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Clay-humus stability of soil organic matter and microbial biomass under conservation tillage and residue management practices of rice-wheat cropping system: A review

RK Naresh, RK Gupta, SS Dhaliwal, Kanti Tyagi, Saurabh Tyagi, KS Krishna Prasad, Lali Jat and Prachi Tyagi

RK Naresh
Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

RK Gupta
Borlaug Institute for South Asia (BISA), New Delhi, India

SS Dhaliwal
Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab, India

Kanti Tyagi
Syngenta India Ltd. North SBU Office Chandigarh, India

Saurabh Tyagi
Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

KS Krishna Prasad
Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Lali Jat
Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Prachi Tyagi
Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Correspondence
RK Naresh
Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

Abstract

Soil tillage can affect the stability and formation of soil aggregates by disrupting soil structure. Frequent tillage deteriorates clay-humus stability of soil organic matter and microbial biomass causing them to be susceptible to decay. Different types of tillage systems affect soil physical properties and organic matter content, in turn influencing the formation of aggregates. The objective of this review paper was to evaluate the effect of conventional tillage on clay-humus stability of soil organic matter and microbial biomass, soil aggregates and aggregate associated carbon in an inceptisol of western Uttar Pradesh, India under rice-wheat cropping system and to identify the optimal conservation tillage and residue management practices in this system. Moreover, irrespective of tillage practices, residue retention resulted in 22.56% and 25.61% higher WSC as compared to the non-residue treatments in surface and sub-surface soil, respectively. Residue incorporation increased the SOC stock by 3.1Mgha–1 or 6.8%. Average annual SOC sequestration was 78 kg ha^{-1} year^{-1}. The average difference in C input due to residue incorporation was 2.3Mgha^{-1} year^{-1}. The MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 100% RDN as CF+ VC @ 5tha^{-1} and 75% RDN as CF+ VC @ 5tha^{-1} treated plots compared to 100% RDN as CF fertilizer and unfertilized control plots. 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 and 6 tha^{-1} residue retention and CT treatments.

SOC storage decreased with soil depth, with a significant accumulation at 0-20cm depth. Across treatments, aggregate-associated C at a depth of 0–10cm was higher in the conservation agriculture (CA) treatment than in the conventional tillage (CT) treatment. The advantage of the CA treatment weakened with soil depth, while the amount of aggregate-associated C remained higher for the CT treatment. There were more macro-aggregates in the CA treatment than in the CT treatment, while CT treatment had more micro-aggregates. The sum of macro-aggregate contributing rates for clay-humus stability of soil organic C (SOC) was significantly superior to that of the micro-aggregates. Water-stable aggregates increased by 34.5% in the CA with residue retention treatment, effectively improving the soil structure. Furthermore, 0.25–1.00 and 1–2mm aggregates had the highest SOC microbial biomass storage and responded rapidly to the various tillage treatments. Hence, they can serve as indicators for the long-term influence of different tillage treatments on the distribution of aggregates and clay-humus stability of SOC.

Keywords: soil tillage; fertilization; humic substances, soil organic matter, SOC storage

Introduction

A key element of soil quality is soil organic matter (SOM) (Reeves 1997) [66]. The content of SOM is the result of a balance between the processes of miner- alisation and humification. Changes in the landscape related to tillage and land use significantly affect the carbon cycle at the regional level as well as globally (Lal 2002) [49]. The rate of SOM decline varies depending on the soil type, tillage, crop and climate system (Derpsch *et al.* 2014) [18]. As mentioned earlier, agro-technical operations and environmental changes modify the amount and turnover of SOM. Accumulation and distribution of organic C in soil is affected by different tillage practices and time after initiation of tillage. Generally, intensive tillage systems are the main reason of SOM decline (Norton *et al.* 2012; Khorramdel *et al.* 2013; Naresh *et al.*, 2015) [63, 44, 59].

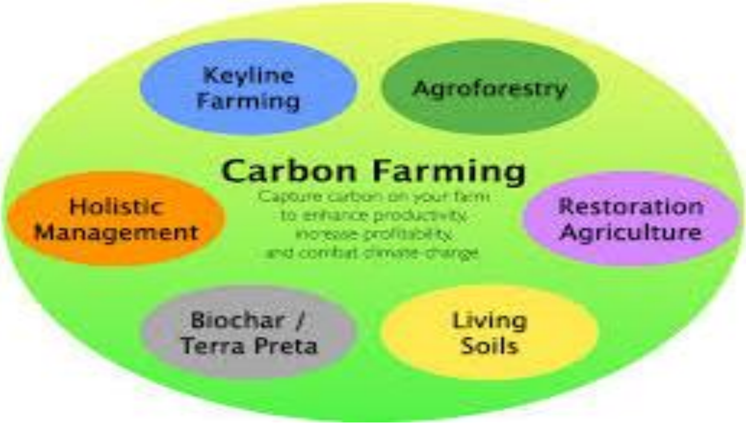
Crop residue retention is also important for sequestering soil organic carbon (SOC), controlling soil erosion and improving soil quality (Blanco-Canqui & Lal 2007). Mineral fertilizers can also improve residue quantity and quality, but this does not necessarily increase the SOC pool. However, fertilizers may also decrease SOC concentration when compared to unfertilized soil (Halvorson *et al.* 2002) [32]. Improving the quantity and quality of SOM in arable soils is important if requirements of sustainable agriculture are to be satisfied.

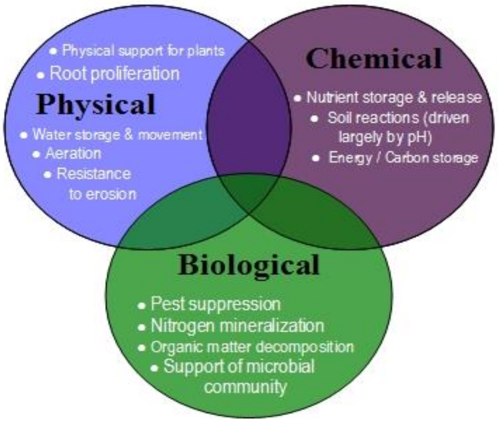
Agricultural SOC accumulation is influenced by numerous factors, such as tillage practices (Liu *et al.*, 2014) [54], soil aggregate size (Zhang *et al.*, 2013; Devine *et al.*, 2014) [88, 19], and microbial functional diversity (Gathala *et al.*, 2011) [29, 48]. Tillage practices can affect the stability or composition of SOC (Devine *et al.*, 2014) [19], and thus affect SOC concentration and SOC density of the plough layer. Conventional intensive tillage (CT) can decrease soil aggregate stability and accelerate soil organic matter oxidation thereby threatening sustainable crop production Mathew *et al.* (2012) [56]. Conservation tillage significantly reduces soil physical disturbance Uri, (1999) [82], promotes soil aggregation, and improves soil microorganism dynamics because of more beneficial environmental conditions (Guo *et al.*, 2015) [31]. Therefore, investigating the effects of conservation tillage on SOC is necessary for further understanding soil sequestration. Zhang *et al.* (2013) [88] also reported that previous studies mainly focused on the effects of microorganisms on the vertical and horizontal orientations of soil profiles and ignored the effects on the micro-spatial dimension of soil physical structure. Therefore, investigation of SOC driven by soil microbial community processes within soil aggregates will help elucidate the regulation of soil biota in soil C storage.

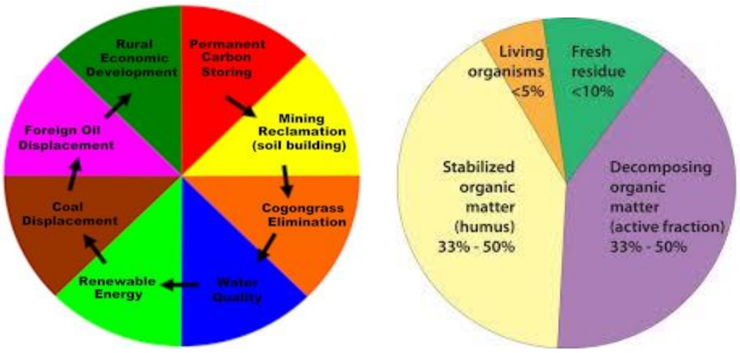
Farming systems significantly affect not only the quantity, but also the quality of soil organic matter (Tobiašová 2012). The SOM on an average contains 30% labile and 70% stable components, however, the values are not rigid and these may vary from soil to soil and are influenced by management history (Schnitzer 1991) [69]. The quantity as well as stability of SOC has tremendous implications on long-term storage of SOC for carbon sequestration. The chemical, biochemical, physical and thermal stability of SOC ultimately enhances its mean residence time (MRT) in soil. It is suggested that low quality organic carbon is related to the strong chemical inter-molecular interactions of organic carbon with reactive mineral phases (Wiaux *et al.*, 2013; Naresh *et al.*, 2017) [60]. Amorphous and poorly crystalline mineral components have a high chemical capacity to establish covalent links with organic matter (Kleber *et al.*, 2007) under the form of mineral protected organic carbon (Mikutta *et al.*, 2005) [57].

Soil microorganisms significantly affect the health of an agro-ecosystem through their functions in residue decomposition and nutrient cycling, as well as their associations with other organisms Dong *et al.* (2014) [21]. The activities and compositions of soil microbial community and their interactions with environmental factors affect SOC dynamics and crop productivity (Dong *et al.*, 2014) [21]. Direct measurements of metabolic diversity of soil microbial communities are likely to provide more relevant information regarding soil functions compared with measurements of species diversity Giller *et al.* (1997) because soil micro-organisms generally present in resting or dormant stages, in which they are not functionally active White and MacNaughton, (1997) [54]. Biology system, a rapid community-level approach for assessing patterns of sole C source utilization, is used to study microbial community metabolic activities (Nautiyal *et al.*, 2010) [61]. Several studies used the biology system to differentiate microbial communities from diverse habitats (Nautiyal *et al.*, 2010) [61]. However, only a few these studies determined the relationship between soil microbial metabolic activities and SOC, especially within aggregates, in rice–wheat cropping systems.

The effects of conservation tillage on rice–wheat cropping systems are well demonstrated (Guo *et al.*, 2015; Kumari *et al.*, 2011; Naresh *et al.*, 2012) [31, 58]. However, limited attention has been given to the relationship between SOC and microbial metabolic characteristics within aggregate fractions under conservation tillage in the rice–wheat system. Thus, this paper reviewed that (1) microbial metabolic activity is improved by conservation tillage at the small-scale in soil in the plow layer, and (2) the microbial metabolic activity is correlated to SOC within aggregates under conservation tillage. Conceicao *et al.* (2005) [15] investigated soil tillage and cropping systems in the Alfisol and reported that the use of NT and crop rotation for 15 years results in the highest soil quality in relation to other treatments. In our study, treatments with frequent tillage operations and a lack of crop rotation had the lowest CPI [Fig. 1b]. Under NT, the CPI values were 0.91 to 0.98 in R_0 and R_2, respectively, representing an increase of 7.1% which was statistically different [Fig. 1b]. Therefore, CT neglected the impact of crop rotation on the CPI index, while under NT the intensified cropping system resulting in the highest CPI. Previously, Amado *et al.* (2006) [2] studied C-sequestration rates under tillage and crop systems and reported that CT negates the crop rotation effect.

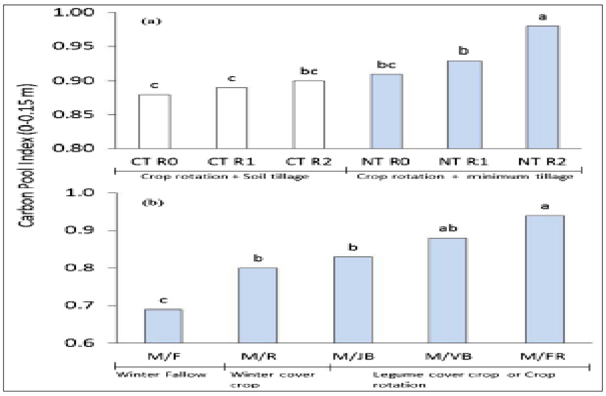






(a)

Fig 1(a): Carbon stock recovery in extra-large Macro-aggregates (8–19 mm) within the 0–20 cm soil depth



(b)

Fig 1(b): Soil quality in response to improvements on soil management and crop rotation systems. (a) Oxisol; (b) Alfisol. CT = conventional tillage; NT = no-tillage.

Ingram and Fernandes (2001) [39] also found that the soil type, rainfall and temperature limit the amount of soil organic matter generated via plant biomass and subsequently stored as humus for the long term. As a result, soils rarely reach their theoretical potential for organic matter storage [Fig. 2a]. Management practices also have a significant influence on whether actual soil organic matter (and carbon) reaches its attainable level as determined by climate [Fig. 2a]. To maintain or increase a soil's stock of organic carbon long term, increased amounts of organic matter must be continually added. Any decline in the amount of organic material being returned to soils will result in a decrease in the soil's organic carbon content.

Hoyle *et al.* (2011) [38] reported that a more rapid turnover of SOC occurs in soils with little or no clay content; hence it is more difficult to increase the SOC content of coarse-textured, sandy soil from crop residues alone. An example of the influence of clay content on SOC is demonstrated in [Fig. 2b]. This shows the range of SOC values measured under a cereal–legume rotation, where the clay content varied from 3% to 52%. Soil organic carbon values increased with clay content, over a fivefold range in values (min. 0.7%, max. 3.4%), reflecting differences in the amount of plant growth as well as physical protection as clay content increased.

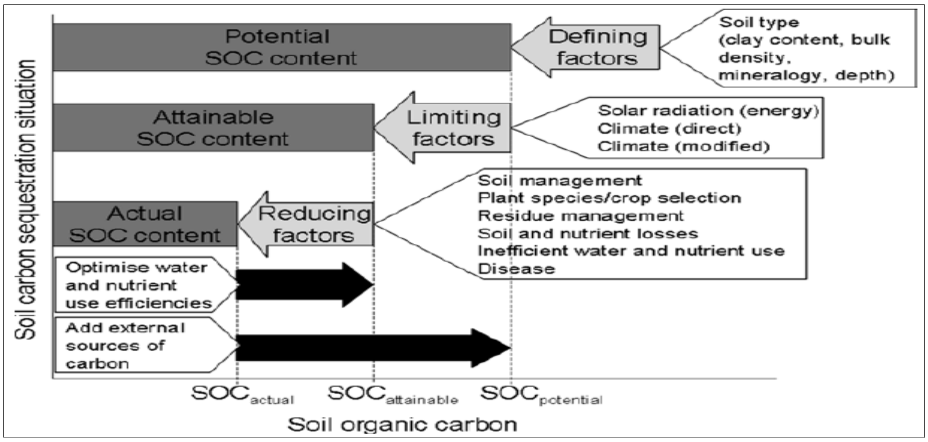


Fig 2(a): The influence of soil type, climate and management factors on the level of soil organic carbon (SOC) that can be attained in a given soil

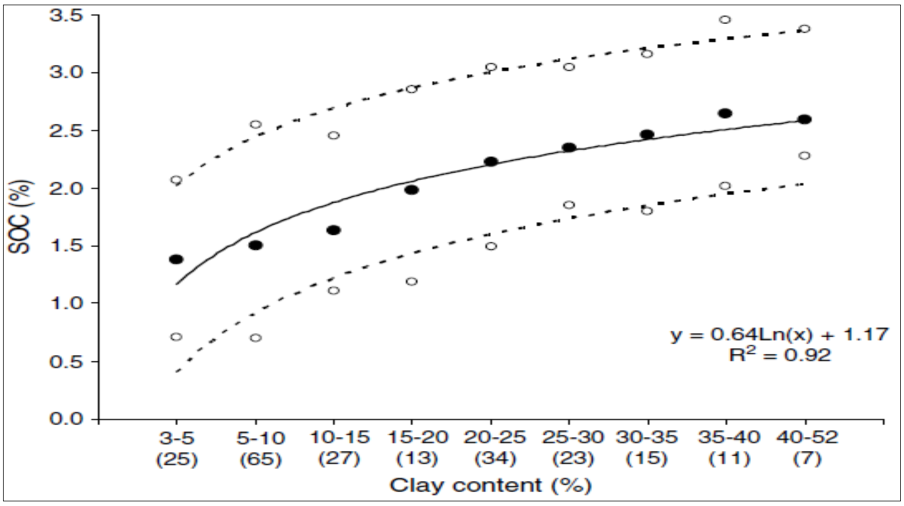


Fig 2(b): Influence of clay content on the range of soil organic carbon (SOC)

Shen *et al.* (1989) also found that Soil organic carbon exists in a range of different types of materials that vary in size, chemical composition, stage of decomposition and age. Newly incorporated organic material is approximately seven times more decomposable than inherent SOC. However, inherent SOC is usually a much larger pool (15–225 t C/ha for the 0–30 cm soil layer). Though the decomposition rate of inherent SOC may be low, it can result in significant mineralisation of both carbon and nutrients [Fig.3a]. A number of SOC fractionation schemes are in use and these differ in the means by which separate components of SOC are recovered. One such fractionation scheme [Fig.3a] involves the separation of SOC based on different size classes and chemical composition.

