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Soil organic carbon stabilization for different land uses and soil management practices in a rice–wheat system of the North West indo-Gangetic plains: A review

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Abstract
World soils possess the largest organic carbon (C) stock in terrestrial ecosystems and small changes in soil organic C (SOC) stabilization can significantly affect atmospheric C concentrations. This review has identified a range of emerging agricultural management practices in croplands and highlighted knowledge gaps and mechanisms with potentials to increase SOC stabilization that may vary with site-specific conditions. The key practices rely on the principles of: (1) Decreasing C output by minimizing disturbance to soils from tillage, and eliminating fallowing, stubble burning; and (2) Increasing C inputs by retaining stubble, adding C-rich amendments, practicing integrated nutrient management and increasing crop diversity. Effects of different land uses and soil management on dynamics of soil organic carbon (SOC) and their stabilization stock changes remains unclear under intensively cultivated rice–wheat soil profile. Results revealed that balanced fertilization and combined use of chemical fertilizers and manure increased the SOC in all the plots except the unfertilized control. Balanced fertilization (NPK) and integrated fertilization (NPK+FYM) resulted in similar increases in particulate organic carbon, carbon mineralization and microbial biomass carbon, whereas particulate organic nitrogen and microbial biomass nitrogen were more in integrated fertilization (NPK+FYM) compared with control treatment. Soil organic C and carbon stabilization stock changed positively across the fertilizer and manure treatments over the control. In the control plot, at 0–15 cm depth the soil carbon was 15.1 Mg ha^{-1}, respectively which increased to the 19.5 Mg ha^{-1} in NPK+FYM. As compared to the initial (13.7 Mg ha^{-1}), the SOC stock in 0–15 cm depth increased under all the fertilized treatments in the order: NPK+FYM> N+FYM> NPK> FYM> N> control. The rate of increase in SOC (carbon sequestration) due to different land uses alone varied between 57 and 89 kg ha^{-1} yr^{-1}, while for soil management i.e. FYM addition the rate of increase was 61 to138 kg ha^{-1} yr^{-1} highest being in NPK+FYM.

Keywords: Aggregation, carbon sequestration, particulate soil organic matter, land use changes

Introduction

Different ecosystem types store different amounts of carbon depending on their species compositions, soil types, climate, relief, and other biophysical features. Of the estimated over 150 million km^2 of terrestrial ecosystems area, forests account for more than 40 million km^2 (about 28 percent). Savannahs and grasslands both cover about 23 percent, while croplands occupy about 11 percent. Among the biomes, vegetation carbon stocks range from 3 Gt for croplands to 212 Gt for tropical forests, while soil carbon stocks range from 100 Gt for temperate forests to 471 Gt for boreal forests. The tundra biome, covering an area of less than 10 million km^2, has the highest density of carbon storage. Soils generally hold more carbon than vegetation across biomes and account for 81 percent of terrestrial carbon stock at the global level.

Land-use changes, especially the conversion of native forest vegetation to cropland and plantations in tropical region, can alter soil C (Chen *et al*. 2003) [15]. Therefore, soil organic C (SOC) concentrations reflect soil and ecosystem processes as well as past management practices for both agricultural and non-agricultural soils (Collins *et al*. 2000) [18]. However, Murty *et al*. (2002) [54] found no significant overall change in SOC due to land use change from forest to pasture, although changes in soil C at individual sites ranged from −50% to +160%.These findings showed a high variability in soil C stocks in the changed ecosystems and possibly even within one ecosystem. Hence, ecosystems may lose or gain C, depending on soil type, tillage operations, soil management practices, plant residue retention or removal, fertilizer applications, organic manures/residues -additions, and integrated nutrient management (Fearnside and Barbosa, 1998) [26]. Although the effects of no tillage on soil organic matter (SOM) have been well documented, the information on land use and soil management effects on SOM is scarce. Sometimes the trend is inconsistent because of many factors such as soil type, cropping systems, residue management, and climate (Reicosky *et al*. 1995) [62].

Accumulating evidence suggests that certain fractions of SOC are more important sensitive indicators of management practices (Naresh *et al*. 2017). The SOM fractions that are considered important include microbial biomass C (MBC), particulate organic C (POC) and C mineralisation (C_{min}) (Rudrappa *et al*. 2006). Soil organic matter plays a vital role in maintaining soil quality because of its direct influence on physical, chemical and biological properties of the soil. There is an urgent need to increase our knowledge and understanding of the dynamics of SOC stock and the role that soil may play in the accumulation of atmospheric C through its sequestration. This need comes out of the fact that soil is a key reservoir of the terrestrial C, which contains globally about 1550 Pg C as organic C. It together with inorganic carbon constitutes about 3.3 times the size of the atmospheric pool and 4.5 times that of the biotic pool (Batjes, 1996) [5]. Any attempt that aims to enrich this reservoir through atmospheric C sequestration is likely to mitigate the harmful effects of the greenhouse gases and also ensure global food security to a great extent (Lal, 2004) [43].

Active C and N fractions, such as microbial biomass carbon and nitrogen (MBC and MBN), potentially mineralizable C and N, particulate organic C and N (POC and PON) which respond rapidly to changes in management practices, can better reflect changes in soil quality and productivity by altering the nutrient dynamics through immobilization–mineralization processes (Dong *et al*., 2012a, 2012b) [22, 23]. Particulate organic C and N that contain coarse fraction of organic matter are considered intermediate between active and slow fractions of SOC which change rapidly due to management practices (Cambardella and Elliott, 1992) [12]. These soil fractions are likely to be more sensitive to management practices than the total SOC (Awale *et al*., 2013) [4] and are the fine indicators of soil quality which influence soil function in specific ways (e.g., immobilization–mineralization). Thus, these soil C and N fractions may serve as indicators of future changes in total SOC that are presently undetectable (Dalal *et al*., 2011; Spargo *et al*., 2012; Xu *et al*., 2011) [19, 73, 78]. The pool sizes of labile C and N fractions provide an insight into the consequences of management practices that could not be garner from studies of total SOC alone. More resistant fractions of SOC generally have much longer turnover times, and thus have the long-term potential for SOC sequestration (Lal, 2016) [44]. To date, very less information is available on the long-term effects of the above land uses and soil managements on SOC stabilization and its different fractions.

Soil carbon stabilization

Das *et al*. (2016) [20] revealed that total organic C increased significantly with the integrated use of fertilizers and organic sources (from 13 to 16.03 g kg^{-1}) compared with unfertilized control (11.5 g kg^{-1}) or sole fertilizer (NPKZn; 12.17 g kg^{-1}) treatment at 0-7.5 cm soil depth. Averaged across soil depths, labile fractions like microbial biomass C (MBC) and permanganate – oxidisable C (PMOC) were generally higher in treatments that received farmyard manure (FYM), sulfitation press mud (SPM) or green gram residue (GR) along with NPK fertilizer, ranging from 192 to 276 mg kg^{-1} and from 0.60 to 0.75 g kg^{-1}, respectively compared with NPKZn and NPK+ cereal residue (CR) treatments, in which MBC and PMOC ranged from 118 to 170 mg kg^{-1} and from 0.43 to 0.57 g kg^{-1}, respectively. Oxidisable organic C fractions revealed that very labile C and labile C fractions were much larger in the NPK+FYM or NPK+GR+FYM treatments, whereas the less-labile C and non-labile C fractions were larger under control and NPK+CR treatments. Memon *et al*. (2018) [52] also found that the average SOM content in 2016–2017 significantly increased ($p < 0.05$) by 3.08% to 17.07% under all residue-incorporated treatments. Plots without straw incorporation showed a decreased SOM content (1.69–3.97%) compared with pre-treatment values under reduced and conventional tillage methods. However, the SOM content was higher (25.12, 24.06, 23.83, 23.80, 22.41, and 22.12 g/kg) in the RTsi60, RTsi100, CTsi100, CTsi60, RTsi30, and CTsi30 treatments, respectively, compared to RTns (21.10 g/kg) and CTns (20.61 g/kg) [Fig. 1].

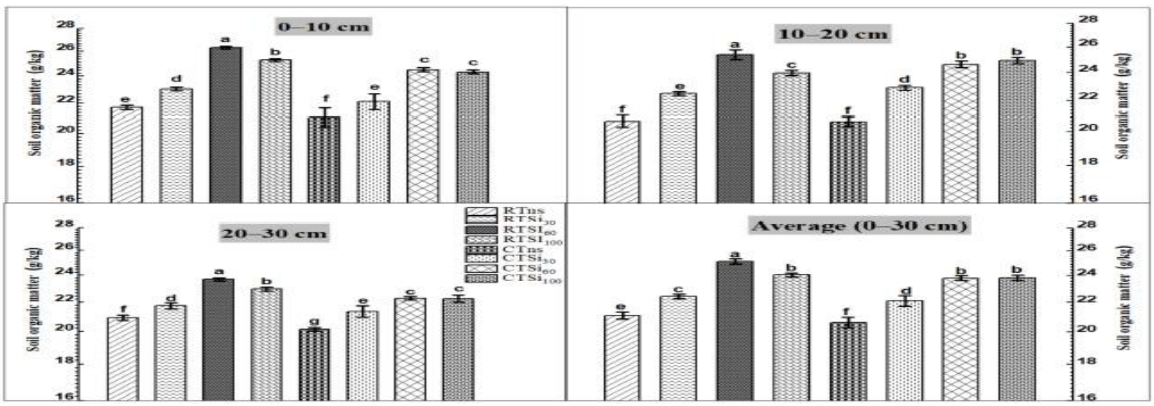


Fig 1: Depth-wise distribution of mean soil organic matter (SOM) under each treatment.

Note: RTns: RT without straw incorporation, RTsi30: RT with straw incorporation (SI) at 30%, RTsi60: RT with SI at 60%, RTsi100: RT with SI at 100%, CTns: CT without straw incorporation, CTsi30: CT with SI at 30%, CTsi60: CT with SI at 60%, and CTsi100: CT with SI at 100%.

Naresh *et al*. (2018) [55] reported that WSC was found to be 5.48% higher in surface soil than in sub-surface soil (Table 1). In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to CT, FIRB and ZT coupled with 6tha^{-1} CR increased 35.6% WSC in surface soil and 33.1% in sub surface soil.The WSC content in surface soil (0–15 cm) was significantly higher in

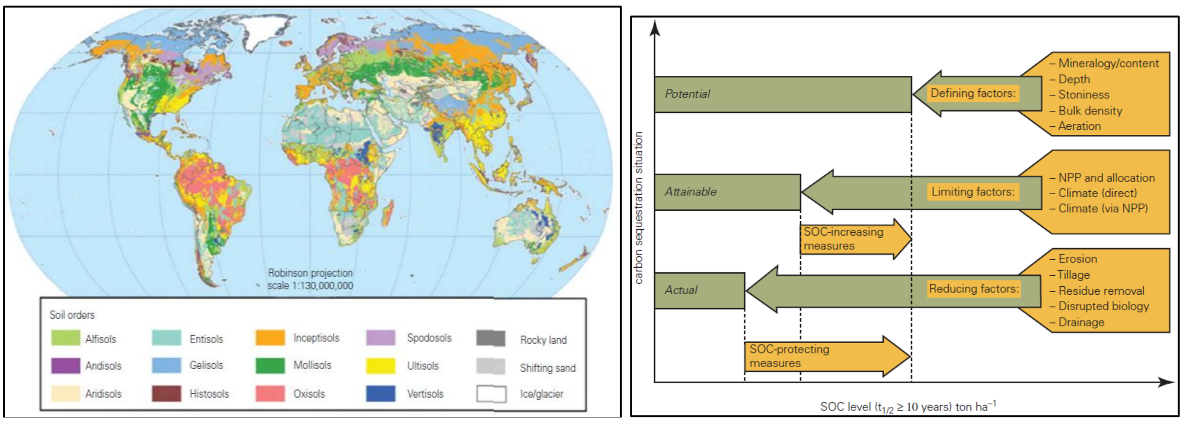
100% RDN as CF+ VC @ 5tha^{-1} (F_5) treatment (32.5 mg kg^{-1}) followed by 75% RDN as CF+ VC @ 5tha^{-1} (F_4) (29.8 mgkg^{-1}) and least in unfertilized control plot [(F_1) (21.9 mgkg^{-1}) (Table 1)]. It is evident that the MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 100% RDN as CF+ VC @ 5tha^{-1} (F_5) and 75% RDN as CF+ VC @ 5tha^{-1} (F_4) treated plots compared to 100% RDN as CF (F_2) fertilizer and unfertilized control plots (Table 1). The values of MBC in surface soil varied from 116.8 mgkg^{-1} in unfertilized control plot to 424.1 mgkg^{-1} in integrated nutrient use of 100% RDN as CF+ VC @ 5tha^{-1} plots, respectively; while it varied from 106.6 mgkg^{-1} (control) to 324.9 mgkg^{-1} (100% RDN as CF+ VC @ 5tha^{-1} F_5) in sub-surface (15-30 cm) soil layer. The values of MBC increased by 72.5 and 58.4% under 100% RDN as CF+ VC @ 5tha^{-1} (F_5) and 75% RDN as CF+ VC @ 5tha^{-1} (F_4) treatment in surface soil over control. While, there were 34.4% increase of MBC over 100% RDF as CF (F_2) fertilizer, respectively. The values of LFC in surface soil (0-15 cm) were 81.3, 95.7, 107.8, 128.8, 155.2, 177.8 and 52.7 mgkg^{-1} in ZT and FIRB without residue retention, ZT and FIRB with 4 & 6 tha^{-1} residue retention and CT treatments, respectively (Table 1). In the surface layer, the organic treatment accumulated 51.5% greater LFC (183.9 mg kg^{-1}) followed by 44.4% greater in integrated (160.5 mgkg^{-1}) and 27.7% greater in RDN (123.5 mg kg^{-1}) as compared to the control treatment.

