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Macro-aggregate dynamics over time and changes in soil organic carbon concentration and stability variation in top and deep soils under conservation agriculture based practices in rice-wheat system: A review

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Abstract

Deteriorating soil health, diminishing soil organic carbon (SOC), development of subsurface hard compact layer and declining system productivity are barriers to achieving sustainable production in the traditional rice–wheat cropping system (TA) in the North Western Indo-Gangetic Plain of India. Conservation agriculture (CA), which favors minimum soil disturbance and crop residue retention, could be a viable alternative to the TA to address most of those major problems. Zero tillage combined with crop rotation and crop residues retention resulted in a higher proportion of macro-aggregates. In the 0–5 cm layer, plots with a crop rotation and monoculture of maize and wheat in ZT + R had the greatest proportion of large stable macro-aggregates (40%) and highest mean weighted diameter (MWD) (1.7 mm). Compared with CT, RT significantly increased the proportion of small macro-aggregates by 23%–81% in the 10–80 cm layer and the OC content in small macro-aggregates by 1%–58% in the 0–80 cm layer.

RT significantly increased (by 24%–90%) the OC content in mineral-SOC within small macro-aggregates in the 0–60 cm layer, while there was a 23%–80% increase in the 0–40 cm layer with NT. The plots with CT had the largest proportion of micro-aggregates (27%). In the 5–10 cm layer, plots with residue retention in both CT and ZT or with monoculture of wheat in plots under ZT without residues (1.4 mm) had the greatest MWD. The 0–10 cm soil layer had a greater proportion of small macro-aggregates compared to large macro-aggregates and micro-aggregates. The contribution of macro-aggregates to SOC stock was larger (36–66%) under CA in the 0–7.5-cm soil layer. Adoption of CA improved the macro-aggregate content, MWD and GMD of aggregates, and aggregation ratio. The reports show that deep rooted, crop-based systems, have higher total soil C stocks and more C in the smallest (< 53 μm) soil fractions indicating the recalcitrant (longer-term storage) nature of C and implying consequent ecosystem benefit of reduced chances for soil C release back to the atmosphere. Moreover, the mean stratification ratio (SR) (i.e. a ratio of the concentrations of SOC in the soil surface to those in a deeper layer) of SOC for 0–5:5–10, 10–15, 15–20, 20–25 and 25–30 cm were found higher (> 2) under CA practices compared to intensive tillage-based conventional agricultural practice.

Furthermore, because conventional cultivation destroyed aggregates, the dominant aggregate size fractions were < 0.5 mm for farmland and > 0.5 mm for other land uses. Compared to the corresponding values in farmland, the mean weight diameter (MWD) in forestland and grassland increased by 808%–417%, and the stability ratio of water-stable aggregate (WSAR) increased by 920%–553%. Aggregate formation and its dominant size fraction were associated closely with its carbon fractions.

Keywords: Aggregate stability, aggregate-associated organic C, conservation tillage, carbon stocks

Introduction

Soil organic carbon (SOC) plays a key role in forming and stabilizing soil structure, enhancing soil physical properties, and nutrient recycling (Beare *et al*., 1994; Naresh *et al*., 2017) [2, 25]. Soil aggregate, the basic unit of soil structure, mediates many physical and chemical processes in soils (Cates *et al*., 2016; Trivedi *et al*., 2015) [8, 46] such as soil compaction, soil nutrient recycling, root penetration, and crop yield (Naresh *et al*., 2018) [26]. Aggregate stability is frequently used as an indicator of soil structure (Xie *et al*., 2015) [48] because better soil structure and higher aggregate stability are vital to improve soil fertility, soil sustainability, and productivity (Zhang *et al*., 2016) [51].

SOC influenced aggregate stability and soil structure (Onweremadu *et al*., 2007; Durigan *et al*., 2017) [29, 12]. The stability of organic carbon in different size aggregates is different. The soil organic matters of rice-wheat cropping systems differed based on the quantity and quality of the crop residue coverage and the environment, affecting the organic carbon contents of the soil and the aggregate stability (Novara *et al*., 2015) [27]. The rice-wheat cropping systems mainly create conditions for the decomposition and transformation of soil organic matter by changing the distribution of soil organic carbon and the active habitat of microorganisms, thereby causing changes in soil aggregates (Qi *et al*., 2011) [33].

Soil aggregation, the spatial arrangement of soil particles and voids, is an important physical property and is imperative for soil fertility as it controls erosion and arbitrates soil aeration, water movement and retention (Hu, & Li, 2017). Thus, it has great bearing on root development, plant growth and crop productivity (Berisso *et al*., 2013) [3]. Aggregates are formed by various binding agents and soil constituents simultaneously at multiple levels (Bronick & Lal, 2005) [6]. Soil management, such as tillage and crop residue or straw management and seasonal variability, has the most direct bearing on aggregates, by either physical force or modifying the aggregation process (Huang *et al*., 2018) [16]. Conventional tillage impairs the aggregation process directly by physically breaking down the aggregates (Somasundaram *et al*., 2017) [42] and indirectly by altering the biochemical environment of the soil (Wilcke, & Rillig, 2010). In contrast, no-tillage promotes the formation of aggregates by omitting physical disturbance and favors the formation of continuous pores, especially bio-pores, by decaying crop residue or faunal activities which can affect the transport functions of soil (Fleige, & Horn, 2012).

The rice–wheat cropping system is practiced in an area of about 13.5 M ha on the Indo-Gangetic Plain, which is fundamentally important for the food security of the region (Jat *et al*., 2019). The puddling carried out during rice cultivation destroys the soil structure and is also reported to form a hard-compact layer (Mondal *et al*., 2019) [22] that restricts root movement and impairs soil fertility. This cropping system is currently experiencing yield plateauing and therefore the sustainability of the system is at stake. Progressive soil degradation, residue burning, lower application of organic manures and imbalanced use of fertilizer are also posing serious problems for achieving food security. Therefore, the resource-intensive conventional rice–wheat system needs to be modified with efficient management practices that are in harmony with soil quality, resource conservation and sustainability of the system. Although the information on the short- and medium term effects of CA on soil aggregation and SOC in the North Western Indo-Gangetic Plain is available, research information is lacking on the long-term impacts of CA on soil aggregate size distribution and associated C in the subsoil layers. Moreover, most of the previous studies focused on soil properties and much less importance was given to system productivity. The review study relates the conversion of the traditional rice–wheat cropping system to diversified conservation agriculture improves soil health, amasses more SOC and increases the stability variation in top and deep soils. Thus, the objectives were to assess the aggregate size distribution and associated OC, quantify SOC accumulation under different tillage, residue management.

Aggregate distribution and stability

Ou *et al*. (2016) [30] reported that the tillage systems obviously affected the distribution of soil aggregates with different sizes. The proportion of the >2 mm aggregate fraction in NT+S was 7.1% higher than that in NT-S in the 0.00-0.05 m layer. There was no significant difference in the total amount of all the aggregate fractions between NT+S and NT-S in both the 0.05-0.20 and 0.20-0.30 m layers. NT+S and NT-S showed higher proportions of >2 mm aggregate and lower proportions of <0.053 mm aggregate compared to the MP system for the 0.00-0.20 m layer. The proportion of >0.25 mm macro-aggregate was significantly higher in MP+S than in MP-S in most cases, but the proportion of <0.053 mm aggregate was 11.5-20.5% lower in MP+S than in MP-S for all the soil layers. Du *et al*. (2013) [11] reported that the NT system did affect the SOC stock distribution in the soil profile but not the total quantity. Tillage regimes obviously influenced soil aggregation distribution in the soil profile. In the upper 0.00-0.05 and 0.05-0.20 m layers, the NT system improved the formation level of the >2 mm aggregate but reduced the formation level of <0.053 mm aggregates, compared to the MP system, suggesting that mechanical operation reduced large-macro-aggregate formation and disrupted soil macro-aggregates into individual particles.

Fuentes *et al*. (2012) [13] reported that the proportion of small macro-aggregates was the largest in CTW-R (64.2%) and CTR-R (61%) and the lowest in ZTW+R (32%), ZTW-R (34%) and ZTR+R (41%). The greatest percentage of micro-aggregates was found in CTM-R (36.0%) and the lowest in ZTR+R and ZTM+R (both 19%). The greatest MWD was found in the ZTW+R (1.88 mm), ZTW-R (1.70 mm) and ZTR+R (1.68 mm) treatments and the lowest in the CTM-R treatment (0.52 mm) (Fig 1a). Residue management had a highly significant effect on the percentage of large macro-aggregates in soil under maize and maize-wheat rotation and on the percentage of micro-aggregates in soil under monoculture of maize. Tillage had a highly significant effect on the percentage of large macro-aggregates for all rotations and on the percentage of small and micro-aggregates in soil under monoculture of maize.

In the 5–10 cm layer, the ZTW+R, CTW+R and ZTW-R treatments had the highest proportion of large macro-aggregates (38%, 35% and 34% respectively). Conventional tillage without residues under monoculture of maize and maize-wheat rotation and ZTM-R had the lowest proportion of large macro-aggregates (11.5%, 12.5% and 13.7% respectively). All the treatments with monoculture of maize (regardless residues management or type of tillage) had the greatest proportion of small macro-aggregates (average 62%) (Fig.1b). The greatest MWD was found in ZTW+R (1.53 mm), CTW+R (1.40 mm) and ZTW-R (1.47 mm) and the lowest in CTR-R (0.70 mm), CTM-R (0.71 mm) and ZTM-R (0.72 mm) (Fig. 1b). Residue management had a significant (effect on large macro-aggregates for all crop rotations and on small macro-aggregates in soil with monoculture of wheat and rotation.

