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Spatial and temporal variations of soil organic carbon fractions and soil carbon storage in rice-wheat cropping system under varying tillage, straw and fertilizer management: A review

RK Naresh, RK Gupta and AS Panwar

Abstract

In agricultural ecosystem, soil organic carbon dynamics (SOC) and carbon sequestration (CS) are important indexes in estimating the soil carbon stock, soil fertility and soil quality. This paper examines the temporal and spatial variation of SOC and CS in a Typic soil area in north western IGP. The seasonal variation of SOC was attributed to plant growth and crop residue returning back to soil, while the spatial variation was mainly resulted from the fertilization practice. Maintaining the food security of about 127 crore populations is the hard challenge for Indian agriculture where 10 million hectare land is occupied by rice- wheat cropping system. In most of the rice cultivating region the climatic, resource input and management factors forces to adopt the lowland raising of paddy with puddling, which is describes as the boon for paddy; but curse for succeeding upland wheat crop because of disturbed soil physico- chemical and biological properties. Tillage and nutrient management may become as the solution for maintaining the productivity of both the crops with sustainability.

Conservation management of degraded land has the potential to build soil fertility, restore soil functions as a consequence of surface soil organic matter accumulation. Literature from different sources were reviewed and synthesized to: (i) quantitatively evaluate the magnitude and rate of soil organic C (SOC) sequestration with conservation agricultural management; (ii) evaluate how conservation management affects surface SOC accumulation and its implications on ecosystem services; and (iii) recommend practical soil sampling strategies based on spatial and temporal issues to improve the detection of statistically significant SOC sequestration. Soil organic C sequestration was 0.45±0.04MgC ha^{-1} yr^{-1} with conservation tillage compared with conventional tillage cropland.

Keywords: Soil organic carbon; temporal-spatial variability; soil nitrogen balance, soil tillage, straw return

Introduction

The baseline soil organic carbon (SOC) stocks in cultivated mineral soils are often low compared with those in soils under grassland or forest (Freibauer *et al*. 2004) [24]. Increasing the SOC level in cultivated soils is important for soil fertility and ecosystem resilience under a changing climate (Lorenz and Lal 2015) [51]. Moreover, the potential to sequester atmospheric carbon dioxide (CO_2) in those soils to mitigate climate change is high. Lal (2004) [41] estimated that the carbon (C) sink capacity of agricultural and degraded soils at global scale accounts for 50–66% of historic C losses due to land use change, amounting to 42–78 Gt. Globally, SOC stocks are estimated at an average of 1 500 PgC in the first meter of soil, although their distribution is spatially and temporally variable.

Soil organic matter (SOM) is an important indicator of soil fertility and productivity because of its crucial role in soil chemical, physical and biological properties (Gregorich *et al*., 1994) [27]. Therefore, maintenance of satisfactory level of SOM is necessary for sustainable agro-ecosystems. There are two ways to increase soil organic C (SOC): (1) increase of C input, or (2) decrease of SOC loss and decomposition. Carbon input can be increased and decomposition decreased by adopting residue management and using conservation tillage (no tillage or reduced tillage). However, short- and medium-term SOC changes are difficult to detect because of high background C content and its temporal and spatial variability (Bosatta and Agren, 1994). Cropland soil organic carbon (SOC) sequestration is crucial for both food security and climate change mitigation. It has been reported that increasing soil carbon (C) pool can help to enhance not only crop productivity but also yield stability (Pan *et al*., 2009) [63]. Furthermore, soil is the largest reservoir of C in the terrestrial ecosystems, and a slight variation in this pool can result in substantial changes in the atmospheric CO_2 concentration, thus potentially affecting global climate change (Davidson and Janssens, 2006).

Agricultural practices such as tillage methods are conventionally used for loosening soils to grow crops. But long-term soil disturbance by tillage is believed to be one of the major factors reducing SOC in agriculture (Baker *et al*., 2007). Frequent tillage may destroy soil organic matter (SOM) (Hernanz *et al*., 2002) and speed up the movement of SOM to deep soil layers (Shan *et al*., 2005). As a consequence, agricultural practices that reduce soil degradation are essential to improve soil quality and agricultural sustainability. Crop residue plays an important role in SOC sequestration, increasing crop yield, improving soil organic matter, and reducing the greenhouse gas (Liu *et al*., 2006). As an important agricultural practice, straw return is often implemented with tillage in the production process. Although numerous studies have indicated that tillage methods combined with straw return had a significant effect on labile SOC fractions, the results varied under different soil/climate conditions. For example, both no tillage and shallow tillage with residue cover had significantly higher SOC than conventional tillage without residue cover in Loess Plateau of China (Chen *et al*., 2009) [11, 15], while Wang *et al*. (2013) [86] reported that the difference between the treatments of plowing with straw return and no-tillage with straw return on TOC in central China was not significant. Rajan *et al*. (2012) showed that in Chitwan Valley of Nepal, no-tillage with crop residue application at upper soil depth had distinctly higher SOC sequestration than conventional tillage with crop residue. Suitable soil tillage practice can increase the SOC content, and improve SOC density of the plough layer (Duan *et al*., 2012) [21]. The effect size of tillage methods on SOC dynamics depends on the tillage intensity (Yang *et al*., 2003). Compared to conventional tillage (CT), no-tillage and reduced tillage could significantly improve the SOC content in crop land. 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 (Duan *et al*., 2012) [21].

SOC change rates and C sequestration duration

Soil organic carbon (C) is the largest terrestrial carbon reservoir and has attracted much attention because of its significance to soil fertility, food security, and climate change mitigation (Yan *et al*., 2010). Increased soil organic carbon typically benefits crop production through provision of an energy source for microbial nutrient cycling and improved soil physical and chemical properties. In turn, increased crop net primary production can lead to greater above- and below-ground plant residue that can be returned to the soil, benefiting soil carbon sequestration in agro-ecosystems (Pan *et al*., 2009) [63]. However, even when mineral fertilizers are applied, the carbon input from increased plant growth (returned residues and below-ground biomass) will not necessarily balance the continued decline in soil organic matter due to microbial decomposition (Jiang *et al*., 2014). Application of organic amendments to soil in the form of livestock manure and returned crop residues including straw is commonly recommended because of their positive effects on soil organic carbon accumulation (Liu *et al*., 2014).

Schlesinger, (1999) revealed that total soil organic carbon stock between NPKM and NPK treatments, gave a similar retention rate (4.4%) for manure-derived carbon. However, there was a positive, linear, and significant relationship between cumulative carbon input and increases in soil organic carbon stock [Fig. 1a], except for the period 1986–2003, which was due to a large variation in soil organic carbon stocks between treatments [Fig. 1b].

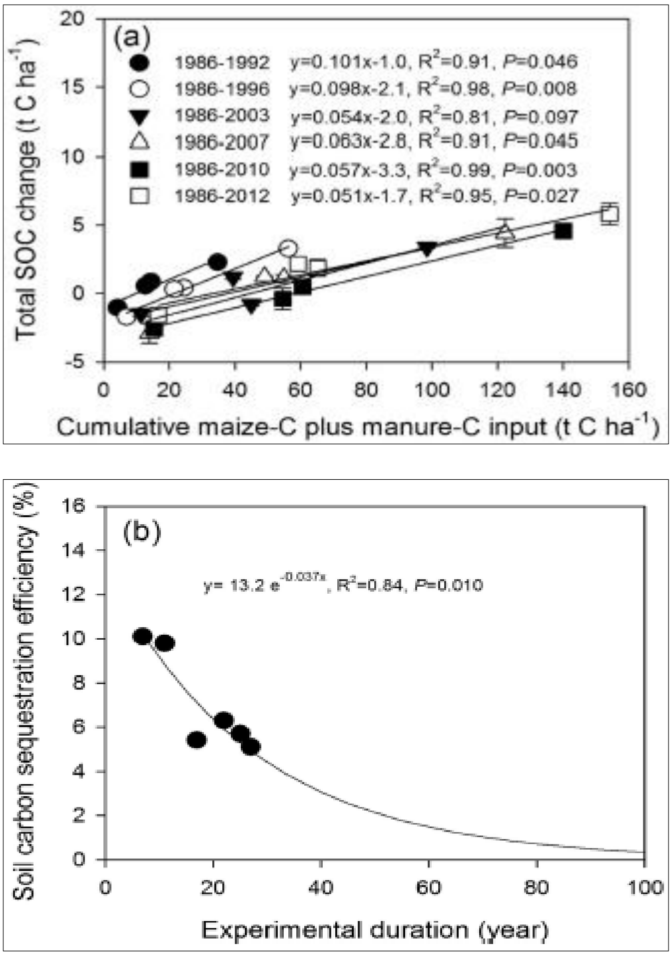


Fig 1a&b: Relationships between total soil organic carbon (SOC) and cumulative maize-derived C plus manure-derived C input for the periods 1986–1992, 1986–1996, 1986–2003, 1996–2007, 1986–2010, and 1986–2012.

Miyata *et al*. [200] also found that flooded or drainage conditions of paddy soils had strong effects not only on CH_4 emissions but also on CO_2 emissions. Lower CH_4 emissions due to water drainage may increase CO2 emission. However, during the submerged period of paddy rice cultivation, CO_2 production in the soil is severely restricted under flooding condition. This effect can be explained with two basic mechanisms Maier *et al*. (2011), which could be observed in a paddy soil [Fig. 2a]. First, flooding a field for subsequent rice cultivation cuts off the oxygen supply from the atmosphere and the microbial activities switch from aerobic (i.e. oxic condition) to facultative (i.e. hypoxic condition) and to anaerobic (i.e. anoxic condition) conditions Kogel-Knabner *et al*. (2010). As a consequence, biological activity reduction under anoxic condition, rather than completely, inhibits CO_2 production. At the same time, water replaces the gaseous phase in the soil pores. Since CO_2 diffusion rates in water are four orders of magnitude lower than those in air, a part of the produced CO_2 is stored in the soil. Hence, the soil CO_2 fluxes can be dramatically reduced by flooding during the paddy rice cultivation.

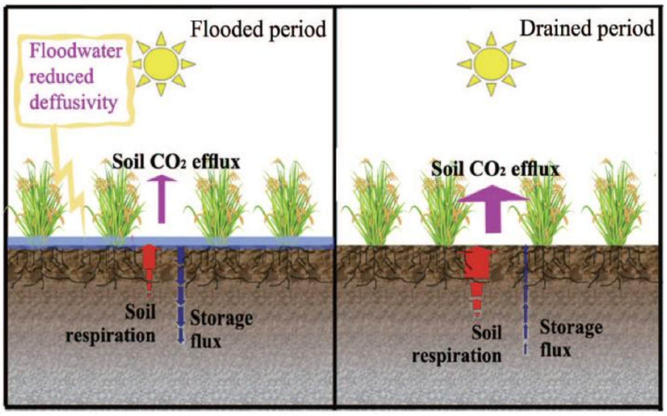


Fig 2a: Schematic comparison of soil CO_2 flux processes under the flooded and the drained conditions in rice paddies.

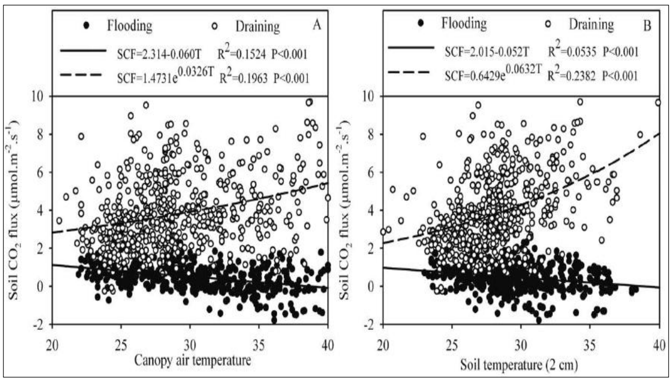


Fig 2b: Relationship between soil CO_2 fluxes and temperature under both flooded and drained conditions

Linear and exponential regression analyses were used to model the influence of temperature on soil CO_2 flux rates under both flooded and drained conditions. Negative linear correlations between temperature and soil CO_2 fluxes were found under flooded conditions ($R^2 = 0.1524$, $P<0.001$ and $R^2 = 0.0535$, $P<0.001$ for canopy air and soil temperatures, respectively), presumably because standing water limited soil CO_2 emissions. On the contrary, soil CO_2 flux rates increased as an exponential function of temperature under drained conditions ($R^2 = 0.1963$, $P<0.001$ and $R^2 = 0.2382$, $P<0.001$ for canopy air and soil temperatures, respectively) [Fig. 2b]. Chang *et al*. (2008) found strong relationships between CO_2 flux and soil temperature and indicated that the rates of CO_2 emission increased exponentially with increases in soil temperature. Liu *et al*. (2010), on the other hand, reported a significantly ($P<0.01$) linear relationship between soil CO_2 flux and soil temperature at a depth of 5 cm.

Hu *et al*. (2016) reported that the straw mulching decreased soil carbon emissions by 16%, in comparison to treatments without mulch. However, topsoil organic carbon (C) increased by 0.9 (0.7–1.0, 95% confidence interval (CI)) g kg^{-1} (10.0%, relative change, hereafter the same), 1.7 (1.2–2.3) g kg^{-1} (15.4%), 2.0 (1.9–2.2) g kg^{-1} (19.5%) and 3.5 (3.2–3.8) g kg^{-1} (36.2%) under unbalanced application of chemical fertilizers (UCF), balanced application of chemical fertilizers (CF), chemical fertilizers with straw application (CFS), and chemical fertilizers with manure application (CFM), respectively. The C sequestration durations were estimated at 28–73 years under CFS and 26–117 years under CFM but with high variability across climatic regions. At least 2.0 Mg ha^{-1} yr^{-1} C input is needed to maintain the SOC in ~85% cases [Fig. 3a&b] Zhao *et al*. (2016) stated that the straw mixing could increase soil organic carbon content, and improve the composition of micro-aggregates better than straw mulching.

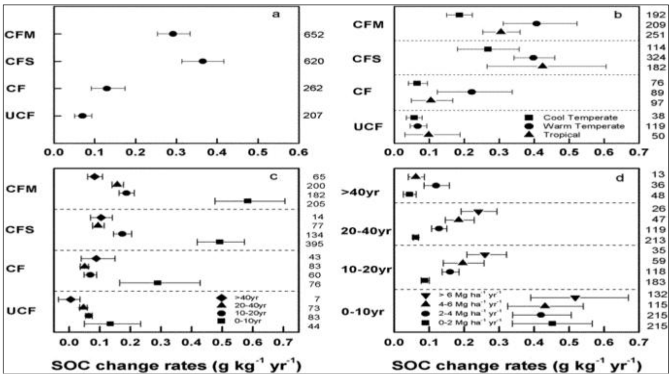


Fig 3a: Rates of SOC change with different impact factors. The letters (a–d) denote fertilization group, climate zone, experiment duration and C input, respectively.

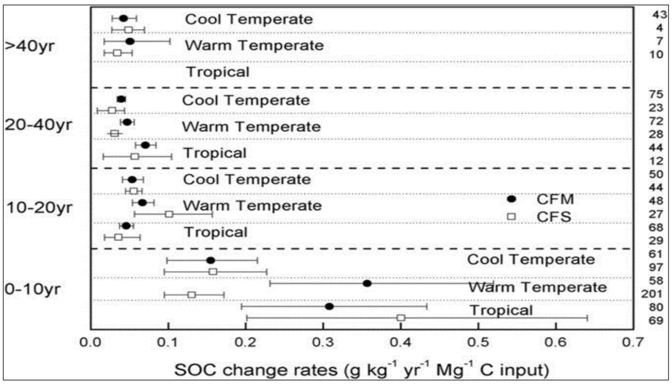


Fig 3b: Comparisons of rates of SOC change per Mg C input of manure and straw.

Labile soil organic carbon fractions

The labile soil organic C pools were able to distinguish SOC changes due to tillage treatments: MBC, DOC, HWC, $KMnO_4$-C, and POC all were significantly higher in the conservation tillage treatments (ST and NT) than conventional tillage in the surface soil, but not in the subsurface layer (except $KMnO_4$-C). Chen *et al*. (2009) [11, 15] showed that conservation tillage effects occurred mainly in the top soil and also reflected the build-up of labile C pools under conservation tillage after 11 years. The first explanation for the differences of the labile C pools between CT and conservation tillage (NT and ST) is the result of tillage practices. Frequent tillage under CT breaks down aggregates and exposes protected organic matter to microbial decomposition and increases the loss of labile C (Chen *et al*., 2007; Naresh *et al*., 2017) [11, 15]. A second explanation emerges from the different quantity of residues retained between CT and the conservation tillage: 3.8 t ha^{-1} residues in ST and NT vs. residue removal in CT. Plant residue might enter the labile C pools, provide substrate for soil microorganisms, and contribute to accumulation of labile C (Naresh *et al*., 2016). An increase in labile C fractions leads to improvement of soil fertility under conservation tillage through increase of labile sources of nutrients. Therefore, conservation tillage is an important factor for increase of labile C compared to conventional tillage.