Table 1: Concentrations of different soil organic matter carbon fractions $_f$POM and $_c$POM at different soil depths as affected by tillage and nutrient management to the continuous RW cropping system [Naresh *et al.*, 2018].

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

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

At the global level, the soil organic carbon pool is concentrated in five major soil orders: histosols, inceptisols, entisols, alfisols, and oxisols. In the tropics, the largest amount of soil organic carbon is found in oxisols, histosols, ultisols, and inceptisols [Fig.2a]. Ingram and Fernandes, (2001).\ reported that the potential carbon sequestration is controlled primarily by pedological factors that set the physico-chemical maximum limit to storage of carbon in the soil. Such factors include soil texture and clay mineralogy, depth, bulk density, aeration, and proportion of coarse fragments [Fig. 2b].



a) b)

Fig.2a: Global Soil Regions **Fig. 2b:** Factors Affecting Soil Carbon Sequestration

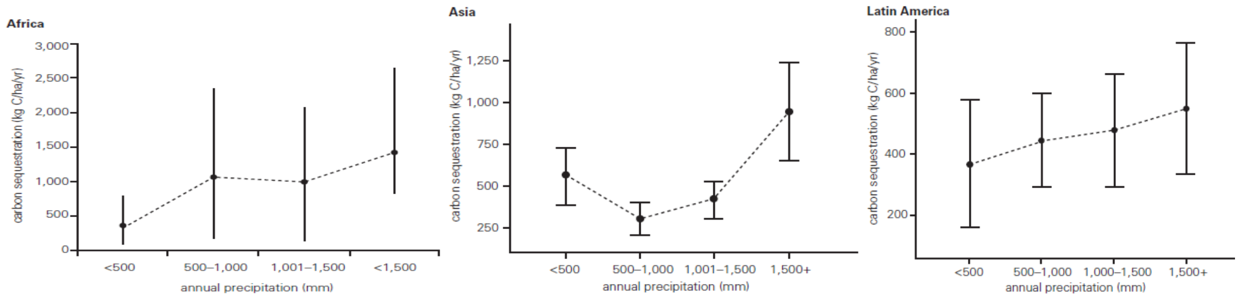


Fig 3: Soil Carbon Sequestration and Precipitation

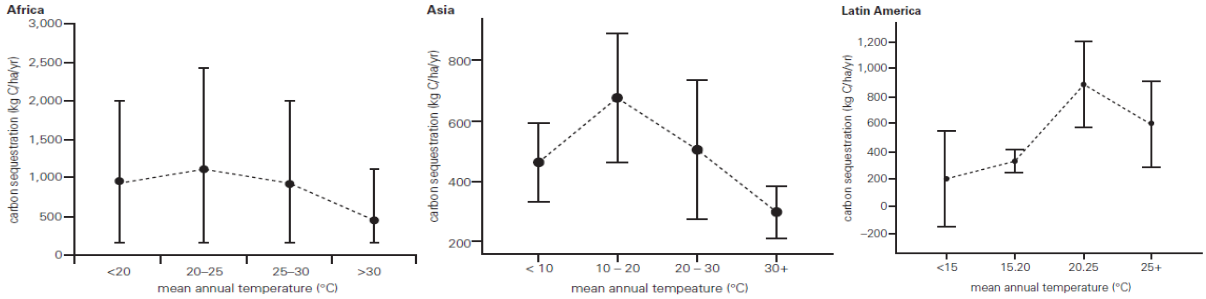


Fig 4: Soil Carbon Sequestration and Temperature

Potter *et al.* (2007) [60] revealed that an increase in soil temperature exacerbated the rate of mineralization, leading to a decrease in the soil organic carbon pool (SOC). However, decomposition byproducts at higher temperatures may be more recalcitrant than those at lower temperatures. Carbon sequestration rates were highest and also highly variable on inceptisols in Africa and Latin America. Inceptisols are relatively young soils characterized by having only the weakest appearance of horizons, or layers, produced by soil-forming factors. Inceptisol soil profi les give some indication of humus, clay minerals, or metal oxides accumulating in their layers. In Asia, the highest sequestration rates and variability were observed on oxisols, formed principally in humid tropical zones under rain forest, scrub, or savanna vegetation on fl at to gently sloping uplands. Oxisols are typically found on old landscapes that have been subject to shifting cultivation for several years [Fig.5].

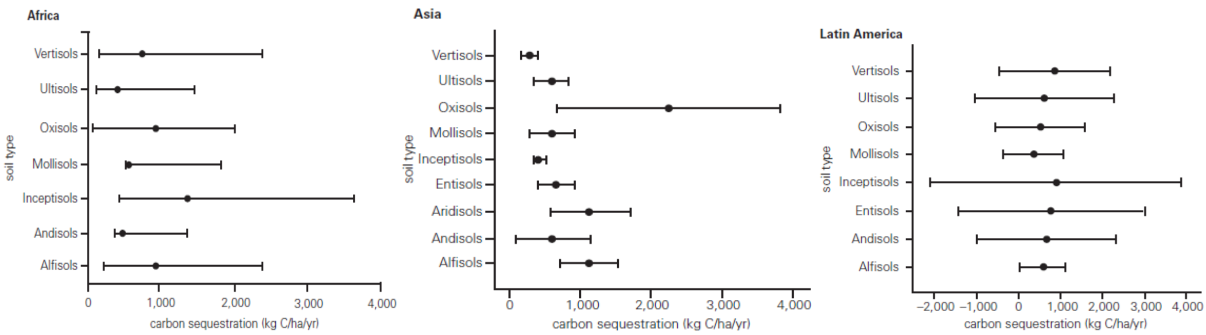


Fig 5: Soil Carbon Sequestration and Soil Order

Scott *et al*. (2012) [66] reported that most of the potential soil carbon sequestration takes place within the first 20 to 30 years. The pattern of change in sequestration rates is nonlinear and differs between major groups of practices, with the highest rates at intermediate times and low or even negative rates in the short term [Fig.6]. Acharya *et al*. (2007) [1] observed that the quality and quantity of residues markedly influence the amount of carbon sequestered [Fig. 7a]. The quantity of residue produced is a function of the cropland area and agronomic practices, including tillage method. Cereals are two to three times better than legumes at sequestering carbon. Ge *et al*. (2010c) also found that there is a tendency toward higher sequestration rates in triple cropping systems, but variation is high [Fig.7b]. The apparent lower level for double compared to single or triple cropping may reflect differences in soils, climate, and cropping systems rather than effects of cropping intensity. Replacing annual crops with perennials increased soil carbon sequestration on average by 1 t C ha^{-1} yr^{-1}.

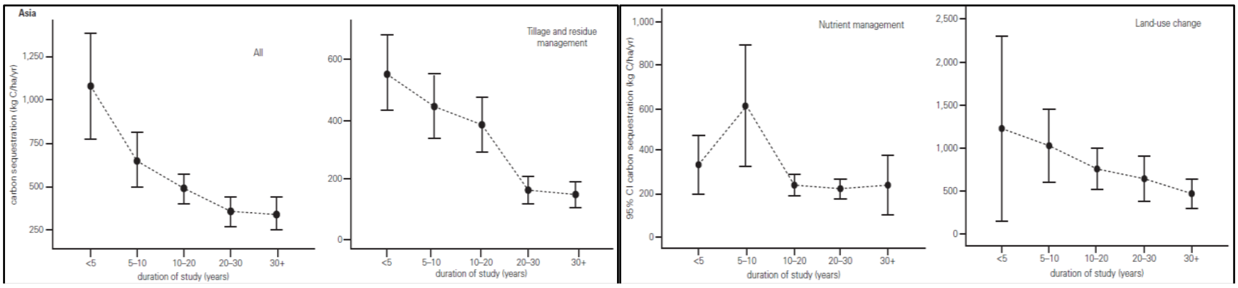
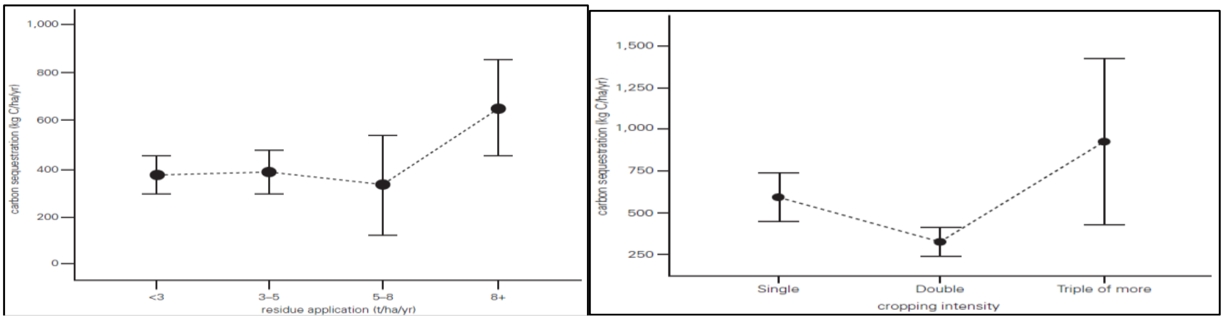


Fig. 6: Soil Carbon Sequestration and Time



(a) **(b)**

Fig. 7a: Mean Soil Carbon Sequestration and Levels of Residue Returned
Fig.7b: Mean Soil Carbon Sequestration and Cropping Intensity

Soil Carbon saturation

Soil C saturation is limit to C stabilization as a function of C input levels (at steady state) based on the cumulative behavior of these four C pools (i.e., chemically-, physically-, biochemically protected, and non-protected pools). The importance of carbon is not just about forming the organic matter of soil. Carbon acts as a source of energy for microbial activities in soil, which is a vital indicator of soil health (Reeves, 1997) [61]. Among other indicators of soil health which are greatly affected by the presence of soil organic carbon are plant available water capacity in soil, infiltration ratio, aggregate formation and stability in soil structure, soil bulk density, cation exchange capacity (CEC), presence of adequate soil enzymes and the level of activity of invertebrate soil bio indicators. Using soil as a carbon sink can turn the surplus farmlands into natural ecosystems, which can provide various ecosystem services (Follet, 1993). Carbon changes through various stages and phases in soil ecosystem [Fig. 8b] and the most concerning parts of the cycle are ones which intensify the concentration of carbon dioxide in atmosphere (seen as upward arrows). Naresh *et al*. (2018) [55] also found that the values of MBC in surface soil varied from 116.8 mgkg^{-1} in unfertilized control plot to 424.1 mgkg^{-1} in integrated nutrient use of 100% RDN as CF+ VC @ 5tha^{-1} plots, respectively; while it varied from 106.6 mgkg^{-1} (control) to 324.9 mgkg^{-1} (100% RDN as CF+ VC @ 5tha^{-1} F_5) in sub-surface (15-30 cm) soil layer. The values of MBC increased by 72.5 and 58.4% under 100% RDN as CF+ VC @ 5tha^{-1} (F_5) and 75% RDN as CF+ VC @ 5tha^{-1} (F_4) treatment in surface soil over control. While, there were 34.4% increase of MBC over 100% RDF as CF (F_2) fertilizer, respectively [Table 2]. The values of LFC in surface soil (0-15 cm) were 81.3, 95.7, 107.8, 128.8, 155.2, 177.8 and 52.7 mgkg^{-1} in ZT and FIRB without residue retention, ZT and FIRB with 4 & 6 tha^{-1} residue retention and CT treatments, respectively [Table 2]. In 15-30 cm layer, the increasing trends in LFC content due to use of tillage practices and residue retention were similar to those observed in 0-15cm layer; however, the magnitude was relatively lower [Table 2]. In the upper 15 cm depth, the $_f$POM content was between 1.9 and 2.8 times higher under ZT and FIRB with residue retained than under CT. The lower $_c$POM content under ZT with residue removal than under CT in the two soil layers (2–2.6 times less) can be explained by the farmer’s practice of removing crop residues from the ZT field [Table 2]. These values represent between 50.7 and 64.8% more $_f$POM with residue retained ZT and FIRB, averaging about 76.5% more.