Hoyle *et al.* (2011) [38] revealed that the clay particles provide a large surface area for cation exchange, which renders soil organic matter increasingly less important as clay content increases. By comparison, humus can be seen to be equally important for the provision of nutrients across all soil types and in particular it is critical to the supply of potentially mineralisable nitrogen [Fig. 3b]. At high clay contents SOC is not required to attain acceptable levels of CEC and thus the CEC shape in [Fig. 3b] does not extend past 60% clay. Within the shapes, the width of each shaded area reflects the perceived relative contribution that the different fractions of SOC will make. For the structural stability shape, at low clay contents, the POC fraction would be expected to be the most critical form of SOC; while, at high clay contents, the humus form would be expected to be most critical.

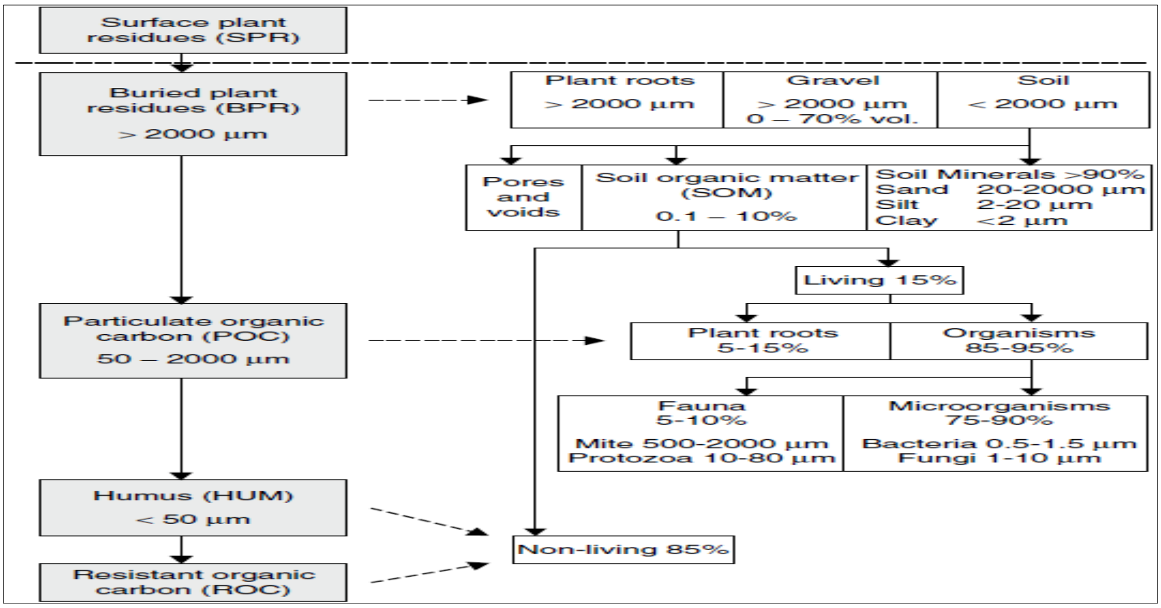


Fig 3(a): Schematic of soil organic matter fractionation scheme that represents different stages of soil organic matter decomposition

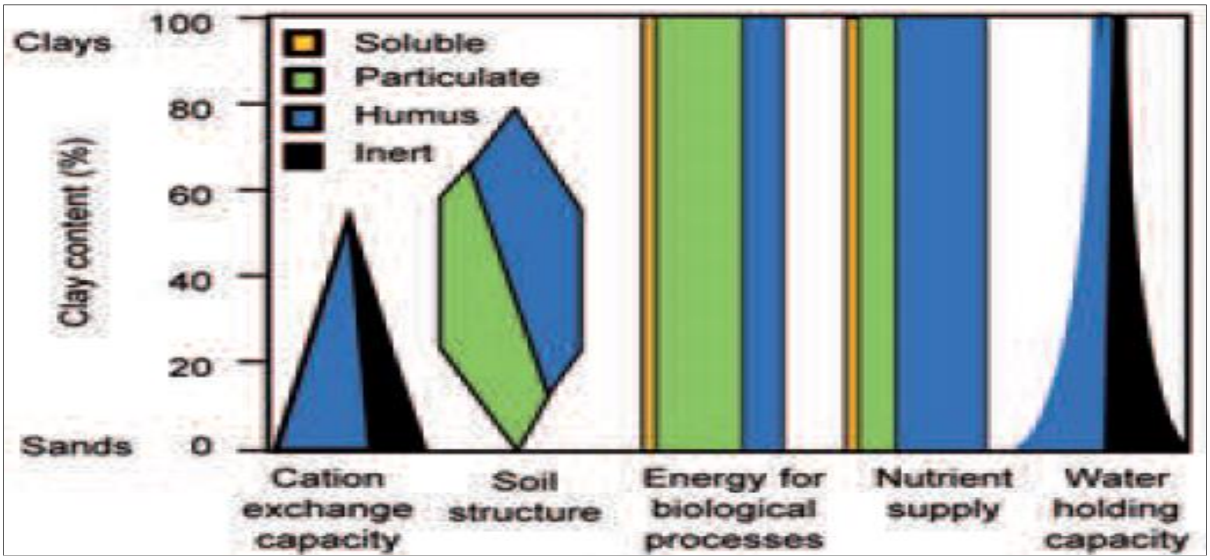


Fig. 3(b): Conceptual role of different soil organic carbon fractions (soluble, particulate, humus, inert) on a range of soil functions

Lal, (2002) [49] revealed that the increasing MBC and soil biodiversity also leads to a greater suppression of crop pathogens and pests (Larkin and Van Alfen 2015) [51]. Robust microbial communities can lead to either general suppression or specific suppression of diseases. Thus, depending on microbial communities, soil may range from conducive to suppressive. Mechanisms of disease- suppressive attributes include (Janvier *et al.* 2007) [42]: (1) slow establishment and persistence of pathogens; (2) lower severity of diseases; and (3) ineffectiveness of pathogens. General principles of enhancing soil health, and thus disease- suppressive attributes, include the following: (1) improve SOC pool; (2) adopt CA; (3) increase soil biodiversity; (4) diversify land use and maintain a live vegetable cover; (5) use organic amendments such as mulch, compost; and (6) adopt integrated nutrient management options. A judicious management of chemical fertilizers, in conjunction with the use of organic amendments, is also important to enhancing soil health (Singh and Ryan 2015) [73]. However, total disease control cannot be achieved by techniques which improve soil health [Fig. 4b], but the incidence of soil- borne diseases can be reduced. Soil health improvement may not strongly influence the foliar-borne diseases, but healthy soils support population of beneficial microorganisms and can lead to induced resistance to both soil- borne and foliar disease. Further, plants grown on healthier soils are relatively more resilient and are less susceptible to pathogens (Larkin and Van Alfen 2015) [51]. Use of some organic amendments (e.g., compost) can impact disease- suppressive properties. Management of soil through these concepts would do more than just improving plant nutrients, it would also enhance the environment (Ehmke 2013) [25].

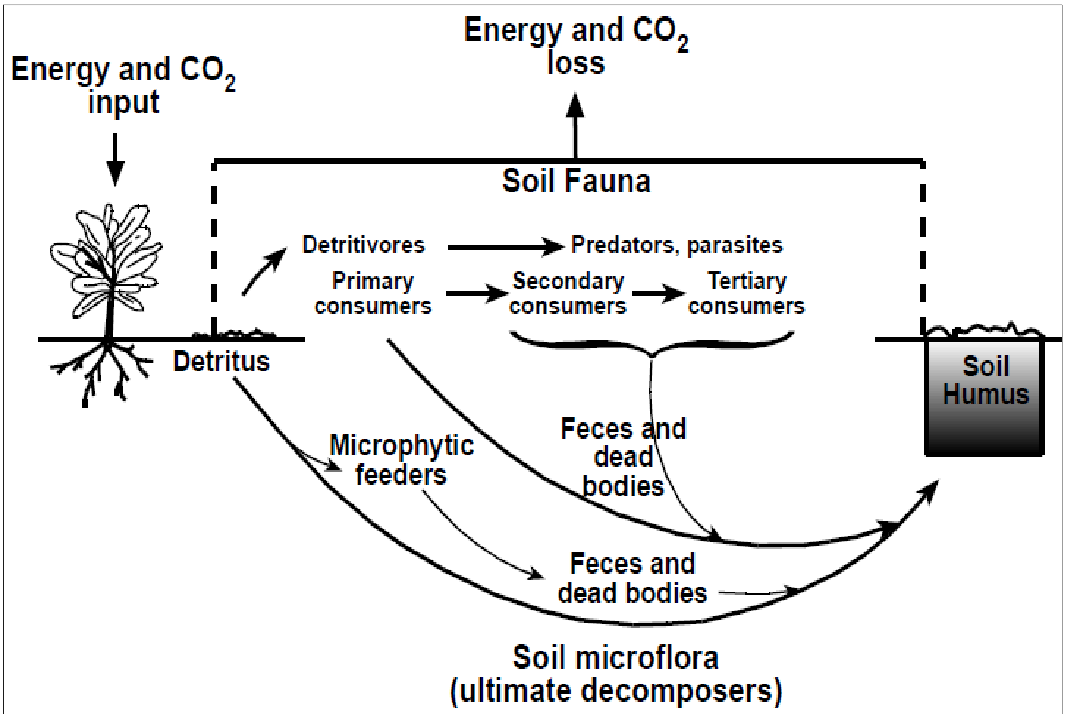


Fig 4 (a): Diagram of the general pathway for the breakdown of higher plant tissue.

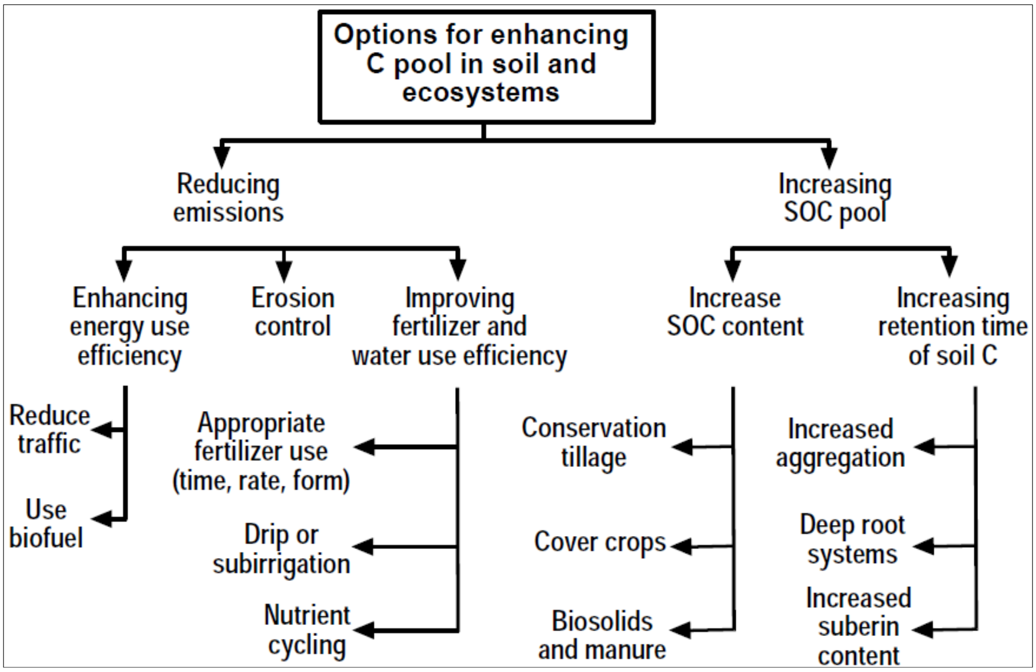


Fig 4(b): Technological options for enhancing C pool in soil and ecosystems

Poeplau *et al.* (2017) [65] revealed that the long-term incorporation of crop residues had a significant positive overall effect on total SOC, while the difference was not significant for any individual N fertilizations level. After 40 years of treatment, the average SOC stock in RR was 45.7Mgha^{-1}, while the average SOC stock in the RI treatments was 48.8Mgha^{-1} [Table 1]. Thus, residue incorporation increased the SOC stock by 3.1Mgha^{-1} or 6.8%. Average annual SOC sequestration was 78 kg ha^{-1} year^{-1}. The average difference in C input due to residue incorporation was

2.3Mgha^{-1} year^{-1}. He also embodied that on average, only 3.3% of the total residue-derived C had been stabilized in the soil. The difference in NPP between the unfertilized treatments and the high N rates increased only in the first decade and remained relatively constant thereafter. However, the SOC stocks in both the RR and RI treatments were not influenced by N level [Fig 5a], which did not interact with residue management. The difference in SOC stock between RI and RR at the highest N rate (240N) was 2.9Mgha^{-1}, while the difference at the lowest N level (0N) was 3.1Mgha^{-1}, despite the difference in annual C input between RI and RR for these two N extremes being 0.43Mgha^{-1} year^{-1}. Moreover, SOC sequestration due to residue incorporation lasted for 23 years [Fig.5 b]. The average SOC stock difference between RI and RR decreased from 4.6Mgha^{-1} year^{-1} in 1989 to 3.1Mgha^{-1} year^{-1} in 2006 [Fig.5 b]. However, this was not related to less residue input after the rotation change, as the average estimated difference in C input between RI and RR was 2.37Mgha^{-1} year^{-1} in the period 1966–85 and 2.34Mgha^{-1} year^{-1} in the period 1986–2006. However, the inter-annual variability in residue-derived C inputs, which is a function of NPP, increased considerably. In the first period (1966–85) the coefficient of variance was 27%, while in the second period (1986–2006) it was 45%. On average 92% of the total SOC stock was found in the silt and clay (SC) fraction (sum of fractions SC-rSOC and rSOC) [Table 1, Fig.5c]. The coarse fractions SA and POM and the liquid DOC fraction contributed only 4%, 2.3% and 1.7% respectively to the total SOC stock. Furthermore, 93% of the total surplus of SOC due to 40 years of residue incorporation was found in the SC fraction [Table 1]. Within the SC fraction, the greatest change in SOC stock (significant at $P < 0.001$) occurred in the more active SC-rSOC fraction, while the more passive rSOC on average did not change at all [Table 1, Fig.5 c].