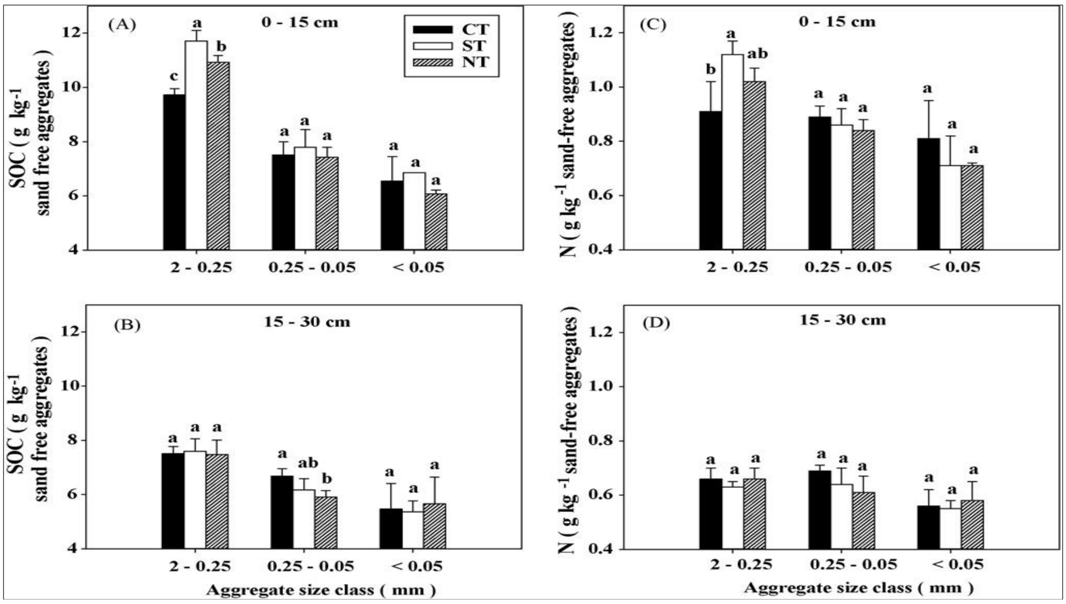


Fig 4a: Soil organic carbon (SOC) and nitrogen content (g kg^{-1}) of sand-free aggregates from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT)

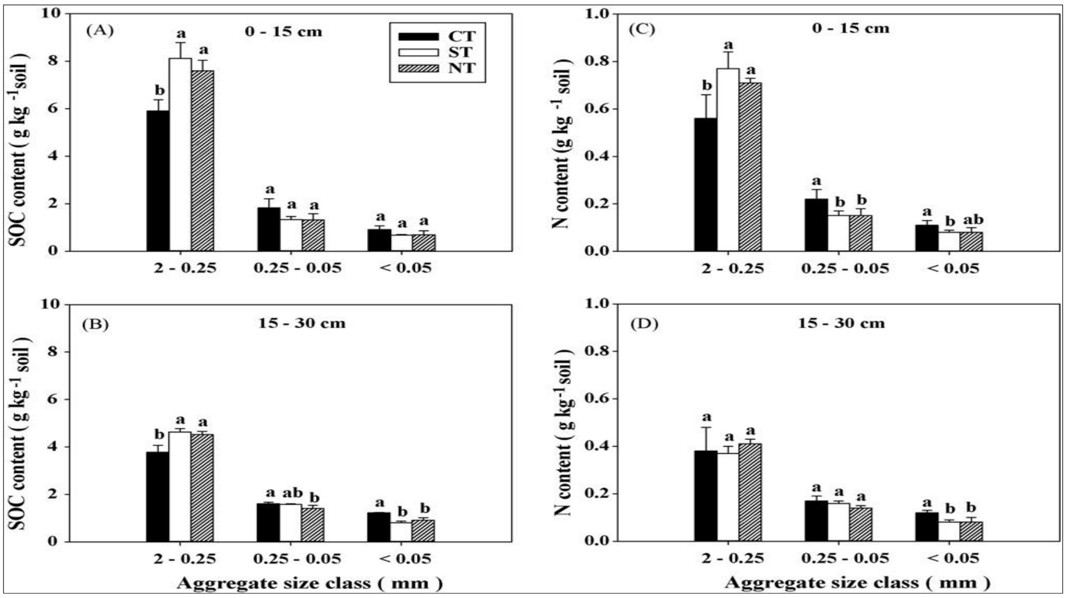


Fig 4b: Soil organic carbon (SOC) and nitrogen content of aggregates in g kg^{-1} soil from two depths under conventional tillage with residue removal (CT), shallow tillage with residue cover (ST), and no-tillage with residue cover (NT)

Bhattacharyya *et al*. (2012) also found that significant improvement in very labile and labile C pools (Chan *et al*., 2001) has been reported as a result of medium-term (6-10 years) CA practices as compared to conventional farming in a rain-fed RW system in Himalayan region (Table 1). Day *et al*. (2016) revealed that significant effect of ZT, green manuring (GM; Green gram residue retention) and brown manuring BM; Dhaincha residue retention) was recorded on very labile SOC, albeit in the 0-15 cm soil layer only.

Treatments ZT-ZT, ZT-ZT+BM and ZT-ZT+GM increased very labile SOC by 35, 25, and 38%, respectively over conventional practice (CT-CT) (Table 2).

Table 1: Impact of tillage practices on soil organic carbon pools (g C kg^{-1} dry soil) after six years of rain-fed cropping in north-western Himalayas (Bhattacharyya *et al*., 2012)

Treatment	Very labile SOC		labile SOC		Less labile SOC		Non- labile SOC	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
CT-CT	3.82^b	3.01^a	1.83^b	1.80^b	2.61^b	2.48^a	3.76^a	3.65^a
CT-ZT	4.48^a	3.18^a	1.97^b	2.03^a	2.67^{ab}	2.58^a	4.05^a	3.36^a
ZT-CT	4.51^a	3.11^a	2.20^a	1.92^{ab}	2.89^a	2.64^a	3.88^a	3.43^a
ZT-ZT	4.79^a	3.21^a	2.39^a	2.02^a	2.98^a	2.59^a	3.81^a	3.66^a

Values followed by a similar letter within a column are not significantly different at $p < 0.05$ level of significance.

Labile soil organic C fractions: MBC, DOC, HWC, $KMnO_4$-C, and POC were significantly and positively correlated with SOC concentrations in the surface soil (0–15 cm) (Chen *et al*., 2009) [11, 15]. Such correlations suggested that SOC was a major determinant of the labile C fractions present. Likewise, depletion in labile C pools could also give an early indication of the decline of SOC. MBC, DOC, POC and HWC were significantly and positively correlated with each. However, KMnO$_4$-C was significantly and positively correlated with MBC and HWC. These correlations indicated that they all provided an index of labile soil organic C, and also showed that they were closely interrelated.

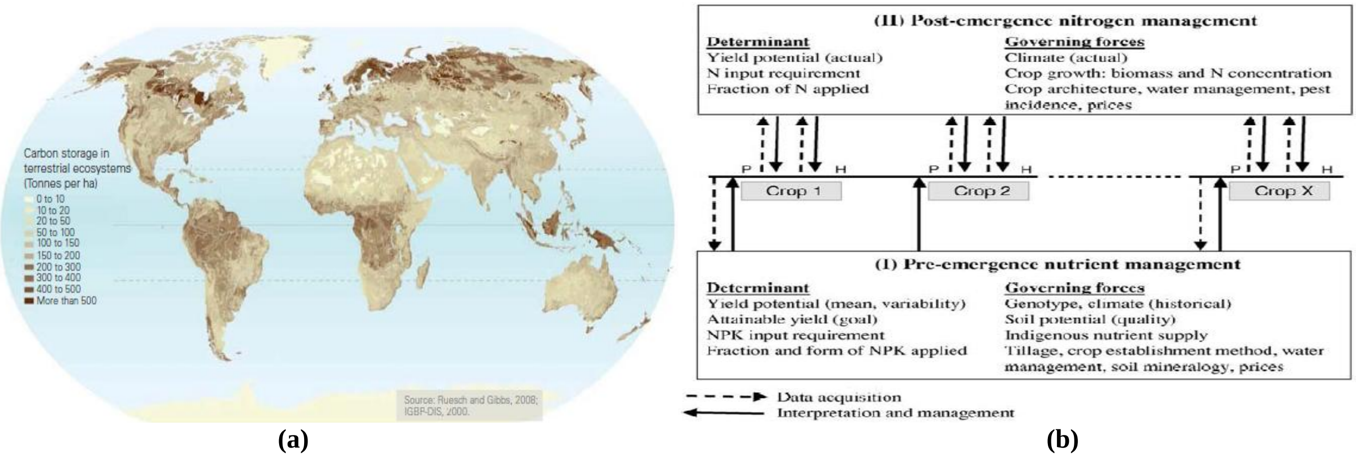
Dou *et al*. (2008) observed MBC, POM-C, DOC, hydrolysable C, and SOC were all positively correlated with each other. Rudrappa *et al*. (2006) reported that POC, KMnO$_4$-C, MBC, total C mineralization (C_{min}) and total organic C were significantly correlated with each other. Ghani *et al*. (2003) showed that HWC was positively correlated with MBC, water-soluble C, and total organic C. There were large differences in portions among the five labile C fractions. Soil microbial biomass C was 2.8–3.9%, DOC was 0.8– 1.0%, HWC was 2.9–4.7%, POC was 33.2–59.6%, and KMnO$_4$-C was 7.1–32.9% of SOC in our study (Rudrappa *et al*., 2006). Although the responses of the five labile C fractions to tillage effects were similar, their sensitivities to tillage effects were different. The magnitude of changes of labile C fractions between conservation tillage treatments and conventional tillage for 0–15- cm depth ranged in the order: KMnO$_4$-C (87.9–158.9%) > POC (42.0–69.2%) > HWC (37.0–47.7%) > DOC (13.1–30.8%) and MBC (21.7–8.4%). So that KMnO$_4$-C, POC and HWC were the most sensitive to tillage effects than total SOC which showed 25.6–34.2% enrichment. The lower sensitivity of MBC and DOC to tillage compared with KMnO$_4$-C, POC and HWC might be due to their smaller sizes and highly labile nature (Janzen *et al*., 1992).

Table 2: Soil organic carbon pools as affected by continuous two years of conventional vis-à-vis conservation agriculture practices in an irrigated rice-wheat system of north-western Indo-Gangetic Plains (Dey *et al*., 2016)

Treatment	Very labile SOC (g kg^{-1})		Labile SOC (g kg^{-1})		Less labile SOC (g kg^{-1})		Non-labile SOC (g kg^{-1})	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
CT-CT	2.40	1.55	2.00	0.45	0.85	0.75	1.75	1.23
CT-ZT	2.20	1.79	2.05	0.55	0.90	0.61	1.79	1.20
ZT-ZT	3.23	1.41	1.91	0.87	0.55	0.61	1.50	1.54
ZT-ZT+BM	3.00	1.65	1.95	1.20	0.85	0.75	1.27	0.82
ZT-ZT+GM	3.31	1.64	2.14	0.95	0.55	0.80	1.28	1.01
Mean	2.97	1.62	2.07	0.88	0.72	0.69	1.45	1.06
LSD ($p < 0.05$)	0.61	NS	NS	0.27	NS	NS	NS	NS

Soil Organic Carbon Dynamics

Different ecosystem types store different amounts of carbon depending on their species compositions, soil types, climate, relief, and other biophysical features [Fig. 5a]. 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 3Gt 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.



(a) (b)

Fig.5a: Carbon Stocks in Biomass and Soils ***Fig. 5b:*** Determinants and their controlling factors in a general, dynamic, site-specific nutrient management scheme for non-legume field crops (P – planting; H – harvest). Crop-based estimates of the indigenous nutrient supply in nutrient omission plots were used because soil testing methods did not sufficiently predict this parameter. Different N management schemes were developed for each domain to account for regional variation in the primary factors driving N use efficiency [Fig. 5b].

Zhang *et al*. (2007) also found that the slope of the line can be viewed as the average fraction of applied synthetic N taken up by crops in the year, while the intercept of the line can be viewed as the average N uptake by crops from all other sources. Clearly, with the increase in N input, the fraction of applied synthetic N taken up by crop within a year decreased, from around 0.5 in the early-1980s to around 0.3 in the late-2000s [Fig. 6a]. Tian *et al*. (2012) reported that [Fig. 6b] shows that the determinant co-efficient between fertilizer application rate and crop N uptake R^2generally decreased with fertilizer application rate, indicating the loosening of the link between fertilizer input and crop N uptake. The rapid decreasing in determinant co-efficient when national average fertilizer N application rate was above 190 kg N ha^{-1} probably indicates over fertilization at such rate. Liu *et al*. (2013) observed that estimated accumulative recovery efficiencies were 10%–46% higher than their corresponding recovery efficiencies in annual terms due to the residual effect of N [Fig. 6c].

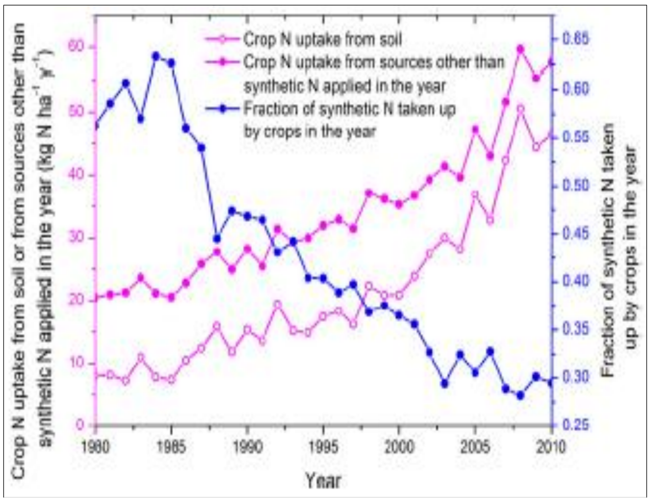


Fig 6a: Changes in the average fraction of applied synthetic N taken up by crops in each year, as well as crop N uptake from soil or sources other than synthetic N applied that year.

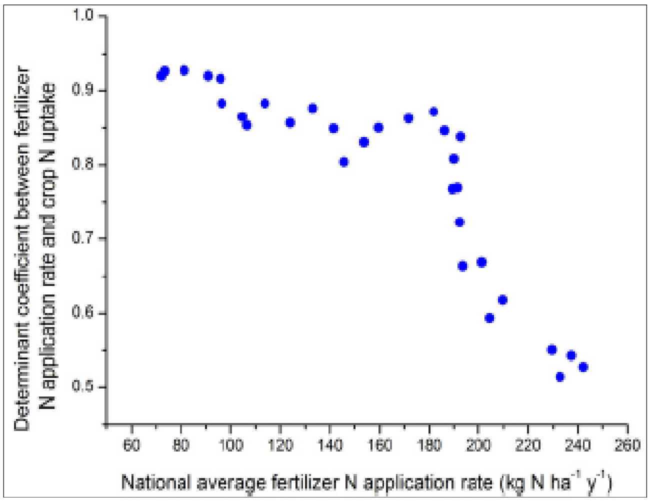


Fig 6b: The change in determinant coefficient between fertilizers N application rate and crop N uptake with fertilizer application rate.

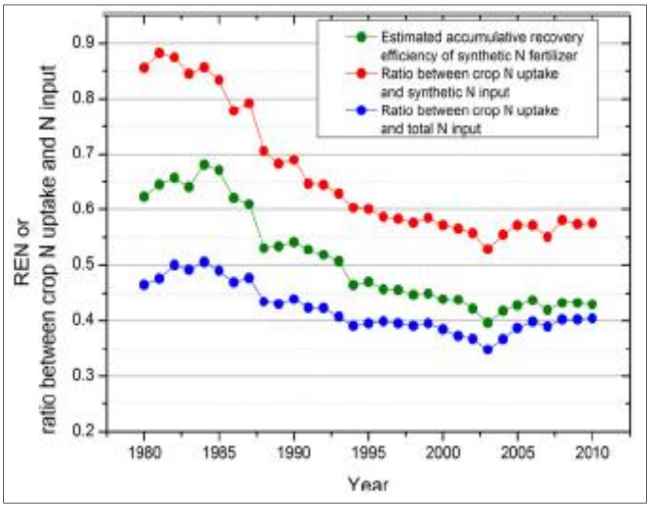


Fig 6c: Estimated RE$_N$, as well as the ratio between crop N uptake and synthetic N input or total N input.

