratification of Carbon Fractions and Carbon Management Index in Deep Soil Affected by the Grain-to- Green Program in China. *PLoS ONE* 9**(6):** e99657. doi:10.1371/journal.pone.0099657

[71] Zheng, H., Liu, W., Zheng, J., Luo, Y., Li, R., Wang, H., et al. 2018. Effect of long-term tillage on soil aggregates and aggregate-associated carbon in black soil of Northeast China. *PLoS ONE* 13 **(6)**: e0199523.

[72] Zhu, L.Q., Zhang, D.W., and Bian, X.M. 2011.Effects of continuous returning straws to field and shifting different tillage methods on changes of physical-chemical properties of soil and yield components of rice. *Chinese J Soil Sci*. 42 **(1):**81-85.