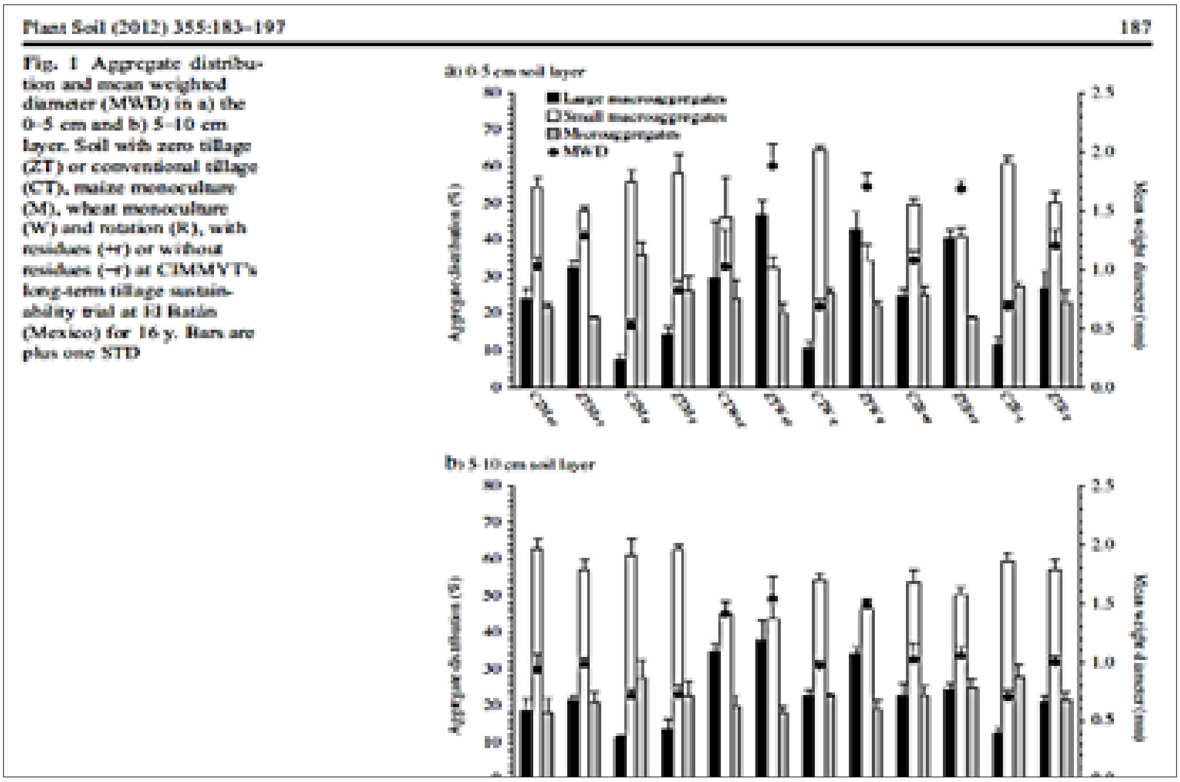
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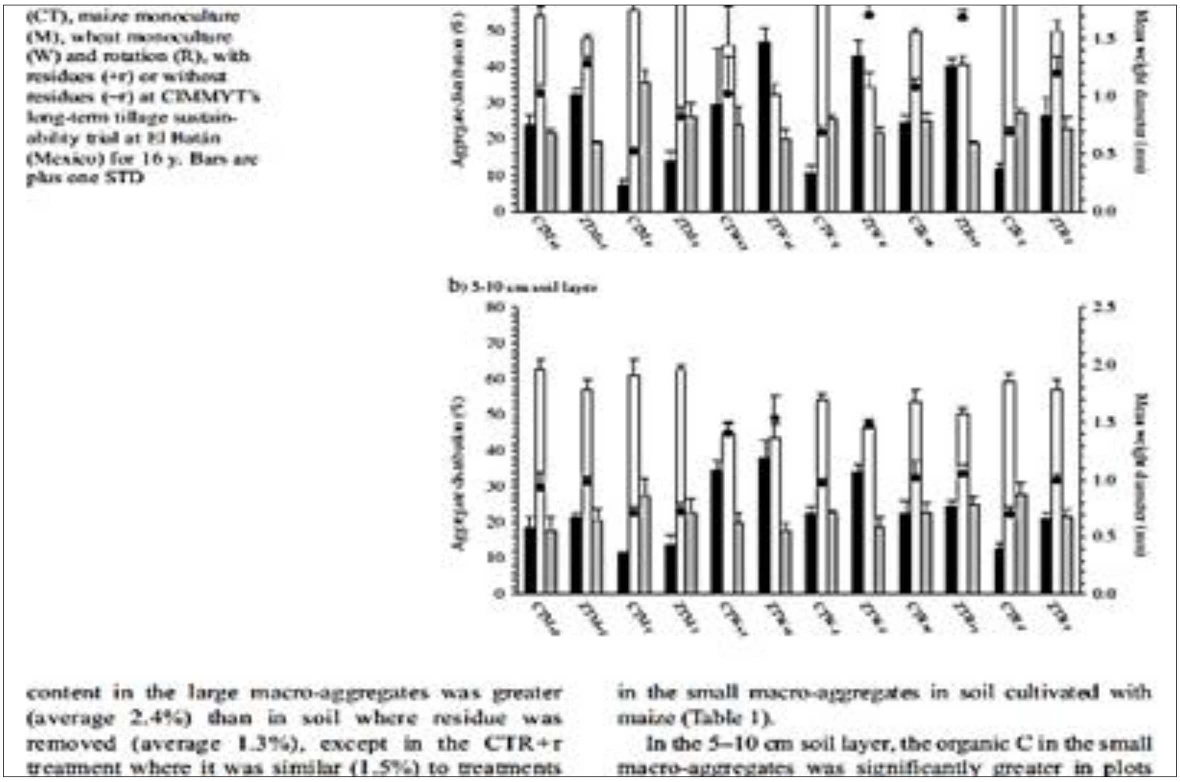
Fig. 1 Aggregate distribution and mean weighted diameter (MWD) in a) the 0–5 cm and b) 5–10 cm layer. Soil with zero tillage (ZT) or conventional tillage (CT), maize monoculture (M), wheat monoculture (W) and rotation (R), with residues (+r) or without residues (−r) at CIMMYT's long-term tillage sustainability trial at El Batán (Mexico) for 16 y. Bars are plus one STD

(a)


(CT), maize monoculture (M), wheat monoculture (W) and rotation (R), with residues (+r) or without residues (−r) at CIMMYT's long-term tillage sustainability trial at El Batán (Mexico) for 16 y. Bars are plus one STD

content in the large macro-aggregates was greater (average 2.4%) than in soil where residue was removed (average 1.3%), except in the CTR+r treatment where it was similar (1.5%) to treatments

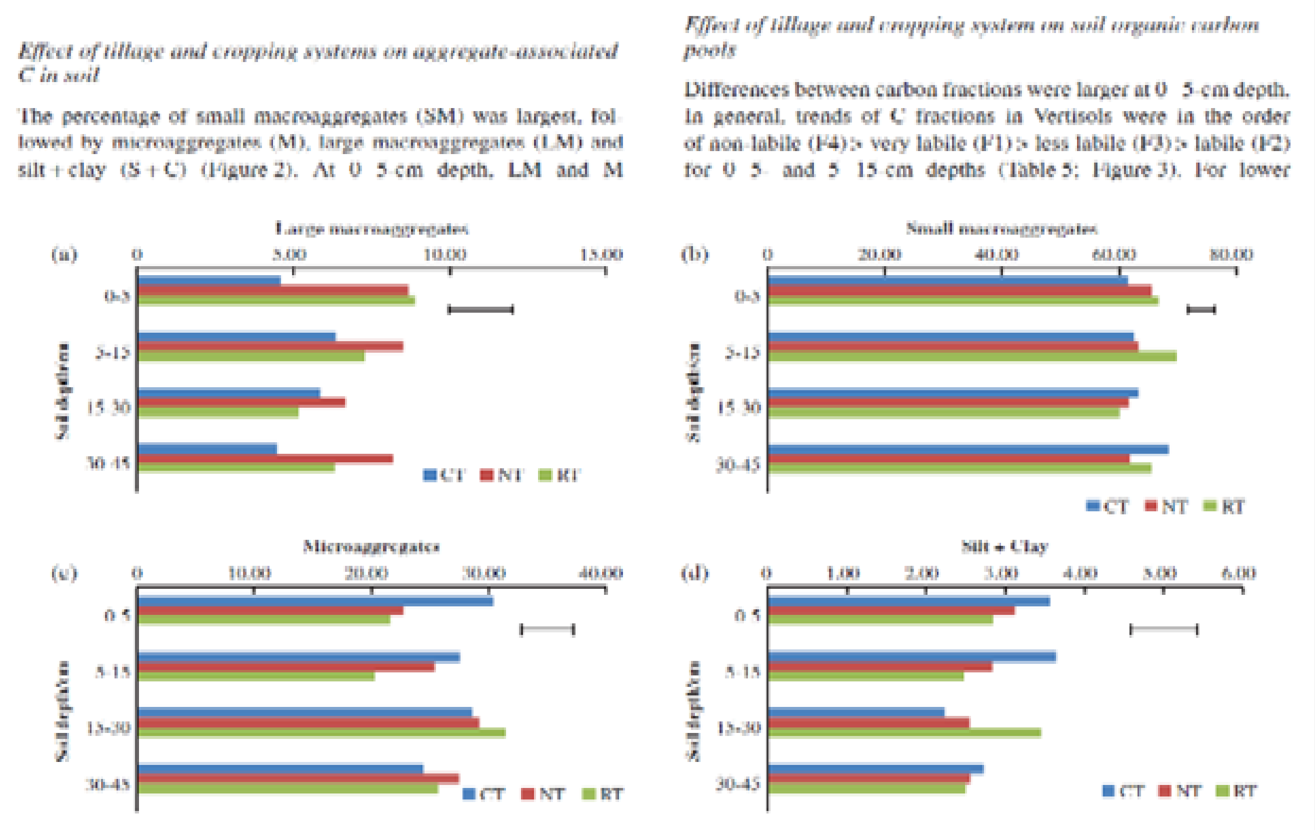
in the small macro-aggregates in soil cultivated with maize (Table 1).