Campbell *et al*. (1996) reveled that cropping frequency did not affect soil organrc C or total N content but soil C and N were greater under no-tillage (NT) than under mechanically tilled continuous wheat (*Triticum aestivum* L) (Cont w) and fallow-wheat (F-W) rotations. Effects were apparent in the 0 to 7.5- and 7.5 to l5-cm depths. Over the 11-yr period F-W (minimum tillage) gained no additional C; cont W (conventional tillage) gained 2t C ha$^{-1,}$ and both Cont W (NT) and F-W (NT) gained 5t C ha^{-1}. Changes in organic C and N were greatest in the final 4 yr of the experiment when crop residue production was greatest [Fig. 7a]

Mohanty *et al*. (2015) observed that the tillage reduction in association with residue retention increased the total SOC by approximately 20% over conventional systems in an alluvial soil of Odisha. Protecting the soil under cover crops during dry season also enhanced the SOC contents by 7% over plots with no cover crops. Soil organic C was greater under zero tillage (ZT) and residue retained plots than under moldboard ploughing. Bulk density (BD) was greater under ZT than under mold-board ploughing, probably due to more aggregated structure under ZT (Roldan *et al*., 2007).

Intensive ploughing broke soil aggregates and increased soil porosity, thus causing a decrease in soil BD. Total SOC stocks also increased under ZT, as a result of higher SOC concentrations and BD. Yaduvanshi and Sharma (2008) reported significant increase in SOC under ZT plots (3.17 g kg^{-1}) compared with conventional plots (2.84 g kg^{-1}) in an alluvial soil of NW-IGP under RW system. They reported lower CO_2 fluxes. Han *et al*. (2016) revealed that the C sequestration efficiency, manure is usually more efficient than straw in most regions, especially in warm temperate regions during the first 10 yr, with C sequestration rates of 0.36 under manure application and 0.13 g kg^{-1} yr^{-1} under straw retention per Mg C input [Fig. 7b]. Notably, these differences slowly diminished after 40 yr. Sanderman *et al*. (2010) noted that changes in soil carbon obtained through the adoption of 'carbon friendly' management relative to more intensive management strategies ranged from 0.1 to 0.5 Mg C ha^{-1} year^{-1} over the 0–15 cm soil layer. At a rate of change of 0.5 Mg C ha^{-1} year^{-1}, it would take 3–4.5 years to detect a change in soil carbon content equivalent to 0.1% of the total 0–15 cm soil mass, depending on bulk density [Fig. 7c]. If higher rates of carbon accumulation can be achieved, this time will decrease (e.g. for an increase of 2.0 Mg C ha^{-1} year^{-1}, 0.75–1.13 years would be required). The implication of this observation is that, unless a management practice induces significant increases in soil carbon (>0.3 Mg C ha^{-1} year^{-1} for the 0–15 cm layer or >0.6MgCha^{-1} year^{-1} for the 0–30 cm layer), it will take >5 years to detect changes equivalent to 0.1% of the soil mass. Another implication is that the potential for detecting a change in soil carbon will increase as the thickness of the soil layer decreases. Given that carbon tends to accumulate to a greater extent near the soil surface, where an assessment of changes in SOC stocks for the 0–30 cm layer are required, a greater capability to detect change would exist where this layer is broken up into 0–10, 10–20, and 20–30 cm layers.

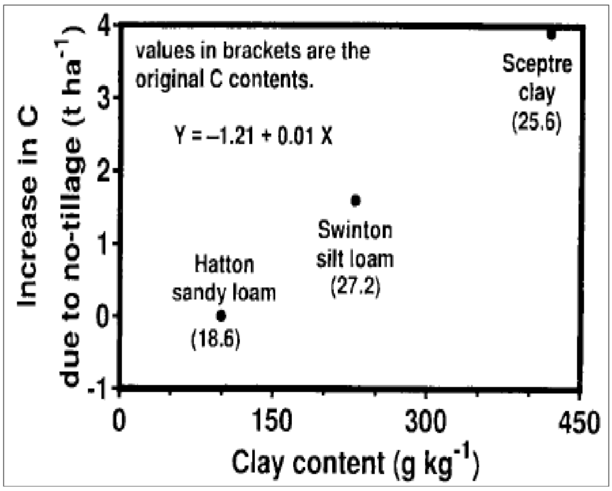


Fig 7a: Soil texture influences carbon gains in 0- to I 5-cm depth of soil after 11- 12yr of no-tillage

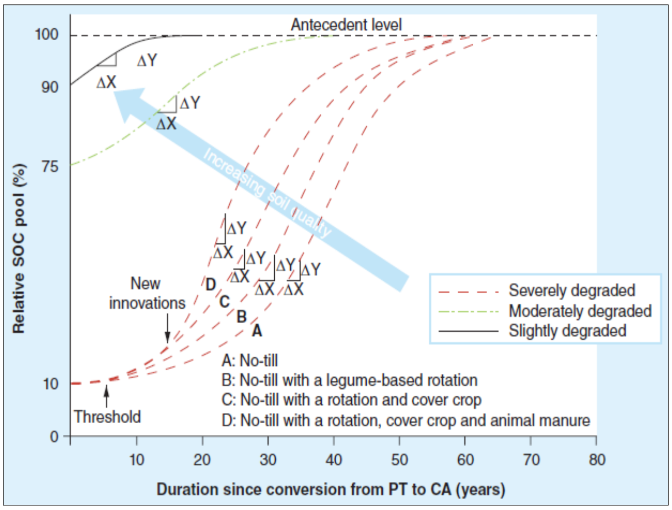


Fig 7b

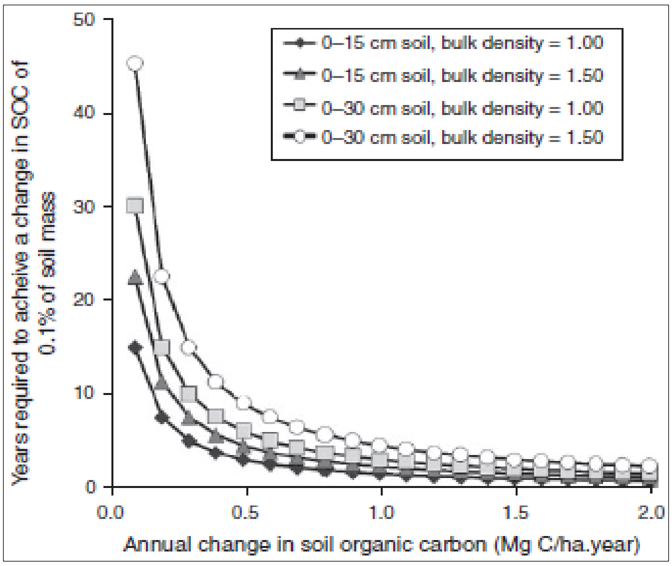


Fig 7c: Duration required to detect a change in the soil carbon content of the 0–30 cm layer that would be equivalent to 0.1% of soil mass for annual values of soil carbon increase ranging from 0.1 to 2.0 Mg C ha^{-1} year^{-1}.

Liu *et al*. (2014) showed that 17 years of ZT had ~ 8.3% higher cumulative SOC stocks at depths of 0–60 cm compared with CT the treatment effect was more prominent in the 0-10 cm of upper soil layer.

Fertilizers and organic amendments such as manure, compost and crop residues are added to improve the fertility of soils. These nutrient amendments can influence C-storage through both biomass input and organic matter decomposition [Fig. 8a, b &c]. Applications of organic amendments such as manures, composts and bio-char can lead either to a build-up of soil C over time or a reduction in the rate at which organic matter is depleted from soils (Favoino and Hogg, 2008).

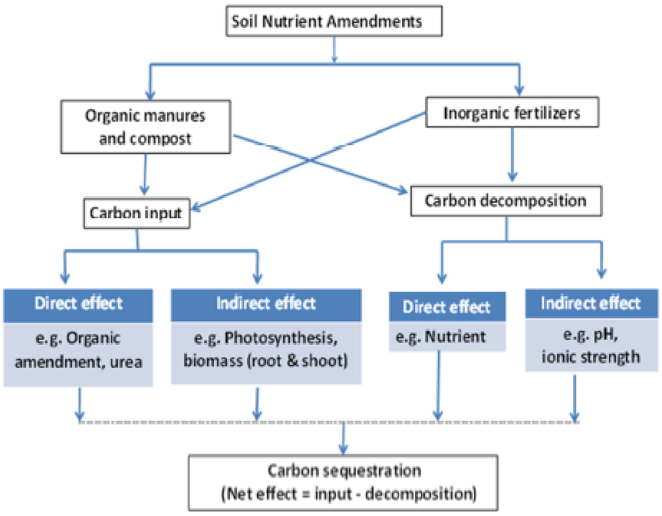


Fig 8a: The effect of nutrient amendments on carbon sequestration in soil

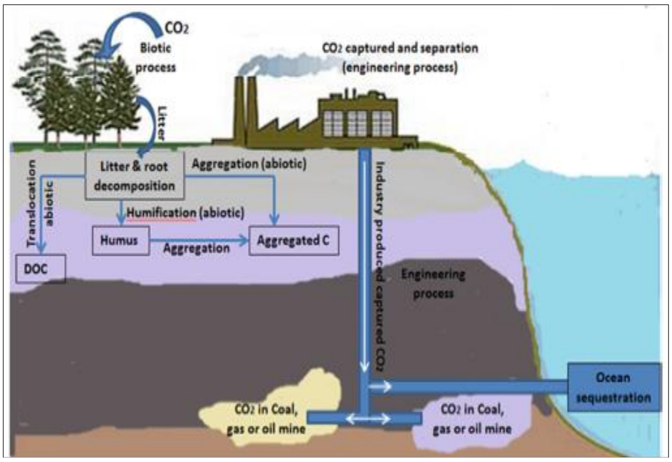


Fig 8b: Schematic representation of the processes involved in carbon sequestration (adapted from Lal, 2008a)

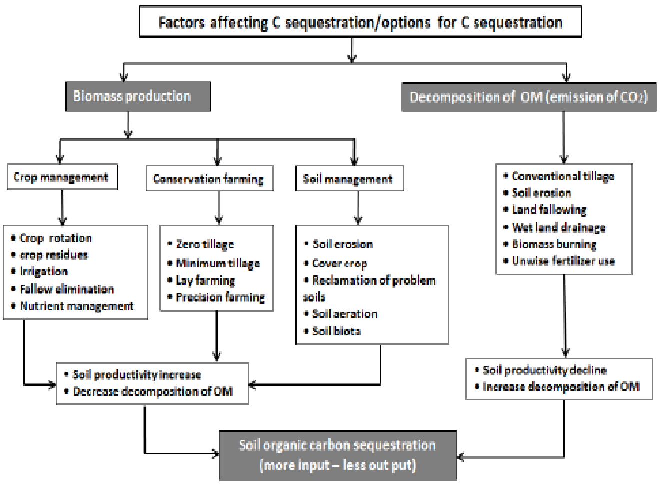


Fig 8c: Agricultural practices affect carbon sequestration in arable land (adapted from Lal, 2003)

Fertilizer additions have often been shown to increase soil C, which is primarily attributed to increased plant biomass production (Mazumder and Kuzyakov, 2010). However, fertilizer addition has also been shown to increase the rate of decomposition of SOM, especially in highly fertile soils, thereby depleting C content (Kirkby *et al*., 2013). Bell and Lawrence (2009) suggested that SOM cannot increase in low fertility soils unless the limiting nutrients such as N and P are added. Kirkby *et al*. (2014) also suggested that appropriate use of fertilizers in nutrient limited soils can enhance productivity and thus return more residues to the soil. The net effect of fertilizers on soil C depends on the productivity, C saturation and nature of the C pool. The loss in soil C observed with intensification mainly occurs from labile pools (Ghani *et al*., 2003), with implications for reduced retention of N and other nutrients in the soil, leading to lowered nutrient availability for plant uptake and greater losses to the environment.

Organic Carbon Fractions

The SOC strongly influences soil quality and productivity and can be classified into labile and recalcitrant fractions based on their chemical characteristics and residence time (McLauchlan *et al*., 2006). The labile fraction of SOC is the key to interpret changes in quality (Kapkiyai *et al*., 1999). The SOC associated with the sand fraction is a labile pool of C and hence influenced by land use and management (Shrestha and Lal, 2007) whereas SOC associated with the clay fraction is more stable and is altered more by physical and chemical processes than by land use changes (Khanna *et al*., 2001). Chen *et al*. (2009) [11, 15] reported that reduced tillage (RT) contained 7.3% more SOC and 7.9% more N stocks than plough tillage (PT) in the 0–20-cm depth, respectively, and estimated that RT accumulate an average 0.32 Mg C ha^{-1} year^{-1} and 0.033 Mg N ha^{-1} year^{-1} more than PT over an average period of 11 years, respectively.

The SOC fractions, such as dissolved organic C (DOC) and microbial biomass C (MBC) and particulate are considered to be more sensitive indicators of treatment induced changes than the total SOC (Dong *et al*., 2009). Chen *et al*., (2009) [11, 15] reported that labile organic C fractions are sensitive to SOC changes, with sensitivities decreasing in the order of POC >DOC > MBC. The DOC is an important C pool in soils and influences many chemical and biological processes (Chantigny, 2003) and may indicate short-term responses to crop management practices. It generally decreases with depth due to retention by soil surfaces (Qualls and Haines, 1992). However, the contribution of crop residues and root exudates to the DOC pool is not entirely understood. Cropping systems have varying effects on soil C, N, and DOC pools by production of residues of variable quantity and quality (Lorenz and Lal, 2015) [51]. The MBC is a relatively small component of the SOM. It comprises only 1-3% of total soil C. The MBC also considered as labile C, serves as a source (mineralization) or a sink (immobilization) of nutrients (Hu *et al*., 1997) with a turnover time from days to years (Tedla *et al*., 2004). This microbial C is largely influenced by tillage practices and soil moisture (Skopp *et al*., 1990). Among arable land, in the top layer the soil of NT was better than PT on forming MBC to C sequestration. So these implied that long time land use of land management of NT could promote C sequestration. The depth distribution of microbial biomass was impacted by long-term tillage, which may influence the potential nutrients supply to crops. No till management regime which promoted maintenance of crop residues at the soil surface may have beneficial impacts on soil fertility through maintenance of microbial biomass and supply of mineralizable nutrients. Tillage significantly influenced the light fraction (LF) and heavy fraction (HF) of carbon. The NT system increased LF and HF by 10 and 12%, respectively, compared to CT for the 0–10 cm soil depth. Liang *et al*. (1998) reported that ratios of LF of C/ SOC were greater in light-textured soils than those in fine-textured soils. LF of C/SOC is directly proportional to sand content. The minimum disturbance in NT systems promotes the interaction between clay particles and slower decomposing C inputs to form soil aggregates. However, faunal populations and microbial biomass (especially fungal biomass) are also greater under NT (Frey *et al*., 1999) and these organisms play an important role in soil aggregation. Furthermore, the root system has been considered an effective agent for stabilization of macro aggregates in NT systems, whereas new C inputs from surface residues seem to not contribute as much to macro aggregate-associated C pools (Gale *et al*., 2000).

Liang *et al*., (2004) however, observed the increase in soil organic N at the depth of 0-7.5 cm due to no-tillage treatment. They indicated that the fractions responsible for the increase of soil organic N on no-tillage treatment was more labile than the soil humus. Reddy *et al*. (2003) reported that amino acid-N was highly correlated to mineralizable N and the least with the non-hydrolysable. The significantly highest correlation of hydrolysable unknown N and non-significant correlation of non-hydrolysable N with grain yield and N uptake of rice and wheat crops imply that hydrolysable N fractions are the potential contributors towards plant available N. Amino acid N, amino sugar N and hydrolysable NH_4-N were also found to be the most active N pools and the major source of N potentially available to plants (Sharma and Verma, 2001). The effect of CA is more spectacular on the labile pools of SOC. Significant improvement in very labile and labile C pools (Chan *et al*., 2001) has been reported as a result of medium-term (6-10 years) CA practices as compared to conventional farming in a rain-fed RW system in Himalayan region (Bhattacharyya *et al*., 2012). Similarly, in an irrigated RW system of NW-IGP, two-years of CA did not exhibit any visible effect on relatively stable SOC pools in surface or sub-surface soil layer (Dey *et al*., 2016).

Meenakshi, (2016) reported that zero tillage practice in wheat increased the organic carbon content and carbon stock as compared to conventional tillage in soils [Fig. 9a]. The zero tillage increased dissolved organic carbon, microbial biomass carbon light and heavy fractions of carbon in soils at both the depths. Microbial utilization of organic carbon is an important characteristic which reflect the quality of the soil, the higher the efficiency, the less energy which required maintaining the same microbial, indicating the soil environment conducive to microbial growth, relatively high quality (Xianli *et al*., 2006).