Bol *et al.* (2009) [10] found 67% and 23% of SOC stored in the clay and silt fraction, respectively, while Christensen (2001) [14] reported that 50–75% and 20–40% SOC is usually attached to clay and silt particles, respectively, in temperate soils. Flessa *et al.* (2008) [26] found 88% of SOC in the silt and clay fraction of two German arable soils and suggested that the main stabilisation mechanism is the formation of organo mineral complexes. Wiesmeier *et al.* (2014) [86] suggested that tillage might promote the formation of such organo-mineral complexes due to mixing of fresh organic material with unsaturated mineral surfaces. Stemmer *et al.* (1999) [75] showed that mixing residues and mineral soil resulted in higher SOC contents in the silt and clay fraction than applying residues on the surface of the mineral soil. Li *et al.* (2016) studied labelled residues mixed into mineral soil over two years and found that after 60 days, 61% of the applied residue C was left in the soil, with 75% of it still stored in particles >2000 mm and only 0.1% was stored in micro-aggregates <53 mm, which correspond to the SC fraction. After 780 days, 26% of the applied C was left in the soil, with only 39% of it stored in the >2000 mm particles and 2.4% stored in the SC fraction. This indicates that the transformation from decomposed coarse particulate organic matter to stabilised, complexes C in the fine fraction occurs relatively rapidly. Villamil *et al.* (2015) [83] did not find consistent degradation of any soil property after seven years of residue removal and suggested that this practice does not cause any threat to the sustainability of the cropping system. However, this might only be true for fertile soils, as straw incorporation is acknowledged for its positive effects on numerous soil properties, such as soil structure, earthworm abundance, aggregate stability, and water-holding capacity.

Table 1: Soil organic carbon (SOC) stocks in all SOC fractions and in bulk soil for treatments with residues removed (RR) and residues incorporated (RI), averaged over all N fertilisation rates [Poeplau *et al.* (2017) [65]

Fraction	RR (Mgha^{-1})	s.d.	RI (Mgha^{-1})	s.d.	Absolute change (Mgha^{-1})	Relative change (%)	Proportion of total SOC (%)	
							RR	RI
Bulk	45.8	2.5	48.8	3.6	3.1	6.7*		
POM	1.1	1.1	1.1	1.3	0.0	–0.2	2.4	2.3
DOC	0.7	0.2	0.9	0.3	0.2	25.2*	1.6	1.9
SA	2.0	0.8	2.0	1.2	0.0	0.3	4.3	4.1
SC-rSOC	24.3	2.5	27.1	3.6	2.8	11.7*	53.1	55.6
rSOC	17.6	1.9	17.6	2.7	0.0	0.0	38.5	36.1

POM, particulate organic matter; DOC, dissolved organic carbon; SA, sand and stable aggregates; SC-rSOC, NaOCl-oxidisable silt and clay sized SOC; rSOC, resistant SOC

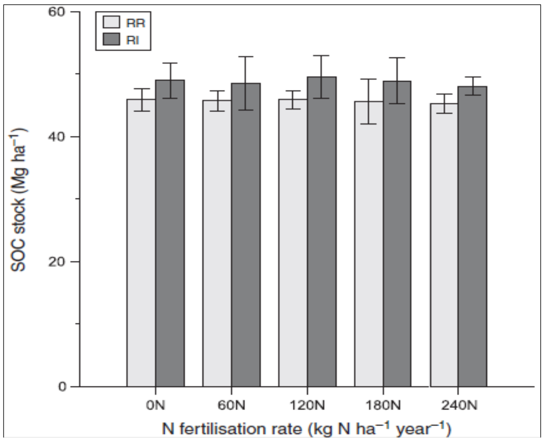


Fig. 5 (a): Soil organic carbon (SOC) stocks in the residue removed (RR) and residue incorporated (RI) treatments under five different N fertilizer rates

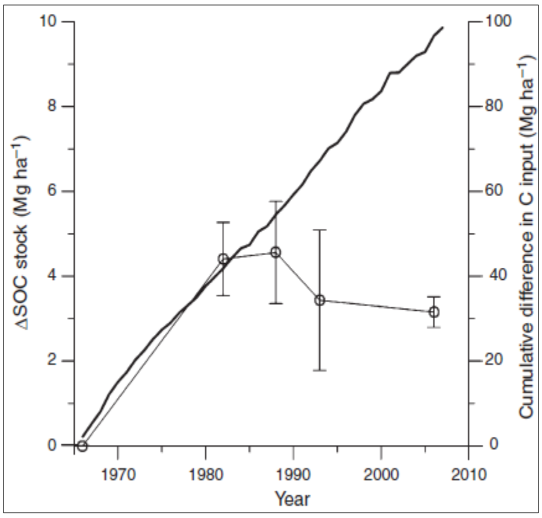


Fig 5 (b): Average difference in soil organic carbon stock (DSOC stock) over time (1966–2006) between treatments of residues incorporated (RI) and residues removed (RR)

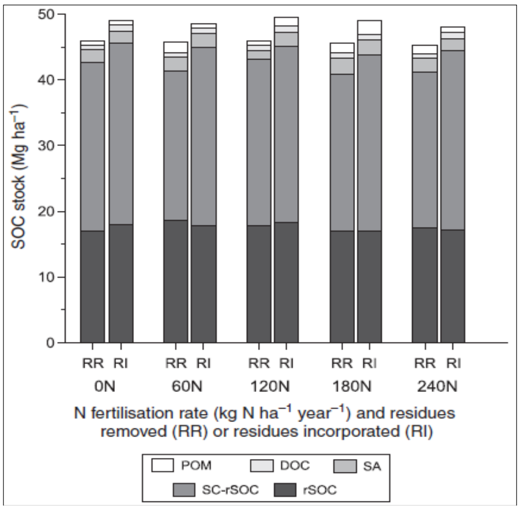


Fig 5 (c): Soil organic carbon (SOC) stock in different fractions for residues removed (RR) and residues incorporated (RI) treatments at different nitrogen (N) fertilization rates after 40 years of residue incorporation

Table 2: TOC (%) in of size classes of aggregates in a clay and sand-clay Oxisol under long-term no-till [Ademir *et al.*, 2016]

Textural	Depth	Attributes	Size classes of aggregates, mm					
Class	cm	(%)	19-8	8-4	4-2	2-1	1-0.5	0.5 – 0.25
Oxisol	0-5	Aggregate size class	75.85	2.70	2.42	2.14	3.60	4.57
clay		TOC in each size class	86.36	2.66	2.60	2.27	2.97	3.15
	5-20	Aggregate size class	74.63	2.70	2.25	2.47	3.97	4.35
		TOC in each size class	85.59	2.80	2.34	2.43	3.62	3.23
Oxisol	0-5	Aggregate size class	71.75	2.85	2.43	2.25	3.39	4.72
Sand-clay		TOC in each size class	83.98	3.06	3.00	2.75	3.53	3.69
	5-20	Aggregate size class	73.09	2.99	2,56	2.44	3.12	3.70
		TOC in each size class	85.93	3.16	2.75	2.62	2.92	2.61

A.de Oliveira Ferreira *et al.* (2018) [16] reported that in 5–20 cm depth, the extra-large macro-aggregates also represented a large part of aggregated soil mass, equivalent to 74.6% and 73.1% of SdC and CL, respectively. For 0–20 cm depth [Fig.6 b], the extra-large macro-aggregates also represented high percentage of soil mass (i.e., 75.2% and 72.4% in SdC and CL, respectively). At 0–5 cm depth, the soil mass of large macro-aggregates (2–8 mm) was lower than those of extra-large macro-aggregates and represented 5.1% and 5.3% in the SdC and CL, respectively. Also for 5–20 cm depth, the percentage of aggregates ranged between 4.9 and 5.5% of the aggregate soil mass, respectively. At 0–5 cm depth, the small macro-aggregates (0.25–2 mm) represented the smallest category (size) between macro-aggregate classes, and comprised of 10.3% and 10.4% of the aggregate classes' soil mass for SdC and CL, respectively. The same trend of distribution of proportional macro-aggregate mass was observed in 5–20 and 0– 20 cm depths [Fig. 6 b].

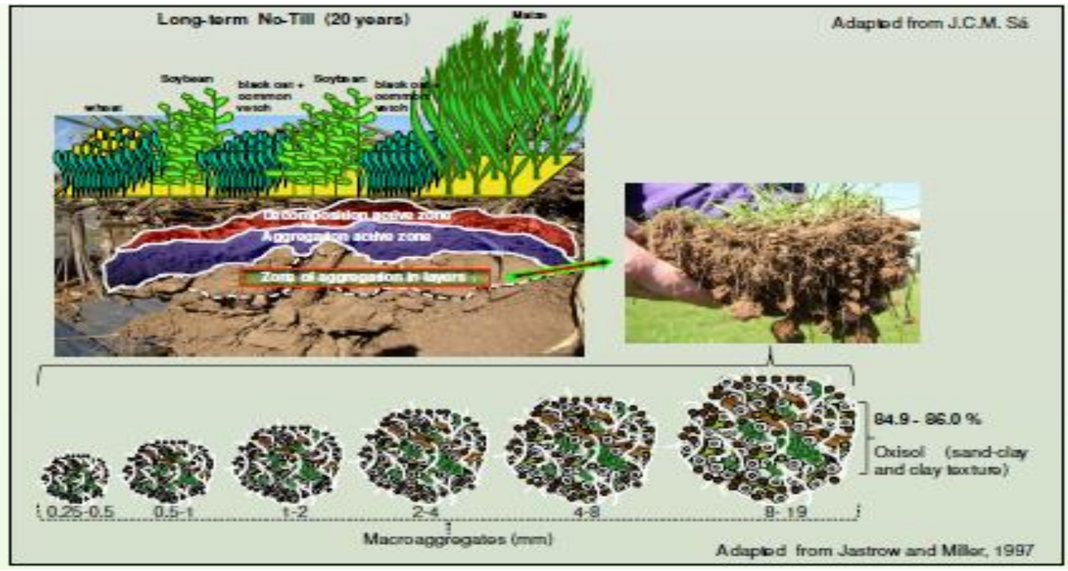


Fig 6 (a): Schematic diagram illustrating the effect of long-term no-till on soil macro-aggregation

The 8-19 mm size macro-aggregates represented 86.0 and 84.9 % of soil mass of all aggregates l size classes of sand-clay and clay oxisol respectively.

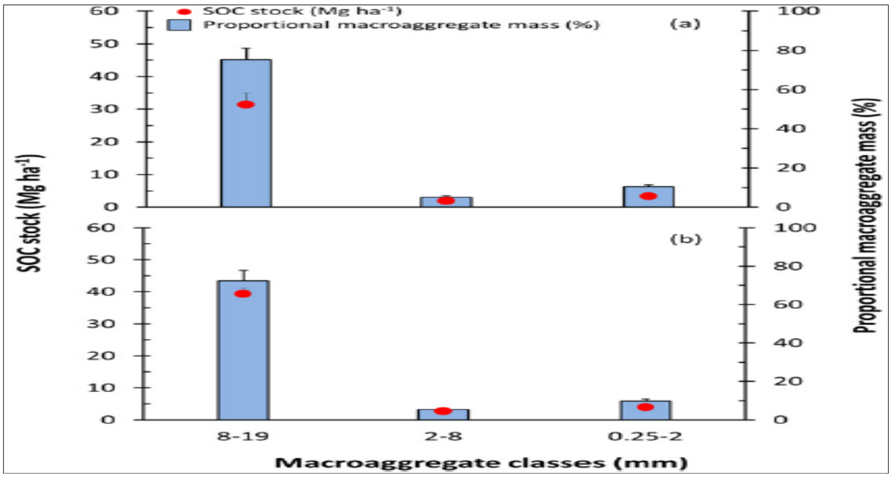


Fig 6 (b): Proportional macro-aggregate mass (%) and soil organic carbon (SOC) stocks (Mgha^{-1}) of small (0.25–2 mm), large (2–8 mm) and extra-large (8–19 mm) macro-aggregates.

In 0–5 cm depth for SdC and CL, 52.5% and 64.3% of POC stock was retained in the extra-large (8–19 mm), and 20.0% and 14.5% in the large (2–8 mm), and 27.4% and 21.1% in the small (0.25– 2 mm) macro-aggregates, respectively. However, in 5–20 cm depth, the POC stock increased slightly in SdC and CL, and was 60.9% and 67.8% of POC in extra-large (8–19 mm), 17.7% and 15.8% in the large (2–8 mm), and 21.3% and 16.3% in the small (0.25–2 mm) macro-aggregates, respectively. In 0–20 cm depth, POC stock in SdC and CL was 56.7% (5.3 Mg C ha^{-1}) and 66.1% (7.7 Mg C ha^{-1}) in the extra-large (8–19 mm), 18.8% (1.7 Mg C ha^{-1}) and 15.2% (1.8 Mg C ha^{-1}) in the large (2–8 mm), and 24.4% (2.1 Mg C ha^{-1}) and 18.7% (2.0 Mg C ha^{-1}) in the small (0.25–2 mm) macro-aggregates, respectively [Fig. 7a].

The SOC distribution (proportional mass) among macro-aggregates in 0–5 and 5–20 cm depths followed the order of: 8–19 mm N 2–8 mm≈ 0.25–2 mm. The high proportion of extra-large macro-aggregates observed in the under long term study NT (20 years) indicates a high degree of physical protection of SOC (Tivet *et al.*, 2013) [79]. Such protection is mainly provided by the continuous SOC flow generated by decomposition of crop residues (Li *et al.*, 2016; Tivet *et al.*, 2013) [79]. Consequently, there is a predominance of extra large macro-aggregates especially with high input of biomass-C, low soil disturbance, leading to a better soil structural quality and promoting an alternative to increase water infiltration and reduce risks of soil erosion (Tivet *et al.*, 2013) [79]. The macro-aggregation is also enhanced by the performance of agents (e.g., roots and fungal hyphae) and transient (e.g., polysaccharides) compounds. One of the aspects which have contributed to the C recovery within macro-aggregates was the C addition through crop residues over the 20 years. There was a total input of 140.4 Mg ha^{-1} of biomass-C, approximately 7 Mg ha^{-1} per annum, over 20 years of cultivation in CL. Similarly, there was a total input of 119.6 Mg ha^{-1} of biomass-C input, 5.9 Mg ha^{-1} per annum, over 20 years of cultivation in SdC [Fig 7b]. Increasing SOC stocks in the extra-large macro-aggregate class is an important determinant of soil quality, in ameliorating soil structure, improving gaseous exchange, enhancing water infiltration rate, increasing soil porosity and improving aggregate stability (De Oliveira Ferreira *et al.*, 2012; Tivet *et al.*, 2013) [79, 17]. Restoration of SOC in the clayey Oxisols from subtropical environment, managed with high crop intensity and input of residues for 20 years and 29 years within extra-large macro-aggregates in 0–20 cm depth was 73.1 and 95.2% of the antecedent SOC stock, respectively (Fig. 7b).