In the 5–10 cm soil layer, the organic C in the small macro-aggregates was significantly greater in plots

(b)

Fig. 1: Aggregate distribution and mean weighted diameter (MWD) in a) the 0–5 cm and b) 5–10 cm layer. Soil with zero tillage (ZT) or conventional tillage (CT), maize monoculture (M), wheat monoculture (W) and rotation (R), with residues (+R) or without residues (−R) [Source: Fuentes *et al*., 2012] [13]

Somasundaram *et al*. (2018) [43] observed that the percentage of small macro-aggregates (SM) was largest, followed by micro-aggregates (M), large macro-aggregates (LM) and silt+clay (S+C) (Figure 2). At 0–5-cm depth, LM and M aggregates were significantly affected by tillage system. Small macro-aggregates showed no significant effect among the tillage systems. At 5–15-cm depth, SM and M aggregates were significantly affected by tillage system, whereas LM and S+C were not. At depths 15–30 and 30–45 cm tillage had no significant effect on aggregate-size distribution.



Effect of tillage and cropping systems on aggregate-associated C in soil

The percentage of small macroaggregates (SM) was largest, followed by microaggregates (M), large macroaggregates (LM) and silt + clay (S + C) (Figure 2). At 0 5 cm depth, LM and M

Effect of tillage and cropping system on soil organic carbon pools

Differences between carbon fractions were larger at 0 5 cm depth. In general, trends of C fractions in Vertisols were in the order of non-labile (F4) > very labile (F1) > less labile (F3) > labile (F2) for 0 5 and 5 15 cm depths (Table 5; Figure 3). For lower

Fig 2: Aggregate-size distribution (%) for (a) large macro-aggregates, (b) small macro-aggregates, (c) micro-aggregates and (d) silt + clay at the depths examined under different tillage treatments. CT, conventional tillage; RT, reduced tillage; NT, no tillage (averaged over cropping system) [Source: Somasundaram *et al*., 2018] [43]

Singh and Benbi, (2021) [38] reported that on a mass basis (w/w) macro-aggregates (0.25 to >2.0 mm) comprised 38.5–40.8% of the WSA, compared with 31.4–32.6% as micro-aggregates (<0.25 mm). Soils under maize–wheat had a significantly higher proportion of macro-aggregates than the soils under the other two investigated cropping systems, which did not differ significantly from each other. Conversely, soils under rice–wheat and maize–- wheat had a significantly lower proportion of micro-aggregates than the soils under cotton–-wheat. The relative distribution of macro-aggregates revealed the dominance of MesoA (0.25 to <2.0 mm) compared to CMacA (>2.0 mm). Within the MesoA, the 0.25–0.50mm fraction was the greatest in amount (17.2–18.2%), while the 1.0–2.0mm fraction was the lowest in amount (6.0–6.3%). The effect of different cropping systems on the distribution of aggregates in the 0.25 to 0.50mm size fraction was statistically non-significant. The MesoA of size 0.5–2.0mm was significantly higher in soils under maize–wheat compared to the other two cropping systems, which did not differ significantly from each other. However, CMacA (>2.0 mm) constituted the smallest proportion of WSA (2.9–3.2%) in soils under different cropping systems. Among micro-aggregates, CMicA (0.11–0.25 mm) was the greatest in amount (25.8–26.6%), while the FMicA (0.053–0.11 mm) was the lowest in amount (5.4–6.0%). The CMicA (0.11–0.25 mm) was significantly lower in soils under maize–wheat compared with soils under the other two investigated cropping systems. In contrast, FMicA (0.053–0.11 mm) did not differ significantly in soils under rice–wheat and maize–wheat, but was significantly higher in soils under cotton–- wheat. The formation of WSA was associated with the fine fraction (silt + clay) of the soil (Fig. 3a).

However, aggregate-associated C was higher in macro-aggregates compared with micro-aggregates. Among MesoA, the C concentration decreased with the size of aggregates (Fig. 3b). The C concentration in CMacA ranged between 5.70 and 6.84 g kg^{-1}, compared with CMicA with a C concentration between 4.10 and 5.15 g kg^{-1}. The CMacAC was higher by 39, 41 and 26% in soils under rice–wheat, maize–wheat and cotton–wheat cropping systems, respectively, compared with CMicAC. Within MesoA, the C concentration was higher in 1.0–2.0mm aggregates (5.39 to 6.67 g kg^{-1}), followed by 0.50–1.0mm aggregates (5.10 to 6.33 g kg^{-1}). Smaller MesoA (0.25–0.50 mm), on the other hand, had the lowest concentration of organic C (4.83 to 6.07 g kg^{-1}). Organic C concentration within a given aggregate class was significantly higher under maize–wheat than in the soils under rice–wheat. It did not differ significantly in soils under maize–wheat versus cotton–wheat cropping systems. Macro-aggregate-associated C increased with an increase in the proportion of water-stable macro-aggregates (Fig. 3b).

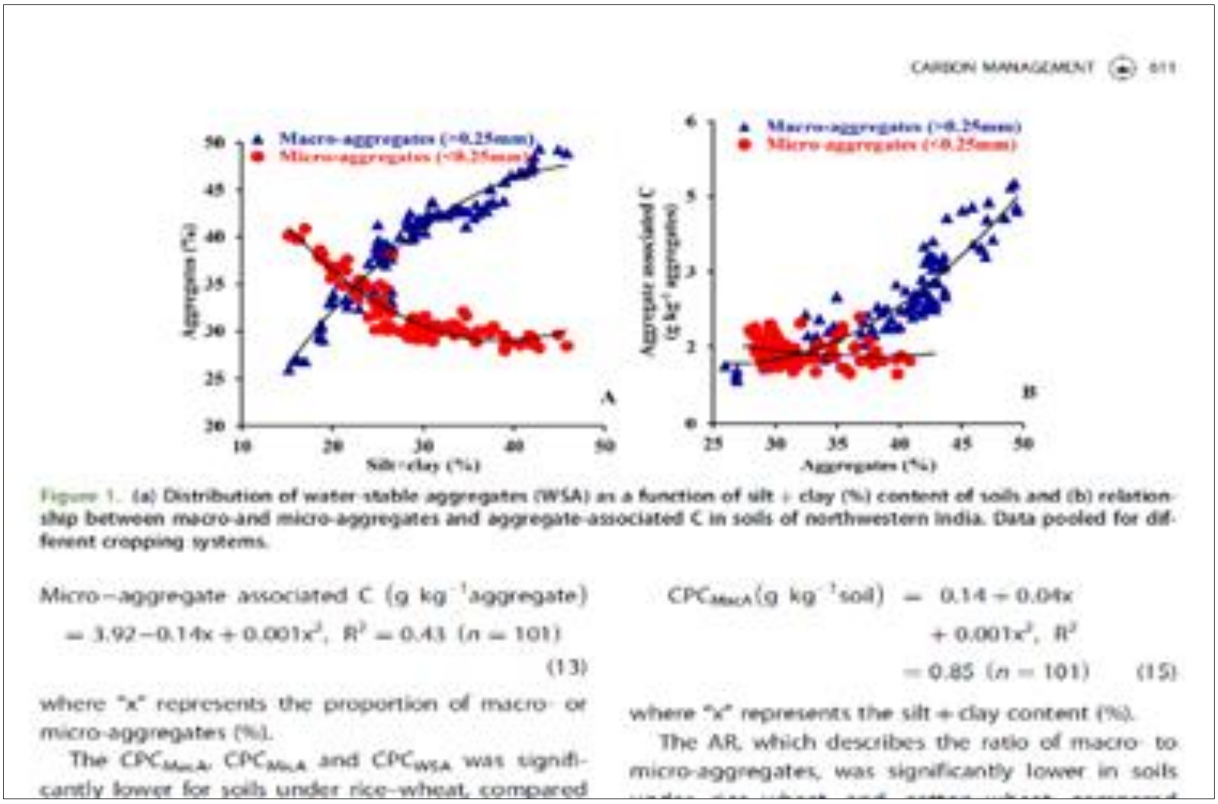


Figure 1. (a) Distribution of water stable aggregates (WSA) as a function of silt + clay (%) content of soils and (b) relationship between macro-and micro-aggregates and aggregate-associated C in soils of northwestern India. Data pooled for different cropping systems.

$$\text{Micro-aggregate associated C (g kg}^{-1}\text{aggregate)} = 3.92 - 0.14x + 0.001x^2,\ R^2 = 0.43\ (n = 101) \quad (13)$$

where "x" represents the proportion of macro- or micro-aggregates (%).