González- Prieto *et al*., (1997) reported the extent of depletion in THN fraction more (26.6%) than in non-hydrolysable N (NHN) fraction (20.4%) over their initial status due to continuous cropping. The relatively greater decrease in THN supports the observation that hydrolysable N is more vulnerable to mineralization and could be considered as a major source of potentially available N for plants than non-hydrolysable N [Fig. 9b]. Total hydrolysable nitrogen was found highest in clay loam followed by loam and sandy loam soils. Highest values of non-hydrolysable nitrogen, amino acid nitrogen, and hydrolysable ammonium nitrogen were observed in zero tillage practice as compared to conventional practice [Fig. 9c].

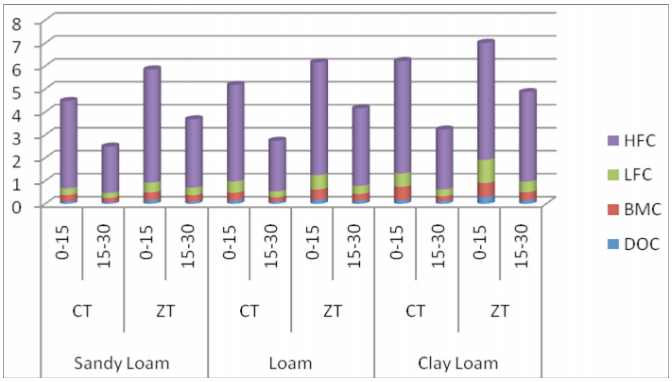


Fig 9a: Different fractions of organic carbon (g/kg) at 0-15 and 15-30 cm soil depths under conventional (CT) and zero (ZT) tillage practice in different textured soils

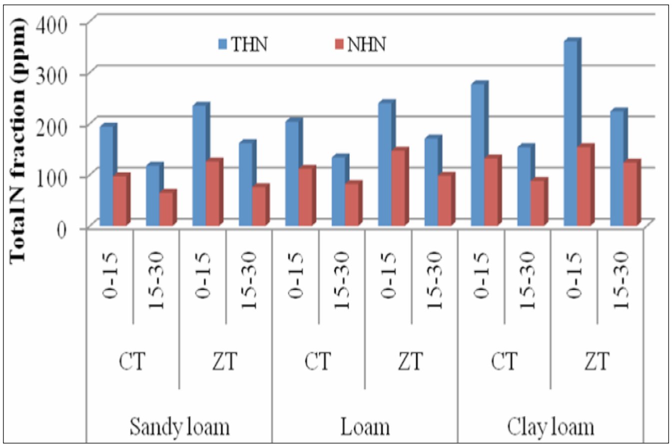


Fig 9b: Total hydrolysable nitrogen (THN) and non-hydrolysable nitrogen (NHN) at 0-15 and 15-30 cm soil depths under conventional (CT) and zero (ZT) tillage practice in different textured soils

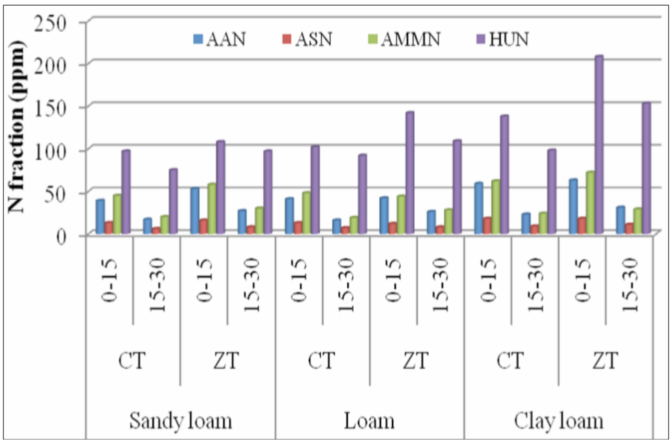


Fig 9c: Different fractions nitrogen at 0-15 and 15-30 cm soil depths under conventional (CT) and zero (ZT) tillage practice in different textured soils [Adopted from Meenakshi, 2016]

(HFC-, heavy carbon fractions, LFC-light carbon fractions, MBC- microbial biomass carbon, DOC- dissolved organic carbon, AAN-amino acid nitrogen; AMMN-hydrolysable ammonium nitrogen; ASN-amino sugar nitrogen; HUN-hydrolysable unknown nitrogen)

Mi *et al*. (2016) revealed that the TOC and TN concentrations were both highest in the upper 0–5 cm depth and then decreased with increasing depth [Fig. 10a]. No significant differences in TOC were recorded between CK and F treatment at any of the four soil depths. However, addition of organic materials resulted in significant increases in TOC concentrations compared to the CK, ranging from 16.0–29.5% in the 0–5 cm depth, and 18.3–28.9% in the 5–10 cm depth, respectively. Generally, no significant differences in TOC concentrations were observed between treatments at the deeper soil depth (20–30 cm) [Fig. 10a]. All fertilized treatments showed significant increases in soil TN in the 0–20 cm soil layer compared to the control [Fig. 10a]. In comparison with NPK alone, the TN concentration in the FM treatment was 19.1% higher in the 0–5 cm depth, and increased by 5.9%, 12.7% and 7.6% in the FG, FM and FS treatments in the 5–10 cm depth, respectively [Fig. 10a]. Zhou *et al*. (2016) reported similar extraneous C input from manure was more effective than rice straw in soil organic carbon sequestration due to enhanced CO_2 and CH_4 emissions in the rice straw treatment.

The FG and FM treatments had a significantly higher POC concentration (51.9% and 117.6%) than the F treatment in the 0–5 cm depth. In the 5–10 cm depth, cattle manure amendment showed the most profound effect on POC concentrations among all treatments, increasing by 80.8%, 59.2%, 50.6% and 78.7% compared to F, FR, FG and FS treatments, respectively. In the upper soil (0–5 cm depth), NPK fertilizer plus organic materials treatments contained higher MBC concentrations (range 24.1%-62.7%) than the CK [Fig. 10b]. With increasing soil depth, MBC concentrations declined, but to different extents. However, the FR and FM treatments still produced significantly higher MBC concentrations than the CK and F treatments in the 5–10 cm and 10–20 cm depths. The MBC concentrations in the FR and FM treatments increased by 23.2% and 48.9% in the 0–5 cm depth, 42.4% and 61.6% in the 5–10 cm depth and, 30.7% and 43.3% in the 10–20 cm depth respectively compared to the F treatment [Fig.10b].

Rudrappa *et al*. (2006) reported only half of the POC accumulation in the 15–30 cm compared to upper soil layers, probably because the largest proportion of organic substances remains in the surface soil layers. Chakraborty *et al*. (2011), who reported that, recommended application rates of NPK fertilizer increased MBC by 63.2% compared to CK after 37 years. However, in this research, the level of MBC was indistinguishable between no fertilized and NPK alone in the 0–5 cm and 10–20 cm soil depths [Fig. 10b]. Tu *et al*. (2006) indicated that the quality of organic inputs is one of the most important factors affecting microbial biomass due to various compositions of organic materials have profound impact on microbial utilization of C and nutrients.

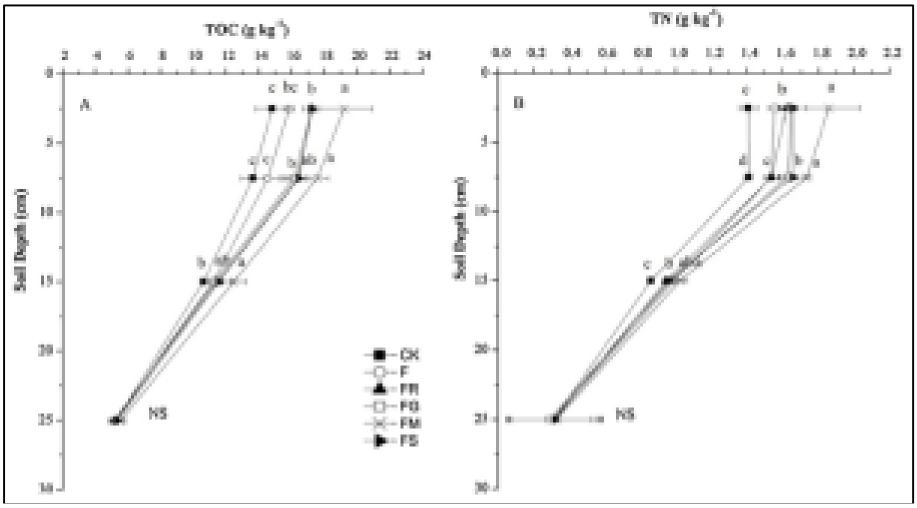


Fig 10a: Soil total organic C (TOC) (A) and total N (TN) (B) at different soil depth under different fertilizer managements at 0–5 cm, 5–10 cm, and 10–20 cm and 20–30 cm soil depths.

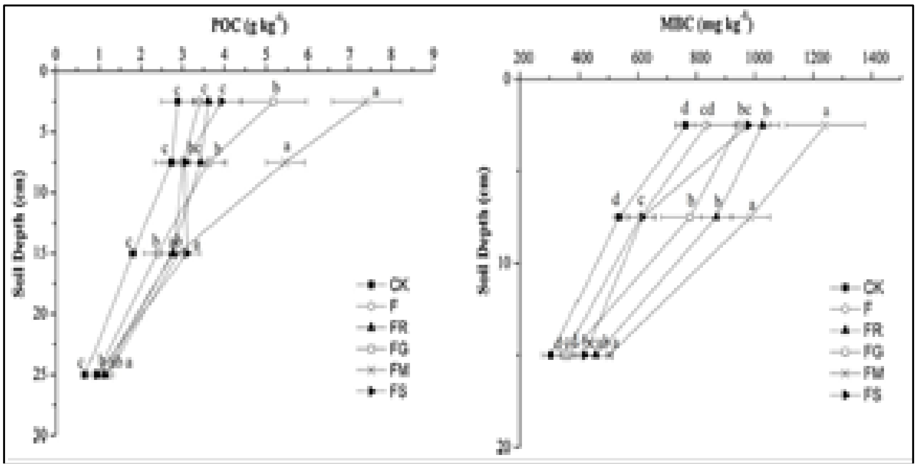


Fig 10b: Contents of particulate organic C (POC) and microbial biomass C (MBC) at 0–5 cm, 5–10 cm, 10–20 cm and 20–30 cm soil depths under different fertilization managements.

TOC, soil total organic carbon; TN, soil total nitrogen; CK, no fertilizer; F, chemical fertilizer alone; FR, chemical fertilizer with spent mushroom compost; FG, chemical fertilizer with green manure; FM, chemical fertilizer with cattle manure; FS, chemical fertilizer with straw residue.

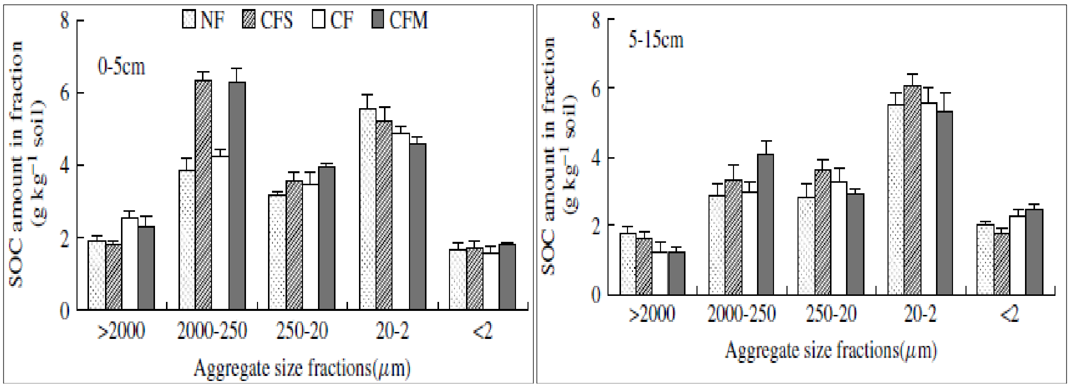


Fig 11a: SOC amount in aggregate size fractions from treated plots.

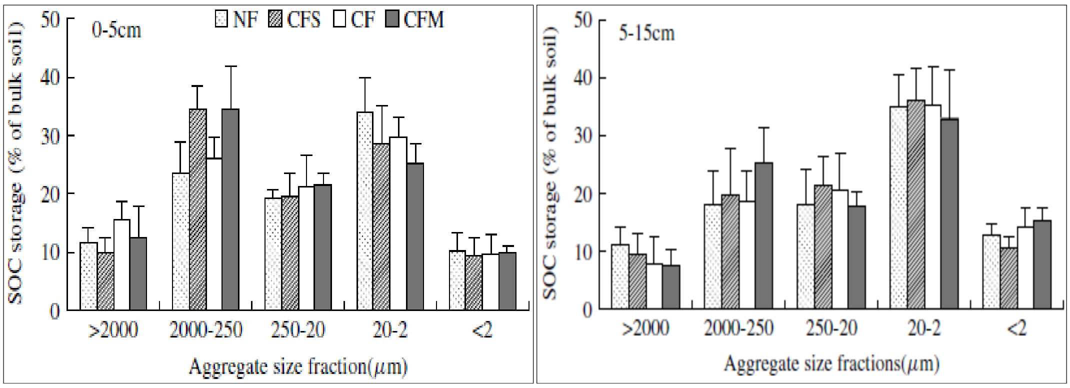


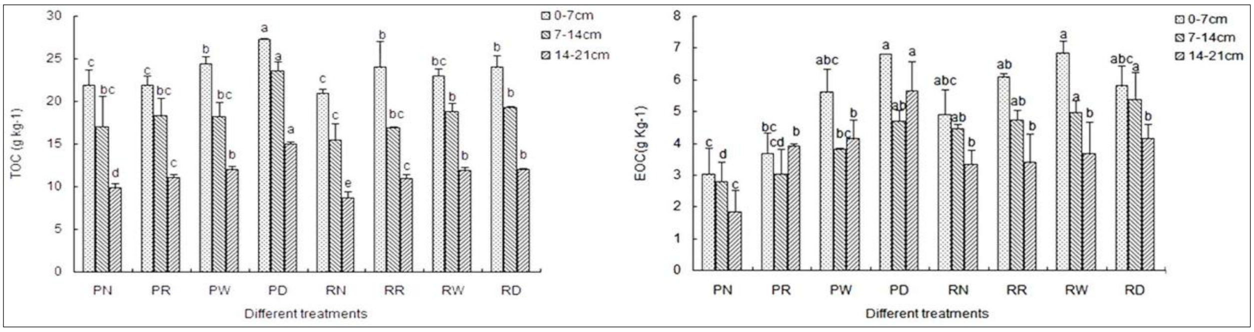
Fig 11b: SOC storage by aggregate size fractions (SOC contents of bulk soil under NF, CF, CFS and CFM were 16.40, 16.32, 18.30 and 18.21 g kg^{-1} at 0–5cm depth and 5.73, 15.78, 16.81 and 16.24 g kg^{-1} at 5–15 cm depth respectively).

Li *et al*. (2007) also found that the surface layer, SOC and N_t concentrations appeared as a bimodal peak in the 2000–250 and <2μm fractions. SOC concentration increased by 38.6, 40.8 and 17.2% and N_t concentration by 30.0, 16.8 and 38.4% in the 2000–250μm fractions under chemical fertilizers plus pig manure (CFM), chemical fertilizers with straw return (CFS) and chemical fertilizers (CF) respectively as compared with NF treatment [Fig 11a&b]. Zhu *et al*. (2014) also found that soil TOC and labile organic C fractions contents were significantly affected by straw returns, and were higher under straw return treatments than non-straw return at three depths. At 0–7 cm depth, soil MBC was significantly higher under plowing tillage than rotary tillage, but EOC was just opposite. Rotary tillage had significantly higher soil TOC than plowing tillage at 7–14 cm depth. However, at 14–21 cm depth, TOC, DOC and MBC were significantly higher under plowing tillage than rotary tillage except for EOC. The reason might be that rotary tillage and plowing tillage mixed crop straw into the deeper soil layer, making SOM well distributed at different depths Consequently, under short-term condition, rice and wheat straw both return in rice-wheat rotation system could increase SOC content and improve soil quality [Fig.12]. Naresh *et al*. (2017) reported that 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 and $KMnO_4C$ fractions compared with unfertilized control plots. Nevertheless, application of F_5 or F_6 significantly increased contents of POC and MBC relative to F_1 (by 49.6%and 40.9% or70.2% and 63.4%, respectively) (Table 3).

Table 3: Effect of 15 years of application of treatments on contents of various biological fractions of carbon in soil [Naresh *et al*., 2017].