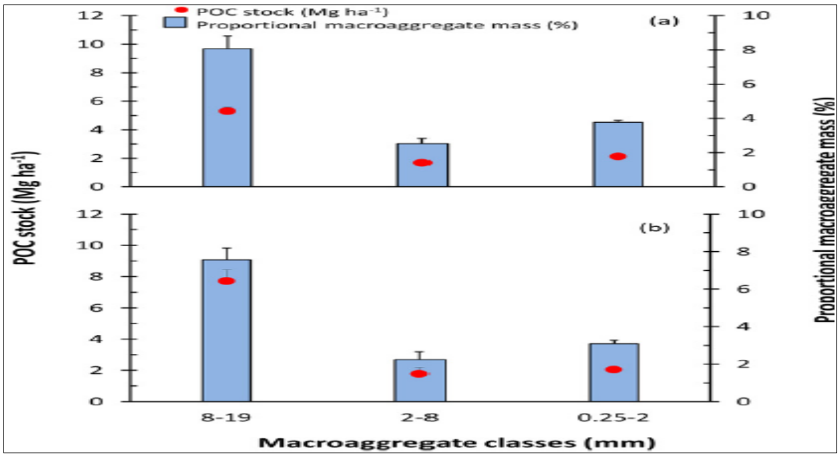


Fig 7(a): Proportional macro-aggregate mass (%) and particulate organic carbon (POC) stocks (Mg ha^{-1}) of small (0.25–2 mm), large (2–8 mm) and extra-large (8–19 mm) macro-aggregates

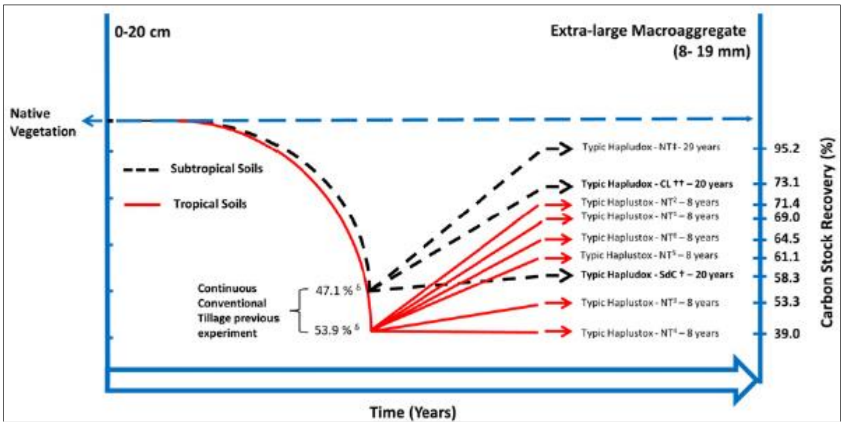


Fig 7(b): Carbon stock recovery in extra-large Macro-aggregates (8–19mm) within the 0–20 cm soil depth according to the management system along the years for this present study (†SdC=Sandy clay Oxisol; ††CL=Clay loam Oxisol)

Zheng *et al.*, (2018) [87] also found that the SOC storage in macro-aggregates under different treatments significantly decreased with soil depth [Table 3]. However, no significant variation was observed in the micro-aggregate associated C storage with depth. SOC storage increased with aggregate size from 1±2 to > 2mm and decreased with a decrease in aggregate size. The SOC storage in macro-aggregates of all sizes from 0-30cm depth was higher in the ST treatment than in other treatments. From 30-60cm, trends were less clear. SOC storage in micro-aggregates showed the opposite trend, with significantly higher levels in the CT treatment from 0-30cm, and no significant differences between treatments below this depth. Using suitable tillage and increasing the soil organic matter can improve the formation of soil aggregates and increase their stability (Li *et al.*, 2008). The no-tilling (NT) method promotes the formation of soil aggregates in the topsoil (0-10cm depth) and improves the aggregate stability due to the presence of high stubble. However, the MP and CT treatments strongly disturb the soil, which can reduce the aggregate degree and stability of soil aggregates at the tillage depth of 0-20cm due to erosion and rainfall. Another demonstrated advantage of deep tillage was the 34.49% increase in the number of water-stable aggregates under the ST treatment compared to the other treatments, which could improve the formation of soil aggregate structure in the black soil of Northeastern China. Furthermore, spacing tillage (ST) promoted the enrichment of > 0.25mm water-stable aggregates, thereby improving the soil structure. Our study showed a greater influence of tillage treatment on macro- and micro-aggregates at 0±10, 10±20, and 20±30cm layers than at other depths, suggesting an aggregate stratification phenomenon. This is due to the result of different operations of the secondary tillage. An additional reason may be the difference in the straw returned to soil under the different tillage systems.

Table 3: Distribution of soil organic carbon storage in water-stable aggregates in different soil layers and tillage treatments [Zheng *et al.*, 2018] [87].

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

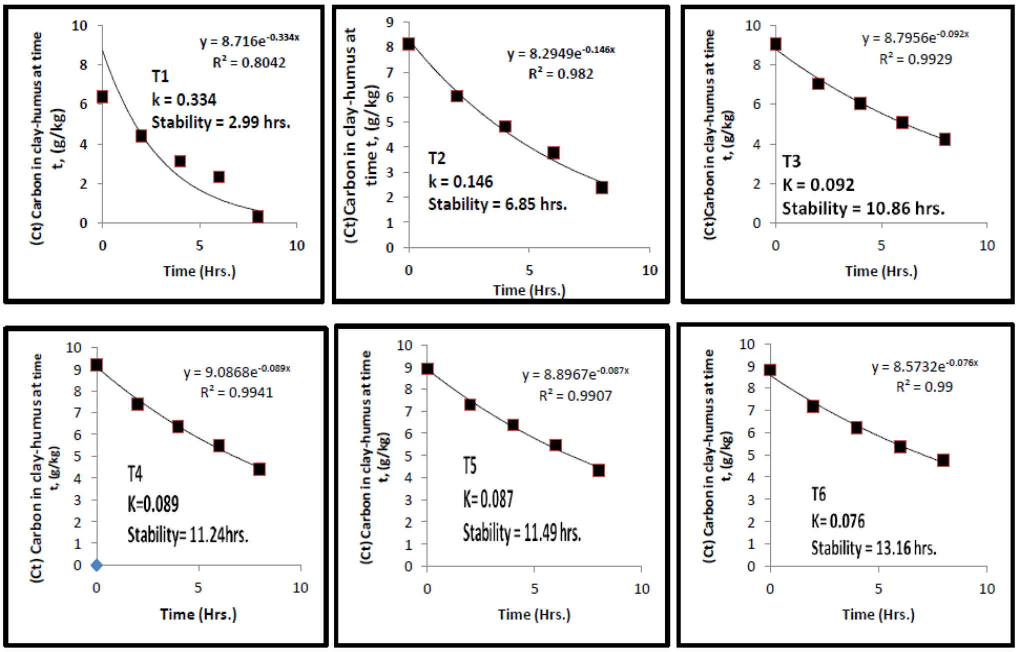
[¶] Data are represented as means ± S.D., and data with the same letters within each column indicate no significant difference at $P = 0.05$ level.

Kumar, (2015) [87] revealed that the stability is judged on the basis of mean residence time that is, how much time it is stable in soil against the physical perturbation. The organic amended treatments performed progressively well over unfertilized control, might be due to the fact that organic matter in turn provides the basis for complexion and aggregation in soil. It is known that in soil where organic carbon content is low mainly less than 1% the aggregates are held together by transient binding agents in soil. These transient binding agents are nothing, but polysaccharides produced by microorganisms and root exudates Soil organic carbon (SOC) is having a significant impact on physical, chemical and biological properties of soil. Haynes and Naidu (1998) [38] reported that if manure and crop residues being applied for organic matter supply then it will favors microbial activities and the production of macro-aggregate. A large range of stable aggregates is desirable, as they can sustain a range of pore sizes and promote aeration, water infiltration, and drainage. This stability of clay-humus complex is an indication of how much the soil is fit against physical perturbation or the disturbance [Fig 8].

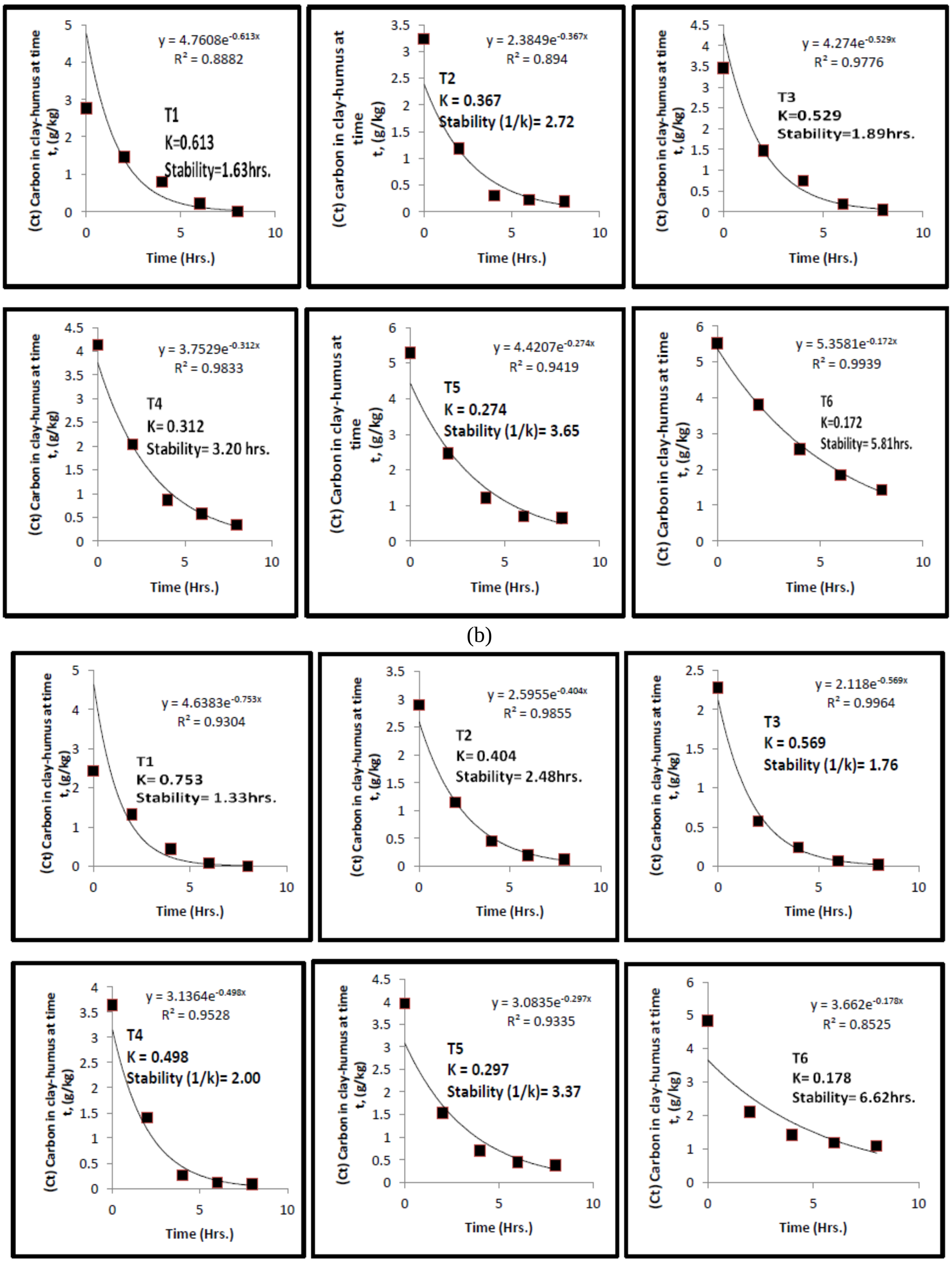
The organic amended plots had more aggregate associated carbon in 0-15 cm depth as compared to that in subsurface soil though the data were mostly non-significant. The FYM alone and FYM along with other organic amendments showed higher carbon in micro-aggregate (0.25-0.053 mm) and (silt +clay) size (< 0.053 mm) fractions. The increased carbon in macro-aggregate fraction somewhere, suggests the fact that macro-aggregate play an important role in SOC sequestration. This fraction constituted a major fraction of total nitrogen which varied from lower range in control plots to higher range in organic treated plots [Fig. 9]. Bandyopadhyay *et al.* (2010) [4] compared the effect of farmyard manure, paddy straw, green manure and inorganic fertilizer on aggregate and found that receiving organic amendments enhances soil aggregation. Among these organic treatments green manure was less efficient at increasing aggregate stability. Aggregate stability affects soil carbon dynamics and is a key factor in physical soil fertility. Soil aggregate stability correlates significantly with SOC, because of the binding action of humic substances and other microbial by-products (Goh, 2004) [30]. Singh *et al.* (2007) [74] have also shown that addition of various organic manures along with inorganic fertilizers in rice–wheat system improved the aggregation status of the soil. The cropping systems and the management practices that could provide C input higher than the above critical level are likely to sustain the SOC level and maintain good soil health in the subtropical regions of the Indian subcontinent (Mandal *et al.*, 1996) [55].

Dube *et al.* (2012) [23] also found that the effects of cover cropping, fertilization regime and cover crop type on POM fractions ($\text{POM}_{50–250}$, $\text{POM}_{250–2000}$ and POMT) at all soil depths, were not significant. However, the cover cropping effect was significant ($P < 0.05$) [Fig. 10a]. The oat and vetch rotations produced higher POM50–250 levels than the weedy fallow treatments. At 20–50 cm, the cover cropping x cover crop type interaction was significant with grazing vetch giving higher $\text{POM}_{250–2000}$ than oat and weedy fallow rotations. The higher amount of SOM obtained in the top 0–5 cm compared to lower depths across all treatments (stratification ratios >1) was obviously due to the lack of incorporation of plant residue into the soil. However, a lack of fertilization reduced the SOM stratification within the 0–20 cm layer or, in other words, increased the proportion of SOM in the lower profile and this is probably attributable to deeper penetration of roots as they seek nutrients.

Korschens *et al.* (1998) [43] recommended HWC as an integrated indicator of SOM quality due to its close relationship with microbial biomass, soil respiration and nitrate ion release in arable soils from a number of long-term plots where organic and mineral fertilizers were continuously applied. The higher amounts of HWC on the cover cropping treatments compared to weedy fallows in this study suggested that the maize–cover crop rotations are better able to supply N than the weedy fallow rotations [Fig.10b]. On the other hand, a regression analysis of fertilizer N input and SOM at 0–5 cm for the oat cover crops shows a strong positive linear relationship (r^2 = 0.766, [Fig. 10c]. This suggested that N fertilization is important for increasing SOM in oat rotations although less so for the N fixing vetch covers crops. This is in agreement with Fourie (2007) [27] who reported that N fertilization increased the biomass production for oat, with little increase observed for vetch owing to N fixation on a loamy sand soil.