The CPC_{MacA}, CPC_{MicA} and CPC_{WSA} was significantly lower for soils under rice–wheat, compared

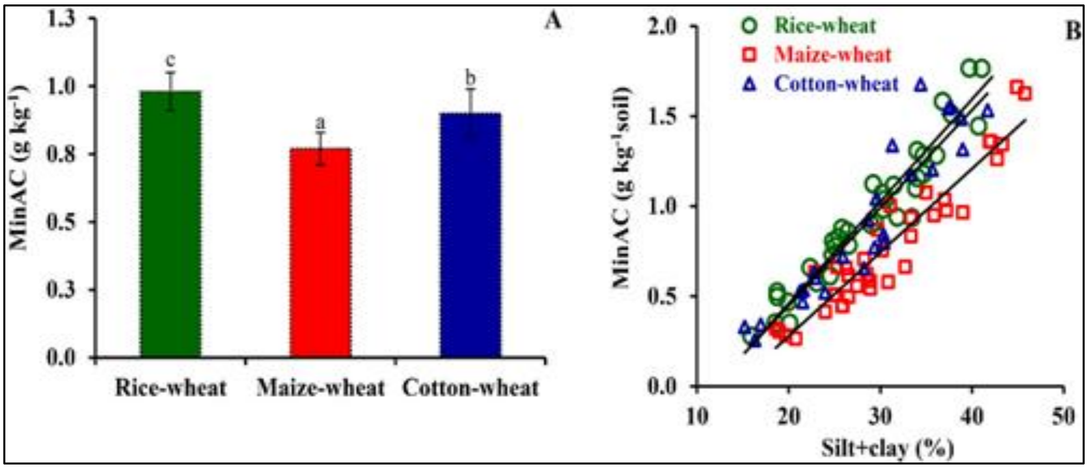
$$CPC_{MacA}(\text{g kg}^{-1}\text{soil}) = 0.14 + 0.04x + 0.001x^2,\ R^2 = 0.85\ (n = 101) \quad (15)$$

where "x" represents the silt + clay content (%).

The AR, which describes the ratio of macro- to micro-aggregates, was significantly lower in soils

(a)

Fig 3a: (a): Distribution of water-stable aggregates (WSA) as a function of silt + clay (%) content of soils and **(b)** relationship between macro- and micro-aggregates and aggregate-associated C in soils of northwestern India [Singh, P., and Benbi, D.K. 2021] [38]



(b)

Fig 3b: (a) Mineral-associated carbon [MinAC, (siltþclay)-C] content and (b) its relationship with siltþclay (%) in soils under rice–wheat, maize–wheat and cotton–wheat cropping systems in northwestern India [Singh, P., and Benbi, D.K. 2021] [38]

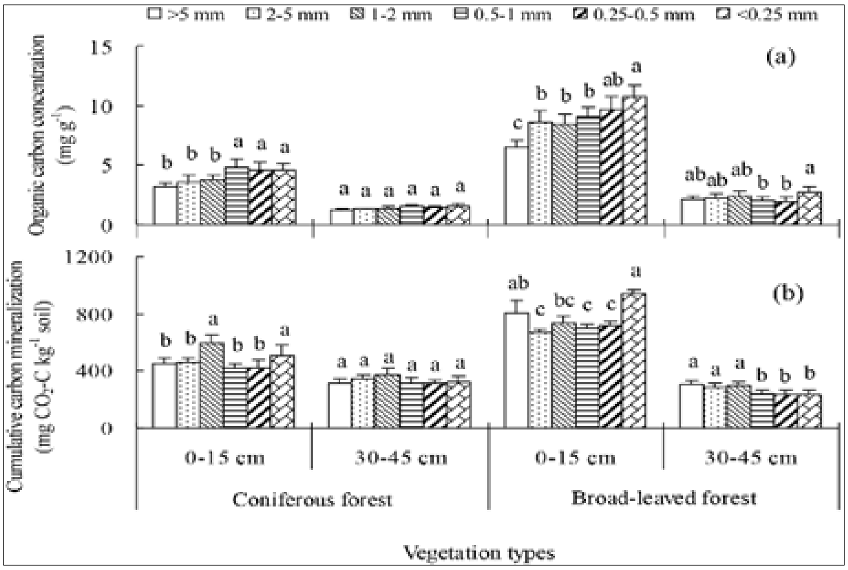
Soil organic carbon stability

The term SOC sequestration is defined as the process of transferring atmospheric CO_2 into the soil C pool through humification of crop residues and other soil organic materials which are not immediately re-emitted back into the air (Olson *et al*., 2014) [28]. SOC sequestration could be achieved by the following: (i) retaining crop residue (below and above-ground plant biomass) within the soil to be converted into organic carbon; (ii) increasing crop growth for more residue retention; (iii) reducing decomposition and soil erosion to protect and stabilize organic carbon content; and (iv) enhancing soil C budget by increasing synergisms between crop plants, soil, and atmospheric processes in order to gain saturated soil C sink capacity. Increasing SOC content and its management through soil-based and crop-based management practiced by the application of C-enriched material and organic fertilizers and judicious use of land resources are key factors that determine the SOC sequestration (Zhang *et al*., 2017; Lal, 2018) [50, 20].

The strategy refers to the adoption of best management practices that protect the environment and natural resources and ultimately crops yield. It is among the most suitable approaches for mitigating GHG emissions. Low C agriculture practice is primarily based on the adaption of the best agricultural management practices to reduce the CO_2 emissions from land use. In addition, LSA also reflects the efficient use of energy resources by involving following operations: (i) decreasing the fossil fuel input by adaption of no or reduced tillage practices, (ii) enhancing nutrient use efficiency by increasing crop diversity and use of cover crops, and (iii) strengthening biological N fixation by including legume crops in crop rotation (Robertson *et al*., 2004) [34].

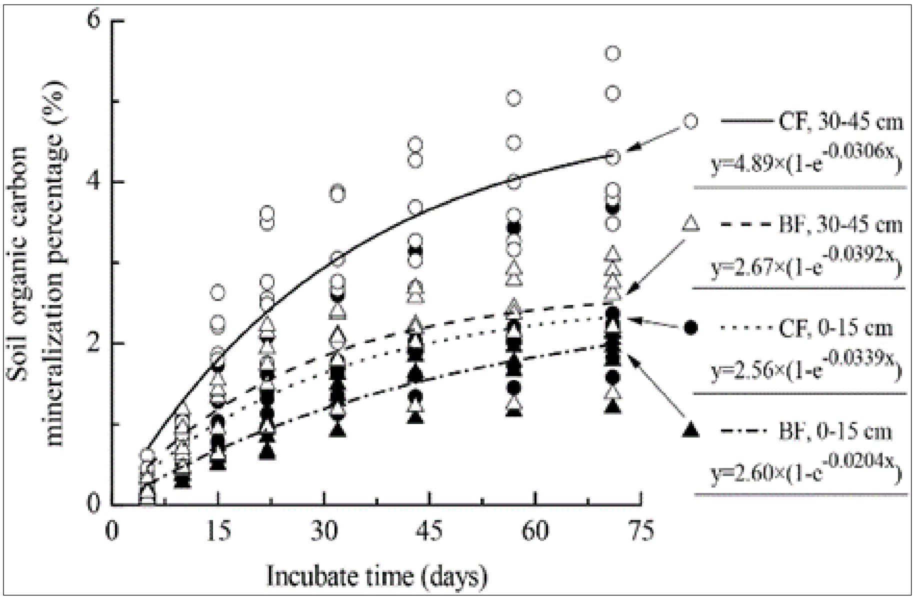
The process of soil carbon sequestration involves three basic mechanisms including the formation of soil micro-aggregates, its long-term stability, and improvement in soil structure with the deep placement of SOC in the sub-soil layers (Bossuyt *et al*., 2002) [5]. These processes are commonly addressed as physical and chemical mechanisms. The formation of clay domains and micro-aggregates and cementation of primary particles is based on the foundation of organo-mineral complexes. Micro-aggregate dynamics are influenced by the humic substances and other persistent compounds, including polymers (Kobierski *et al*., 2018) [19]. A stabilization of macro-aggregates can protect soil organic matter (OM) against soil microbial activity. Furthermore, climatic conditions, soil properties, tillage practices, and availability of soil nutrients also define the humification efficiency of biomass C. Himes (2018) [15] reported that ~28 Mg of C in 62 Mg of oven-dry residue is needed to sequester the 10 Mg of C in crop residue into 17.241 Mg of humus. Under the soils with mulch application, a similar amount of SOC stocks (25.6 Mg C ha^{-1}) has been recorded both for with and without application of fertilizers. However, with mulch application, additional accretion of SOC occurs only where additional fertilizer was applied. The adoption of the no-till system does not essentially increase the SOC pool without adequate fertilization (Campbell *et al*., 2001) [7]. Continuous tillage practices can result in reducing the mean weight diameter of soil aggregates to facilitate the erosion process. The dissolved organic carbon has numerous sources from below ground and above ground and flows through the land to the aquatic streams. Fang *et al*. (2015) also found that the mass of soil aggregates of >5 mm diameter was the greatest followed by 2–5 mm, 0.5–1mm, 0.25–0.5 mm, and <0.25 mm, and that of 1–2 mm aggregates was the lowest [Fig.4a]. Moreover, smaller aggregates had a higher OC concentration (0.5–1 mm, 0.25–0.5 mm and <0.25 mm) than larger aggregates (>5 mm, 2–5mm and1–2 mm) in CF topsoil, and OC concentration decreased with increasing aggregate size in BF topsoil. In contrast, the OC concentration varied very little between aggregate size classes at deep soils in both forests [Fig 4b]. The C_{min} during the first 15 days was the highest in aggregates of 1–2 mm and <0.25 mm, followed by >5 mm and 2–5 mm, and the lowest in aggregates of 0.5–1 mm and 0.25–0.5 mm in CF topsoil [Fig.4b]. Similarly in BF topsoil, the C_{min} during the first 15 days was higher in <0.25 mm aggregates than in other aggregates, and did not differ significantly between the six aggregate categories at deeper soil depths in either vegetation type [Fig.4b]. In CF topsoil, the C_{min} measured over 43 and 71 days were generally higher in aggregates of 1–2 mm and <0.25 mm than in other aggregates, but such patterns were not observed in deep soil. In BF topsoil, the C_{min} measured over 43 and 71 days were generally higher in aggregates of >5 mm and <0.25 mm than in other aggregates, and higher in larger aggregates (>5 mm, 2–5 mm and 1–2 mm) than in smaller aggregates (0.5–1 mm, 0.25–0.5 mm and <0.25 mm) in deep soils [Fig. 4b].