Hao *et al*. (2008) [79] who observed that the microbial biomass was considerably greater in soils receiving FYM along with NPK fertilizer than in plots receiving merely NPK fertilizer in three subtropical paddy soils. Mandal *et al*. (2007) [51] also reported that the microbial biomass was greater in soils due to addition of straw plus inorganic NPK for 34 years than that of inorganic NPK fertilizers. Similarly, Kaur *et al*. (2005) also observed that in general, MBC tends to be smaller in unfertilized soils or those fertilized with chemical fertilizers compared to soil amended with organic manures.

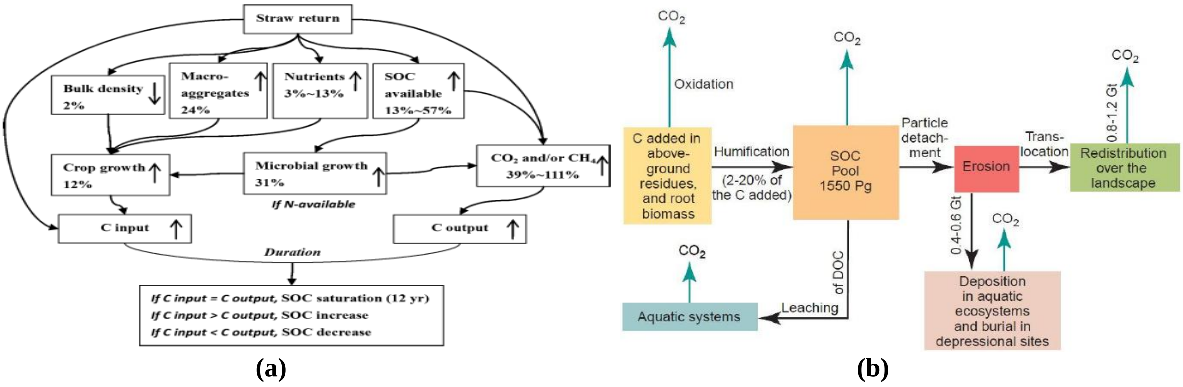


Fig 8b: The dynamics, forms and the amount of carbon inputs and outputs in soil ecosystem on the earth crust. The arrows upward indicate CO_2 flux into the atmosphere.SOC: Soil Organic Carbon, DOC: Dissolved Organic Carbon. Adapted from Lal (2004) [43]

Table 2: Concentrations of different soil organic matter carbon fractions $_f$POM and $_c$POM at different soil depths as affected by tillage and nutrient management to the continuous RW cropping system [Naresh *et al*., 2018].

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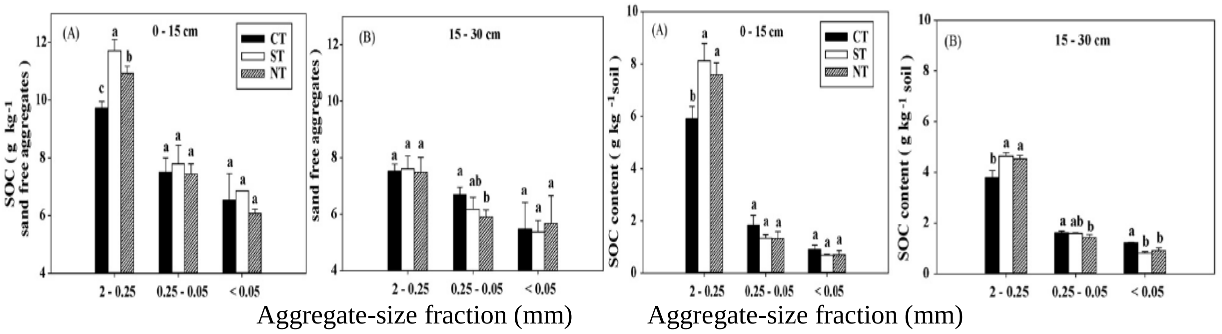
F_6	28.9	210.3	133.2^{c}	0.66	1.19	19.8	178.2	76.4	0.51	0.63

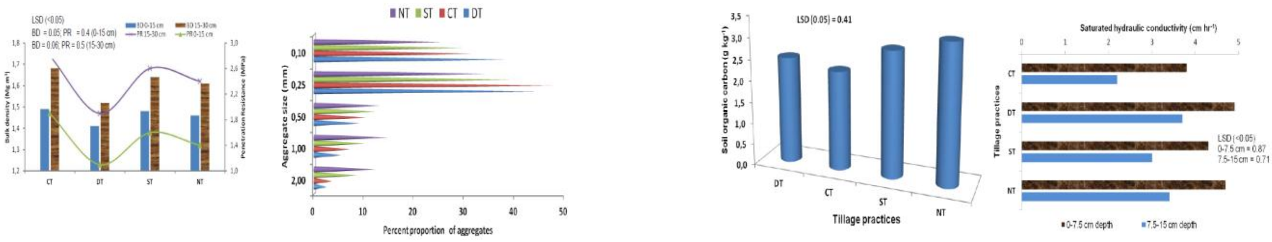
****** Different letters within columns are significantly different at P=0.05 according to Duncan Multiple Range Test (DMRT) for separation of means. WSC = water soluble carbon, MBC = microbial biomass carbon, LFC = labile fraction carbon, $_c$POM = coarse particulate organic carbon, $_f$POM = fine particulate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

Kong *et al*. (2005), however, reported a preferential stabilization of SOM in the micro-aggregate fraction. The treatments only affected the SOC content of large micro-aggregates and coarser fractions. In fact, crop residues incorporated into the soil were first stored in >75 µm fractions and were then transferred to the silt and clay fractions. The differences among the CSs W and WB were not significant. Tillage seemed, however, to influence the SOC concentration in the large macro-aggregate (75–250 µm) fraction. Differences could be detected between CT and DL whereas NT did not differ from these. The contribution of large macro-aggregates (>250 µm) to the total SOC is definitely influenced by the tillage and CSs. This is also reflected by the high standard deviation of the SOC concentration. With WB, the contribution of the macro-aggregates to the total SOC was almost zero. Distinct differences can be seen between DL and CT or NT. In addition and similarly to the WB crop rotation, the DL tillage reduced the contribution of the macro-aggregates to SOC to almost zero. CT and NT showed similar values of SOC in the macro-aggregates. Alvaro-Fuentes *et al*. (2008), agricultural management that increases biomass input into soils and reduces tillage intensity leads to a higher accumulation of total C in the soil. West and Post (2002) found, on average, that a change from CT to NT can give rise to a sequestration rate of 57.14 g Cm^{-2} y^{-1}, excluding wheat fallow systems which may not result in a SOC accumulation with a change from CT to NT. The small differences between NT and CT could be also due to the high clay content of the soils (Ouedraogo *et al*., 2005) that finally protects SOM from a quick degradation under a more intensive use. Chen *et al*. (2009) [16] reported that the ST and NT treatments had significantly higher SOC in the 0.25–2 µm fraction at both depths. However, ST and NT treatments had 14.2 and 13.7% higher SOC stocks than CT in the upper 15 cm, respectively [Fig.9].



(a) (b)

Fig 9: Soil organic carbon (SOC) of sand-free aggregates [a] and soil organic carbon (SOC) of aggregates [b] in g kg-1 from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT)



(a) (b) (c) (d)

Fig.10a: Effect of tillage practices on soil bulk density and penetration resistance recorded at the end of wheat-maize cropping system (DT = deep tillage; CT = conventional tillage; ST = strip tillage; NT = no-tillage)

Fig.10b: Percent proportion of aggregate size fractions under different tillage practices

Fig.10c: Soil organic carbon under different tillage practices

Fig. 10d: Saturated hydraulic conductivity as affected by tillage practices at 0-7.5 and 7.5-15 cm soil depth

Kahlon and Khurana, (2017) reported that by shattering soil up to 45 cm depth, the deep tillage helped in improving infiltration rate by 31 % over conventional tillage. However, the no-tillage improved soil aggregation by 38 % than deep tillage. At subsurface depth (15-30 cm) the soil bulk density and penetration resistance were found to be significantly lower under deep tillage (1.52 Mg m^{-3} and 1.9 MPa) than conventional tillage (1.68 Mg m^{-3} and 2.8 MPa), respectively [Fig.10 a, b, c & d]. Carter *et al*. (2002) revealed that the dynamic of soil organic matter accumulation and stabilization could be characterized by the total organic matter level as a proportion of the “capacity level” and by the POM [Figs. 11 a to d]. If soil organic matter is below the capacity level, then both clay plus silt and POM will increase until the former is saturated (Carter *et al*., 2002). In contrast, when soil organic matter is at or near the clay plus silt capacity level, then only the POM fraction will show an increase under conditions of increasing organic matter. Generally, the approach to characterize soil organic matter retention and stabilization has been two-fold: (1) the relation and nature of soil organic matter with soil particles, such as clay and fine silt, and (2) the relation and nature of soil organic matter in micro- and macro-aggregates. The soil organic matter retention can be simplified by use of two factors: organic matter stored in clay plus silt particles and in POM. These two parameters allow a logical differentiation of soil stored or retained organic matter. Undoubtedly, organic matter exists as a continuum in soil from strongly stabilized to non-protected forms. For instance, clay plus silt and POM can be further fractionated to provide numerous other fractions. Furthermore, although the POM is considered labile, its rate of decomposition would be dependent on the chemical characteristics of the organic inputs (Carter 1996).

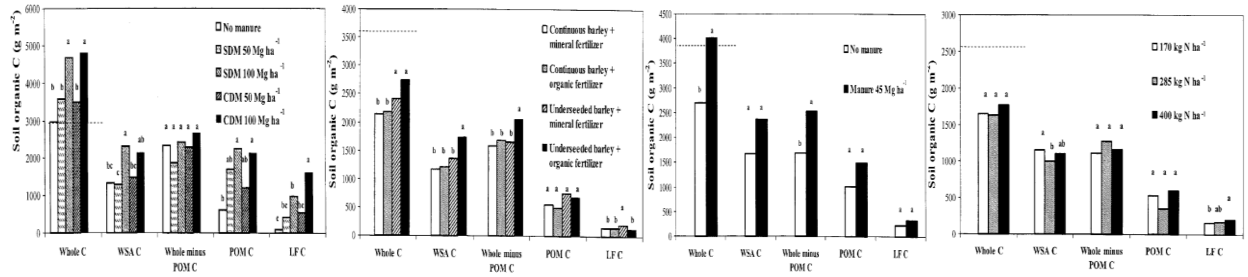


Fig. 11(a): Influence of solid (SDM) and composted dairy manure (CDM) at two rates (50 and 100 Mg ha^{-1} SOC at the 0 to 10-cm soil depth, of whole soil, WSA, whole soil minus POM, POM, and LF.

Fig. 11(b): Influence of crop rotation and organic and mineral fertilizer on SOC at the 0- to 10-cm soil depth, of whole soil, WSA, whole soil minus POM, POM, and LF.

Fig.11(c): Influence of an organic amendment on SOC at the 0- to 10-cm soil depth, of whole soil, WSA, whole soil minus POM, POM, and LF

Fig. 11(d): Influence of N fertilizer on SOC at the 0- to 10-cm soil depth, of whole soil, WSA, whole soil minus POM, POM, and LF

Soil carbon fractionation

Barbera *et al*. (2010) revealed that the annually sequestered SOC with W was 2.75-times higher than with WB. SOC concentrations were also higher. Both NT and CT management systems were the most effective in SOC sequestration whereas with DL system no C was sequestered. The differences in SOC concentrations between NT and CT were surprisingly small. Cumulative C input of all cropping and tillage systems and the annually sequestered SOC indicated that a steady state occurred at a sequestration rate of 7.4MgCha^{-1} y^{-1}. Independent of the CSs, most of the SOC was stored in the silt and clay fraction. This fraction had a high N content which is typical for organic matter interacting with minerals. Macro -aggregates (>250mm) and large micro-aggregates (75–250mm) were influenced by the treatments whereas the finest fractions were not. DL reduced the SOC in macro-aggregates while NT and CT gave rise to higher SOC contents [Table 3].