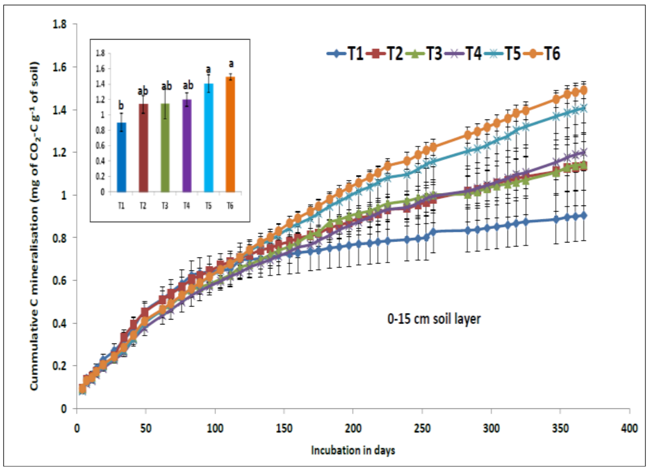
(a)



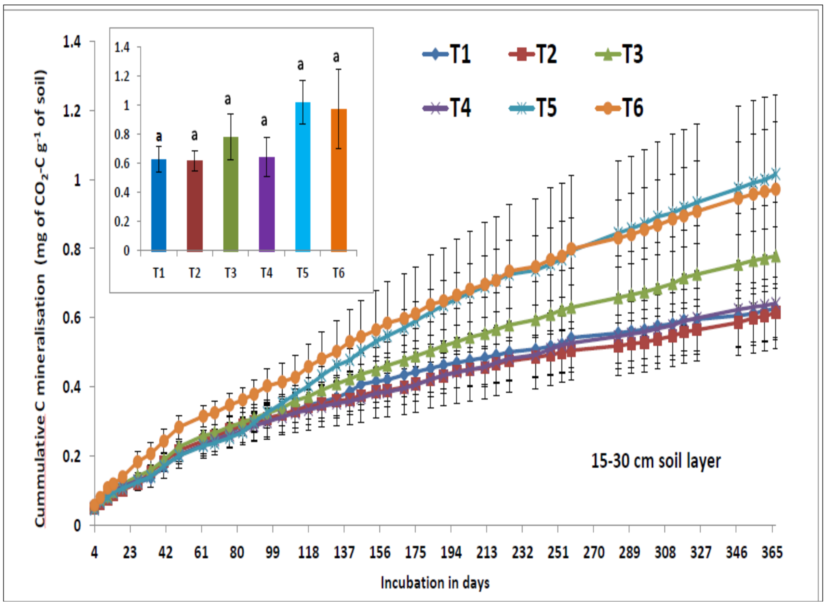
(b)

(c)

Fig 8: Effect of organic manures and bio fertilizers on clay-humus stability in (a) 0-15 cm; (b) 15-30 cm and (c) 30-60 cm depth under rice-wheat cropping system



(a)



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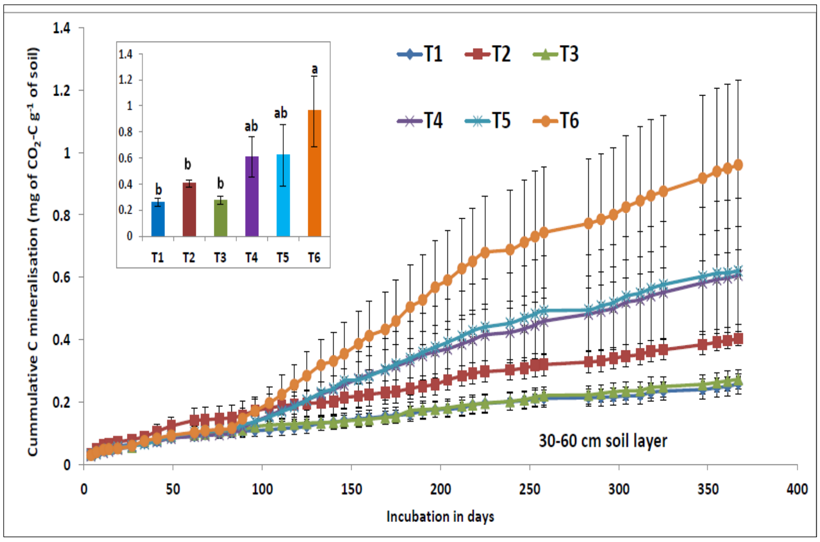


(c)

Fig 9: Long term effect of organic manure and bio fertilizers addition on cumulative C mineralization in (a) 0-15 cm; (b) 15-30 cm; and (c) 30-60 cm soil layer under rice-wheat cropping system.

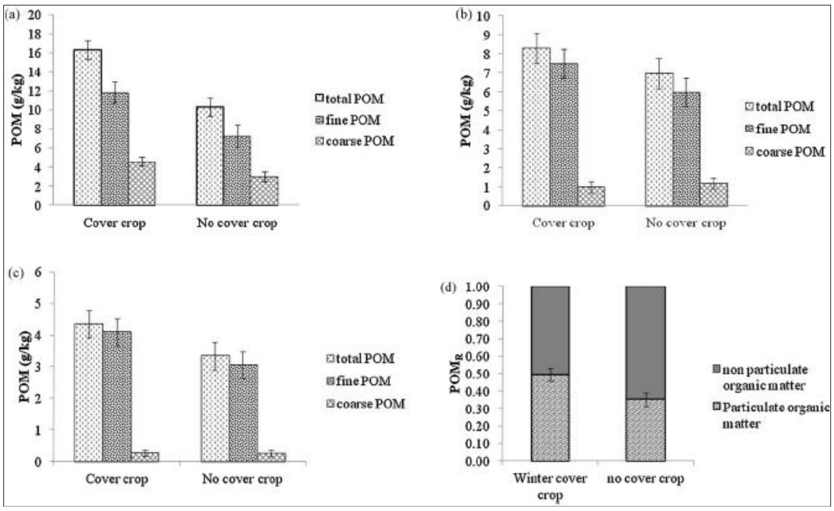


Fig 10 (a): Winter cover cropping effects on particulate organic matter (POM) fractions at (a) 0–5 cm, (b) 5–20 cm and (c) 20–50 cm soil depths. Fine POM = 50–250 μm, coarse POM = 250–2000 μm and total POM = fine POM + coarse POM.

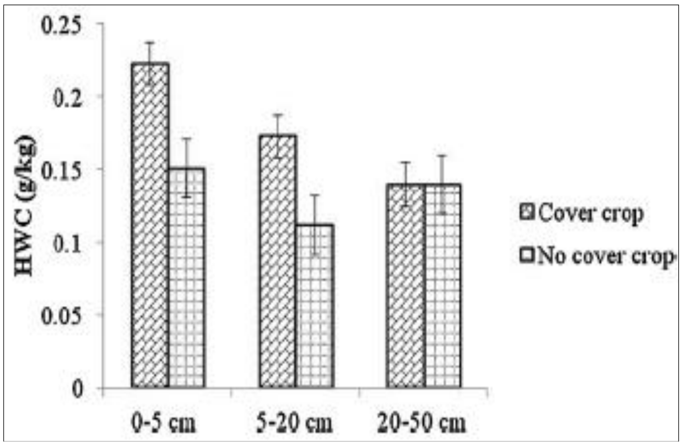


Fig 10 (b): Winter cover cropping effects on hot water soluble carbon (HWC) at 0–5, 5–20 and 20–50 cm soil depths.

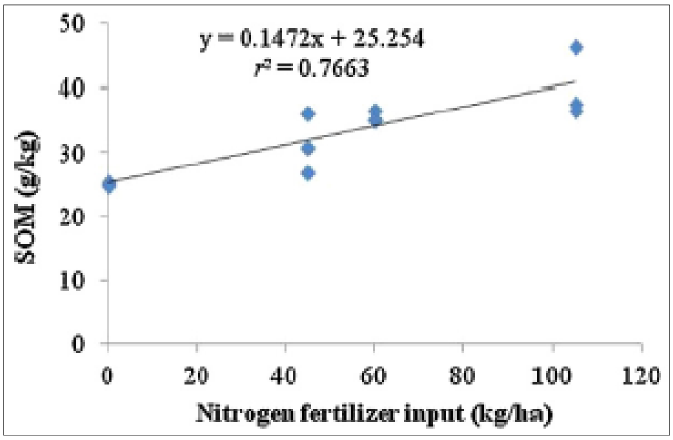


Fig 10 (c): Relationship between nitrogen fertilizer input and SOM in the 0–5 cm soil depth for oat–maize rotations.

Macro- and micro-aggregate-associated C decreased with an increase in the soil depth [Table 4], with a higher aggregate-associated C content in the topsoil compared to the sub-layer. Macro-aggregate-associated C content was highest in the ST treatment at the 0±10, 10±20, and 20-30cm depths for all sizes of macro-aggregates, and at the 30±40 and 40-50cm depths for macro-aggregates on average. For each depth 0-60cm, the micro-aggregate-associated C was highest in the ST treatment for water-stable aggregates of each size. Soil aggregates are the foundation of the soil structure and soil substance, energy conservation, and metabolism (Bronick, and Lal, 2005) [6]. The quantity and quality of soil aggregates directly determine soil quality and fertility (Al-Kaisi *et al.*, 2014) [1]. The stability of soil aggregates determines the ability of the aggregates to resist exogenic action and to remain stable when exposed to changes in the external environment. In addition, aggregates are known to closely correlate with the soil erodibility and appear to play an important role in maintaining the stability of soil structure. The conservation strategies of spacing tillage and no-tillage improved soil structure and increased the number of macro-aggregates by reducing the disturbance frequency of tillage and keeping high stubble cover, which served to prevent erosion. This result is in agreement with previous findings from long-term studies in geographic areas across similar latitudes (Ismail *et al.*, 1994) [41].

Table 4: Distributions of water-stable aggregate-associated C at 0-60cm depth of soil under different tillage treatments [Zheng et a., 2018] [89].

Depth (cm)	Treatments	Macro-aggregate-associated C (g kg^{-1})				Micro-aggregate-associated C (g kg^{-1})			
		> 2 mm	2–1 mm	1–0.25 mm	sum	0.25–0.053 mm	0.053–0.002 mm	< 0.002 mm	sum
0–10	ST	18.19±0.13a¶	14.54±0.05a	14.94±0.07a	47.68±0.01a	15.49±0.73a	14.96±0.03a	20.48±0.07a	50.93±0.73a
	NT	17.53±0.04b	14.58±0.01a	14.13±0.05c	46.24±0.06b	14.31±0.16ab	14.17±0.16b	15.78±0.13b	44.26±0.14b
	MP	13.98±0.05d	11.31±0.01c	13.54±0.06d	38.84±0.01 c	11.62±0.16c	11.05±0.11c	11.28±0.23d	33.95±0.04d
	CT	16.78±0.11c	13.74±0.05b	14.64±0.13b	45.16±0.07 b	13.86±0.03b	14.03±0.27b	12.22±0.01c	40.12±0.31c
10–20	ST	18.15±0.06a	15.79±0.03a	16.13±0.15a	50.08±0.21a	18.68±0.08a	16.01±0.12a	21.98±0.06a	56.67±0.14a
	NT	15.37±0.10c	14.54±0.05c	14.64±0.13b	44.55±0.28c	12.30±0.07c	13.34±0.02d	16.95±0.07c	42.60±0.12c
	MP	12.37±0.04d	13.15±0.03d	12.69±0.02c	38.21±0.10d	11.62±0.16d	13.97±0.16c	13.69±0.02d	39.28±0.01d
	CT	17.74±0.01b	15.19±0.03b	14.63±0.05b	47.56±0.08b	14.31±0.16b	15.12±0.05b	20.42±0.02b	49.84±0.14b
20–30	ST	16.22±0.16a	15.11±0.05a	15.61±0.07a	46.94±0.04a	14.49±0.01a	16.21±0.06a	18.67±0.04a	49.37±0.11a
	NT	14.01±0.05c	13.60±0.04c	13.65±0.04c	41.27±0.05c	12.76±0.09c	11.41±0.03d	13.61±0.08d	37.78±0.09d
	MP	15.48±0.09b	14.18±0.08b	14.12±0.12b	43.78±0.12b	13.96±0.08b	13.85±0.01c	17.27±0.09b	45.08±0.18b
	CT	13.79±0.09c	12.40±0.14d	12.53±0.02d	38.72±0.06d	12.54±0.01d	14.43±0.05b	15.33±0.31c	42.30±0.26c
30–40	ST	12.77±0.14b	11.07±0.15a	11.50±0.03a	35.35±0.04a	10.05±0.05a	10.04±0.07a	14.19±0.16a	34.28±0.28a
	NT	8.78±0.01c	8.25±0.04d	7.40±0.03d	24.43±0.07d	7.86±0.01c	9.21±0.15c	6.10±0.05d	23.16±0.21d
	MP	13.16±0.01a	10.47±0.11b	10.47±0.07b	34.10±0.16b	8.49±0.02b	8.39±0.04b	10.70±0.03b	27.58±0.03b
	CT	8.20±0.07d	9.01±0.03c	8.20±0.06c	25.41±0.05c	7.39±0.03d	8.08±0.01d	9.25±0.06c	24.72±0.08c
40–50	ST	11.10±0.06a	6.15±0.01b	6.62±0.01a	23.87±0.08a	6.08±0.03a	8.03±0.16a	7.92±0.12a	22.03±0.31a
	NT	7.52±0.02d	5.46±0.10d	4.58±0.10d	17.56±0.22d	4.70±0.06b	5.02±0.03c	6.10±0.05c	15.82±0.14c
	MP	10.83±0.12b	6.47±0.06a	5.06±0.03c	22.36±0.09b	4.58±0.12b	5.09±0.01c	6.03±0.02c	15.70±0.12c
	CT	8.47±0.06c	5.76±0.06c	5.80±0.05b	20.03±0.06c	5.87±0.08a	5.90±0.01b	6.91±0.10b	18.68±0.19b
50–60	ST	6.39±0.10ab	5.07±0.01b	4.06±0.03c	15.52±0.12b	5.37±0.10a	6.71±0.04a	5.60±0.05a	17.68±0.18a
	NT	6.23±0.02b	4.64±0.02c	4.29±0.06b	15.16±0.06c	3.97±0.06d	5.06±0.07c	5.55±0.01a	14.58±0.12c
	MP	6.48±0.01a	5.40±0.09c	4.72±0.01a	16.60±0.10a	4.39±0.02c	4.52±0.02d	5.15±0.05b	14.06±0.05d
	CT	4.78±0.04c	4.34±0.01d	4.12±0.03c	13.24±0.03d	4.71±0.01b	5.28±0.01b	5.54±0.06a	15.52±0.06b

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

Simansky, (2016) [72] reported that the contents of humic substances (HS) and fulvic acids (FA) under RT increased by 1.6% and 4.4%, respectively, compared to CT during the years 1994–2011. On the other hand, contents of humic acids (HA), HA-to-FA ratios, colour quotient of HS and colour quotient of HA under CT increased by 2.0%, 2.5%, 1.8% and 2.3%, respectively, compared to RT. In CT and RT, HS declined at an average speed of 0.33% and 0.53% per year, respectively. In CR + NPK treatments and application, only NPK fertilizer caused a decline of HS at an average speed of 0.52% and 0.33 % per year, respectively [Fig.11].