Fang *et al*. (2015) revealed that in CF topsoil, the SOC_{min} was significantly higher in aggregates of 1–2 mm than that in aggregates of 0.5–1mm and 0.25–0.5 mm, while the highest value of OC mineralization percentage was found in aggregates of >5mm in BF topsoil. Likewise, the soil OC mineralized potential (C_0), mineralization constant (k) and decomposition days of half mineralizable carbon ($t_{0.5}$) varied with aggregate size, vegetation type and soil depth. The C_0 was higher in CF than in BF soil aggregates at both depths, while the $t_{0.5}$ in BF topsoil aggregates exceeded those in topsoil aggregates of CF. In CF, the C_0 and $t_{0.5}$ were higher in deep soil aggregates than in topsoil aggregates, however, the $t_{0.5}$ was lower in deep soil aggregates than in topsoil aggregates in BF [Fig.4c]. Generally, physical protection is one of the important mechanisms to carbon stability. Compared with BF, CF had smaller soil aggregates and fewer larger soil aggregates, and the MWD was lower in CF than that in BF deep soils, which means the stability of the soil OC was better in CF Martens, (2000) [23]. However, the value of SOC_{min} was significantly higher in CF than in BF and there was no difference of C_{min} in deep soil of CF and BF [Fig. 4b].



(a & b)

Fig. 4a&b: The organic carbon concentration and mineralization of aggregate soil within 71 days at various soil depths in two restored plantations [Source: Fang *et al*., 2015]



(c)

Fig 4c: The weighted mean of soil organic carbon mineralized percentage in various aggregates vary with incubation days in two soil depths under two restored plantations. CF and BF indicate coniferous forest and broad-leaved forest, respectively. Organic carbon mineralization modeling $C_m = C_0 (1\text{-}e^{-kt})$. C_m and C_0 indicates the accumulative amount of organic carbon mineralization percentage within the incubation days and potential mineralization percentage, respectively; k and t indicate the mineralization constant and days, respectively [Source: Fang *et al*., 2015]

Generally, physical protection is one of the important mechanisms to carbon stability. Compared with BF, CF had smaller soil aggregates and fewer larger soil aggregates, and the MWD was lower in CF than that in BF deep soils, which means the stability of the soil OC was better in CF (Martens, 2000) [23]. However, the value of SOC_{min} was significantly higher in CF than in BF and there was no difference of C_{min} in deep soil of CF and BF. Soil organic matters were the adhesive in the formation of soil aggregates (Silver *et al*., 2000) [36] which mainly came from root exudates and decomposition of microbes on plant residue (Rumpel and Koegel-Knabner, 2011) [35]. Soil aggregates might not be a major factor controlling OC stability when soil OC concentration was both low both in CF and BF at the early stages of vegetation restoration (21yr). Thus SOC_{min} was not lower in CF with relatively higher percentage of smaller soil aggregates than in BF.

Fuentes *et al*. (2012) [13] observed that in both the 0–5 cm and the 5–10 cm layer, the C in the small macro-aggregates contributed most to the total organic C for all treatments (average 55%), except for ZTW+R where the major contribution came from the large macro-aggregates (average 50%) (Fig.5). In maize monoculture and residue removal (ZTM-R and CTM-R) and CTR-R, the micro-aggregates contributed more C to the total organic C than in the other treatments (average of 0 to 10 cm CTM-R 32.5%, ZTM-R 29.5% and CTR-R 27.5% respectively) (Fig. 3). Organic matter stabilizes aggregates by at least two different mechanisms: (1) by increasing the inter-particle cohesion within aggregates thereby decreasing their breakdown and (2) by increasing their hydrophobicity and thus decreasing their breakdown by slaking.

Six *et al*. (2002) [39] found a greater accumulation of organic C in the top-soil of systems with ZT compared to CT due to a better preservation of aggregates in ZT. The C not exposed is longer retained in the soil (Six *et al*., 2004a) [40]. It has been reported that the stability of a soil can be related to the proportion of large macro-aggregates, normally containing most of the C in the soil (Six *et al*. 2004b) [41]. Stewart *et al*. (2008) [44] stated that the C sequestration capacity of a soil is determined mainly by the protection of C in the aggregates. Soil C stocks change with tillage and management practices (Govaerts *et al*. 2009a) [14]. Fuentes *et al*. (2010) [13] reported that the SOC content in the 0–10 cm layer was affected by tillage and residue management. The highest SOC content was found in the 0–5 cm layer of the ZT+R compared other treatments. The soils with ZT+R showed higher percentages of SOC and SOC stock than CT+R and CT−R. Consequently, the combination of ZT with residue retention is what makes aggregates more stable, protects C and thus increases C sequestration and not zero tillage or residue retention separately.