Treatments	**0-5 cm layer**				**5-15 cm layer**			
	PMN ($mgkg^{-1}$)	**MBC ($mgkg^{-1}$)**	**MBN ($mgkg^{-1}$)**	**DOC ($mgkg^{-1}$)**	**PMN ($mgkg^{-1}$)**	**MBC ($mgkg^{-1}$)**	**MBN ($mgkg^{-1}$)**	**DOC ($mgkg^{-1}$)**
Tillage crop residue practices								
T_1	5.7^{c}	311.4^{c}	12.1^{cd}	153.5^{bc}	4.6^{cd}	193.9^{cd}	11.7^{de}	146.7^{cd}
T_2	$7.5b^{c}$	345.2^{bc}	17.9^{b}	176.9^{ab}	6.6^{bc}	219.8^{c}	16.3^{bc}	162.9^{bc}
T_3	10.6^{ab}	481.7^{a}	25.7^{a}	206.4^{a}	8.9^{ab}	294.8^{ab}	24.9^{a}	198.6^{a}
T_4	6.6^{c}	306.5^{c}	9.8^{de}	142.5^{cd}	5.6^{c}	187.5^{cd}	9.5^{ef}	137.6^{d}
T_5	9.3^{b}	398.6^{b}	14.9^{c}	164.1^{b}	7.5^{b}	240.9^{bc}	14.1^{cd}	151.2^{c}
T_6	12.4^{a}	535.8^{a}	20.3^{b}	197.6^{a}	11.2^{a}	361.8^{a}	19.6^{b}	178.6^{ab}
T_7	3.3^{e}	266.7^{c}	7.1^{e}	114.9^{d}	2.4^{d}	145.9^{d}	6.5^{f}	102.8^{e}
Nutrient Management Practices								
F_1	3.6^{e}	116.8^{c}	7.7^{d}	103.7^{d}	2.8^{d}	106.6^{d}	7.1^{d}	92.3^{d}
F_2	$8.9c^{d}$	239.9^{bc}	14.7^{cd}	136.4^{c}	7.4^{c}	196.8^{bc}	13.8^{bc}	119.6^{c}
F_3	9.8^{c}	280.7^{b}	16.1^{bc}	155.7^{bc}	8.2^{bc}	219.9^{bc}	15.9^{b}	126.4^{bc}
F_4	7.3^{d}	189.2^{c}	10.9^{de}	128.3^{c}	5.9^{c}	166.8^{cd}	10.3^{cd}	106.9^{cd}
F_5	14.6^{a}	424.1^{a}	26.2^{a}	189.8^{a}	12.8^{a}	324.9^{a}	25.6^{a}	161.9^{a}
F_6	12.5^{ab}	343.9^{ab}	22.4^{ab}	167.9^{ab}	10.4^{ab}	267.3^{a}	21.5^{ab}	142.3^{ab}
F_7	11.4^{bc}	341.7^{b}	19.1^{b}	160.6^{b}	8.9^{b}	260.3^{b}	17.9^{b}	131.1^{b}

Values in a column followed by the same letter are not significantly different ($P < 0.05$).
PMN = potentially mineralizable N, MBC = microbial biomass C, MBN = microbial biomass N, DOC = dissolved organic carbon



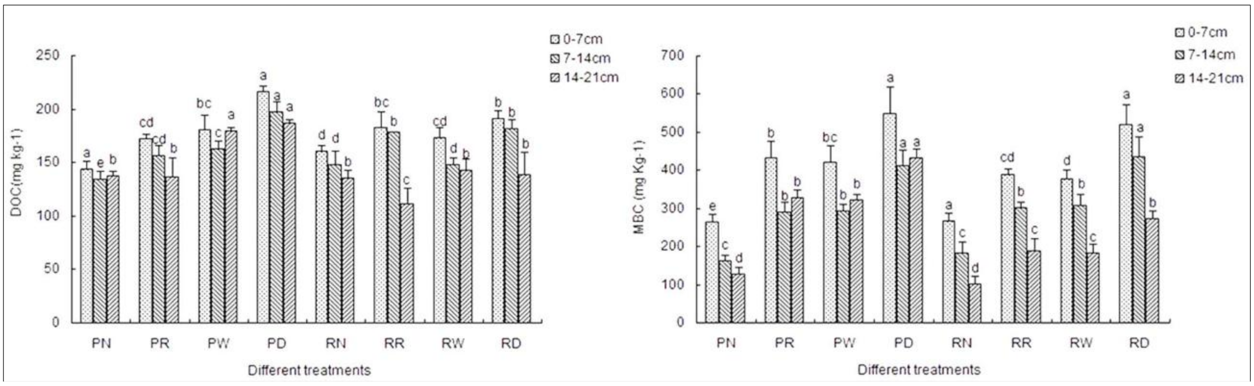


Fig 12: Effects of different tillage and straw treatments on soil TOC, and labile organic carbon fractions contents [EOC, DOC and MBC] contents at three depths.

Soil organic carbon stocks

The aggregate-size distribution and stability are important indicators of soil physical quality (e.g. soil structure, aggregation and degradation) (Shrestha *et al*., 2007). Tillage reduced the proportion of 2–0.25 mm aggregates in comparison with the conservation tillage treatments and there was a corresponding increase in the proportion of micro-aggregates (0.25–0.05 mm and/ or <0.05 mm fraction). Macro-aggregates are less stable than micro-aggregates, and therefore more susceptible to the disruption forces of tillage (Cambardella and Elliott, 1993). Six *et al*. (2000a) observed that the rate of macro-aggregate turnover was reduced under NT compared with CT. Zotarelli *et al*. (2005) reported that the MWD of the aggregates was on average 0.5 mm greater under NT compared with CT in the 0–5-cm depth interval in Oxisols. Zibilske and Bradford (2007) showed that plow tillage had significantly lower MWDs than no-tillage and ridge tillage at both 0–5- and 10–15-cm depths in a Higalgo sandly clay loam soil.

The reduction in macro-aggregates and MWD and GMD with CT could be mainly due to mechanical disruption of macro-aggregates from frequent tillage operations and reduced aggregate stability. Tillage increases the effect of drying–rewetting and freezing–thawing, which increase macro-aggregate susceptibility to disruption (Mikha and Rice, 2004). Furthermore, NT and ST had greater residue cover than CT, which promoted aggregation. Fresh residues are C source for microbial activity and nucleation centers for aggregation, and the enhanced microbial activity induces the binding of residue and soil particles into macro-aggregates (Six *et al*., 1999).

Venkanna *et al*. (2014) also found that the SOC stocks ranges from 22.68 to 94.83 Mg ha^{-1} with a mean of 52.84 Mg ha^{-1} in Alfisols, 34.37 to 73.67 Mg ha^{-1} with a mean of 51.26 in Inceptisols and 27.80 to 74.20 Mg ha^{-1} with a mean of 49.33 Mg ha^{-1} in case of Vertisols and associated soils. The SIC ranges from 4.14 to 25.54 Mg ha^{-1} with a mean of 12.39 Mg ha^{-1} in Alfisols, 7.23 to 34.17 Mg ha^{-1} with a mean of 17.47 Mg ha^{-1} in Inceptisols and 9.08 to 71.78 Mg ha^{-1} with a mean of 22.93 Mg ha^{-1} in Vertisols and Vertic intergrade. In most of the cases, surface SOC is greater than deeper layers, whereas the reverse trend is observed for SIC in most of the cases. Total carbon stock ranges from 30.81 to 116.42 Mg ha^{-1} (mean 65.24 Mg ha^{-1}) in Alfisols, 43.12 to 107.20 Mg ha^{-1} (mean 68.73 Mg ha^{-1}) in Inceptisols and 39.39 to 145.98 Mg ha^{-1} (mean 72.26 Mg ha^{-1}) in Vertisols and associated soils [Fig 13a]. Ratio of organic to total carbon stock is maximum in Alfisols followed by Inceptisols and Vertisols. Mazumdar *et al*. (2015) revealed that Concentration of C was higher in macro-aggregates as compared to micro-aggregates. Irrespective of treatments, C concentration was highest in 1-2 mm followed by 0.5-1mm size of macro-aggregates and the concentration decreased as the aggregates became smaller in size [Fig. 13b]. Incorporation of organic manures induces decomposition of organic matter where roots, hyphae and polysaccharides bind mineral particles into micro-aggregates and then these micro-aggregates bind to form C rich macro-aggregates. Naresh *et al*. (2018) showed that, soil organic carbon buildup was affected significantly by tillage and residue level in upper depth of 0-15 cm but not in lower depth of 15-30 cm. Higher SOC content of 19.44 g kg^{-1} of soil was found in zero tilled residue retained plots followed by 18.53 g kg^{-1} in permanently raised bed with residue retained plots. Whereas, the lowest level of SOC content of 15.86 g kg^{-1} of soil were found in puddled transplanted rice followed by wheat planted under conventionally tilled plots. Zero tilled residue retained plots sequestrated 0.91gkg^{-1}yr^{-1} SOC in the year 2015-16 which was 22.63% higher over the conventionally tilled residue removed plots after seven seasons of experimentation (Table 4).

Table 4: 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 [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}

****** Different letters within columns are significantly different at P=0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

There are five global C pools, of which the largest oceanic pool is estimated at38 000 Pg and is increasing at the rate of 2.3 Pg C yr^{-1} [Fig.13c]. The geological C pool, comprising fossil fuels, is estimated at 4130 Pg, of which 85% is coal, 5.5% is oil and 3.3% is gas. Proven reserves of fossil fuel include 678 Pg of coal (3.2 Pg yr^{-1} productions), 146 Pg of oil (3.6 Pg yr^{-1}of production) and 98 Pg of natural gas (1.5 Pg yr^{-1} of production; Schrag 2007). Thus, the geological pool is depleting, through fossil fuel combustion, at the rate of 7.0 Pg C yr^{-1}. The third largest pool is pedologic, estimated at 2500 Pg to 1 m depth. It consists of two distinct components: soil organic carbon (SOC) pool estimated at 1550 Pg and soil inorganic carbon (SIC) pool at 950 Pg.

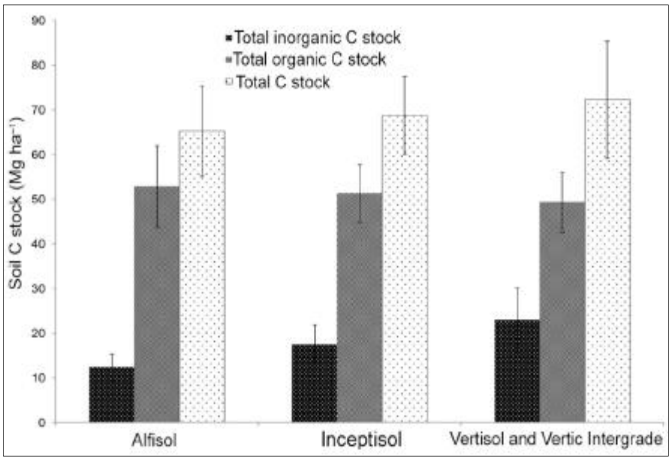


Fig 13a: Distribution of carbon stock (total, organic and inorganic) in Alfisols, Inceptisols and Vertisols and associated soils for 0–60 cm soil depth.

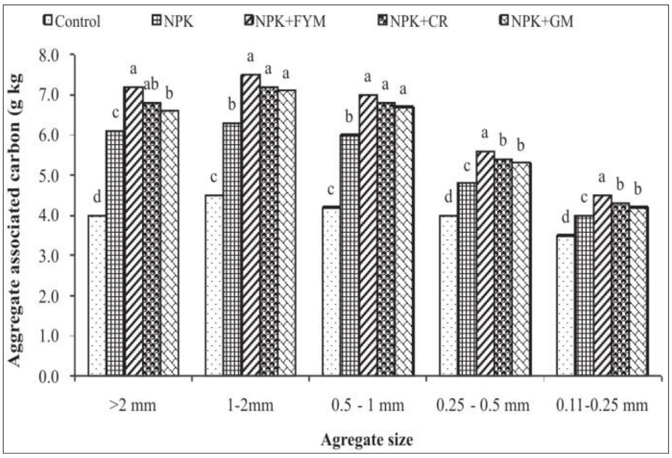


Fig 13b: Effect of long term integrated nutrient management practices on aggregate associated carbon in the soil

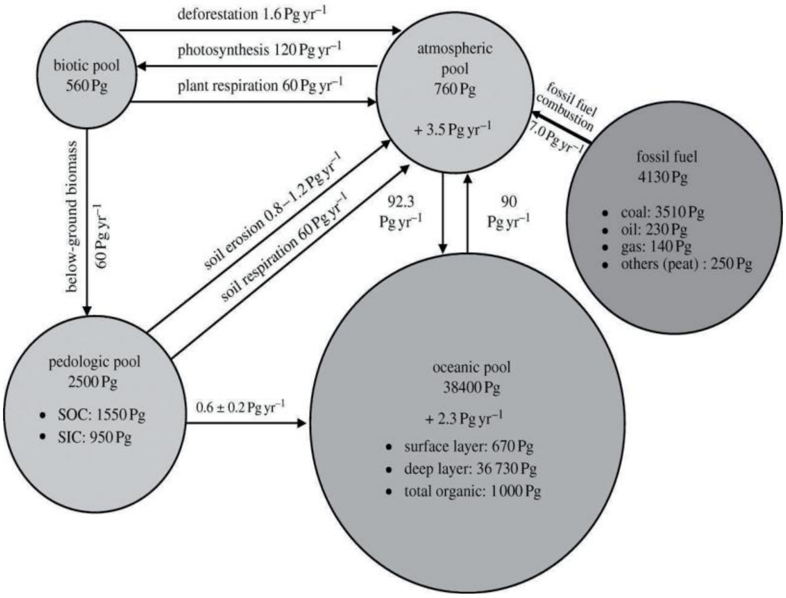


Fig 13c: Principal global C pools and fluxes between them

Saswat, (2014) found that Soil organic carbon status was seen declining with increase in soil depth. The average SOC amount was found to be 10.33, 8.73, 7.19 and 3.34 g kg^{-1} at soil depths of 0-15 cm, 15-30 cm, 30-45 cm and 45-60 cm after harvest of the crop. Treatment T$_5$ was found to have highest SOC in the upper most layer 11.80g kg^{-1}. Highest SOC stock and SOC sequestration rate were found in treatment T$_5$ (46.29 t ha^{-1} and 4.00 t ha^{-1} year^{-1}) (Table 5).

Table 5: Effect of organic nutrient management on soil organic carbon stock and carbon sequestration rate [Saswat Pradhan, 2014]

Treatments	**soil organic carbon content (g kg^{-1})**				**Soil profile organic carbon (g kg^{-1})**		**Total soil organic carbon stock (t ha^{-1})**			**Soil organic carbon sequestration rate (t ha^{-1} yr^{-1})**
	0-15 cm	**15-30 cm**	**30-45 cm**	**45-60 cm**	**0-15 cm**	**15-30 cm**	**0-15 cm**	**15-30 cm**	**Total**	
T_1	7.81	5.68	4.82	2.93	7.84	5.72	19.40	14.76	34.16	1.98
T_2	10.18	8.93	6.53	3.04	9.32	7.82	22.23	19.12	41.34	3.17
T_3	11.32	9.64	7.41	3.94	11.25	7.26	26.66	17.64	44.30	3.67
T_4	10.44	7.72	7.16	2.51	11.50	7.83	26.91	18.91	45.81	3.92
T_5	11.80	10.15	9.38	3.14	11.43	8.27	26.57	19.72	46.29	4.00
T_6	10.51	9.40	8.37	4.05	10.52	7.73	24.77	18.55	43.32	3.50
T_7	10.25	9.63	6.67	3.82	10.24	17.60	24.27	18.35	42.62	3.35
C.D.5%	-	-	-	-	1.58	1.13	1.275	0.96	3.86	0.81

Awale *et al.* (2013) revealed that compared with CT, ST and NT had significantly higher SOC concentration by 3.8 and 2.7%, SOC stock by 7.2% and 9.2%, CPOM-C by 22 and 25%, and $KMnO_4$-C by 4.8 and 4.1%, respectively in Expt2 and had significantly higher SOC concentration by 3.9 and 6.6%, SOC stock by 11.9 and 8.7%, and CPOM-C by 33 and 45%, respectively in Expt3. The $KMnO_4$-C and 30 d cumulative C_{min} were greater under ST than CT by 3.3 and 23%, respectively in Expt3. The amounts of C_{min} were consistently higher under ST and NT than CT throughout the incubation period except at 7 d, in Expt3. Across the study, CPOM-C was 16.3–22.1%, MBC was 3.4–4.5%, cumulative C_{min} was 0.7–1.4%, and KMnO4-C was 1.6–1.7% of the total SOC. Significant correlations were observed among SOC, CPOM-C and C_{min} in all the experiments. CPOM-C was the most sensitive fraction to tillage changes. Tillage influences on SOC fractions followed the order: physical (CPOM-C) > biological (cumulative C_{min}) > chemical ($KMnO_4$-C) [Fig.14].