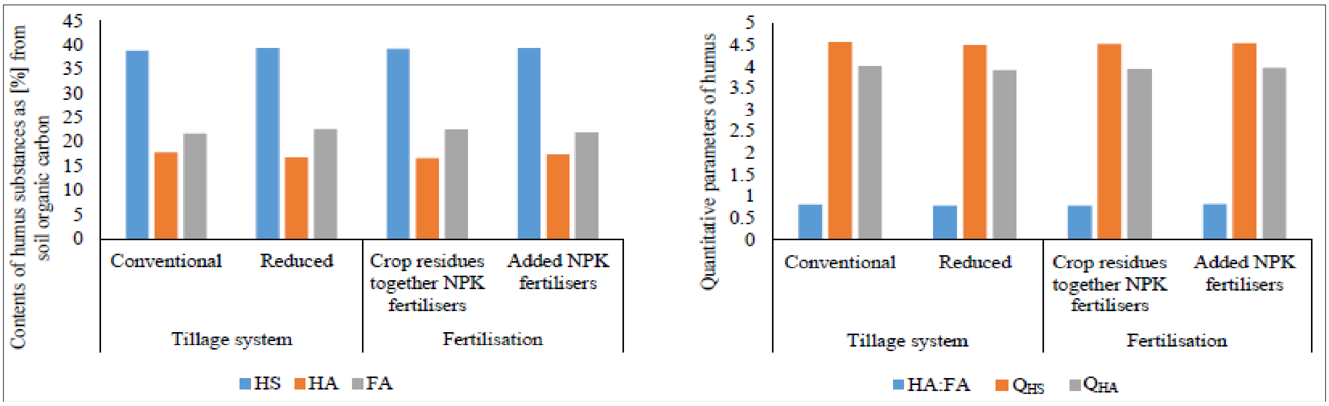


Fig 11: soil organic matter parameters; HS – humic substances; HA – humic acids; FA – fulvic acids; HA: FA – humic acids to fulvic acids ratio; Q_{HS} – colour quotient of humic substances; Q_{HA} – colour quotient of humic acids

Extrinsic factors such as parent material, climate, topography and hydrology may influence potential values of soil properties to such a degree [Fig.12a], that it is impossible to establish universal target values, at least not in absolute terms. Soil quality assessment thus needs to include baseline or reference values in order to enable identification of management effects. Soils often react slowly to changes in land use and management, and for that reason it can be more difficult to detect changes in soil quality before non-reversible damage has occurred than for the quality of water and air (Nortcliff, 2002). Therefore, an important component of soil quality assessment is the identification of a set of sensitive soil attributes that reflect the capacity of a soil to function and can be used as indicators of soil quality. Soil quality and soil health go beyond the reductionist approach of measuring (indicators of) soil properties and processes. Although such measurements remain important from a practical perspective (Kibble white *et al.*, 2008a), the concepts of soil quality and soil health also include the capacity for emergent system properties such as the self-organization of soils, e.g. feedbacks between soil organisms and soil structure (Lavelle *et al.*, 2006), and the adaptability to changing conditions [Fig.12b]. The soil functions in [Fig. 12b] equate almost entirely to the "intermediate services" defined by Bennett *et al.* (2010) [8], which are similar to the soil processes presented by Schwilch *et al.* (2016) [70].

As soil quality plays a role in decision-making in the face of soil threats, the DPSIR (driver–pressure–state–impact–response) framework (European Environment Agency, 1998). Applying the DPSIR framework to soil [Fig. 12c], "drivers" are pedo-climatic conditions and land use policies, while "pressures" are land use and management and the associated soil threats. Pressures and drivers and their variability's and interactions determine the "state" of the soil, with subsequent "impact" on soil and ecosystem functioning, and the "response" in terms of the delivery of ecosystem goods and services.

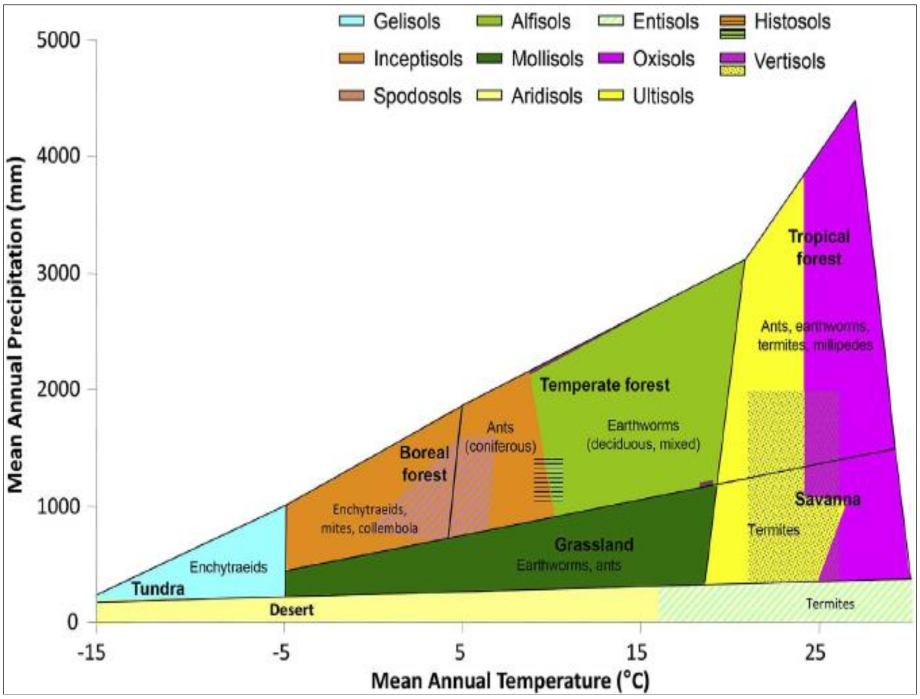


Fig 12 (a): Abiotic and biotic factors constituting soil quality in the soils of the world (Brussaard, 2012).

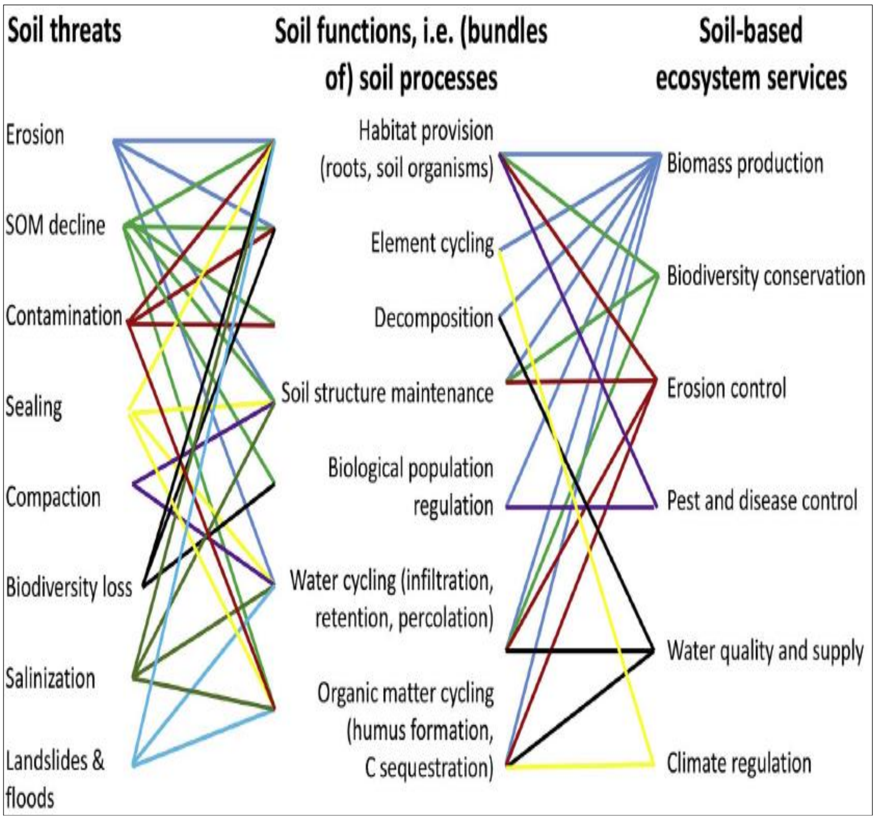


Fig 12(b): Linkages between soil threats, soil functions and soil-based ecosystem services.

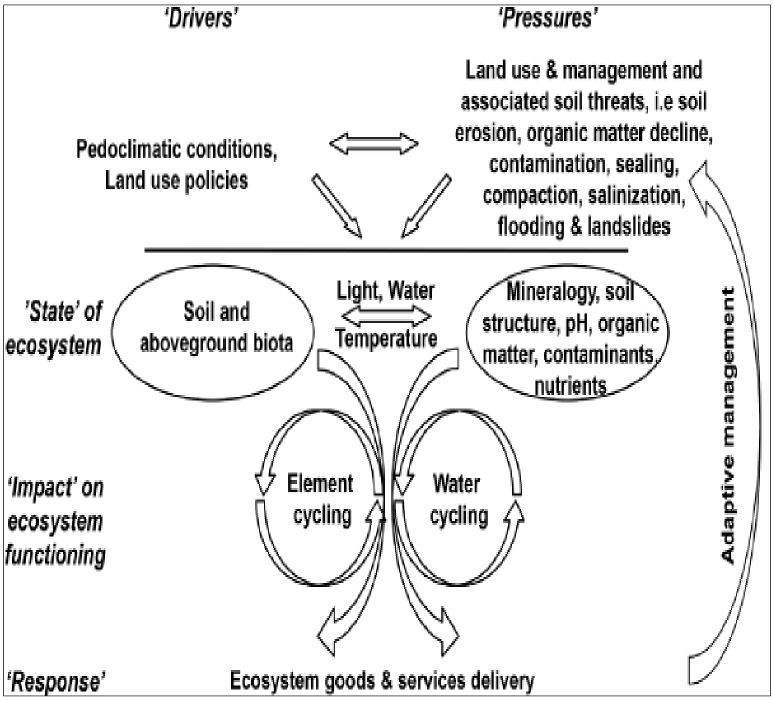


Fig 12(c): The Driver-Pressure-State-Impact-Response framework applied to soil.

Naresh *et al.* (2017) [59] reported that the WSC was found to be 5.48% higher in surface soil than in sub-surface soil [Table 5]. In both the depths, T_6 treatment had the highest WSC as compared to the other treatments studied. Compared to CT, FIRB and ZT coupled with 6tha^{-1} CR increased 35.6% WSC in surface soil and 33.1% in sub surface soil. Among all the treatments, T_6 had significantly higher (19.73%) proportion of WSC than the other treatments compared. Irrespective of tillage practices, residue retention resulted in 22.56% and 25.61% higher WSC as compared to the non-residue treatments in surface and sub-surface soil, respectively. The microbial biomass carbon (MBC) is an important component of the SOM that regulates the transformation and storage of nutrients. The soil MBC regulates all SOM transformations and is considered to be the chief component of the active SOM pool. It is evident that the MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 100% RDN as CF+ VC @ 5tha^{-1} (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 5]. 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. 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 5].

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 5]. The ${}_{c}$POM-, disproportionately to its small contribution to total SOC, has a large effect on nutrient-supplying capacity and structural stability of soils, and for these reasons it is considered a key attribute of soil quality (Haynes, 2005) [34]. Ibrahim *et al.* (2015), indicating that higher C input induced by fertility management practices resulted in significantly larger physically uncomplexed organic carbon (${}_{f}$POM, ${}_{c}$POM and LFC) pools.

Table 5: 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.*, 2017] [60].

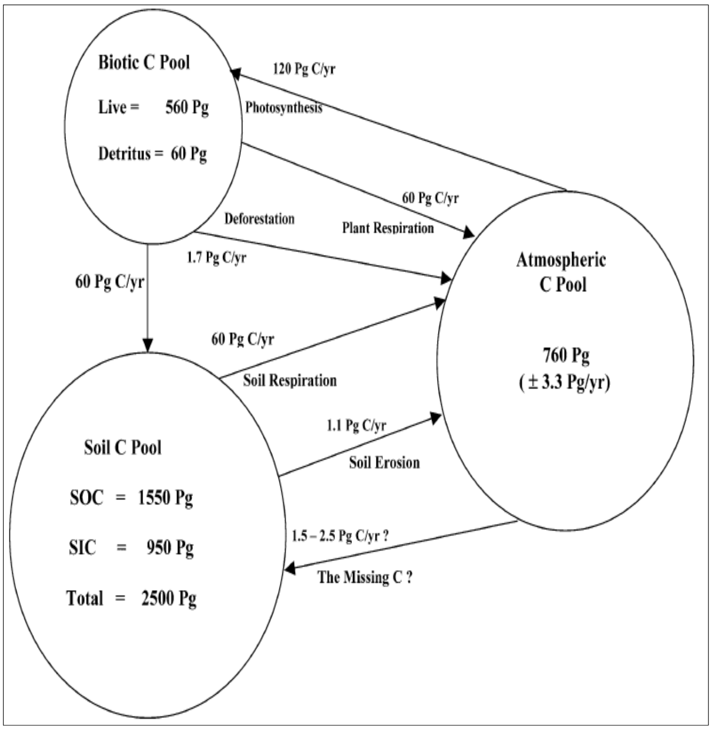
Treatments	**0-15 cm layer**					**15-30 cm layer**				
	WSC (mgkg^{-1})	**MBC (mgkg^{-1})**	**LFC (mgkg^{-1})**	**${}_{f}$POM (g Ckg^{-1})**	**${}_{c}$POM (g Ckg^{-1})**	**WSC (mgkg^{-1})**	**MBC (mgkg^{-1})**	**LFC (mgkg^{-1})**	**${}_{f}$POM (g Ckg^{-1})**	**${}_{c}$POM (g Ckg^{-1})**
Tillage crop 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

The global soil C pool is estimated at 1550 Pg of SOC and 950 Pg of SIC to 1-m depth (Batjes 1996). The soil C pool is about 3.3 times the atmospheric pool (760 Pg) and 4.5 times the biotic pool (560 Pg) [Fig.13a]. Soil C pool can be a source or sink for atmospheric pool depending on land use and management. There is a direct relationship between soil C pool and the atmospheric pool. Increase of soil C pool by 1 Pg is equivalent to reduction in atmospheric CO_2 concentration of 0.47 ppm, and vice versa.

Three predominant components of terrestrial C sequestration include soil, biota and biofuel [Fig. 13 b]. Increase in SOC pool must be assessed to 2-m depth, because significant management-induced changes in SOC pool can occur deep in the sub-soil (Lorenz and Lal 2005). Increase in SOC pool, assessed in terms of either fixed depth or on equal soil mass basis, must be done for major land use and soil management systems. Management induced changes in SOC pool can occur in labile, intermediate or the passive C fractions. Changes in the labile fraction can occur even over a short period, while those in the intermediate and passive fractions occur over a long time horizon. There are three mechanisms or processes of soil C sequestration. Improvement of soil structure and formulation of stable micro-aggregates is an important process (Six *et al.* 2000). Humic substances and other persistent compounds have a long lasting effect on micro-aggregate dynamics (Galeetal.2000a), stabilization of macro-aggregates, thereby encapsulating and physically protecting organic matter against microbial activity. Clay content and mineralogy have strong impact on aggregation. Furthermore, total SOC concentration increases with increase in aggregate size. Himes (1998) reported that sequestration of 10 Mg of C in crop residue into 17.241 Mg of humus would require 28 Mg of C in 62 Mg of oven dry residue. In addition, it would require 833 Kg N, 200 Kg P and 143 Kg S. Thus, humification of residue C can occur only if essential nutrients (e.g., N, P, and S) are available. With low mulch application, SOC stocks were similar (25.6 MgC/ha) with and without fertilizer application. However, when the mulch rate was high, additional SOC accretion occurred only in plots receiving additional fertilizer. Campbell *et al.* (2001) indicated that without adequate fertilization, the adoption of no-till does not necessarily increase SOC pool.