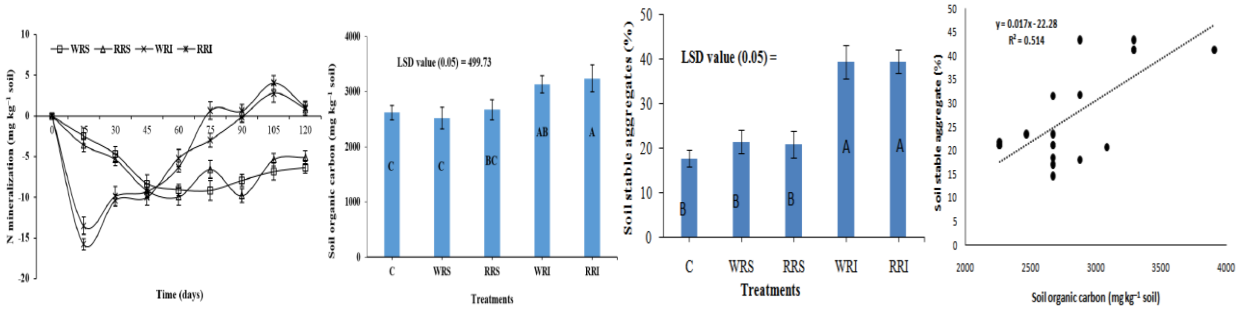
Table 3: Cumulative C input (over a period of 19 years), annual SOC sequestration, and SOC and N concentrations of the bulk soil and particle-size fractions as a function of the tillage and cropping system (CS) [Barbera *et al*., 2010]

Tillage and CS	Cumulative C input (Mg C ha^{-1})	Annual SOC sequestered (Mg C ha^{-1} y^{-1})	SOC bulk (g kg^{-1})	SOC (g C $_{org}$ kg^{-1} bulk soil)				SOC (g C $_{org}$ kg^{-1})			N (g kg^{-1})		N (g kg^{-1} bulk soil)	C/N (g kg^{-1} bulk soil)	
				75–250 µm	25–75 µm	<25 µm	>250 µm	75–250 µm	25–75 µm	<25 µm	bulk	<25 µm	<25 µm	bulk	<25 µm
WCT	7.2a[a]	0.15ab	20.8ab	2.3ab	2.5	14.0	2.0a	24.1ab	18.3b	19.9	1.37a	1.54a	1.09a	15.1c	12.9c
WBCT	6.4b	0.03c	18.6c	3.2a	2.6	12.2	0.6b	25.1a	22.0a	18.2	1.04b	1.32bc	0.88ab	18.0a	13.8c
WDL	6.4b	0.01c	18.3c	2.1b	2.3	13.5	0.4b	23.5b	17.7b	19.4	1.04b	1.37ab	0.95ab	17.9a	14.1c
WBDL	6.2c	0.01c	18.3c	2.4ab	3.3	13.7	0.0c	23.3b	19.1b	20.2	1.12b	1.18bc	0.80b	16.3b	17.2ab
WNT	7.2a	0.17a	21.2a	2.3ab	3.5	13.8	1.6a	24.0ab	19.1b	20.8	1.34a	1.29bc	0.86b	15.8bc	16.2b
WBNT	6.6b	0.08bc	19.6bc	1.8b	2.8	14.6	0.3b	23.3b	19.6ab	20.1	1.12b	1.12c	0.81b	17.6a	18.1a
W	6.9a	0.11a	20.1a	2.2a	2.9	13.8	1.3a	23.9a	18.3b	20.0	1.25c	1.40a	0.97a	16.3b	14.4b
WB	6.4b	0.04b	18.8b	2.4a	2.8	13.5	0.0b	23.9a	20.2a	19.5	1.09b	1.20b	0.83b	13.3a	16.4a
CT	6.8ab	0.09a	19.7a	2.8a	2.5	13.1	1.3a	24.6a	20.1a	19.1	1.20a	1.43a	0.98a	16.6a	13.4c
DL	6.3b	0.01b	18.3b	2.2ab	2.8	13.6	0.0b	23.4b	18.4a	19.8	1.08b	1.27b	0.88a	17.1a	15.7b
NT	6.9a	0. 13a	20.4a	2.0a	3.2	14.2	1.0a	23.7ab	19.3a	20.4	1.23a	1.20b	0.84a	16.7a	17.1a

W, wheat; WB, wheat/faba bean rotation; CT, conventional tillage; DL, dual-layer tillage; NT, no tillage; WCT, wheat conventional tillage; WBCT, wheat/bean rotation conventional tillage; WDL, wheat dual- layer tillage; WBDL, wheat/ faba bean rotation dual-layer tillage; WNT, wheat no tillage; WBNT, wheat/ faba bean rotation no tillage.

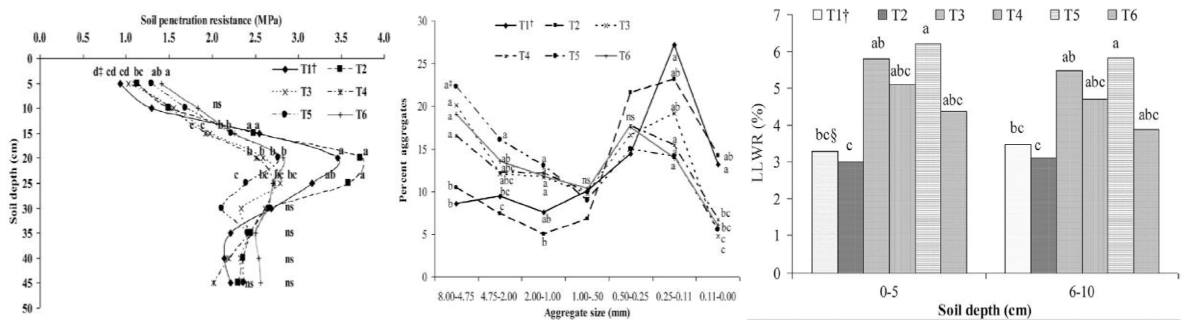
[a]Values followed by a different lowercase letter within one column are significantly different ($p \leq 0.05$) between cropping and tillage systems. Values followed by the same letter within a column are not significantly different at $p \leq 0.05$ (LSD test). Values with no letters do not differ from each other. The statistics rare related to three different groups of tillage and CSs: WCT–WBNT; W–WB; CT–NT.

Ali and Nabi, (2016) reported that the variations between rice and wheat residue either incorporated or surface applied were non-significant. Both rice and wheat residues either incorporated or surface applied immobilized soil mineral N. Peak for N immobilization in the incorporated treatments was on day 15 and then started mineralization while surface applied wheat and rice residue decreased soil mineral nitrogen gradually and continuously up to 75th day of incubation. Incorporated residues increased soil organic carbon and soil aggregate stability significantly by 18% and 55% over control respectively [Fig.12a, b, c & d]. Gathala *et al*. (2011) revealed that soil penetration resistance (SPR) was highest at the 20-cm depth in puddled treatments (3.46‒3.72 MPa) and lowest in ZT treatments (2.51–2.82 MPa). Compared with conventional practice, on average, water-stable aggregates (WSAs) > 0.25 mm were 28% higher in ZT direct-seeding with positive time trend of 4.02% yr^{-1}. The least-limiting water range was about double in ZT direct-seeding than that of conventional practice [Fig 13a, b & c]. Naresh *et al.* (2018) [55] also found that the quantities of SOC at the 0-400 kg of soil m^{-2} interval decreased under T_1, T_4 and T_7 treatments evaluated. Stocks of SOC in the top 400 kg of soil m^{-2} decreased from 7.46 to 7.15 kg of C m^{-2} represented a change of -0.31 ±0.03 kg of C m^{-2} in T_1, 8.81 to 8.75 kg of C m^{-2} represented a change of -0.06 ±0.05 kg of C m^{-2} in T_4, and 5.92 to 5.22 of C m^{-2} represented a change of -0.70 ±0.09 kg of C m^{-2} in T_7 between 2000 and 2016, [Table 4].



(a) (b) (c) (d)

Fig. 12a: N mineralization from rice and wheat residues under different crop residue applications to soil. Where CS, control soil; WRS, wheat residue surface applied; RRS, rice residue surface applied; WRI, wheat residue incorporated; RRI, rice residue incorporated.
Fig.12b: Soil organic carbon under rice and wheat residues with their different applications to soil.
Fig.12c: Soil aggregate stability under rice and wheat residues with their different applications to soil.
Fig.12d: Regression analysis of soil organic carbon and soil aggregate stability



a) (b) (c)

Fig.13a: Effect of tillage and crop establishment methods on soil penetration resistance in a 7-yr rice– wheat rotation
Fig. 13b: Effect of tillage and crop establishment methods on water-stable aggregate size distribution after 7-yr rice–wheat rotation
Fig.13c: Least-limiting water range (LLWR) under different tillage and crop establishment methods during 2008–2009 wheat seasons

Table 4: Soil organic carbon (SOC) stocks and annual rate of change in multiple soil mass intervals (averaged over tillage crop residue practices and nutrient management rate) in 2000 and in 2016 at Meerut, U.P.[Naresh *et al*., 2018]

Tillage crop residue practices	Soil Organic Carbon (± Standard error)											
	0-400 kg of soil m^{-2} (approx. 0-30 cm)			Annual SOC change rate g of $Cm^{-2}\ yr^{-1}$	400-800 kg of soil m^{-2} (approx. 30-60 cm)			Annual SOC change rate g of $Cm^{-2}\ yr^{-1}$	800-1200 kg of soil m^{-2} (approx. 60-90 cm)			Annual SOC change rate g of $Cm^{-2}\ yr^{-1}$
	2000	2016	Difference		2000	2016	Difference		2000	2016	Difference	
	-------------kgm^{-2}-------------											
T_1	7.46	7.15*	-0.31±0.03	-28.2	5.39	5.65	-0.26 ±0.09	-6.9	3.14	3.12	-0.02±0.01	-1.8
T_2	8.98*	9.77	0.79±0.2	66.2	7.03	7.11	0.08±0.2	1.5	3.72	3.81	0.09±0.11	8.1
T_3	9.18*	9.87	-0.69±0.2	57.4	7.62	7.64	0.02±0.2	7.0	5.04	5.08	0.04±0.01	1.7
T_4	8.81	8.75	-0.06±0.05	-25.7	5.82	5.31*	-0.51±0.2	-4.5	2.93	2.67	-0.26±0.02	-4.7
T_5	8.12	9.11*	0.99±0.2	82.1	5.47	5.57	0.10±0.09	8.8	3.38	3.47	0.01±0.11	5.4
T_6	9.15	9.29	0.14±0.9	19.6	5.72	5.88	0.16±0.09	7.3	4.57	4.58	0.01±0.01	0.6
T_7	5.92	5.22	-0.70 ±0.09	-13.4	4.05	3.98	-0.07±0.09	-5.5	2.42	2.37	-0.05±0.02	-3.9

*Significant difference between years at α=0.05

Dou *et al*. (2016) [25] reported that the SOC content of the total organic C pool and LC pool was greater in MNPK- and SNPK-treated soils and lower in IN- and NPK-treated soils than CK in the top layer. However, SOC storage of the total organic C pool was greatest in MNPK-treated soils (5423.3 gC m2, on average) compared with other treatments in both soil layers [Fig. 14]. The SOC content and storage of the RC pool was greater in all fertilized soils than in CK with the decreasing order as follows: MNPK＞ SNPK>NPK/ IN>CK-treated soils. However, the highest RIC (90.44%) and RIN (63.45%) ratios of the all treatments [Fig.14]. In contrast, the lowest RIC (84.16%) and RIN (52.59%) ratios appeared in the IN- and NPK-treated soils.Six *et al*. (2002) reported that physicochemical characteristics inherent to soils define the maximum protective capacity of these pools, which limits increases in SOM (i.e. C sequestration) with increased organic residue inputs [Fig. 15b]. Shahmir *et al*. (2017) revealed that the maximum SOC was observed in AAO (3.3%), followed by GL (3.2%), Clm (2.6%), Clw (2.5%), CAO (2.1%), and SGL (1.2%) at the soil surface layer (0–20 cm). The reason why SGL contained the lowest percentage of SOC among the different types of land use might be that SGL is normally situated near the edge of steep slopes, which experience frequent water erosion due to prevalent rainfall in the area. Meanwhile, SOC percentage decreased with soil depth. SOC played a significant role in the improvement of the physicochemical properties of the soil and the formation of soil aggregates [Fig.15a].