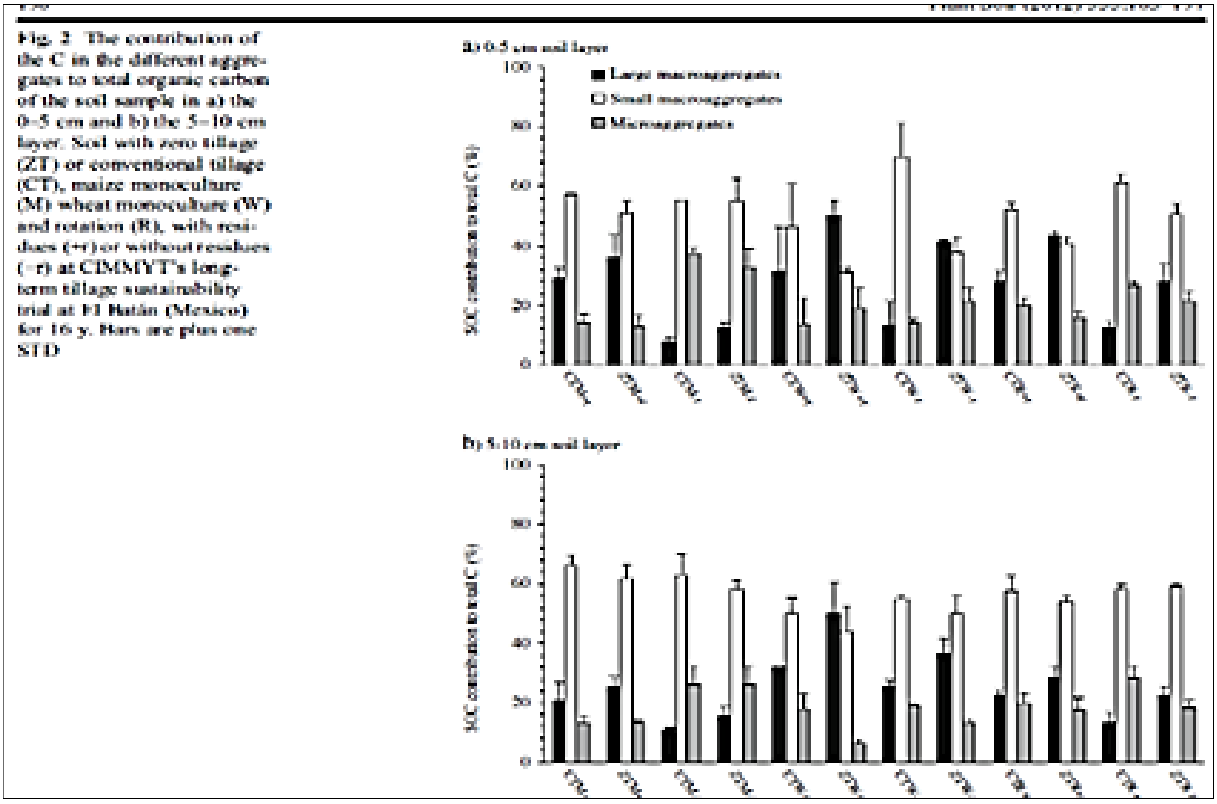
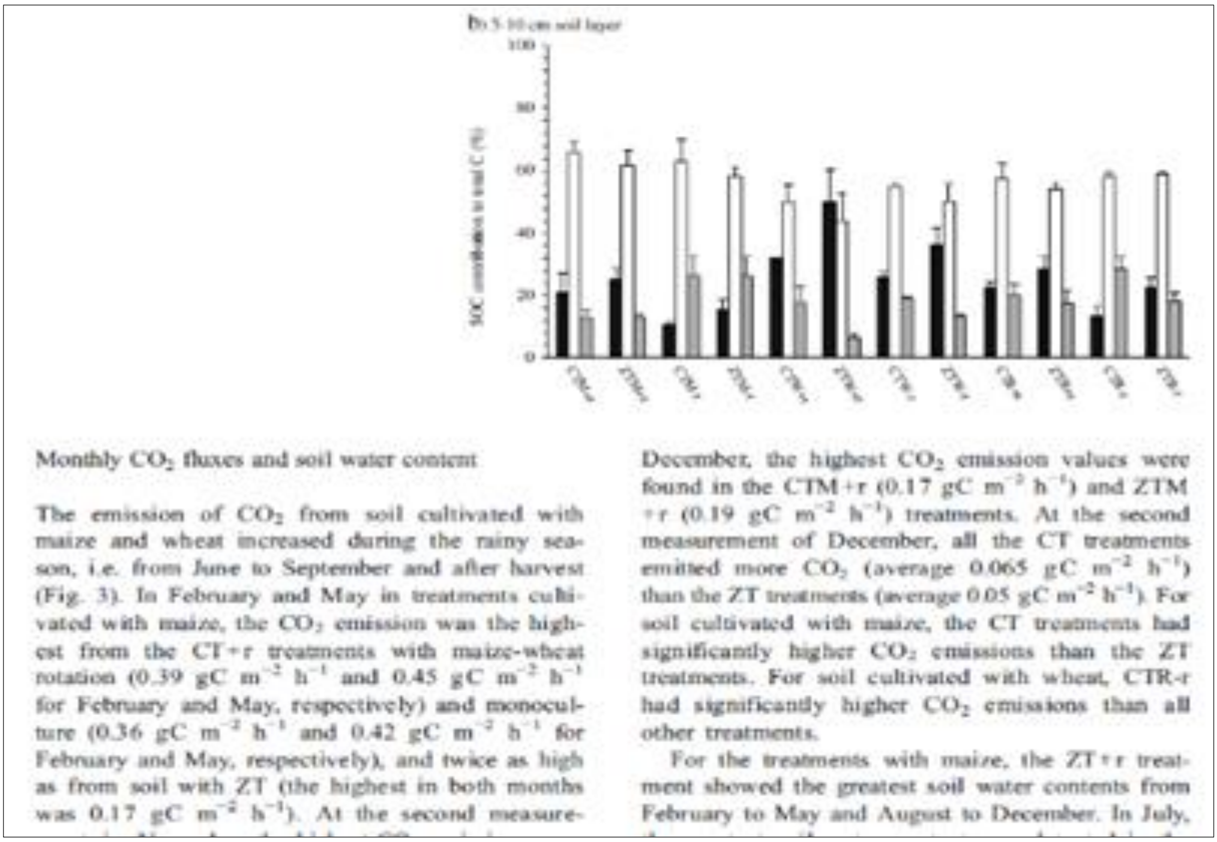


Fig. 2 The contribution of the C in the different aggregates to total organic carbon of the soil sample in a) the 0–5 cm and b) the 5–10 cm layer. Soil with zero tillage (ZT) or conventional tillage (CT), maize monoculture (M) wheat monoculture (W) and rotation (R), with residues (+r) or without residues (−r) at CIMMYT's long-term tillage sustainability trial at El Batán (Mexico) for 16 y. Bars are plus one STD

(a)



Monthly CO_2 fluxes and soil water content

The emission of CO_2 from soil cultivated with maize and wheat increased during the rainy season, i.e. from June to September and after harvest (Fig. 3). In February and May in treatments cultivated with maize, the CO_2 emission was the highest from the CT+r treatments with maize-wheat rotation (0.39 gC m^{-2} h^{-1} and 0.45 gC m^{-2} h^{-1} for February and May, respectively) and monoculture (0.36 gC m^{-2} h^{-1} and 0.42 gC m^{-2} h^{-1} for February and May, respectively), and twice as high as from soil with ZT (the highest in both months was 0.17 gC m^{-2} h^{-1}). At the second measure-

December, the highest CO_2 emission values were found in the CTM+r (0.17 gC m^{-2} h^{-1}) and ZTM +r (0.19 gC m^{-2} h^{-1}) treatments. At the second measurement of December, all the CT treatments emitted more CO_2 (average 0.065 gC m^{-2} h^{-1}) than the ZT treatments (average 0.05 gC m^{-2} h^{-1}). For soil cultivated with maize, the CT treatments had significantly higher CO_2 emissions than the ZT treatments. For soil cultivated with wheat, CTR-r had significantly higher CO_2 emissions than all other treatments.

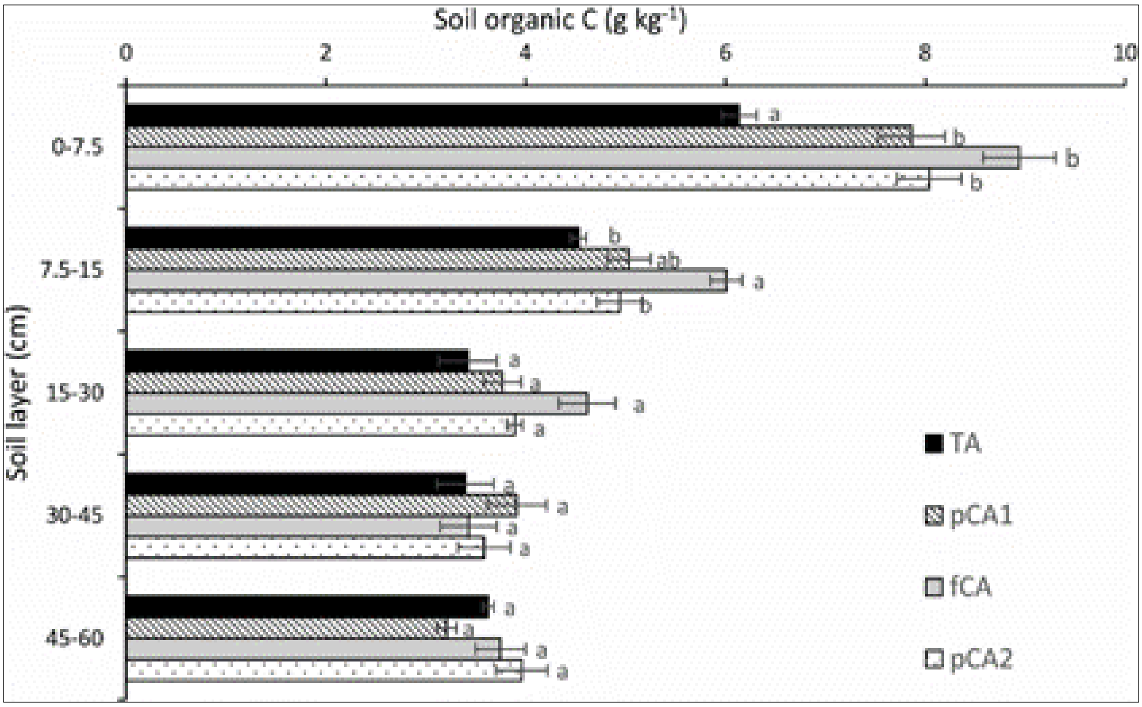
For the treatments with maize, the ZT+r treatment showed the greatest soil water contents from February to May and August to December. In July,

(b)

Fig 5: The contribution of the C in the different aggregates to total organic carbon of the soil sample in a) the 0–5 cm and b) the 5–10 cm layer. Soil with zero tillage (ZT) or conventional tillage (CT), maize monoculture (M) wheat monoculture (W) and rotation (R), with residues (+R) or without residues (−R)