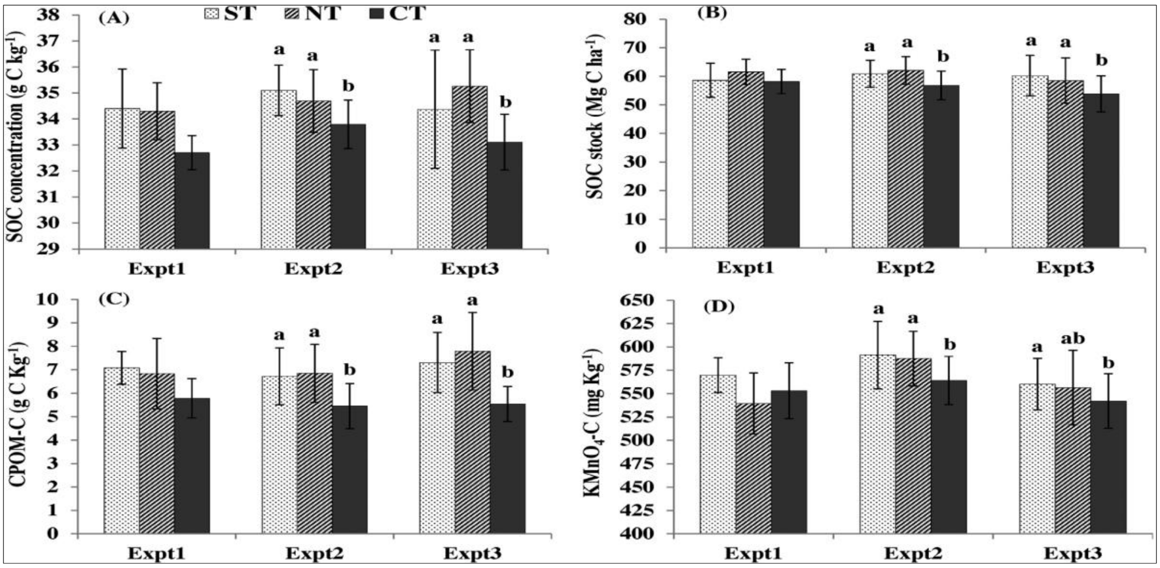


Fig 14: Effect of tillage practices (strip-till [ST], no-till [NT], and conventional till [CT]) on (A) SOC concentration (g kg^{-1}), (B) SOC stock (Mg ha^{-1}), (C) CPOM-C (g kg^{-1}), and (D) $KMnO_4$-C (mg kg^{-1}) within 0–15 cm soil depth

Enzyme activities

Soil enzyme activities may serve to indicate change within the plant-soil system, since these (1) are closely linked to the cycling of nutrients and soil biology, (2) are easily measured, (3) integrate information on both the microbial status and the physicochemical soil conditions, and (4) show rapid response to changes in soil management. The activities of enzymes are potentially sensitive indicators of changes in the components and contents of organic C in soils (Leinweber *et al.*, 2008). A cascade system of heterogeneous extracellular and intracellular enzymes controls the decomposition of organic C (Stemmer *et al.*, 1998). Therefore, measurements of the activity of soil enzymes can be used to evaluate the decomposition mechanisms, temporal patterns of microbial succession and C storage in soil (Fansler *et al.*, 2005).

Yu *et al.* (2012) reported that the mean recoveries of the enzyme activities in aggregates of the seven treatments were 90.8–102.2%, except β -glucosidase at 79.4%. Invertase activities in micro-aggregates were lower than that in macro-aggregates, the silt + clay fraction and soil in all treatments [Fig. 15a]. Long-term compost amendment led to a significant increase in invertase activities in soil, micro-aggregates and the silt + clay fraction, but not in macro-aggregates, compared with CK. The inorganic fertilizer amendment had a slight effect on invertase activities. The specific invertase activities in macro-aggregates and the silt + clay fraction were reduced by all fertilizer applications in comparison with CK. The compost and fertilizer NPK application decreased the specific activities of invertase in macro-aggregates by 59–66 and 39%, respectively.

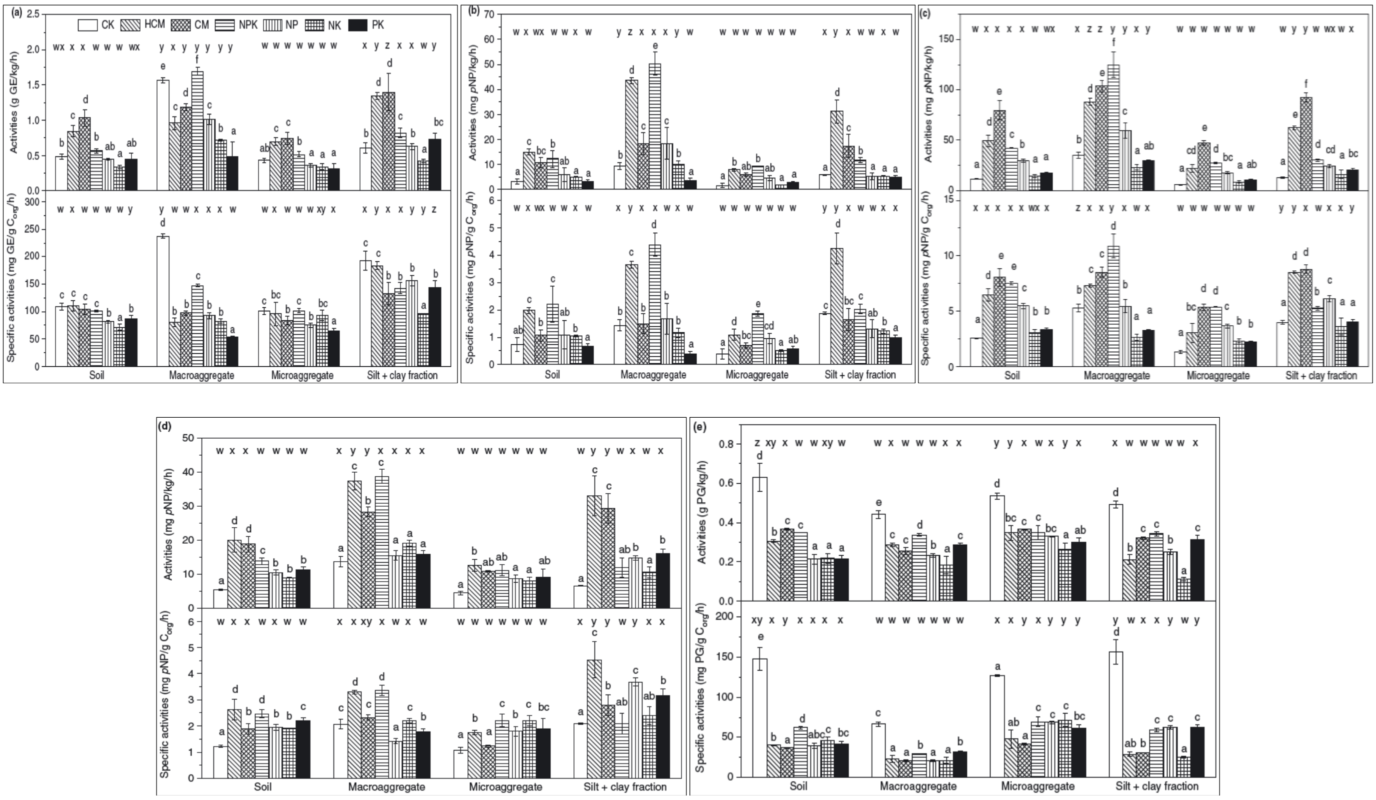


Fig 15: Compost and inorganic fertilizer effects on the activities of invertase (a), cellobiohydrolase (b), β -glucosidase (c), xylosidase (d) and polyphenol oxidase (e) in soil and aggregates

The activities of cellobiohydrolase and its specific activities were smaller in micro-aggregates than in macro-aggregates, the silt + clay fraction and soil [Fig 15b]. Compared to CK, the long-term application of compost, NPK and NP significantly increased the activities of cellobiohydrolase and its specific activities in all aggregates and soil. In macro-aggregates and micro-aggregates, the application of NPK had a more pronounced effect on the specific cellobiohydrolase activities than did compost. In all treatments, the lowest activities of β-glucosidase and its specific activities were in micro-aggregates [Fig. 15c]. Compared to CK, the long-term application of compost and inorganic fertilizers NPK and NP significantly increased the activities of β-glucosidase and its specific activities in soil and all aggregates.

The activities of xylosidase in both macro-aggregates and the silt + clay fraction were higher than in micro-aggregates in all treatments [Fig. 15d]. The long-term application of compost and NPK significantly increased xylosidase activities in soil, macro-aggregates and the silt + clay fraction in comparison with CK. The specific xylosidase activities were enhanced by the application of all the fertilizers in the silt + clay fraction. The NPK amendment had a more pronounced effect on the specific xylosidase activities than did compost in micro-aggregates.

The activities of polyphenol oxidase and its specific activities in micro-aggregates were slightly higher than in soil, macro-aggregates and the silt + clay fraction in all treatments except CK [Fig. 15e]. The long-term application of compost and inorganic fertilizer significantly reduced polyphenoloxidase activities in soils. The application of compost decreased the specific activities of polyphenol oxidase in soil, macro-aggregates, micro-aggregates and the silt + clay fraction by 73–75, 63–68, 62–67 and 80–82%, respectively, whereas the corresponding values were 58, 57, 45 and 62% in the NPK treatment.

Carbon sequestration implies not only increasing the amount of C entering in soil but also decreasing the amount leaving through decomposition and erosion. Attempts to sequester C can therefore, be divided in two distinct but interdependent phases. First phase involves conservation of on-site C by controlling deforestation and erosion and in second phase reclamation and rehabilitation of the degraded lands is carried out to improve growing conditions of plants using modern methods for enrichment of C in soil.

Lu *et al.*, (2014) recently concluded that biochar and residue amendment could enhance the readily oxidized C (measured by $KMnO_4$ oxidation). Zhang *et al.*, (2013a) found that RDN+FYM application resulted in more nitrate in the upper 1 m of soil profile. Further study about residue and RDN+FYM-induced changes in soil biota (i.e., enzyme, microbial community) regarding soil N transformation (nitrification, denitrification) is needed, because the activity of enzymes involved in the N cycle could potentially be linked to N_2O emissions (Wu *et al.*, 2013; Harter *et al.*, 2013). Srinivasan *et al.*, (2012) observed that SOC protection by soil aggregates, the newly added carbon provides physical protection and is then subjected to chemical conversion and structural stabilization; meanwhile, alternation of the properties and distribution of the carbon pool leads to both the diversification of aggregate-scale microbial habitats and the evolution of microbial biota, along with changes in various fertility service functions such as functional groups and enzyme activity, which promote the development of diverse biota and thereby stabilize ecosystem processes.

Bhatt *et al*. (2016) revealed that the dehydrogenase activity in soil due to different treatments ranged from 111.4 to 346.9 μg TPF g^{-1} 24 h^{-1} at harvest of rice and 156.5 to 360.9 μg TPF g^{-1} 24 h^{-1} at harvest of wheat. The dehydrogenase activity in soil significantly increased with increasing NPK levels from 50% to 100%. The application of 100% NPK + 15 t

FYM ha^{-1} further increased the dehydrogenase activity in soil giving significantly higher value over optimal (100% NPK) fertilizer level. Naresh *et al.* (2017) found that the ZT and PRB with 4 and 6 tha^{-1}residue retention increased the number of nitrifying bacteria at the milky stage by 38.7, 53.7 and 72.4% as compared to CT (conventional tillage), respectively. Compared to the ZT method, the PRB method reduced the number of denitrifying bacteria by 49.6, 14.9, and 13.8% under T_4, T_5, and T_6 at the jointing stage but did not significantly decrease it at the booting stage. However, the ZT method increased the number of denitrifying bacteria at the milky stage by 9.4, 15.7 and 19.7% under T_4, T_5, and T_6 methods. Naresh *et al*. (2018) reported that the jointing stage compared with CT, the ZT and FIRB treatments significantly increased nitrifying bacteria **[**Gn] by 77% and 229%, respectively. At the booting stage, the Gn rates in ZT and FIRB soils were 2.16 and 3.37 times greater than that in CT soil, respectively. At the milking stage, the Gn rates in ZT and FIRB soils were 1.96 and 3.08 times greater than that in CT soil, respectively. Similarly, [Table 6] shows the denitrifying bacteria [D] rates at jointing stage, in ZT and FIRB soils were 2.77 and 2.26 times greater than that in CT soil. At the booting stage, compared with CT, the ZT and FIRB treatments significantly increased D by 3.03% and 2.37%, respectively. At the milking stage, the ZT and FIRB treatments increased D by 3.39% and 2.95%, respectively. Significantly highest phosphatase activity of 33.90, 46.08, 24.65 µg of PNP g^{-1} soil h^{-1} was found at jointing, booting and milking stage of wheat in treatment F_5 (100%RDF + VC @ 5 t ha^{-1}). However, the values were on par with F_3 (50%RDF + VC @ 5 t ha^{-1}) and F_4 (75% RDF + VC @ 5 t ha^{-1}) and significantly different from all other treatments [Table 6]. Singh and Ghosal (2013) concluded that application of FYM and wheat straw along with inorganic fertilizer significantly increased the activity of alkaline phosphatase in 0-10 cm soil layer as compared with the application of inorganic fertilizer alone in a double no-till rice-wheat system. Mathew *et al*., (2012) reported that acid and alkaline phosphatase activity was higher under NT than CT soil at 0-5 cm soil depth in a long term tillage experiment in continuous corn system in a silt loam soil.

Table 6: Change in nitrifying and denitrifying bacteria and phosphatase enzyme activity in soil profile as affected by tillage crop residue practices and nutrient management practices [Naresh *et al*., 2018]

Treatments	Nitrifying bacteria ($\times 10^3$/g)			Denitrifying bacteria ($\times 10^4$/g)			Phosphatase (µg PNP g^{-1} h^{-1})		
	Jointing stage	Booting stage	Milky stage	Jointing stage	Booting stage	Milky stage	Jointing stage	Booting Stage	Milky stage
Tillage crop residue practices									
T_1	2.0 ± 0.4^{c}	4.2 ± 6.5^{a}	35.4 ± 4.1^{c}	35.6 ± 10.3^{cd}	42.0 ± 8.5 ^{c}	59.7 ± 5.3^{bc}	20.5± 4.1^{c}	34.8± 4.3^{cd}	16.1± 4.1^{c}
T_2	5.9 ± 1.0^{b}	7.2 ± 0.6^{c}	48.6 ± 9.2^{bc}	41.2 ± 8.8^{bc}	63.8 ± 10.7^{bc}	95.1 ± 20.6^{b}	24.9± 5.7^{cd}	46.3± 9.3^{a}	17.3± 8.5 ^{c}
T_3	6.5 ± 0.7^{b}	13.9 ± 1.3^{b}	64.3 ± 6.2^{b}	69.3 ± 6.6^{a}	110.8 ±10.7^{b}	137.1± 9.9^{a}	25.8± 6.6^{a}	49.1±10.7^{b}	17.9± 8.8^{bc}
T_4	3.9 ± 1.4^{bc}	11.6 ± 0.8^{bc}	48.2 ± 8.2^{bc}	23.8 ± 0.9^{d}	32.8 ± 2.4^{d}	57.3 ± 20.1^{a}	24.5± 5.7^{cd}	38.3± 8.4^{a}	21.3± 7.1^{a}
T_5	9.9 ± 0.7^{a}	19.6 ± 1.0^{b}	107.8 ± 4.1^{a}	34.5 ± 5.7^{cd}	54.3 ± 4.3^{cd}	82.2± 11.6^{a}	29.8± 8.8^{bc}	50.8± 9.9^{a}	27.1± 6.6^{a}
T_6	10.1 ± 1.7^{a}	19.9 ± 0.8^{b}	119.3 ± 8.4^{a}	60.9 ± 3.9^{ab}	82.5 ± 11.8^{b}	114.5 ± 9.3^{a}	31.2± 9.2^{bc}	52.3± 11.8^{b}	29.1± 10.3^{cd}
T_7	1.80± 0.6^{c}	3.9 ± 0.7^{c}	29.8± 3.4^{c}	17.6 ± 2.4^{c}	23.8 ± 3.9^{c}	28.7 ± 4.1^{c}	17.9± 3.9^{ab}	26.2± 3.4^{c}	15.7± 2.4^{c}
Fertilizer Management Practices									
F_1	3.06± 0.21	12.05 ±1.78	17.74 ±3.24	19.6 ± 2.6^{c}	21.8 ± 3.3^{c}	26.7 ± 4.1^{c}	20.65± 2.7^{a}	35.66±3.24^{c}	16.53±2.90^{b}
F_2	5.91 ± 0.13	14.08 ±1.84	22.02 ±2.70	44.2 ± 5.3	53.8 ± 7.7^{bc}	65.1 ± 9.6^{b}	24.30± 4.0^{b}	39.87± 6.2^{b}	19.85± 5.1^{a}
F_3	7.36 ± 0.22	15.36 ±1.29	24.48±3.84	56.3 ± 6.6^{a}	78.8 ±8.7^{b}	97.1± 9.9^{a}	32.75± 5.4^{bc}	44.97± 7.8^{bc}	22.54± 6.3^{bc}
F_4	4.55 ± 0.14	18.57±1.79	20.10 ±1.17	53.8 ± 5.9^{d}	62.8 ± 7.4^{d}	87.3 ± 8.1^{a}	27.92± 4.7^{a}	41.95± 6.6^{a}	21.48± 5.9^{a}
F_5	6.77 ± 0.15	16.54 ±2.18	23.39 ±1.01	74.5 ± 7.7^{cd}	84.3 ± 8.3^{cd}	92.2± 11.6^{a}	33.90± 5.6^{c}	46.08± 9.9^{a}	24.65± 7.6^{a}
F_6	8.92 ± 0.38	20.13 ±1.80	26.23 ±4.59	80.9 ± 8.9^{ab}	92.5 ± 9.8^{b}	98.5 ± 10.3^{a}	34.60±6.29^{a}	47.26±10.7^{b}	26.16± 8.3^{a}

****** Different letters within columns are significantly different at P=0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

Soil organic carbon pool

World soils contain about 3.2 trillion tons of carbon within the top six feet. An estimated 2.5 trillion tons is in the form of soil *organic* carbon. This is the organic matter in the soil that makes it fertile. The remaining 0.7 trillion tons is soil *inorganic* carbon. These are very large numbers. In fact the soil carbon pool is 4.2 times the entire atmospheric pool, and 5.7 times the biotic pool. Thus, even a relatively small increase in soil carbon, if it is taken from the air, could provide a significant reduction in atmospheric carbon. Moreover, because plants feed on carbon dioxide (CO_2) in the air, the primary way to store carbon in soil is to grow plants. Improved agriculture is the key to soil storage of carbon. Soil organic matter is concentrated in the upper 12 inches of the soil. So it is readily depleted by anthropogenic (human-induced) disturbances such as land use changes and cultivation.