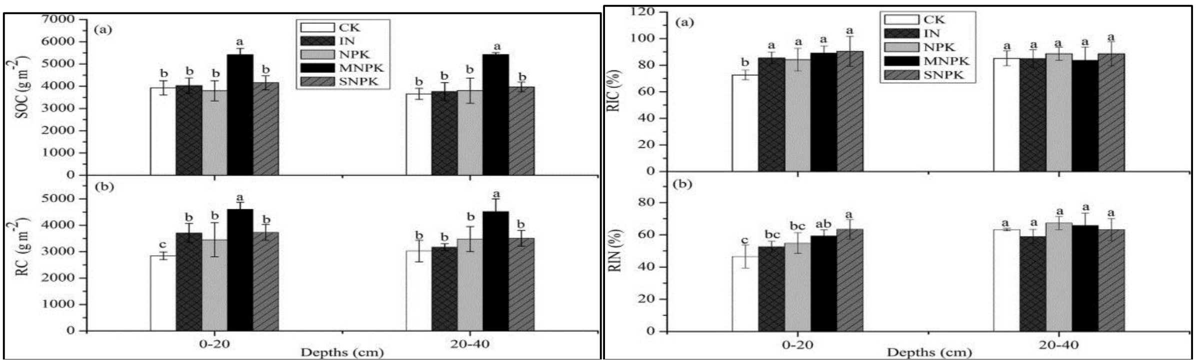
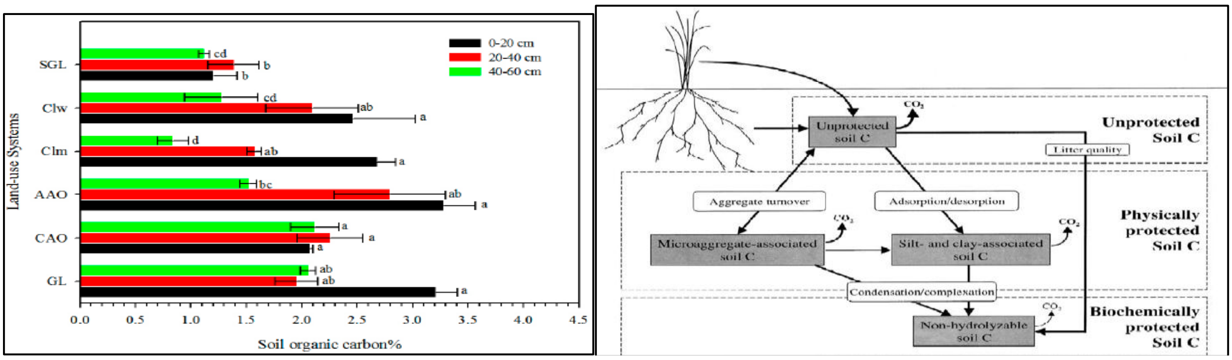


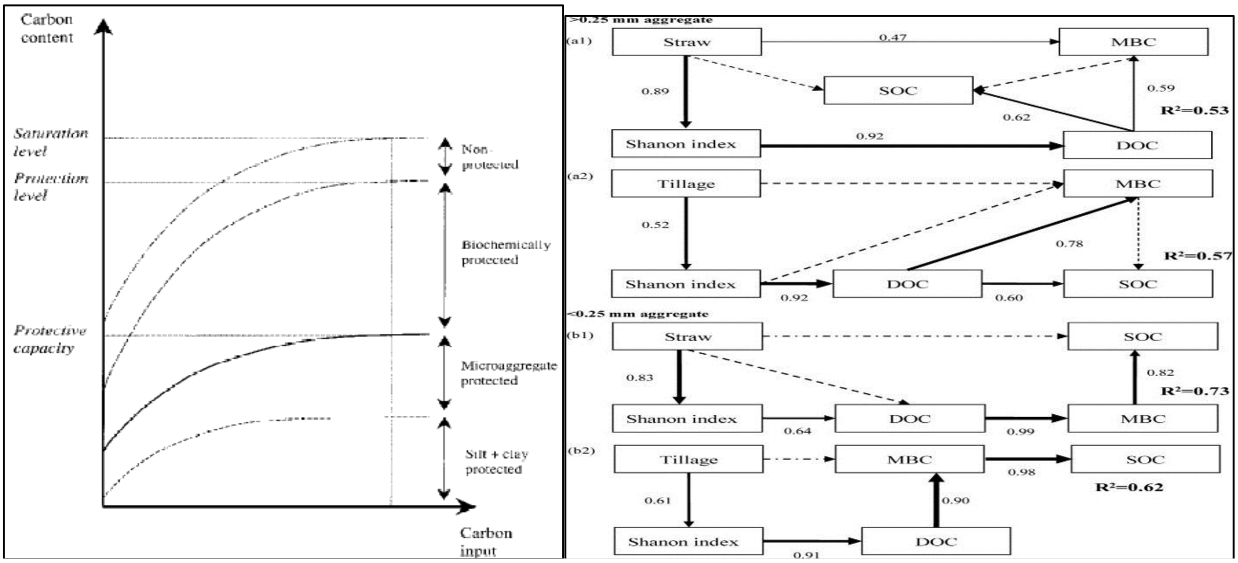
Fig. 14: Long term fertilization alters chemically separated soil organic carbon pools



(a) (b)

Fig. 15a: Soil organic carbon (SOC) under different land-use systems
Fig. 15b*:* Conceptual model of soil organic matter (SOM) dynamics with measurable pools.

Six *et al*. (2002) revealed that biochemical stabilization is understood as the stabilization of SOM due to its own chemical composition (e.g. recalcitrant compounds such as lignin and poly-phenols) and through chemical complexion processes (e.g. condensation reactions) in soil. For our analyses, we divide the protected SOM pool into three pools according to the three stabilization mechanisms described [Fig. 16 a and b]. The three SOM pools are the silt- and clay-protected SOM, micro-aggregate protected SOM (micro-aggregates defined as 53–250μm aggregates), and biochemically protected SOM.



(a) **(b)**

Fig.16a: The protective capacity of soil (which governs the silt and clay protected C and micro-aggregate protected C pools), the biochemically stabilized C pool and the unprotected C pool define a maximum C content for soils.
Fig. 16b: Structural equation modelling relating tillage systems, residue returning and microbial metabolic diversity to SOC in >0.25 mm (a1, χ^2 = 2.791, df = 3, p = 0.432, CFI = 1, GFI = 0.920, RMSEA = 0.001; a2, χ^2 = 6.163, df = 4, p = 0.617, CFI = 0.957, GFI = 0.978, RMSEA = 0.020) and <0.25 mm aggregates (b1, χ^2 = 0.541, df = 4, p = 0.144, CFI = 0.956, GFI = 0.954, RMSEA = 0.010; b2, χ^2 = 7.71, df = 4, p = 0.056, CFI = 0.975, GFI = 0.951, RMSEA = 0.020).

Soil organic carbon storage and distribution as affected by soil depths

Rojas *et al*. (2012) revealed that in Southern Spain total stocks per land use class and soil type under which "Scrub and /or vegetation associations" contain 115.92TgC in 22561.98km^2, "permanent crops" 94.65TgC in 17275.66km^2, "arable land" 84.59TgC in 15468.49km^2 and "forest" 67.60TgC in 15911.37km^2. Soils with the largest SOC stock are Cambisols (162.66Tg), Regosols (91.95Tg) and Vertisols (48.37Tg). The estimated SOC stock in the upper 75cm is 415Tg. Accumulated C stocks for each soil type and land use class are shown in [Figs. 17 a and 17b], respectively. All soil groups store more than 50% of total C in the first 25cm, except vertisols which accumulates less than 45%. The proportion of SOC stock in the 0–25cm layer is on average about 55% (229.69Tg) of the total SOC stock in the upper 75cm, around 30% (122.89Tg) in the 25–50cm layer and 15% (62.62Tg) in the deepest layer (50–75cm) [Fig. 17a and b]. Among all land use types, agricultural uses such as "arable land" and "permanent crops" show low percentages of SOC stock in the first layer (below 50%).

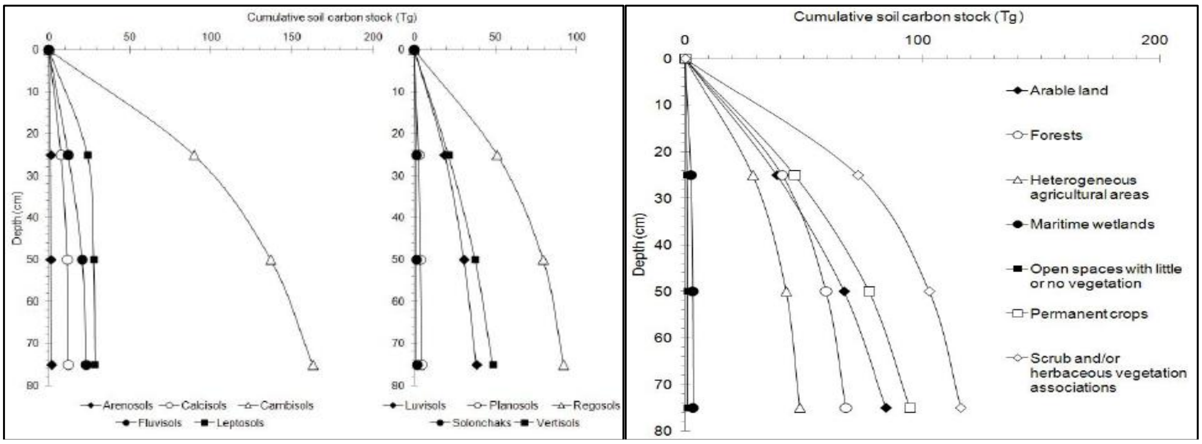
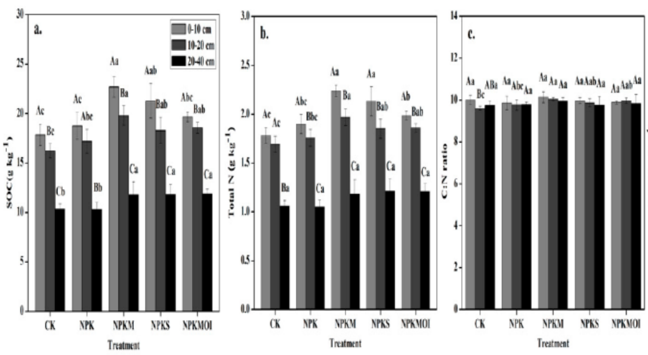


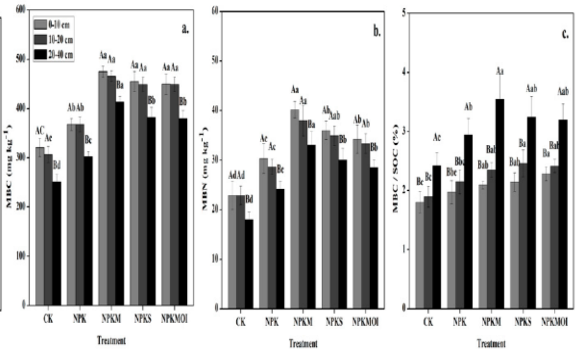
Fig. 17a: Cumulative soil organic carbon stock in depth for each soil class.
Fig. 17b: Cumulative soil organic carbon stock in depth for each land use type.

A high SOC content in Vertisols, which are naturally fertile soils, may be explained by its high clay content and consequently high moisture storage capacity. Similar values of SOCCs for Vertisols were reported in Spain by Rodrıguez-Murillo (2001), 68.9MgCha^{-1}, and in Jordan by Batjes (2006) [6], 37MgCha^{-1} at 0.3m depth and 75MgCha^{-1} at 1m depth with 59MgCha^{-1} for "arable land" and 68MgCha^{-1} for "forest" at 1m depth. Brahim *et al*. (2010) in Tunisia estimated 45.6MgCha^{-1} at 30cm depth and 109.7MgCha^{-1} at 1m depth. Higher values were found in Central and Eastern Europe by Batjes (2002) [7], with 82MgCha^{-1} at 0.3m and 236MgCha^{-1} at 1m depth. Rodrıguez Murillo (2001) reported that higher values for both Fluvisols and Luvisols in Spain, 75.8MgCha^{-1} and 66MgCha^{-1}, respectively, nonetheless our estimations are within the values proposed in France (Arrouays *et al*., 2001). They estimated SOCCs ranging from 27MgCha^{-1} under "permanent crops" to 102MgCha^{-1} under Pastures for Fluvisols and 29MgCha^{-1} MgCha^{-1} under "permanent crops" to 84MgCha^{-1} under Pastures.

Xiaolei Huang *et al*. (2017) found that organic fertilization significantly increased the SOC content compared with chemical fertilization alone [Fig. 18a and b]. The specific C mineralization rate (SCMR, rate per unit SOC) increased with increasing soil depths, suggesting that SOC at the 20- to 40-cm depth was more labile than that from 0 to 20 cm. The percentage of SOC present as microbial biomass carbon (MBC) was significantly positively correlated with SCMR, indicating that soil microorganisms influenced the potential SOC mineralization [Fig. 19a and b]. Soil microorganisms played an important role in balancing the decomposition and accumulation of SOC because microbial products were important components of SOC (Miltner *et al*., 2011). The application of organic fertilizers significantly increased the microbial biomass, microbial biodiversity, and soil enzymatic activity compared with chemical fertilization alone in the rice–wheat cropping system (Zhao *et al*., 2016) [79], which may be somewhat responsible for the relatively labile SOC in soil amended with organic fertilizers. The SCMR increased with increasing soil depth, indicating that SOC in the deep soil layer (20–40 cm) may be more susceptible to decomposition than that in the surface layer (0–20 cm) when exposed to air. This is consistent with the findings of Karhu *et al*. (2016), who demonstrated that the deeper soil layers were more sensitive to the priming effect, defined as the stimulation of SOC decomposition caused by labile C addition, compared with the upper soil layers. Schrumpf *et al*. (2013) noted that association with minerals played the most important role in protecting SOC from microbial decomposition by studying a wide range of European soils different in vegetation, soil types, and land use.