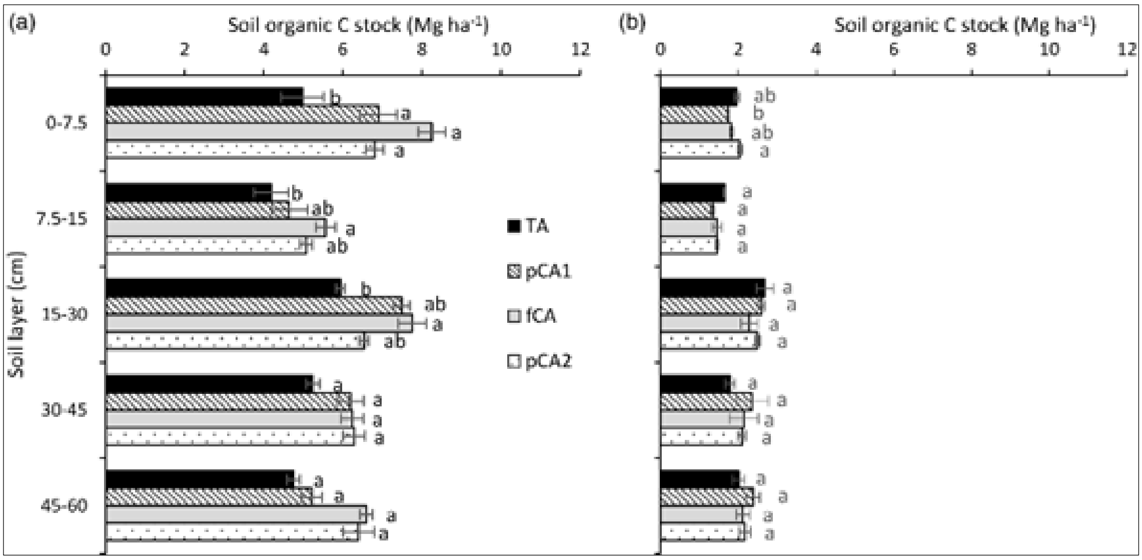
Mondal *et al*. (2021) [22] also found that in the 15–30-cm soil layer, TA recorded 31–46% greater SOC than the conventional system (TA) (Fig. 6a). In the second layer (7.5–15 cm), fCA resulted in significantly larger SOC 22–33% than TA and pCA2 but was at a par with pCA1. SOC stock increased 40.3% due to full CA in comparison to TA in the surface layer. In the subsequent layer, fCA reported 18.9–35.6% larger SOC stock than the rest of the treatments. In the case of the mass basis of SOC stock, all CA practices resulted in a 28.1–45.6% greater SOC stock than TA in the 0–7.5-cm soil layer, whereas a 32.7% greater value was noted in fCA in the 7.5–15-cm soil layer than for the conventional practices. After 15-cm soil depth, SOC stock in both methods was similar for all the treatments. The total SOC stock for the 0–60-cm soil profile was significantly larger, by 19.0 and 22.0%, in fCA than in TA on a volume and mass basis, respectively.

However, the aggregate C stock was calculated and prominent differences were observed among treatments (Fig. 6b). In the surface layer, all treatments that received either partial or full CA had significantly larger 36.8–65.8% macro-aggregate SOC stock than TA. The trend was similar up to 30-cm soil depth but the magnitude decreased and only fCA had a larger (30.7–32.9%) MacA SOC stock than the conventional treatment. The impact of different treatments on MicA SOC stock was absent except for the 0–7.5-cm soil layer, where fCA2 resulted in a larger stock (17.9%; $p < 0.05$) than fCA1. Irrespective of treatments, the MAC SOC stock was two to four times greater than the MicA SOC stock.



(a)

Fig 6a: Soil organic C concentration (g kg^{-1}) as affected by conservation agriculture. fCA, full conservation agriculture; pCA1, partial conservation agriculture 1; pCA2, partial conservation agriculture 2; TA, traditional agriculture [Source: Mondal *et al.*, 2021] [22]



(b)

Fig 6b: Aggregate-associated organic C stock (Mg ha^{-1}) in (a) macro- and (b) micro-aggregates [Source: Mondal *et al.*, 2021] [22]

Total carbon stocks in the fractions and layers up to a 1-m depth

Soil organic carbon (SOC) 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) [49]. 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) [31]. 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) [18]. Jacinthe and Lal, (2009) [17] concluded that the rates of C sequestration were estimated from the temporal trend in the recent SOC pool (0– 40 cm in NR (23.2 Mg C ha^{-1}), 9-yr MP (32.9 Mg C ha^{-1}) and 13-yr MP (33 Mg C ha^{-1}), and ranged between 0.8 and 0.25 Mg C ha^{-1} yr^{-1} during the first and second decades of restoration. Despite a similar amount of crop residue returned (2.8 Mg C ha^{-1} yr^{-1}), recent SOC under 13-yr NT (36.8 Mg C ha^{-1}) exceeded that under 13- yr MP by 3.8 Mg C ha^{-1}.

Devine *et al.* (2014) [10] observed that 0–5 cm, NT and FS aggregate size fractions were significantly elevated for SOC and fine fractions compared to CT. In POC, increasing C from CT>NT>FS was evident in all aggregate sizes but significant at 0.05 for only the >2000 µm. From 5–15 cm, there were no significant differences between CT and NT for any of the size class and C fraction combinations, while the two largest aggregate size classes were significantly elevated in FS with respect to NT for SOC and all three classes were greater for POC. FS also exceeded CT but only in the small and micro aggregate fractions for POC. There were no significant differences for any of the size class and C fraction combinations from 15–28 cm. Mangalassery *et al.* (2014) [21] revealed that zero tilled soils contained significantly more soil organic matter (SOM) than tilled soils. Soil from the 0–10 cm layer contained more SOM than soils from the 10–20 cm layers in both zero tilled (7.8 and 7.4% at 0–10 cm and 10– 20 cm respectively) and tilled soils (6.6% at 0–10cm and 6.2% at 10–20 cm).

Dhaliwal *et al.* (2018) [9] revealed that the mean SOC concentration decreased with dry stable aggregates (DSA) and water stable aggregates (WSA). In DSA, the mean SOC concentration was 58.06 and 24.2% higher in large and small macro-aggregates than in micro-aggregates respectively; in WSA it was 295.6 and 226.08% higher in large and small macro-aggregates than in micro-aggregates respectively in surface soil layer. The mean SOC concentration in surface soil was higher in DSA (0.79%) and WSA (0.63%) as compared to bulk soil (0.52%). Naresh *et al.* (2018) [26] reported that conservation tillage practices significantly influenced the total soil carbon (TC),Total inorganic carbon (TIC), total soil organic carbon (SOC) and oxidizable organic carbon (OC) content of the surface (0–15 cm) soil. Wide raised beds transplanted rice and zero till wheat with 100% (T_9) or with 50% residue management (T_8) showed significantly higher TC, SOC content of 11.93 and 10.73 g kg^{-1},respectively in T_9 and 10.98 and 9.38 g kg^{-1}, respectively in T_8 as compared to the other treatments. Irrespective of residue incorporation/ retention, wide raised beds with zero till wheat enhanced 53.6%, 33.3%, 38.7% and 41.9% of TC, TIC, SOC and OC, respectively, in surface soil as compared to conventional tillage with transplanted rice cultivation. Simultaneously, residue retention caused an increment of 6.4%, 7.4%, 8.7% and 10.6% in TC, TIC, SOC and OC, respectively over the treatments without residue management. Concerning the organic carbon storage, SOCs varied between 31.9 Mgha^{-1} and 25.8 Mgha^{-1} under NT, while, in tilled treatments, SOCs ranged between 28.8 Mgha^{-1} and 24.8 Mgha^{-1}.

Storage of SOC

Patra *et al.* (2018) [32] observed that the SOC storage at 0–10 cm soil depth was the highest under NT-MWMB (12.49 Mg ha^{-1}) followed by NT-RWMB (12.12 Mg ha^{-1}), RT-RWMB (11.52 Mg ha^{-1}) and CT-RW (8.57 Mg ha^{-1}). No statistically significant difference existed among NT-MWMB, NT-RWMB and RT-RWMB treatments. However, storage of SOC at 0–10 cm depth was significantly lower under CT-RW compared to other treatments. The storage of SOC at 0–25 cm depth was the highest under RT-RWMB followed by NT-RWMB, NTMWMB and CT-RW. However, it was only significantly higher than under CT-RW. At 0–30 cm soil depth, NT-RWMB stored the highest amount of SOC (25.32 Mg ha^{-1}) and it differed significantly only from that under CT-RW (20.83 Mg ha^{-1}). However, there were no statistically significant differences among NT-MWMB, NT-RWMB and RT-RWMB and NT-MWMB, RT-RWMB and CTRW. The TN storage at 0–5 cm depth followed the order of NT-MWMB > NT-RWMB > RT-RWMB > CTRW. However, the trend was different with an increase in soil depth. At 0–15 cm, 0–20 cm, 0–25 cm and 0–30 cm soil depths, the storage of TN was the highest under RT-RWMB followed by NT-MWMB, NTRWMB and CT-RW. At these soil depths, the TN storage under RT-RWMB differed significantly only from that under CT-RW.