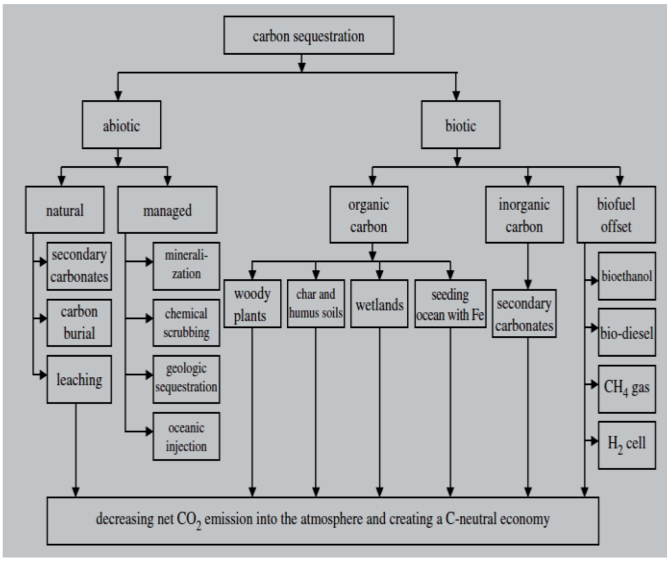


Fig 16a: A wide range of processes and technological options for C sequestration in agricultural, industrial and natural ecosystems.

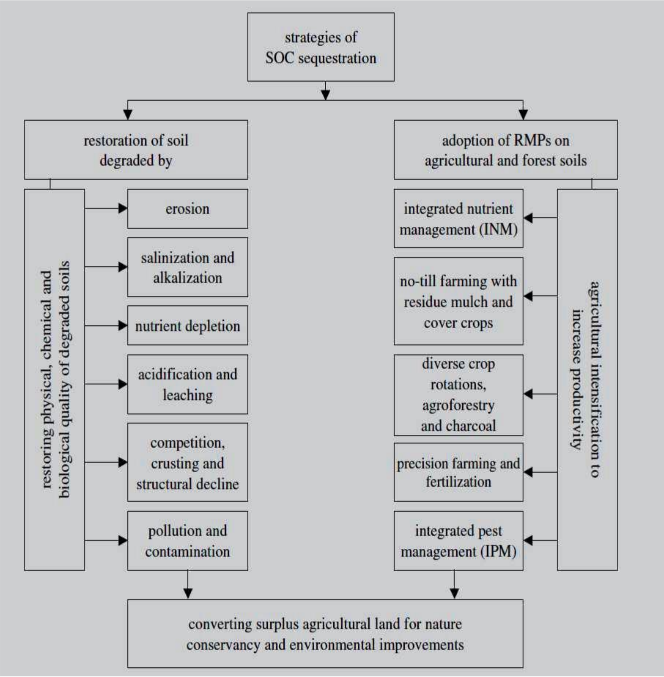
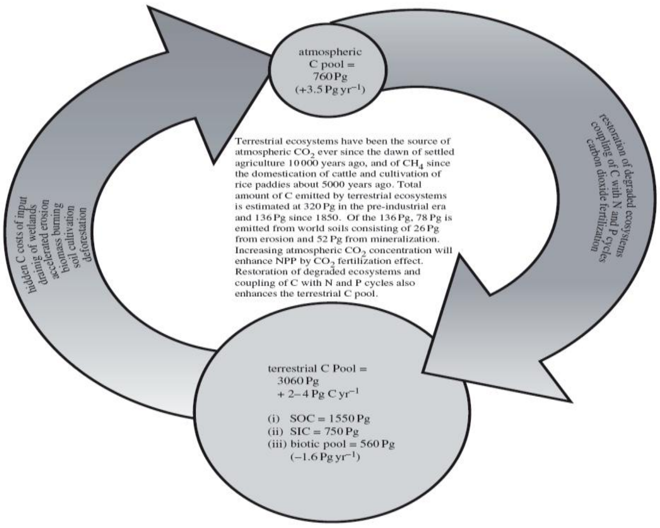


Fig 16b: Management strategies for soil carbon sequestration



Terrestrial ecosystems have been the source of atmospheric CO_2 ever since the dawn of settled agriculture 10 000 years ago, and of CH_4 since the domestication of cattle and cultivation of rice paddies about 5000 years ago. Total amount of C emitted by terrestrial ecosystems is estimated at 320 Pg in the pre-industrial era and 136 Pg since 1850. Of the 136 Pg, 78 Pg is emitted from world soils consisting of 26 Pg from erosion and 52 Pg from mineralization. Increasing atmospheric CO_2 concentration will enhance NPP by CO_2 fertilization effect. Restoration of degraded ecosystems and coupling of C with N and P cycles also enhances the terrestrial C pool.

Fig 16c: The atmospheric C pool is increasing at the rate of 3.5 Pg C yr^{-1}

There are several technological options for sequestration of atmospheric CO_2 into one of the other global pools [Fig.16a&b]. The choice of one or a combination of several technologies is important for formulating energy policies for future economic growth and development at national and global scales.

The smallest among the global C pools is the biotic pool estimated at 560 Pg. The pedologic and biotic C pools together are called the terrestrial C pool estimated at approximately 2860 Pg. The atmospheric pool is also connected to the oceanic pool which absorbs 92.3 Pg yr^{-1} and releases 90 Pg yr^{-1} with a net positive balance of 2.3 Pg C yr^{-1}. The oceanic pool will absorb approximately 5 Pg C yr^{-1} by 2100 (Orr *et al*. 2001). The total dissolved inorganic C in the oceans is approximately 59 times that of the atmosphere. On the scales of millennia, the oceans determine the atmospheric CO_2 concentration, not vice versa (Falkowski *et al*. 2000).The terrestrial C pool contributes approximately 1.6 Pg C yr^{-1} through deforestation, biomass burning, draining of wetlands, soil cultivation including those of organic soils, accelerated erosion and hidden C costs of input. Terrestrial C pools are presently sink of 2–4 Pg C yr^{-1}. Conversion to a judicious land use and adoption of recommended practices in managed ecosystems can make these important sinks especially due to CO_2 fertilization effects [Fig. 16c]. Venkatesh, *et al* (2013) reported that distribution of the carbon pool varied with depth and the size of the active carbon pool was larger than that of the passive carbon pool in the surface soil, whereas in the subsurface soil depth, the size of the passive carbon pool was larger than that of the active carbon pool. However, the total soil organic carbon, and 10 and 15% in soil microbial biomass carbon, respectively, as compared with a conventional maize-wheat system. Application of crop residues along with farmyard manure at 5Mg ha^{-1} and bio-fertilizers resulted in greater amounts of carbon fractions and higher carbon management index than in the control and the recommended inorganic (NPKSZnB) treatment (Fig.17]. Saikia *et al.* (2017) showed that puddled transplanted rice (PTR) with residue retention and zero tillage wheat with 100% residue retention ($ZTWR_{100}$) significantly increased oxidisable soil organic carbon in surface (0-7.5 cm) and sub-surface (7.5-15 cm) soil layer. Averaged across five wheat growth stages, oxidizable organic carbon increased by 50.1% in surface soil layer and 52.05% in sub-surface soil layer, as compared to PTR without residue and conventionally tilled wheat.

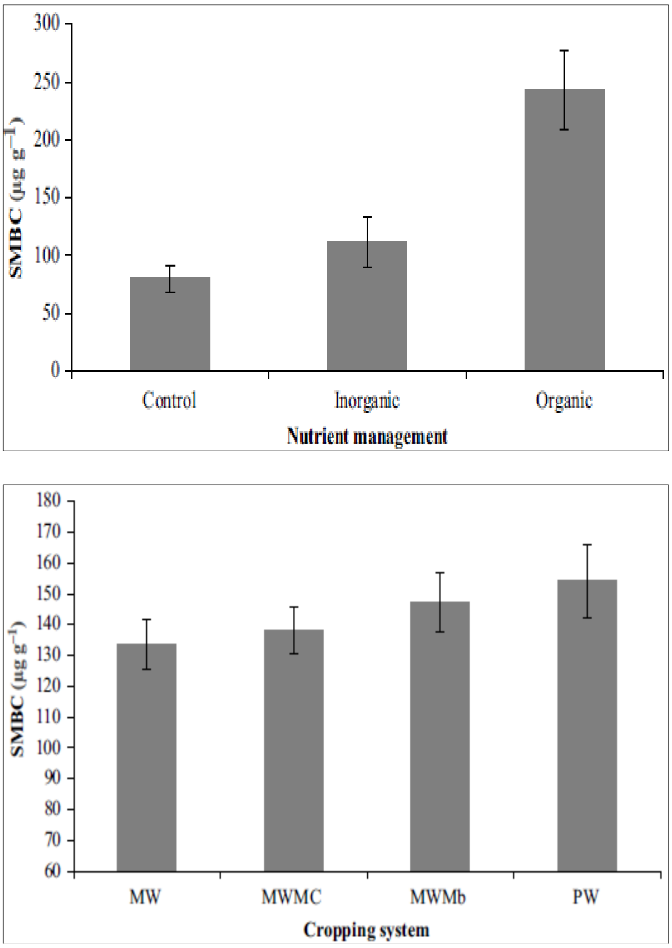


Fig 17: Soil microbial biomass carbon (SMBC) under different cropping systems and nutrient management practices at surface soil depth (0-0.2 m).

Potentially Mineralisable C and N

The amount of mineralisable organic matter in soil is an indicator of organic matter quality, acting as the interface between autotrophic and heterotrophic organisms during the nutrient cycling process (Gregorich *et al*. 1994) [27]. While potentially mineralisable C and N may be measured in both the field and laboratory, it is generally treated as a relative rather than an absolute value due to inconsistencies in methods (Haynes 2008). However, mineralisable organic matter may be a useful indicator to assess soil health under climate change, since it affects nutrient dynamics within single growing seasons, and may be used to compare management regimes and C sequestration over extended periods of time (Gregorich *et al*. 1994) [27]. Ali and Nabi, (2016) reported that the highest peaks for CO_2–C occurred during the first week of the incubation period. Significantly higher emission of CO_2–C occurred from rice and wheat incorporation treatments (50%) followed by surface application treatments (19%) as compared to control soil [Fig. 18a]. 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 [Fig. 18b]. Incorporated residues increased soil organic carbon and soil aggregate stability significantly by 18% and 55% over control respectively [Fig.18c].

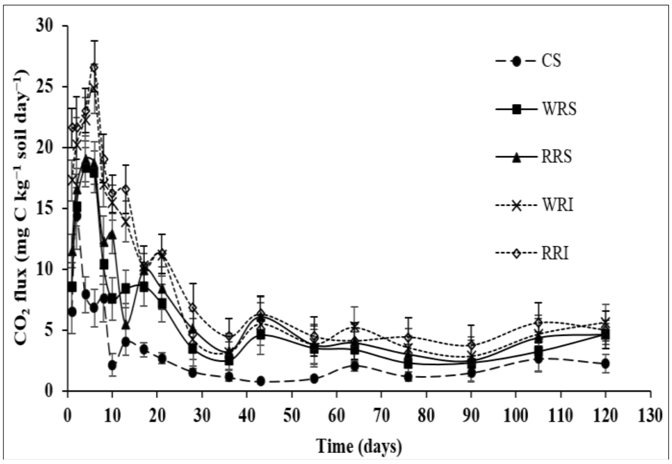


Fig 18a: CO_2–C flux from rice and wheat residues under different crop residue applications to soil.

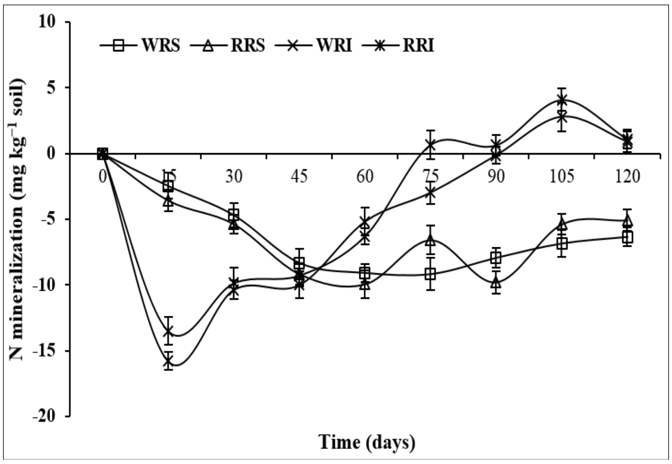


Fig 18b: N mineralization from rice and wheat residues under different crop residue applications to soil.

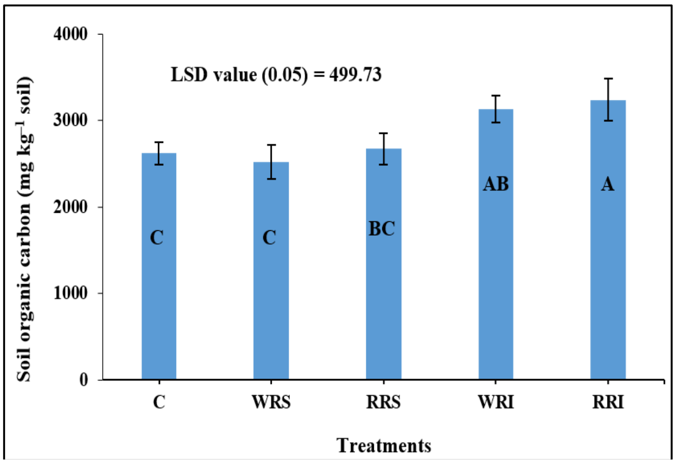


Fig 18c: Soil organic carbon under rice and wheat residues with their different applications to soil.

Where CS, control soil; WRS, wheat residue surface applied; RRS, rice residue surface applied; WRI, wheat residue incorporated; RRI, rice residue incorporated.

A greater SOC accumulation between and within the aggregates occurs, which is evident from significantly higher POM-C under ZT than CT plots (Bhattacharyya *et al*., 2012). Green manuring along with ZT resulted in the highest POM-C, which were 52.7% greater than ZT without residue retention (Dey *et al*., 2016). The SMB-C has been generally greatly affected by tillage and residue management practices with values as high as 232 and 123% in the 0–5 and 5–10 cm soil layers, respectively, under CA compared with CT (Liu *et al*., 2014).