The strategy of soil C management is to increase the amount of crop residues and bio-solids to the soil surface through: (i) minimizing soil disturbance, (ii) providing continuous ground cover, (iii) strengthening nutrient recycling mechanisms, (iv) creating a positive nutrient balance, (v) enhancing biodiversity, and (vi) reducing losses of water and nutrients out of the ecosystem. There are three principal options to achieve these: (i) converting degraded lands to perennial vegetation, (ii) increasing net primary productivity (NPP) of agricultural ecosystems, and (iii) converting plow tillage to no-till farming [Fig. 13 c].



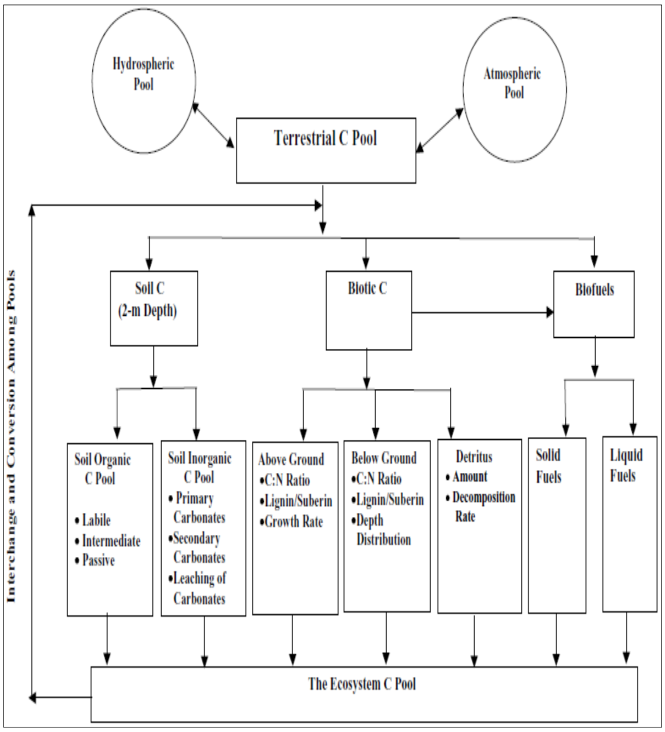


Fig. 13 (a): Intersection between soil carbon pool and the biotic and atmospheric C pools

Fig. 13 (b): Components of terrestrial carbon sequestration

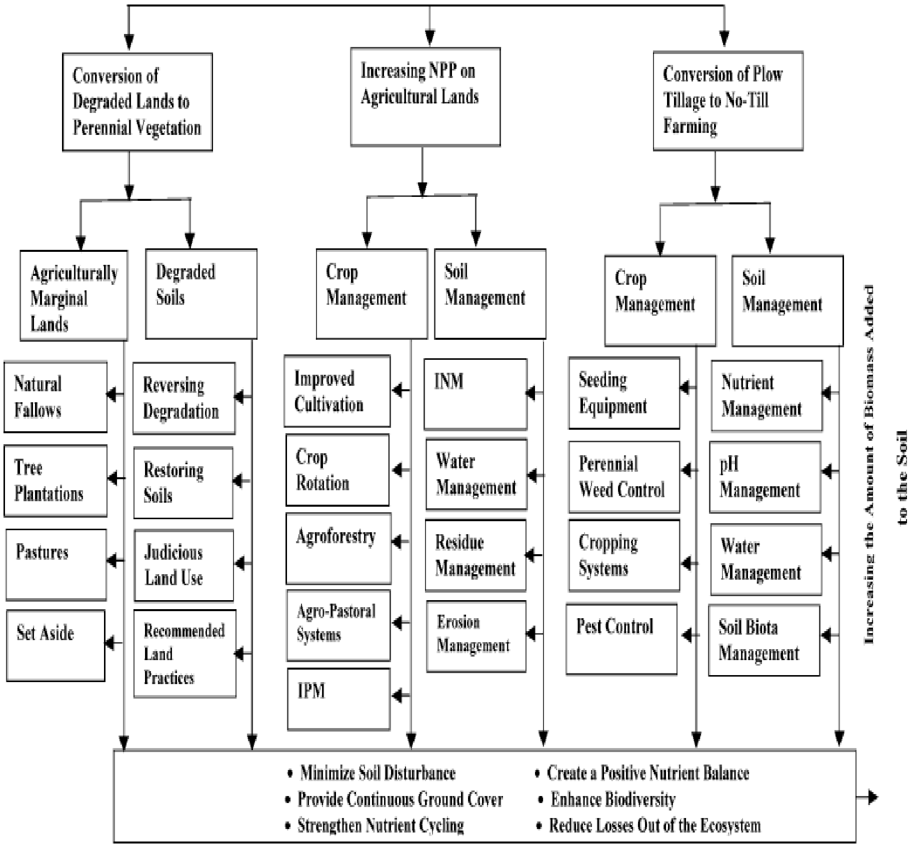


Fig 13 (c): Strategies for soil carbon sequestration

Ahmed *et al.* (2024) reported that the maximum and significant improvement in microbial parameters was recorded in T_4 (20 t ha^{-1} FYM integrated with 50% mineral N and 100% P and K) with 44, 24, 27 and 24.6% increase in total nitrogen (total N), mineralizable nitrogen (MN), microbial biomass nitrogen (MBN), and microbial biomass carbon (MBC) after a 10 day incubation period over the T_3 (100% NPK or the recommended dose), respectively, in the surface soil and 10%, 21%, 24% and 24.2% increase in the corresponding microbial parameters in the sub soil [Fig. 14b,15 a and 15b]. Different doses of mineral fertilizers cause variable rooting depths thereby causing stratification of soil organic C (Lorenz and Lal, 2005) which explains the increase of microbial biomass C with each increment of mineral fertilizers as well as the decreasing content of soil microbial biomass C with depth. Christensen (1988) reported that fertilizers improved total N content both in the surface and sub-surface soils, with maximum values recorded in the plots receiving mixed farmyard manure and mineral fertilizers. Goyal *et al.* (2006) also revealed that the amount of soil organic matter and mineralizable C and N were higher in plots receiving organic treatments.

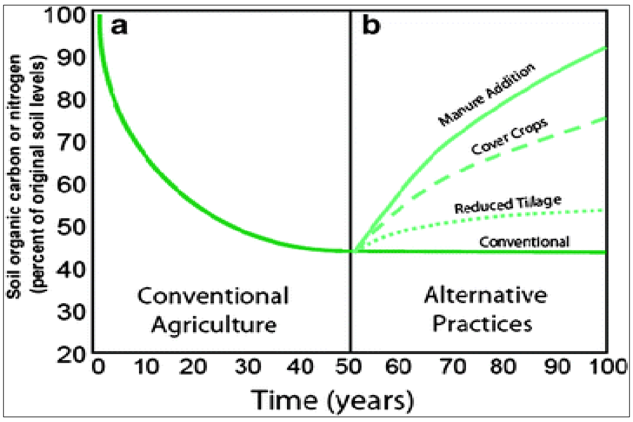


Fig 14 (a): Soil organic carbon content as affected by tillage practices.

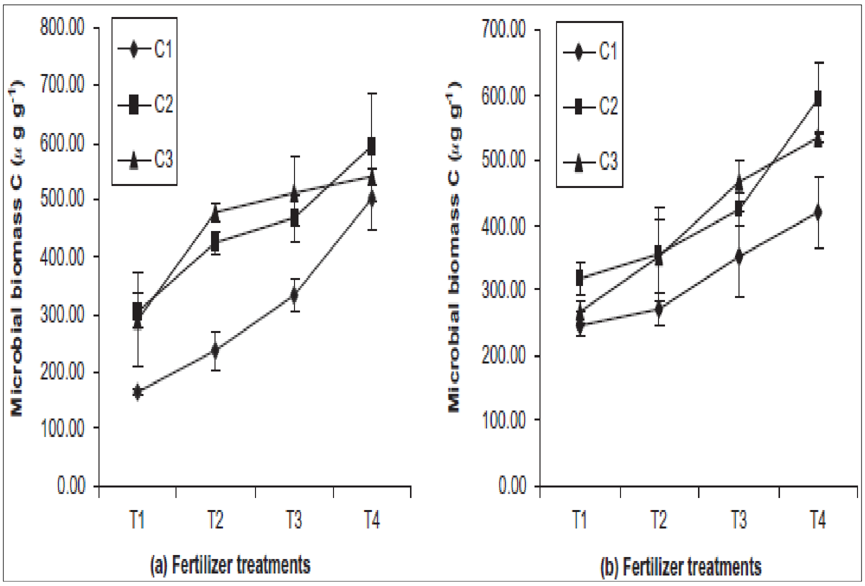


Fig 14 (b): Microbial biomass C (µg g^{-1}soil) at two depths (a) surface (0–20 cm) and (b) sub-surface (20–40 cm) soil as affected by fertilizer treatments and cropping patterns

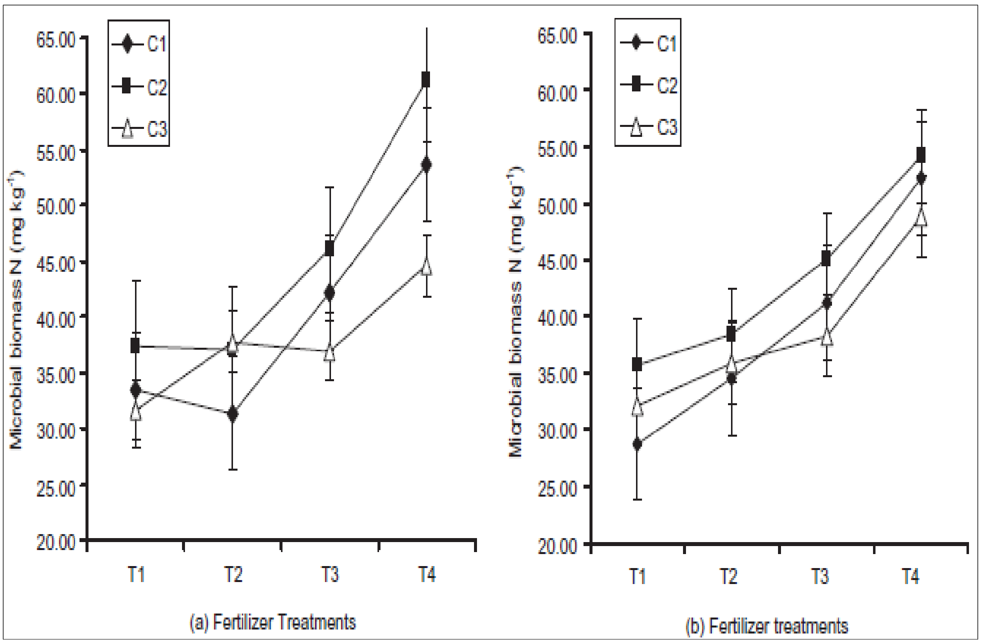


Fig 15 (a): Interactive effect of fertilizer treatments and cropping patterns, on microbial biomass N in (a) surface (0–20 cm) and (b) sub-surface (20–40 cm) soil.

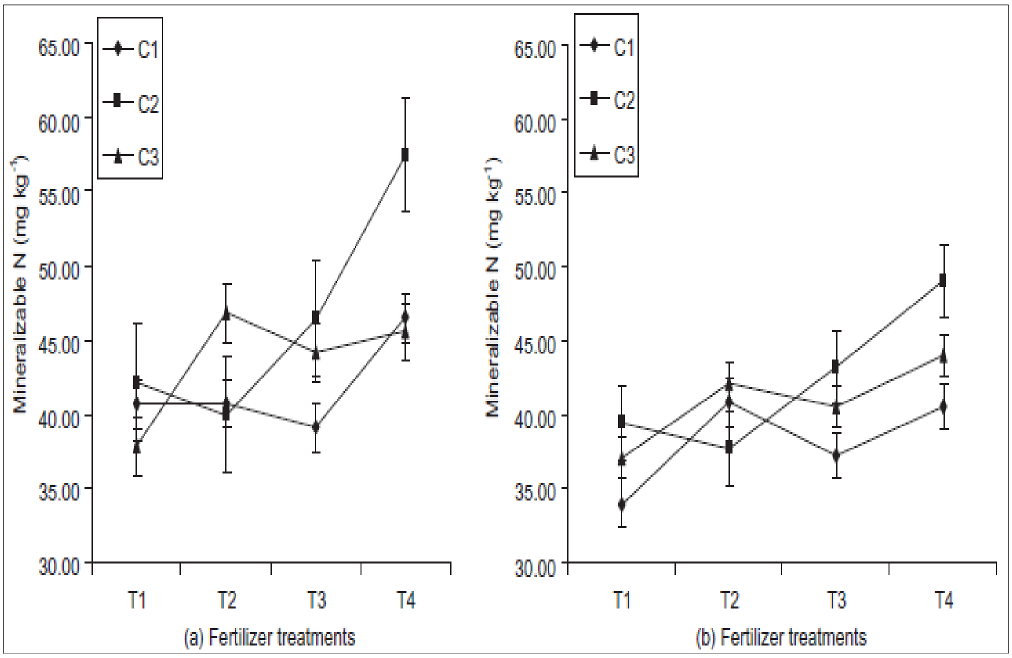


Fig. 15 (b): Interactive effect of fertilizer treatments and cropping patterns, on mineralizable N in (a) surface (0–20 cm) and (b) sub-surface (20–40 cm) soil.

Zhang *et al.* (2018) revealed that the aggregate *D* for the ST and NT treatments were significantly lower than for the MP and CT treatments at the 0±10cm depth. This effect for the NT treatment disappeared with increased soil depth; however, the ST treatment still showed lower *D* for the 10±20 and 20±30cm depths. This variation dwindled at lower depths until 50±60cm, where there was no significant difference in *D* between ST, NT, and MP; however, *D* was significantly lower for the CT than for the ST and NT treatments [Fig.16a]. Moreover, at the 0±10cm depth, the mean SOC varied with treatment, with the conservation tillage (ST and NT) significantly higher than conventional tillage (CT). At 10-30cm, especially, the ST treatment was significantly higher. At 20±30cm, the mean SOC from greatest to smallest was ordered ST>MP>CT>NT, with ST significantly higher than other treatments [Fig.16b].