(a)



(b)

Fig. 18 (a): Soil organic C (SOC), (b) total N, and (c) C/N ratio at the depths of 0 to 10 cm, 10 to 20 cm, and 20 to 40 cm as affected by different fertilization treatments in the rice–wheat cropping system.

Fig. 18 (b): Microbial biomass carbon (MBC), (b) microbial biomass N (MBN) and (c) the percentage of soil organic carbon present as microbial biomass C (MBC/SOC) at the depths of 0–10 cm, 10–20 cm and 20–40 cm as affected by different fertilization treatments in the rice–wheat cropping system.

Treatments CK, NPK, NPKM, NPKS, and NPKMOI represent control, chemical fertilizer, 50% chemical fertilizer plus manure, 100% chemical fertilizer plus straw, and 30% chemical fertilizer plus manure organic-inorganic compound fertilizer, respectively.

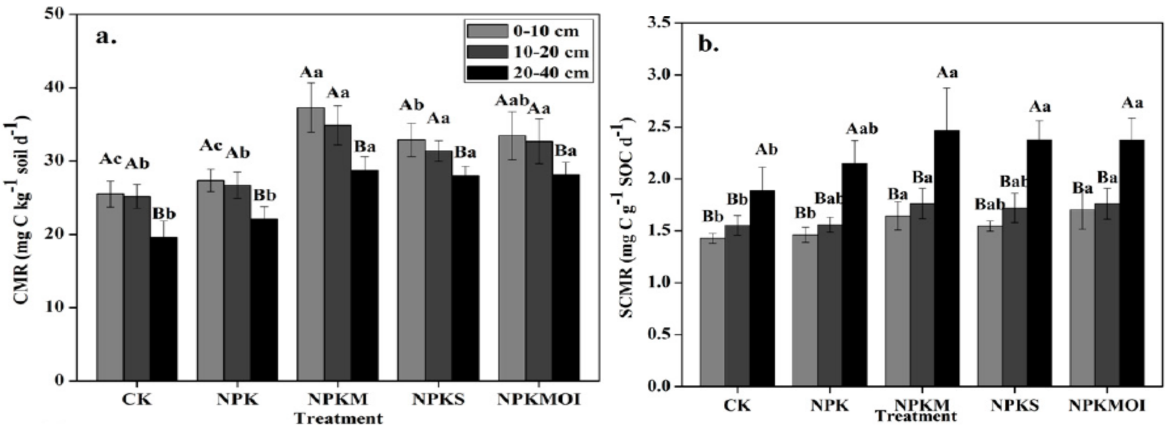
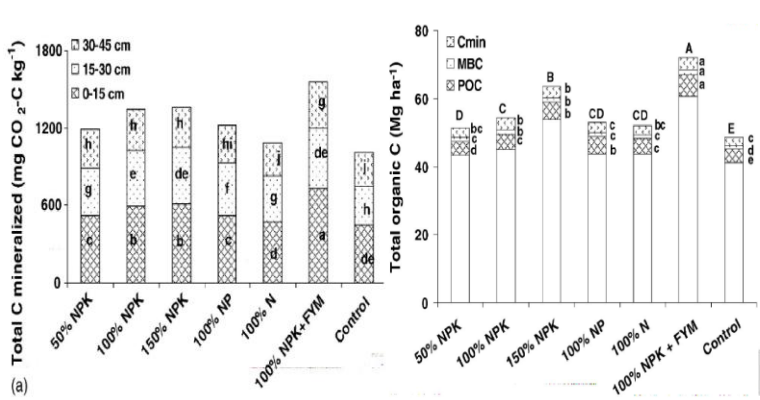
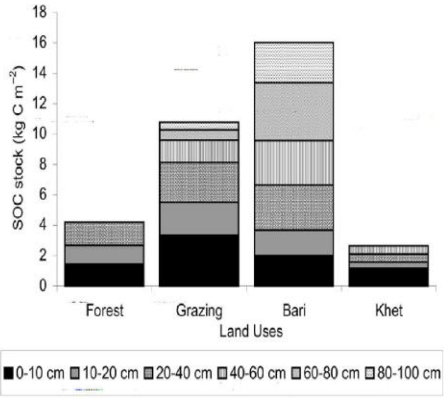


Fig 19: The (a) carbon mineralization rate (CMR, rate per unit dry soil) and (b) specific carbon mineralization rate (SCMR, rate per unit SOC) at the depths of 0–10 cm, 10–20 cm, and 20–40 cm as affected by different fertilization treatments in the rice-wheat cropping system.

Kasper *et al*. (2009) also found that the total amount of C mineralized over 84 days at 0–15 cm was greater in 100% NPK + FYM followed by 150 and 100% NPK (Fig.7). While at 15–30 cm, 100% NPK + FYM, 150% NPK and 100% NP showed similar C mineralization pattern but these were significantly higher over rest of the treatments. There was a significant increase in C mineralization in 100 and 150% NPK over 50% NPK treatment. The balanced application of NPK (100% NPK) significantly increased C mineralization over unbalanced (100% N and 100% NP) fertilization. Greatest accumulation of total organic C was observed with 100% NPK + FYM treatment while control plot showed the lowest value. Irrespective of depths, the balanced application of NPK (100% NPK) showed higher accumulation of soil organic C -over imbalanced use of fertilizers (100% N or 100% NP). The amount of sequestered organic C was highest in 100% NPK+FYM (731 kg $ha^{-1}yr^{-1}$) followed by 150% NPK (462 kg $ha^{-1}yr^{-1}$) and 100% NPK (169 kg $ha^{-1}yr^{-1}$). The other treatments namely 50% NPK, 100% N and 100% NP sequestered 87, 106 and 134 kg C $ha^{-1}yr^{-1}$, respectively. Thus from these results, we can conclude that use of 100% NPK with farmyard manure was the most efficient management system in accumulating as well as sequestering organic C (72.1 Mg C ha^{-1} and 731 kg C $ha^{-1}yr^{-1}$) in 0-45 cm soil profile in a long-term fertilized soil [Fig. 20a]. Shrestha *et al*. (2004) revealed that SOC stock in Bari land was higher than in other land use types [Fig. 20b]. Moreover, in the surface soil, grazing land had the highest SOC stock, followed by Bari, forest and Khet, while in depths below 20 cm Bari lands had the highest SOC stock. The conversion of forestland into Khet land may result in 49% losses of SOC compared to SOC level in the forest. On an area basis, the SOC losses were 2 kg C m^{-2} by converting forest to Khet.



a)



(b)

Fig. 20(a): Total C mineralized and totals organic C under different treatments (Kasper *et al*., 2009).
Fig. 20(b): Effect of land use on soil organic carbon stocks (Shrestha *et al*., 2004).

Different land uses and SOC Stock pool

Land use and its impact on the SOC pool and its dynamics are important and should be addressed in making appropriate policy decisions. Most studies done so far were limited to the surface layers of soil profiles. However, pedogenesis of lower horizons can be affected by disturbances to the surface horizon. Lantz *et al*. (2001) reported that any disturbance in the surface horizons affects soil porosity, internal ped faces as well as water movement and even SOC in the sub-soil. Therefore, studies on quantifying the SOC contents in subsoil may provide information on how land use affects the SOC pool, and such data may help better estimate the potential of different land uses as source or sink for C. Lantz *et al*. (2001) also studied the differences in SOC pools in cropped, pastured and forested sites in Ohio, up to the depth of 170 cm, where pastured sites showed higher SOC pools than the forested ecosystems. Cultivation reduced the SOC pool in the top 0-10cm layer and increased it in the 10-25 cm layer, not decreasing the total SOC pool. Smith *et al*. (2000) reported that SOC levels are known to be influenced by a large number of factors, many of which are mutually interactive e.g., soil colour, soil texture, land use, management, climate, topography and drainage etc. Manipulation of some of these factors, especially management related ones, may be used to increase C sequestration in soils and thus mitigate climate change commitments.

The morphologic significance of soil colour has been widely recognized by soil scientists (Simonson, 1993). This is supported by Franzmeier (1983) who noted relationships between organic matter concentration, soil colour and soil texture for Indiana soils. He also outlines an equation correlating organic matter and Munsell colour value and chroma. On the other hand, Nichols (1984) examined Southern Great Plains soils to determine if SOC concentrations could be predicted from several environmental factors. The percentage of clay content was found to be the best predictor of organic carbon in this study (r= 0.86). Franzmeier (1983) also noted that organic matter concentration generally increased for Indiana Ap horizon soils with increasing clay content. Konen *et al*. (2003) also reported that clay contents was highly correlated (r^2= 0.71) with SOC in Iowa soils and that the SOC increased linearly with the clay content.

Land use change alters the inputs of organic matter, thus affecting SOC and soil organic nitrogen (SON) stores accordingly (Zhou *et al*., 2007). Net losses of SOC and SON due to land use change may occur as a result of decreased organic residue inputs and changes in plant litter composition and increased rates of SOM decomposition and soil erosion (Lugo and Brown, 1993).There is a good relationship between SOC and SON. In this aspect, Jenkinson (1981) noted that immobilization of nitrogen takes place when the C/N ratio of the residues is greater than 30/1. This ratio can be decreased by adding fertilizers or by using the residues and even the nitrogen containing waste. Jenkinson (1981) and Himes (1998) reported increased quantities of C and N sequestered in the fertilized Broad Balk field at Rothamsted over the non-fertilized field [Table 5].The findings are based on a long-term (1843 to 1963) continuous wheat trial. The concentration of organic carbon in the un-manures plot did not vary in the 120 years. The annual application of N, P, K and Mg increased the total C by about 15%. The ratio of the C and N sequestered was 12.8/1. To sequester the 4000 kg of C, 314 kg of N was required. The quantity of C sequestered will be limited if there is insufficient nitrogen. Thus, C/N ratio is a good indicator of the degree of decomposition and quality of the organic matter in the soil.

Table 5: Carbon and nitrogen sequestered in the fertilized Broad Balk Plot at Rothamsted under continuous wheat since 1843-1963 [Jenkinson, 1981; Himes, 1998]

Treatment	Organic C %	Nitrogen %	kg C/ha	kg N/ha
Unmanured	0.90	0.098	20.160	2.195
Manured N P K Mg annually	1.08	0.112	24,192	2,590
Element sequestered	-	-	4,032	314

Batjes (1996) [5] estimated world's soil carbon and nitrogen pool [Table 6]. The average SOC stored in the upper 100 cm was estimated to be between 1462 and 1548 Pg C. Based on this study, SOC in the tropics was estimated to be 201-213 Pg C, 384-403 Pg C and 616-640 Pg C in the 0-30, 0100 and 0-200 cm layers, respectively. Batjes (1996) [5] also used the same methodology to estimate soil nitrogen as that for C pools, with global estimates of 63-67 Pg N at 0-30 cm depths and 133-140 Pg N to a depth of 100 cm. The latter values are greater than the 92-117 Pg N calculated using an ecosystems approach (Zinke *et al*., 1984) possibly because most profile descriptions in World Inventory of Soil Emissions Potentials (WISE) used by Batjes (1996) [5] for agricultural soils may have been amended with N fertilizers.