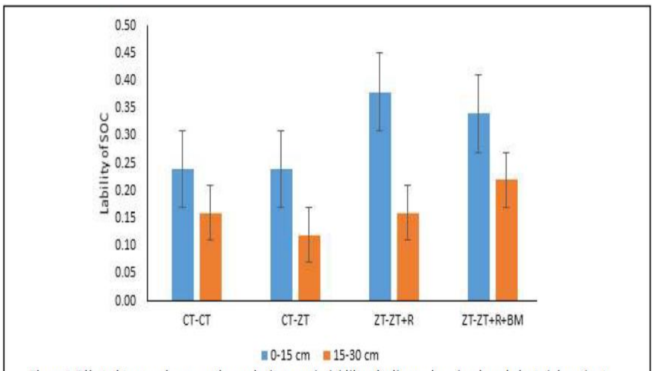


Figure 1. Effect of 6 years of conservation agriculture on the lability of soil organic carbon in an irrigated rice-wheat system of eastern Indo Gangetic Plains (Dey, 2016). Error bars represent least significant difference at $p < 0.05$.

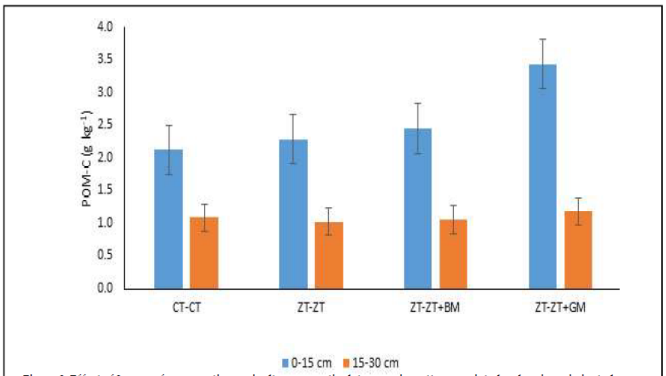


Figure 2. Effect of 2 years of conservation agriculture on particulate organic matter associated carbon in an irrigated RW system of north-western IGP (Dey et al., 2016). Error bars represent least significant difference at $p < 0.05$

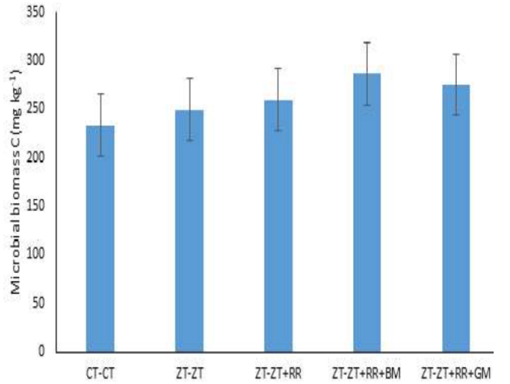


Figure 3. Effect of 2 years of CA on SMB-C in an irrigated RW system of north-western IGP (Dey et al., 2016). Error bars represent least significant difference at $p < 0.05$.

Banger *et al*. (2010) revealed that compared to the control treatment, the increase in SOC was 36, 33, and 19% greater in organic, integrated, and NPK treatments. The much greater changes in water soluble C (WSC), microbial biomass C (MBC), light fraction of C (LFC), and particulate organic matter (POM) than SOC. Of the SOC, the proportion of POM was highest (24–35%), which was followed by LFC (12–14%), MBC (4.6– 6.6%), and WSC (0.6–0.8%). The application of fertilizers and/or FYM helps to sequester C in the soil and that can be used as indicators to determine the amount of C sequestered as a result of different management practices [Fig.20a&b].

Bhaduri and Purakayastha, (2014) reported that puddling and irrigating rice after three days of drainage and using no tillage and two irrigations for wheat emerged as promising management for improved soil quality. Applying 25% of the recommended fertilizer N dose using farm-yard manure (FYM) for rice and domestic sewage sludge for wheat also improved soil quality [Fig.21]. Lal, (2004b) [42] reported that off-site, mulch farming through residues retention and a NT system improve quality of water and air through reduction in erosion, non-point source pollution, sedimentation, and transport of pollutants into the water bodies and aquatic ecosystems. Furthermore, reduction in frequency and intensity of floods causes minimal damages to infrastructure. Productivity of aquaculture and agricultural systems in the flood plains is improved because of less runoff of water, sediments and pollutants. In essence, retention of residues promotes sustainable land because of positive impacts on the environment and ecosystem services (Fig. 22a). Lal and Pimentel, (2007) revealed that there are numerous direct and indirect adverse impacts of residue removal on ecosystem services, including depletion of the SOC pool (Fig. 22b). Important among direct impacts of residue removal are low input of biomass C, reduction in nutrient/elemental cycling, decrease in food/energy source and habitat for soil biota along with the attendant decline in soil quality.

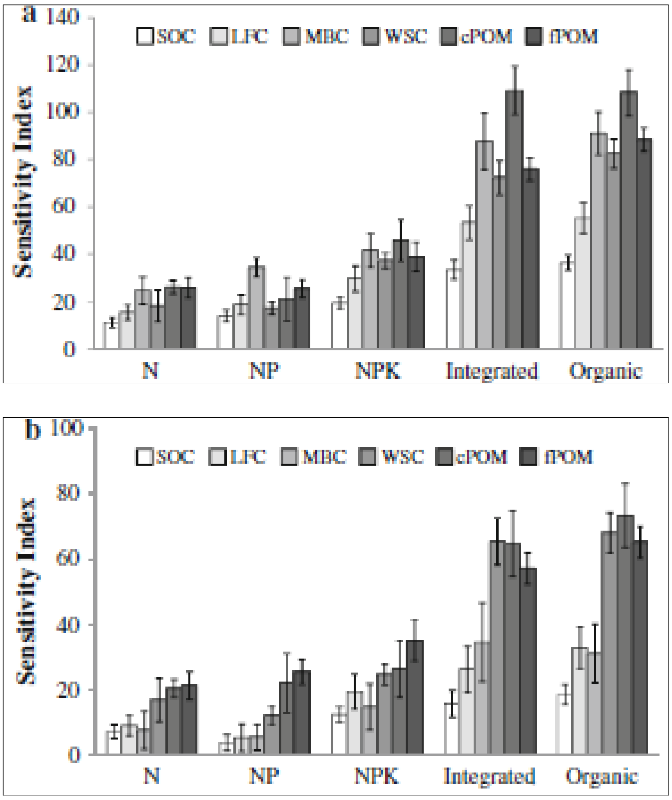
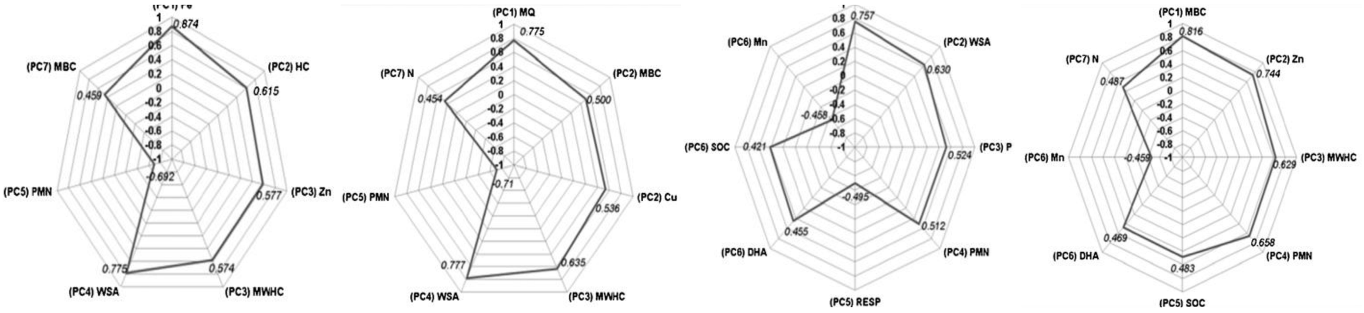


Fig 20: [a] Comparison of the effect of treatments on sensitivity of C fractions at 0–15 cm depth of the soil. **[b]** Comparison of the effects of treatments on sensitivity of C fractions at 15–30 cm of the soil



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

Fig 21: Soil quality indicators under (a) Productivity (P) and (b) Environmental Protection (EP) goal after harvest of rice; (c) Productivity and (d) Environmental Protection (EP) goal after harvest of wheat.

Crop residue and soil carbon

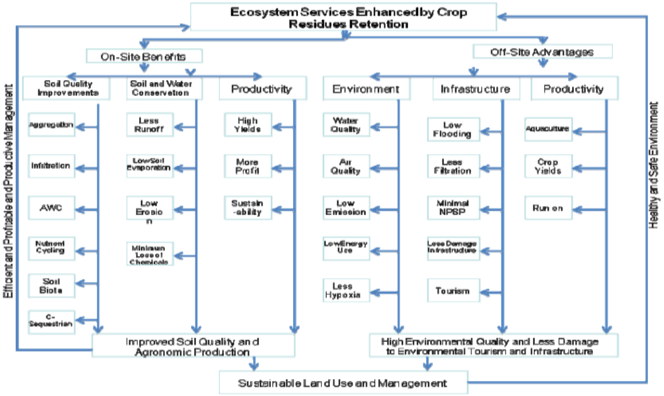


Fig 22a: Agronomic productivity and environmental quality impacts of crop residues retention (AWC = available water capacity, NPSP = non-point source pollution).

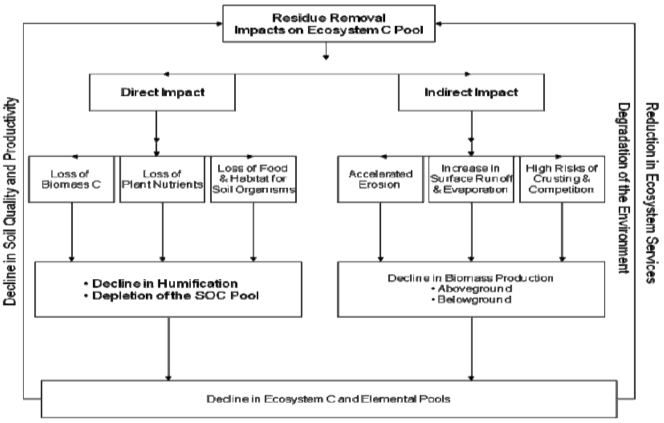


Fig 22b: Adverse impacts of crop residues removal on depletion of the ecosystem carbon pool, decline in ecosystem services, and degradation of the environment.

Jiang *et al*. (2014) revealed that the conversion rate of plant residues to SOC was higher in single-cropping sites than in double-cropping sites. The prediction of future SOC sequestration potential indicated that these soils will be a net source of carbon dioxide (CO_2) under no fertilizer inputs. Even when inorganic nutrients were applied, the additional carbon input from increased plant residues could not meet the depletion of SOC in parts of northern China. Manure or straw application could however improve the SOC sequestration potential at all sites. The SOC sequestration potential in northern China was estimated to be -4.3 to 18.2 t C ha^{-1} by 2100 [Fig.23 a, b & c].

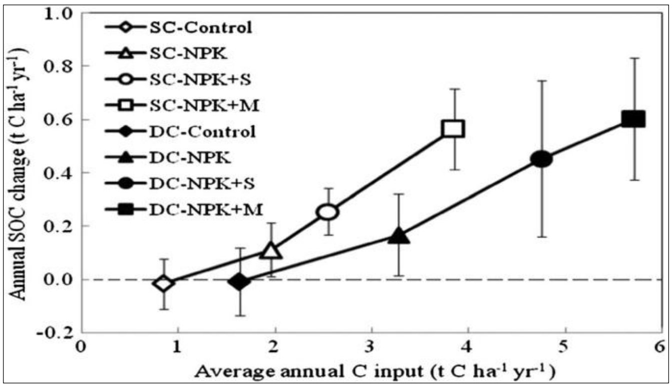


Fig 23a: Comparison of the annual rate of SOC change between single cropping sites and double-cropping sites under different fertilizer treatments from 1979–1990 to 2001–2008.

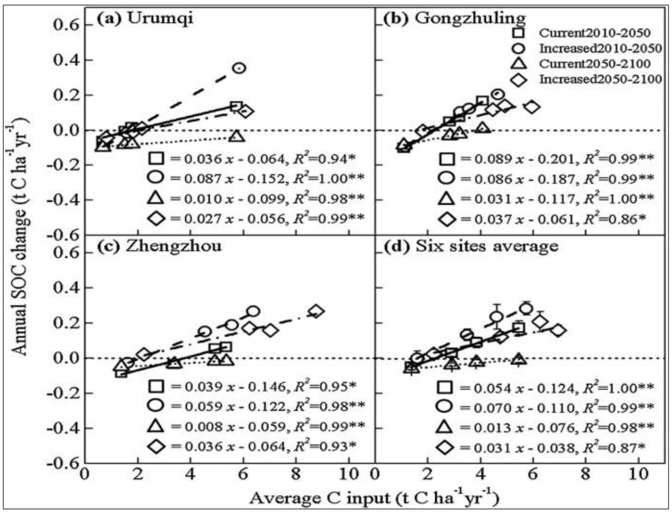


Fig 23b: Annual soil organic carbon (SOC) change between 1990 and 2100 upon the average carbon input rate to soil (1990–2010 data) for each fertilizer treatment where (a and c) total annual SOC change and (b and d) normalized annual SOC change or where (e and f) the total SOC change and normalized annual SOC change.

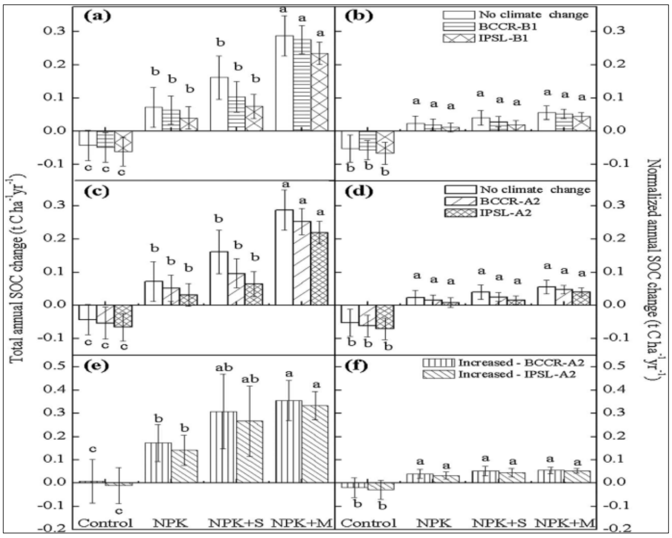


Fig 23c: Comparison of annual soil organic carbon (SOC) change during 2010–2050 and 2050–2100

The significantly highest SOC content (0.87%) was found in minimum tillage (MT) and three crop (rice, wheat and mung bean) residues retention combination whereas the lowest 0.44% SOC content was obtained in combined treatment of (deep tillage) DT with no crop residues retention. The increase of SOC might be due to slow decomposition of high amount of residue retained on soil under MT (Alam *et al*., 2017). The increase of N content in soil suggests N-supplying capacity of soil which can be improved by returning straw to the soil and reducing tillage operation (Malhi *et al*., 2011). Adoption of reduced tillage, fertilization and crop diversity can increase organic N and mineralizable N stored in the soil (Das *et al*., 2016), thus improving soil fertility and nutrient supplying capacity of soil.

Conclusion

The application of fertilizers and/or FYM resulted in greater C sequestration in semi-arid agricultural soils.

The accumulation of SOC was greater in the surface layer of the soil as compared to subsurface layer due to the greater accumulation of the organic residues and external additions of organic matter at the surface layer. The integrated and organic treatments significantly increased the SOC fractions as compared to the chemical fertilizers alone. This suggests that the inclusion of organic manures in fertilization programs can enhance C sequestration in soils.

long-term application of organic manure and inorganic fertilizer increased the content of SOC. SOC concentrations and storage were highest in surface soil and depth interval down to 30 cm under 50% RDF +VC @ 5tha^{-1} and 100% RDF+ VC @ 5tha^{-1}, below which concentrations did not change with depth. At the same time, on average the estimate of soil C storage to 30 cm depth was higher than that for soil C accumulated to 15 cm depth. These findings suggest that the estimate of soil C accumulation to 30 cm depth was more effective than that for soil C accumulated to 15 cm depth. 50% RDF +VC @ 5tha^{-1} were the most efficient management system for sequestering SOC. A large amount of C was also sequestered in soil under 100% RDF+ VC @ 5tha^{-1} treatment. Soil microbial biomass C, POC, $_{c}$POM and $_{f}$POM were all significantly greater under organic manure plus inorganic fertilizers, especially in the surface. The labile fraction organic C contents decreased significantly with increasing soil depth. These labile pools were highly correlated with each other and SOC, indicating that they were sensitive to changes in SOC.

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