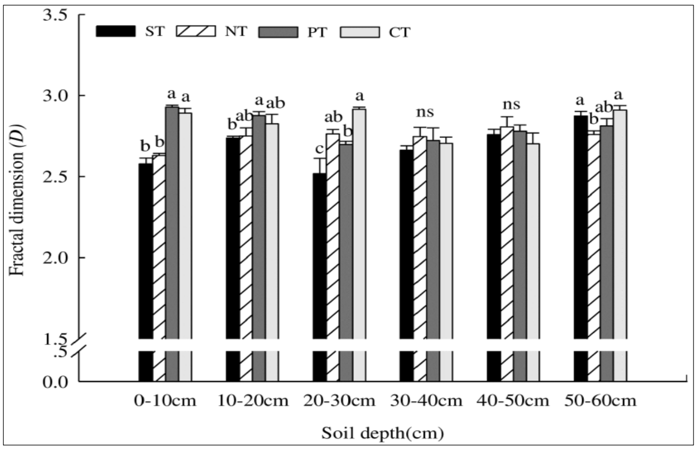


Fig. 16 (a): Effect of tillage methods on fractal dimension (*D*) of water-stable aggregates

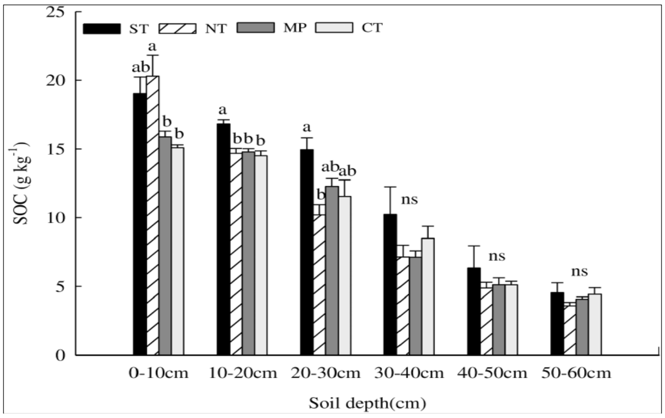


Fig 16 (b): Effect of tillage methods on soil organic carbon

The 0.25±1.00mm diameter aggregates contributed the most to SOC at the 0±10cm depth for each of the tillage treatments [Table 6]. The contributing rate was 34.7%±45.7%, with that of the ST and NT treatments significantly higher than that of MP and CT. The < 0.002mm aggregates contributed the least to SOC, with a contributing rate of 1.5%±13.4%; and those of the ST and NT treatments were significantly lower than those of MP and CT. The total contributing rate of SOC at all depths in macro-aggregates was in the order NT>ST>CT>MP, while that for micro-aggregates was MP>ST>CT>NT. SOC content can directly affect soil fertility and crop yield, and greatly affects the formation and stability of the water-stable soil aggregate structure Cai *et al.* (2009). Moreover, SOC decreases with soil depth and is more abundant in topsoil (0-20cm) than in the sub-layers (below 20cm). SOC content was highest at the 0±10 and 10±20cm depths, accounting for 27.98 and 24.28% of the total SOC, respectively. NT showed a high SOC accumulation at 0±10cm, while ST promoted accumulation at all depths 0±60cm, with significantly higher accumulation at 0±10, 10±20 and 20±30cm. The mechanism and reason for this phenomenon were the higher straw cover in the NT and ST treatments, which can reduce soil erosion, land surface evaporation, and loss of soil organic matter, and can improve the soil structure. Another reason is that straw mulching has moisture preservation effect and benefits the activities of microorganisms, which can accelerate the SOC turnover. Furthermore, the sub-soiling effect can promote root system growth, and a large amount of the root system and stubble can be converted into SOC through decomposition and humification effects, thereby increasing the SOC content in deep soil and enhancing the soil ability to accumulate C under the ST treatment.

Table 6: Contributing rates of SOC in water-stable aggregates in different soil layers for different tillage methods [Zheng *et al*., 2018] [87].

Depth (cm)	Treatments	Macro-aggregate (%)				Micro-aggregate (%)			
		> 2 mm	2–1 mm	1–0.25 mm	Sum	0.25–0.053 mm	0.053–0.002 mm	< 0.002 mm	Sum
0–10	ST	11.5±0.30a¶	34.5±2.02a	42.9±1.88ab	88.9±0.46a	8.1±0.65c	1.5±0.13b	1.5±0.46c	11.1±0.47c
	NT	9.9±0.25b	34.2±2.13a	45.7±2.37a	89.7±0.47a	7.4±0.60c	1.4±0.13b	1.5±0.26c	10.3±0.47c
	MP	2.0±0.06c	23.4±1.70b	34.7±2.55c	60.1±1.03c	14.3±0.35b	12.1±1.32a	13.4±0.26a	39.9±1.02a
	CT	2.6±0.21c	26.1±1.30b	35.6±2.93bc	64.2±1.91b	16.9±0.49a	11.5±1.33a	7.4±2.78b	35.8±1.91b
10–20	ST	12.2±1.65a	31.1±1.64a	41.2±0.82ab	84.5±0.73a	3.3±0.13c	8.4±1.01b	3.8±0.15c	15.5±0.73b
	NT	8.2±0.99b	31.6±0.58a	43.6±1.41a	83.4±0.99a	3.8±0.14bc	7.6±0.65b	5.2±0.20b	16.6±0.99b
	MP	3.5±0.19c	28.5±2.24a	36.9±3.22bc	68.9±1.18b	6.5±1.02a	18.7±0.37a	5.8±0.52b	31.1±1.18a
	CT	6.5±0.11bc	26.7±1.73a	34.7±0.26c	67.9±0.64b	5.3±0.29ab	19.3±0.08a	7.51±0.41a	32.07±0.64a
20–30	ST	13.4±2.81a	30.3±1.29a	40.6±0.99a	84.3±2.38a	9.3±3.06a	5.2±1.51b	1.2±0.60c	15.7±2.38b
	NT	7.7±0.19a	34.5±2.58a	38.6±1.33a	80.8±1.74a	10.9±0.69a	5.4±0.53b	3.0±0.60bc	19.2±1.74b
	MP	11.8±1.44a	31.0±2.21a	39.8±1.61a	82.5±2.03a	11.1±1.19a	3.2±1.15b	3.2±0.33b	17.5±2.04b
	CT	11.4±2.52a	19.0±1.95b	38.2±0.69a	68.7±0.35b	10.3±0.39a	9.5±0.47a	11.6±0.76a	31.3±0.35a
30–40	ST	15.1±0.09a	26.6±0.68ab	39.8±0.31a	81.5±0.82ab	8.0±0.76b	7.6±1.19ab	2.9±0.38ab	18.5±0.82bc
	NT	10.6±1.73b	28.3±1.29ab	35.9±0.80a	74.8±2.22b	8.8±1.00b	10.3±0.70a	6.1±1.93a	25.2±2.22b
	MP	11.3±1.81ab	35.6±3.45a	35.7±2.95a	82.6±0.82a	10.1±0.19b	5.6±0.13b	1.8±0.49b	17.4±0.81c
	CT	6.1±0.48c	15.6±6.89b	43.1±10.69a	64.8±3.32c	21.3±2.49a	9.9±1.11a	3.9±0.28ab	35.2±3.32a
40–50	ST	5.2±1.34b	5.9±2.09ab	3.4±0.77ab	85.5±3.92a	5.2±1.34b	5.9±2.09ab	3.7±0.77ab	14.5±3.92b
	NT	13.6±3.26a	8.2±1.03a	5.9±1.74a	72.3±3.22b	13.6±3.26a	8.2±1.03a	5.9±1.74a	27.7±3.22a
	MP	10.4±1.20ab	0.7±0.36c	4.8±0.44ab	84.2±0.41a	10.4±1.20ab	0.7±0.36c	4.8±0.44ab	15.9±0.40b
	CT	13.8±1.25a	3.4±1.58bc	2.3±0.90b	80.5±0.58ab	13.8±1.25a	3.4±1.58bc	2.3±0.90b	19.5±0.58ab
50–60	ST	7.1±1.40a	24.0±3.65a	39.8±2.88a	70.9±2.51a	10.9±2.88a	8.9±1.30b	9.4±1.03b	29.1±2.51b
	NT	6.3±2.06a	16.4±3.29a	37.5±1.85a	60.1±1.51b	14.3±1.85a	12.5±0.90a	13.1±0.85a	39.9±1.52a
	MP	6.7±4.21a	24.4±2.03a	34.3±3.70a	65.3±1.66ab	13.8±3.70a	10.3±0.35a	10.5±0.99ab	34.7±1.66ab
	CT	6.1±2.72a	19.6±1.03a	34.3±1.03a	59.9±1.70b	13.0±1.03a	13.1±0.20ab	13.9±1.34a	40.1±1.70a

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

Kane *et al.* (2014) revealed that effect of tillage ´row position was observed for PMN with higher levels of PMN in the in-row (IR) position than off-row (OR) and between-row (BR) positions of RT treatments following re-ridging. Plant tissue analyses indicated a significant RT advantage and a structural equation modeling (SEM) analysis indicated that PMN at the 0- to 5-cm depth in the IR position following re-ridging had a significant effect on inorganic N at the same position and, in turn, a strong influence on plant tissue N. Unger (1995) found short-term increases in SOM at the in row position following re-ridging, and several studies have demonstrated short-term increases in functional signals of microbial activity, such as CO_2 respiration and microbial biomass, in the plant row. Functionally, PMN represents a labile organic matter pool that could readily supply nutrients to plants (Drinkwater *et al.*, 1996). Changes in patterns of distribution and tillage effects between the first and second soil samplings [Fig. 17a] imply that these increases at the in-row position may be the effect of RT. Increases of PMN in the ridge could create a zone of higher fertility in the in-row space, potentially making inorganic N more available for plant uptake. Inorganic N at the IR position was lower than in the OR and BR positions in both tillage treatments [Fig. 17b], but inorganic N in the IR position was higher in RT treatments than in CP treatments.

Results from plant tissue N analyses indicate higher N uptake overall in RT plants than in CP plants particularly in the grain fraction [Fig. 18a]. Higher grain N concentrations additionally indicate that N uptake was greater in RT plants during reproductive stages (Below and Gentry, 1992), which is consistent with results from ion strip extractions that show higher overall inorganic N availability in the months of July and August. Higher concentrations of particulate organic matter (POM)-N and PMN in the IR position of RT treatments, as well as higher IR inorganic N in RT treatments relative to CP treatments, may also explain higher plant tissue N concentrations in RT plants. By concentrating labile N-rich residues within the in-row space near plants, RT may improve the availability of inorganic N particularly in the latter part of the season during grain fill. Our results also are consistent with stimulation of microbial-mediated turnover processes by re-ridging, based on inorganic N dynamics and the overall increase in ion strip inorganic N at all positions following re-ridging [Fig.18b].

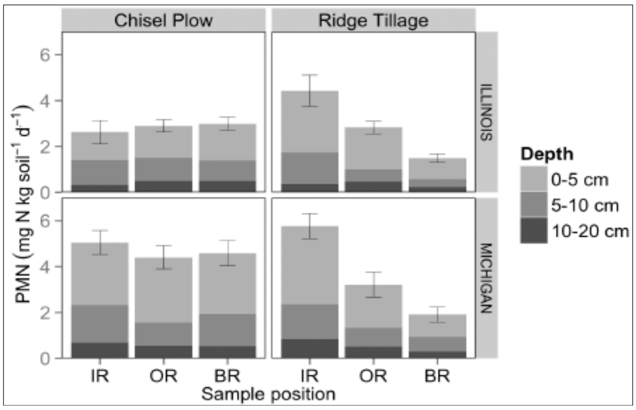


Fig 17 (a): Potentially mineralizable N (PMN) (mg N kg soil^{-1} d^{-1}) at different depths and sample positions (IR, in-row; OR, off-row; BR, between-row)

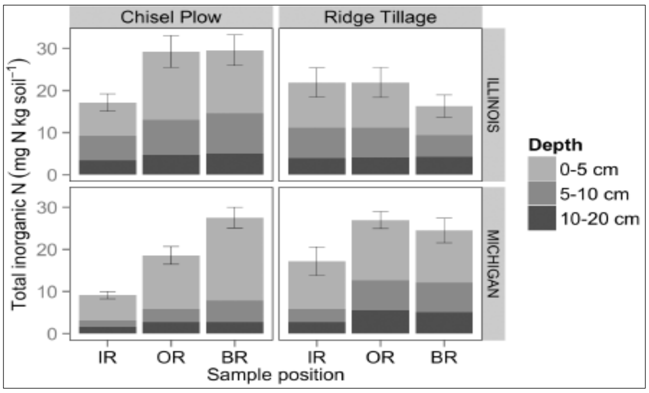


Fig 17 (b): Total inorganic N (mg N kg soil^{-1}) at different depths and sample positions (IR, in-row; OR, off-row; BR, between-row)

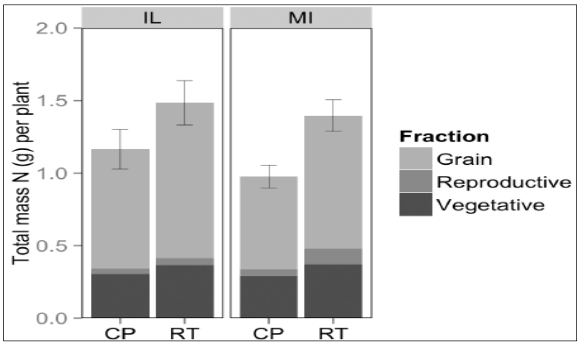


Fig 18 (a): Total per-plant mass N (g) of plants in each tillage treatment (RT, ridge tillage; CP, chisel plow)

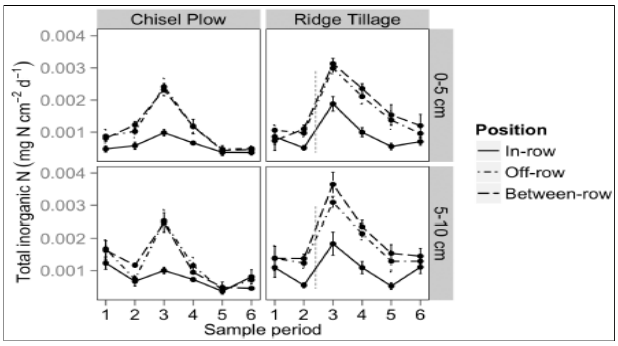


Fig 18 (b): Total inorganic N (mg N cm^{-2} d^{-1}) adsorption by ion exchange resin strips at all depths and sample positions

Conclusion

Plowing seems to be a potential risk in terms of SOC content for each fraction. Beneath the well-known loss from macro-aggregates, mineralization ameliorates SOC content, both in the fine fraction and at the coarse particles. Decades of CA can significantly increase related SOC content. Continuous cultivation triggered SOM molecular size increases in both aggregates and the fine fraction, whereas switching to CA restored the molecular SOM size of the fine fraction only. Therefore, this fraction can be changed, even in short periods. The lack of changes in aggregate-associated SOM was also suggested by the unchanged aggregate stability. Irrespective of tillage practices, residue retention resulted in 22.56% and 25.61% higher WSC as compared to the non-residue treatments in surface and sub-surface soil, respectively. Residue incorporation increased the SOC stock by 3.1Mgha^{-1} or 6.8%. Average annual SOC sequestration was 78 kg ha^{-1} year^{-1}. The average difference in C input due to residue incorporation was 2.3Mgha^{-1} year^{-1}. The MBC contents in both surface and sub-surface soil were significantly higher in plots receiving 100% RDN as CF+ VC @ 5tha^{-1} and 75% RDN as CF+ VC @ 5tha^{-1} treated plots compared to 100% RDN as CF fertilizer and unfertilized control plots. 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 and 6 tha^{-1} residue retention and CT treatments. Addition of manure and crop residues being applied for organic matter supply then it will favors microbial activities and the production of macro-aggregate. The total contributing rate of SOC at all depths in macro-aggregates was in the order NT>ST>CT>MP, while that for micro-aggregates was MP>ST>CT>NT. SOC content can directly affect soil fertility and greatly affects the formation and stability of the water-stable soil aggregate structure.

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