Table 6: World soil carbon and nitrogen pools (Pg) [Batjes, 1996] [5]

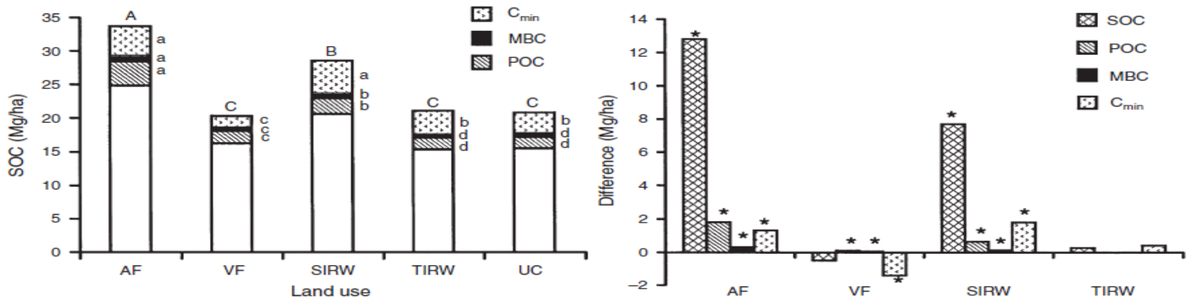
Regions	Soil C and N	Depth range (cm)		
		0-30	0-100	0-200
Tropical regions	Soil Organic C	201-213	384-403	616-640
	Soil Carbonate C	72-79	203-218	-
	Total	273-292	587-621	-
	Soil N	20-22	42-44	-
Other regions	Soil Organic C	483-511	1078-1145	1760-1816
	Soil Carbonate C	150-166	492-530	-
	Total	633-677	1570-1675	-
	Soil N	43-45	91-96	-
World	Soil Organic C	684-724	1462-1548	2376-2456
	Soil Carbonate C	222-245	222-245	-
	Total	906-969	2157-2296	-
	Soil N	63-67	133-140	-

Lal, (1999) [43] revealed that appropriate land use management options like conservation tillage, mulch farming, cover crops, agroforestry farming, biomass production farming as well as crop residue management etc. all enhance SOC. The management practices decrease decomposition, improve soil structure and aggregation, decrease soil degradation processes, and increase nutrient cycling and other ecosystem restorative mechanisms [Table 7]. Vidya *et al*. (2002) also reported highest MBC in natural forest soil among different land use systems.

Table 7: Impacts of land management practices on carbon sequestration (t/C/ha/yr.) in the dry lands and tropical areas [Lal, 1999] [43]

Land management practices	Dry lands	Tropical areas
Conservation tillage	0.1-0.2	0.2-0.5
Mulch farming or plant cover	0.05-0.1	0.1-0.3
Conservation agriculture	0.15-0.3	0.3-0.8
Composting	0.1-0.3	0.2-0.5
Nutrient management	0.1-0.3	0.2-0.5
Water management	0.05-0.1	-
Grassland and pastures	0.05-0.10	0.1-0.2
Agroforestry	-	0.2-3.1

Purakayastha *et al*. (2007) also found that sewage-irrigated rice–wheat soil showed lowest pH particularly in the 0–0.05 and 0.10–0.20m soil layer. Irrespective of soil depths, agro-forestry plantation showed greater SOC followed by sewage-irrigated rice–wheat soil. Nevertheless, agro-forestry soil also showed highest stock of SOC (33.7Mg/ha), POC (3.58Mg/ha), and MBC (0.81Mg/ha) in the 0–0.20m soil layer. Sewage-irrigated rice–wheat jointly with agro-forestry soil showed greatest C min in the 0–0.20m soil layer, although the former supported lower SOC stock. The decrease in SOC (SOC 0–0.05m/SOC 0.10–0.20m) and C_{min} (C_{min} 0–0.05m/ C_{min} 0.10–0.20m) along soil depth was significantly higher in the agro-forestry system than in most of the other land use and soil management systems [Fig. 21 a &b]. The buildup of different C fractions in the agro-forestry plantation is mainly due to long-term additions of C through leaf litter. Nevertheless the soils of this plantation are never disturbed by tillage operations that are otherwise very frequently practiced in other cultivated soils. Sewage-irrigated rice–wheat soil supported higher SOC as well as MBC than other cultivated and uncultivated soils probably are due to accumulation of organic materials added through sewage effluents. Vegetable field, tube well irrigated rice–wheat, and uncultivated soils showed less SOC and MBC. However, very high values of these parameters have been reported in vegetable and paddy fields from China (Chen *et al*. 2003) [15]. Uncultivated soil that supported patches of grasses showed lower organic C, POC, as well as MBC. Particulate organic C, a physically protected moderately labile pool, is generally accumulated in such management systems where soil is not disturbed. In this respect, the agro-forestry plantation protected the POC well due to non-disturbance of soil in this system. Nevertheless there is a greater stratification of POC down the soil layer in this system compared with cultivated land where the soils are disturbed frequently through tillage operations.



(a) (b)

Fig. 21(a): Soil organic C (SOC) pools in the soil profile (0–0.20m) as affected by land use and soil management. POC, particulate organic C; MBC, microbial biomass C; C_{min}, C mineralization; AF, agro-forestry plantation; VF, vegetable field; SIRW, sewage-irrigated rice–wheat; TIRW, tube-well irrigated rice–wheat; UC, uncultivated. The full length of each bar (POC+MBC+C_{min}+ unaccounted) indicates the value of SOC

Fig. 21(b): The difference (more/less) in soil organic C (SOC), particulate organic C (POC), microbial biomass C (MBC), and C mineralization (C_{min}) in agro-forestry plantation (AF), vegetable field (VF), tube-well irrigated rice–wheat(TIRW),and sewage-irrigated rice–wheat (SIRW)soil compared with uncultivated soil (UC).

The decomposition of SOC is also very fast, partly due to the local climate and also unsustainable land management practices. However, if properly managed, croplands in Bangladesh or elsewhere can be a major source for C sequestration. Aggregate formation and organic matter storage in soils are intimately associated with each other. The organo-mineral associations function as aggregate binding and stabilizing agents. The nature of various organo-mineral associations and their spatial locations within soil aggregates determine the extent to which SOC is physically protected and chemically stabilized which results in its storage. A close understanding of the nature and dynamics of organo-mineral associations are necessary for a better understanding of soil structural dynamics and of C cycling and sequestration in soils (Bruce *et al*., 1999). Likewise, Lehmann *et al*. (2007) noted that stabilization of C in soil is mainly achieved through two processes—clay-organic interactions and occlusion of these aggregates by clay particles. Thus, stabilizing C has great importance for biogeochemical cycles of an ecosystem as well as sequestration potential. Lal (2004a) [44] showed strategies of SOC sequestration through land use change and soil and vegetation management [Fig. 22a)]. Shahid *et al*. (2017) also found that balanced fertilization
(NPK) and integrated fertilization (NPK+FYM) resulted in similar increases in particulate organic carbon, carbon mineralization and microbial biomass carbon [Fig. 23], whereas particulate organic nitrogen, nitrogen mineralization and microbial biomass nitrogen [Fig.24] were more in integrated fertilization (NPK+FYM) compared with control treatment. Soil organic C and nitrogen stocks changed positively across the fertilizer and manure treatments over the control. In the control plot, at 0–15 cm depth the soil carbon and nitrogen stock was 15.1 and 1.77 Mg ha^{-1}, respectively which increased to the 19.5 Mg ha^{-1} in NPK+FYM for carbon and 2.25 Mg ha^{-1} in N+FYM for nitrogen [Fig.24].

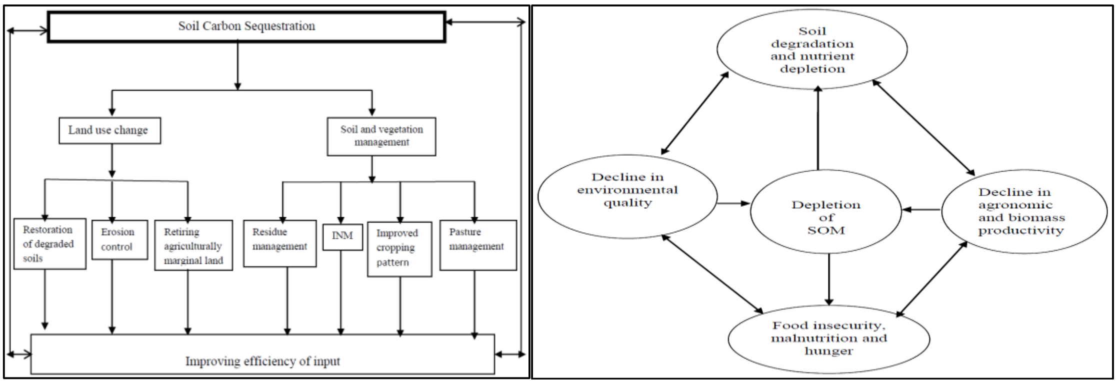


Fig 22(a): Strategies of soil carbon sequestration through land use change, soil and vegetation management (INM: Integrated Nutrient Management (Source: Lal, 2004a) [44]

Fig 22(b): Vicious cycle of soil organic matter (SOM) depletion, declines in environmental quality, Agronomic and biomass productivity (Source: Lal, 2004) [43]

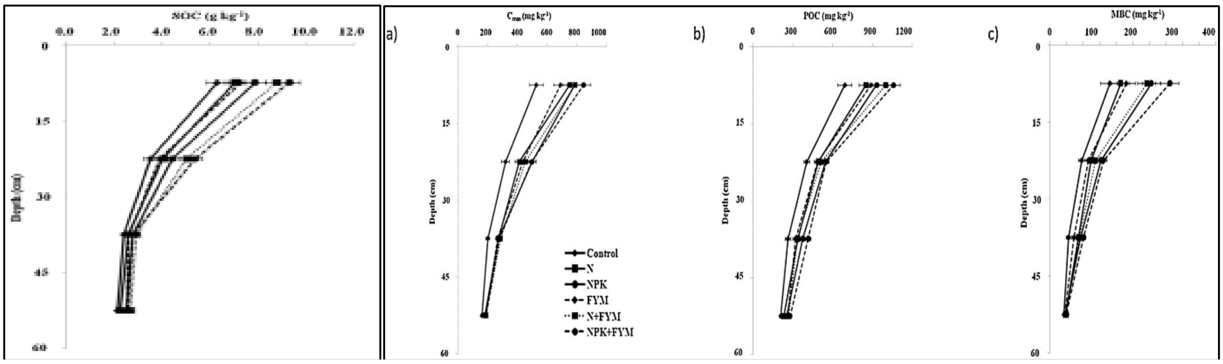


Fig. 23: Soil organic carbon and its fractions in soil layers under 41 years of chemical and organic fertilization in a sub-humid tropical rice-rice system; a) Carbon mineralization (C_{min}), b) Particulate organic carbon (POC), and c) Microbial biomass carbon (MBC).

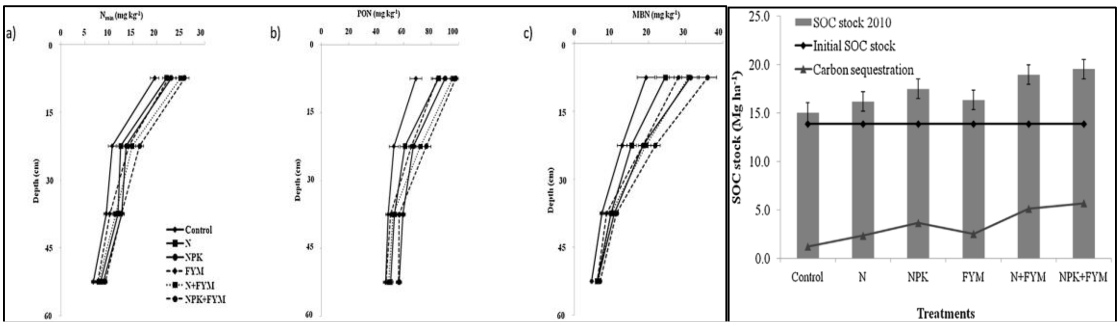
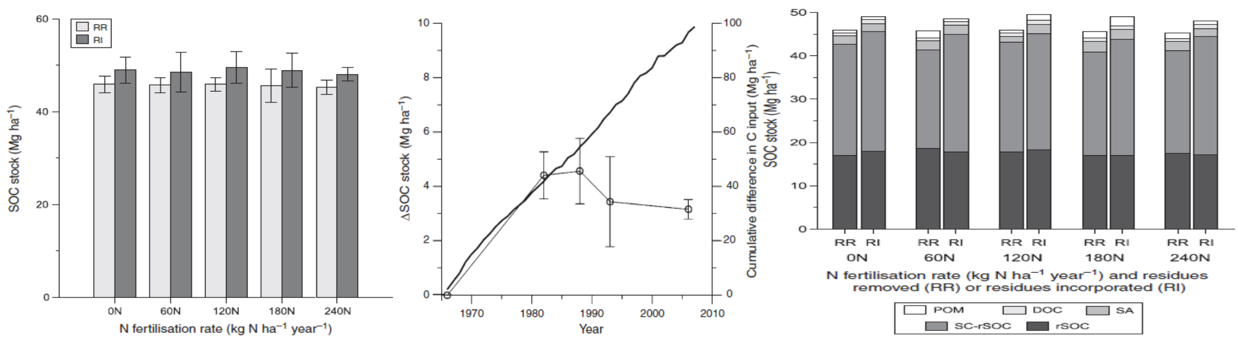


Fig. 24: Soil organic carbon fractions in soil layers under 41 years of chemical and organic fertilization in a sub-humid tropical rice-rice system (a) Nitrogen mineralization (N_{min}), (b) Particulate organic nitrogen (PON), (c) Microbial biomass nitrogen (MBN),Soil organic carbon stocks and carbon sequestration (0–15 cm soil depth)

Soil management practices and SOC Stock

Poeplau *et al*. (2017) reported that the average increase in SOC stock in the 0–30cm soil layer was 3.1Mgha^{-1} or 6.8%, with no difference between N fertilization rates. Retention coefficients of residues did not exceed 4% and decreased significantly with increasing N rate (R^2=0.49).The effect of RI was higher after 20 years (4.6Mgha^{-1}) than after 40 years, indicating that a new equilibrium has been reached and no further gains in SOC can be expected. Most (92%) of the total SOC was stored in the silt and clay fraction and 93% of the accumulated carbon was also found in this fraction, showing the importance of fine mineral particles for SOC storage, stabilization and sequestration in arable soils. No change was detected in more labile fractions, indicating complete turnover of the annual residue-derived C in these fractions under a warm humid climate and in a highly base-saturated soil [Fig.25 a, b and c]. Lugato etal. (2006) calculated a mean annual sequestration rate of residue-derived SOC of 170kgha^{-1}yr^{-1} for 1993, which is more than double the annual sequestration rate measured in this study for 2006 (78kgha^{-1}yr^{-1}). Residue-derived SOC accumulation has not only stopped, but the absolute SOC stock difference between RI and RR has also decreased. Stagnation in SOC stock increase after a management change has often been reported to occur after 20–50 years (Buysse *et al*. 2013; Poeplau *et al*. 2015a), which might be related to C saturation in some cases, or a delayed adjusted increase in output in other cases. After all, the decrease in DSOC from 1986 to 2006 was on average 1.5MgCha^{-1}, which corresponds to a very low concentration change of 0.034% C. Kirkby *et al*. (2014), who reported increasing SOC sequestration upon N addition, numerous studies have shown that N in combination with labile C addition reduces the priming of older SOC (Griepentrog *et al*. 2014; Fisk *et al*., 2015).



(a) (b) (c)

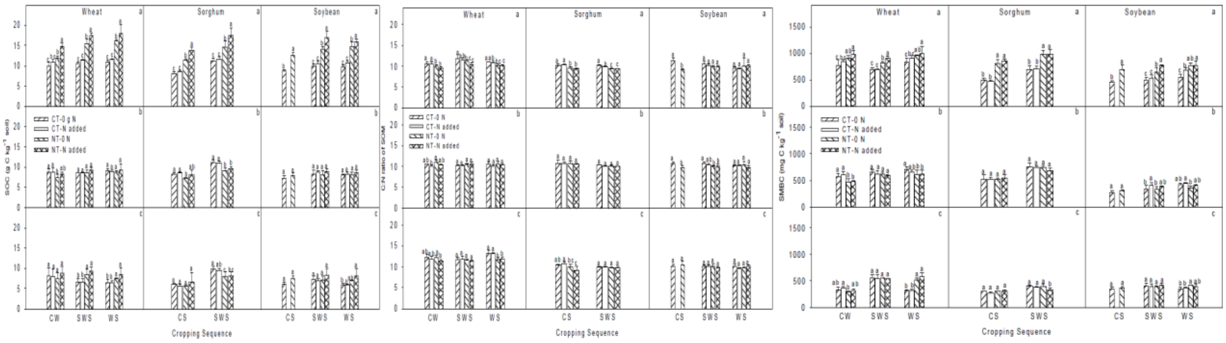
Fig. 25(a): Soil organic carbon (SOC) stocks in the residue removed (RR) and residue incorporated (RI) treatments under five different N fertilizer rates.

Fig. 25(b): Average difference in soil organic carbon stock (DSOC stock) over time (1966–2006) between treatments of residues incorporated (RI) and residues removed (RR).

Fig. 25(c): Soil organic carbon (SOC) stock in different fractions for residues removed (RR) and residues incorporated (RI) treatments at different nitrogen (N) fertilization rates after 40 years of residue incorporation (2006).

On average, we found 92% of total SOC in the silt and clay (SC) fraction, which is atypical magnitude for agricultural soils. Bol *et al*. (2009) also found that 67% and 23% of SOC stored in the clay and silt fraction, respectively, while Christensen (2001) reported that 50–75% and 20–40% SOC is usually attached to clay and silt particles, respectively, in temperate soils. Flessa *et al*. (2008) found 88% of SOC in the silt and clay fraction of two German arable soils and suggested that the main stabilization mechanism is the formation of organo-mineral complexes. Compared with other land use types, such as grassland or forest, the proportion of SOC stored in this fraction is very high in arable soil (Steffens *et al*., 2011; Poeplau and Don 2013), while macro-aggregates do not play a significant role. Dou, (2015) [24] also found that soil organic C (SOC) was highly affected by tillage, cropping sequence, and N fertilization in wheat systems. Two significant interactions in surface soil samples affecting SOC were tillage by N fertilization and tillage by cropping sequence. Under NT, SOC was significantly higher with than without N fertilization. In general, SOC decreased with depth. SOC level is a balance of net input and net output. The greater input of plant residues with enhanced cropping intensity and slower decomposition under

NT may explain higher SOC under NT than CT in wheat systems [Fig 26 i]. The C: N ratio of SOM under CT was greater than with NT through all soil depths in all crop systems. Differences, however, were only significant in surface soil [Fig 26 ii]. Soil microbial biomass (SMB) was more affected by tillage than by cropping intensity or N fertilization in all cropping systems. I.e. in wheat systems, SMBC under NT was 18, 25, and 13% greater in CW, SWS, and WS, respectively, than for CT in surface soil. Lower SMBC under NT than CT was observed at a depth of 5 to 15 cm. At 15- to 30-cm depth, however, there was no consistent change between CT and NT. Nitrogen fertilization also increased SMBC in all cropping systems, although it was not significant [Fig 26 iii].



i) (ii) (iii)

Fig. 26: i) Soil organic C (SOC), **ii)** the C:N ratio of soil organic matter (SOM),and **iii)** Soil microbial biomass C (SMBC) with depth as affected by cropping sequence, tillage, and N fertilization at **a)** 0- to 5-, **b)** 5- to 15-, and **c)** 15- to 30-cm depths. CW, SWS, and WS indicate continuous wheat, sorghum-wheat-soybean, and wheat-soybean, respectively. CS in sorghum and soybean refers to continuous sorghum and soybean, respectively. CT and NT refer to conventional and no tillage, respectively.

Doetterl *et al*. (2015) revealed that generally, AS concentrations per unit C decrease with the size of the fraction and are especially low in the non-aggregated silt and clay fraction. In addition, the non-aggregated silt and clay fraction shows generally the highest differences between topsoil and subsoil abundance of AS per unit C at all slope positions; this is especially pronounced at the stable plateau and eroding slope position. Moreover, the bulk soil AS values are similar for the topsoil along the slope (GalN-C: 22.5±1.9 mgg^{-1} SOC; GluN-C: 34.7±22.2 mgg^{-1} SOC) with highest values at the depositional site. In contrast, sub-soils of the stable plateau (GalN-C: 7.2±0.6 mgg^{-1} SOC; GluN-C: 16.3±4.6 mgg^{-1} SOC) and the eroding slope (GalN-C: 6.3±1.0 mgg^{-1} SOC; GluN-C: 15.7±3.5 mgg^{-1} SOC) profile show significantly lower values compared to sub-soils at the depositional site (GalN-C: 25.1±6.1mgg^{-1} SOC; GluN-C: 54.2±6.9 mgg^{-1} SOC). All fractions contain a large portion of AS per unit C in the topsoil (GalN-C: 19.1±3.5 mgg^{-1} C; GluN-C: 42.0±9.7 mgg^{-1} C), while in sub-soils the contribution of AS to total C is higher in the macro-aggregates (GalN-C: 16.3±2.5 mgg^{-1} C; GluNC: 36.5±7.3 mgg^{-1} C) than in the micro-aggregate (GalNC: 12.7±6.0 mgg^{-1} C; GluN-C: 31.1±13.0 mgg^{-1} C) and the non-aggregated silt and clay fraction (GalN-C: 6.5±5.7 mg g^{-1} C; GluN-C: 12.2±12.2 mgg^{-1} C). Interestingly, at the depositional site, the amount of AS per unit C in the micro-aggregate and non-aggregated silt and clay fraction decreases with depth compared to the macro-aggregate fraction, where no such trend could be observed [Fig. 27]. Wang *et al*. (2014) report, for a cropland slope from the same region with similar topographic setting, a re-aggregation of deposited and buried C within macro-aggregates.

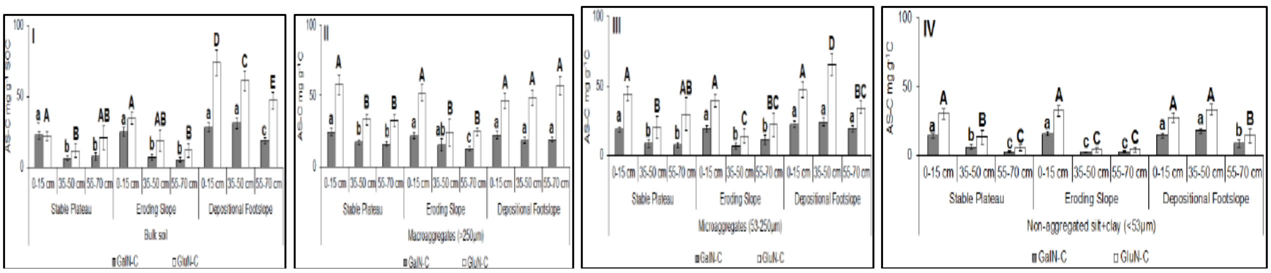


Fig 27: AS per unit SOC in the bulk soil (I) and the fractions (II– IV) along the slope and for different depths

Conclusions

Land use and soil management may affect soil organic carbon stabilization in a rice–wheat system of the North West Indo-Gangetic Plains. Soil cultivation led to a decrease in SOC stocks. In a rice-wheat system, conservation-tillage promoted increases on C stocks in labile and humified SOM fractions, compared to conventional tillage. Light and coarse SOM were the fractions most sensitive to changes in the management system. Compared with labile fractions, a higher absolute C stocks increase occurred in humified SOM fractions under no-tillage. SOC stabilization is higher in the surface soils than the sub surface soils. The topsoil layer (0-20 cm) is tilled and receives residue inputs that are subsequently mineralized, contributing some nutrients to the soil. For this reason, this layer possesses higher SOC than the lower soil layers. Relationships of SOC storage between the soil depths (0-20 cm and 0-60 cm, 0-20 cm and 0-120 cm) showed strong correlations. The effective SOC sequestration in upper depth (0-20 cm) is due to continuous nutrient recycling as crop residue in conservation agriculture. Less carbon content and changed in conventional methods of establishment likely due to continuous losses of carbon during tillage and no recycle of carbon via residue.

Conversion of natural ecosystems into agricultural lands for intensive cultivation severely depletes SOC pools. A judicious management of soils under competing and diverse land uses is the key to increasing SOM. Use of crop residues management in rice-wheat cropping systems combined with NT practices followed by proper fertilization can enhance SOC sequestration. A relevant mechanism of SOC storage in aggregates is the sequestration of plant debris in the core of soil micro-aggregates inaccessible to microbial processes. This mechanism is essential to stabilizing aggregates and sequestering SOC. Magnitude of SOC sequestration in the soil system depends on the residence time of SOC in aggregates. Micro-aggregates are bound to old organic C, whereas macro-aggregates contain younger organic material. The SOC confinement in the interior of micro-aggregates is the source for long-term C sequestration in terrestrial systems. Ultimately, interactions of clay minerals with C-enriched humic compounds control the protection, residence times, and turnover of SOC within the micro-aggregates.

Soil organic C is a key element in the valuation of natural resources and the evaluation of how management affects soil quality and ecosystem services derived from soil. A key to success will be to consider the agronomic, ecological and environmental constraints within a particular farm setting. The magnitude and severity of the depletion of SOC pool are exacerbated through decline in soil quality by accelerated erosion and other degradation processes. Perpetual use of extractive farming practices and mining of soil fertility also deplete the SOC pool. Conversion to a restorative land use and adoption of recommended agricultural management practices, which create positive C and nutrient budgets, can enhance SOC pool while restoring soil quality. Soil carbon sequestration is a win-win-win strategy. The amount of organic carbon stored in various soil pools is the balance between the rate of soil organic carbon input and the rate of mineralization in each of the organic carbon pools. However, the storage of carbon in soil profile is governed by the soil type, climate, management, mineral composition, topography, soil organisms and other unknown factors. More research evaluating impacts of alternative management systems on SOC stabilization is required. Specifically, understanding SOC and nutrient dynamics during transition from conventional to conservation systems are required. SOM stabilization process involving interactions with variable charge minerals is probably important in maintaining and restoring soil and environmental quality in tropical and subtropical regions.

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