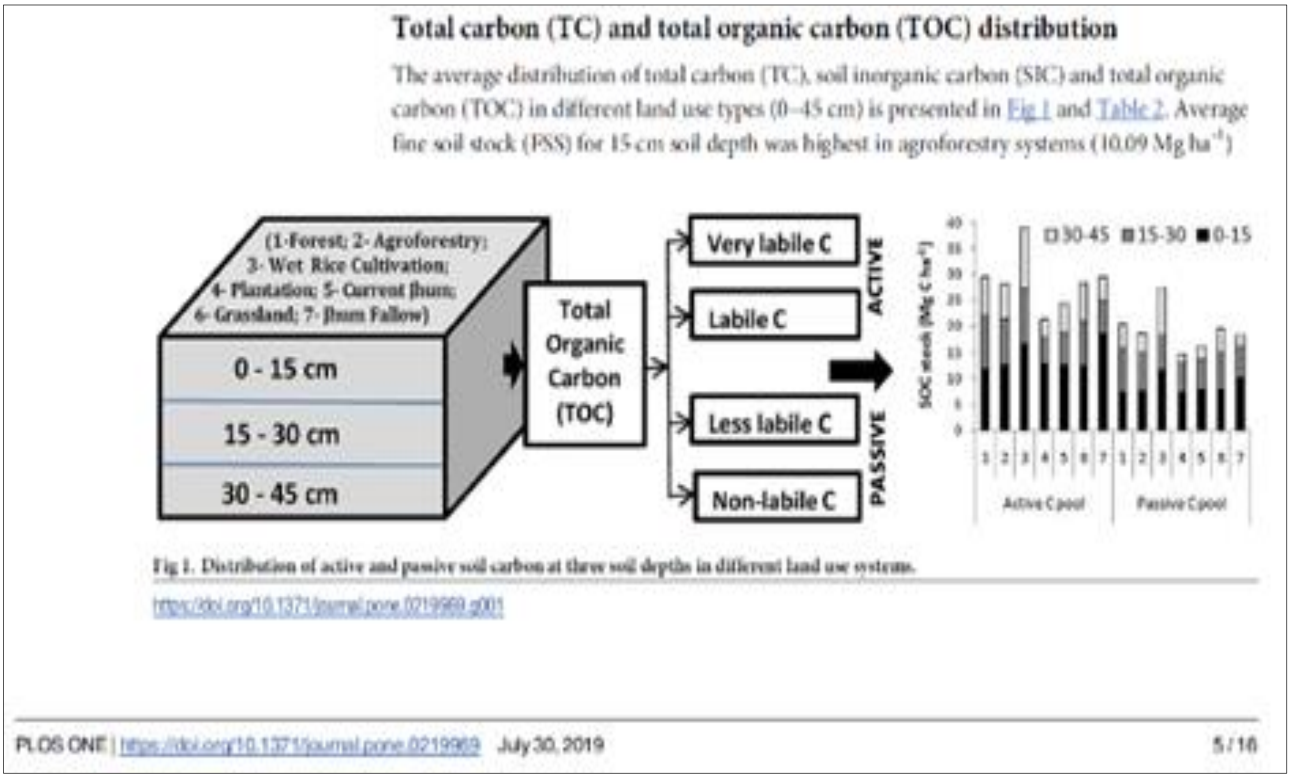
Zheng *et al.* (2018) [52] observed that the SOC storage in macro-aggregates under different treatments significantly decreased with soil depth. However, no significant variation was observed in the micro-aggregate associated C storage with depth. SOC storage increased with aggregate size from 1±2 to > 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 0-30 cm, and no significant differences between treatments below this depth.

Wang *et al.* (2019) [47] also found that the SOC contents in all treatments displayed a decreasing trend from topsoil (0–10 cm) to deep soil (80–100 cm). RT resulted in the highest SOC content in all layers except the 80–100 cm layer. Compared with the CT treatment, RT significantly increased SOC contents in the 0–10, 10–20, 20– 40, 40–60, and 60–80 cm layers, with values of 59%, 28%, 29%, 77%, and 24%, respectively. NT significantly increased SOC contents in the 0– 10, 10–20, 20–40, and 40–60 cm layers, with values of 20%, 19%, 3%, and 23%, respectively. There was no significant difference in the SOC content between RT and CT in the 80–100 cm layer. In the deep soil of the 60–80 and 80–100 cm layers, the SOC content in NT soil was significantly lower than that in CT soil.

Zhou *et al.* (2020) concluded that the SOC concentration in the $\text{WSA}_{2\text{-}5\ \text{mm}}$, $\text{WSA}_{0.5\text{-}1\ \text{mm}}$, $\text{WSA}^{0.25\text{-}0.5}\ _{\text{mm}}$, $\text{WSA}_{0.106\text{-}0.25\ \text{mm}}$, and $\text{WSA}_{<0.106\ \text{mm}}$ were all significantly increased by 15.2%, 26.2%, 20.7%, 41.6%, and 28.7% from SC treatment; by 11%, 35.6%, 24.5%, 34.2%, and 33.8% from CS treatment; and by 20.2%, 25.8%, 29.7%, 43.5%, and 27.4% from FS treatment in comparison with the CC treatment, respectively. Simultaneously, compared with CC treatment, CS and FS treatments both significantly increased SOC concentration in the $\text{WSA}_{>5\ \text{mm}}$ by 22.4% and 19.4%, as well as SC and CS treatments both significantly increased SOC concentration in the $\text{WSA}_{1\text{-}2\ \text{mm}}$ by 21.4% and 14.1%, respectively. In addition, the CS and FS treatments both significantly increased SOC concentration by 17.6% and 14.1% compared with the CC treatment in bulk soils. Across all treatments, the SOC stock in the seven aggregates' sizes showed a similar tendency in the SOC concentration. CS treatment had the highest SOC stock in the $\text{WSA}_{>5\ \text{mm}}$, $\text{WSA}_{0.5\text{-}1\ \text{mm}}$, and $\text{WSA}_{<0.106\ \text{mm}}$ with 8.89 t hm^{-2}, 8.59 t hm^{-2}, and 3.75 t hm^{-2}, respectively. While the FS treatment had the highest SOC stock in the $\text{WSA}_{2\text{-}5\ \text{mm}}$ (7.64 t hm^{-2}), $\text{WSA}_{0.25\text{-}0.5\ \text{mm}}$ (7.10 t hm^{-2}), respectively. Furthermore, the SC treatment demonstrated the biggest SOC stock in the $\text{WSA}_{1\text{-}2\ \text{mm}}$ (8.80 t hm^{-2}) and $\text{WSA}_{0.106\text{-}0.25\ \text{mm}}$ (6.64 t hm^{-2}), respectively. Except for $\text{WSA}_{0.106\text{-}0.25\ \text{mm}}$ and $\text{WSA}_{<0.106\ \text{mm}}$, the FC treatment documented the lowest SOC stock in all five other aggregate sizes. Furthermore, the SOC stock in the $\text{WSA}_{2\text{-}5\ \text{mm}}$, $\text{WSA}_{1\text{-}2\ \text{mm}}$, $\text{WSA}_{0.5\text{-}1\ \text{mm}}$, $\text{WSA}_{0.25\text{-}0.5\ \text{mm}}$, $\text{WSA}_{0.106\text{-}0.25\ \text{mm}}$, and $\text{WSA}_{<0.106\ \text{mm}}$ from the SC treatment, the stock in the $\text{WSA}_{>5\ \text{mm}}$, $\text{WSA}_{0.5\text{-}1\ \text{mm}}$, $\text{WSA}_{0.25\text{-}0.5\ \text{mm}}$,$\text{WSA}_{0.106\text{-}0.25\ \text{mm}}$, and $\text{WSA}_{<0.106\ \text{mm}}$ from the CS treatment were all significantly increased by 8%, 19.6%, 29.5%, 18.3%, 63.1%, and 34.7%; and by 16.7%, 43.1%, 20.6%, 40.2%, and 39.4% compared with CC treatment, respectively. Similarly, the SOC stock in the $\text{WSA}_{0.106\text{-}0.25\ \text{mm}}$ and $\text{WSA}_{<0.106\ \text{mm}}$ from the FC treatment, and the stock in the $\text{WSA}_{>5\ \text{mm}}$, $\text{WSA}_{2\text{-}5\ \text{mm}}$, $\text{WSA}_{0.5\text{-}1\ \text{mm}}$,$\text{WSA}_{0.25\text{-}0.5\ \text{mm}}$, $\text{WSA}_{0.106\text{-}0.25\ \text{mm}}$, and $\text{WSA}_{<0.106\ \text{mm}}$ from the FS treatment were also significantly increased by 10.7%, and 23.8%; and by 12.3%, 13.8%, 24.7%, 32.4%, 62.3%, and 27.9 in comparison with the CC treatment, respectively.

Sahoo *et al.* (2019) [37] revealed that the average distribution of total carbon (TC), soil inorganic carbon (SIC) and total organic carbon (TOC) in different land use types (0–45 cm) (Fig 7a). Average fine soil stock (FSS) for 15 cm soil depth was highest in agro-forestry systems (10.09 Mg ha^{-1}) followed by wet rice cultivation systems (9.88 Mg ha^{-1}) and the least in current jhum systems (6.08 Mg ha^{-1}). SIC concentrations of these soils were small and averaged 0.14 to 0.31% under different land use types. TOC was highest in forest (2.75%) compared to other land use types, but the differences were non-significant (Current Jhum > Agroforestry > Wet Rice Cultivation > Jhum Fallow > Plantation > Grassland.

Moreover, soil VLC concentration in the different land uses ranged 0.22 to 1.43% along the soil profile up to 45cm depth. Soil LC and LLC contents of different land uses varied in a range of 0.15– 0.62% and 0.15–0.72% respectively. Soil NLC concentration was maximum (0.71%) in 0-15cm of forest and minimum (0.05%) in 30-45cm of grassland (Fig. 7b). The VLC fraction constituted a higher proportion of TOC with an average of 40.27% ranging from 36.11 to 42.74% in the different land use types. The proportion of active carbon pool (VLC and LC) was higher (59.76%) than the passive carbon pool (LLC and NLC) in all the land use types (Fig 7b). Active carbon pool was highest in wet rice cultivation (61.64%) and the least in forest (58.71%). All organic carbon pools were significantly related to TOC.



Total carbon (TC) and total organic carbon (TOC) distribution

The average distribution of total carbon (TC), soil inorganic carbon (SIC) and total organic carbon (TOC) in different land use types (0–45 cm) is presented in Fig 1 and Table 2. Average fine soil stock (FSS) for 15 cm soil depth was highest in agroforestry systems (10.09 Mg ha^{-1})

Fig 1. Distribution of active and passive soil carbon at three soil depths in different land use systems.

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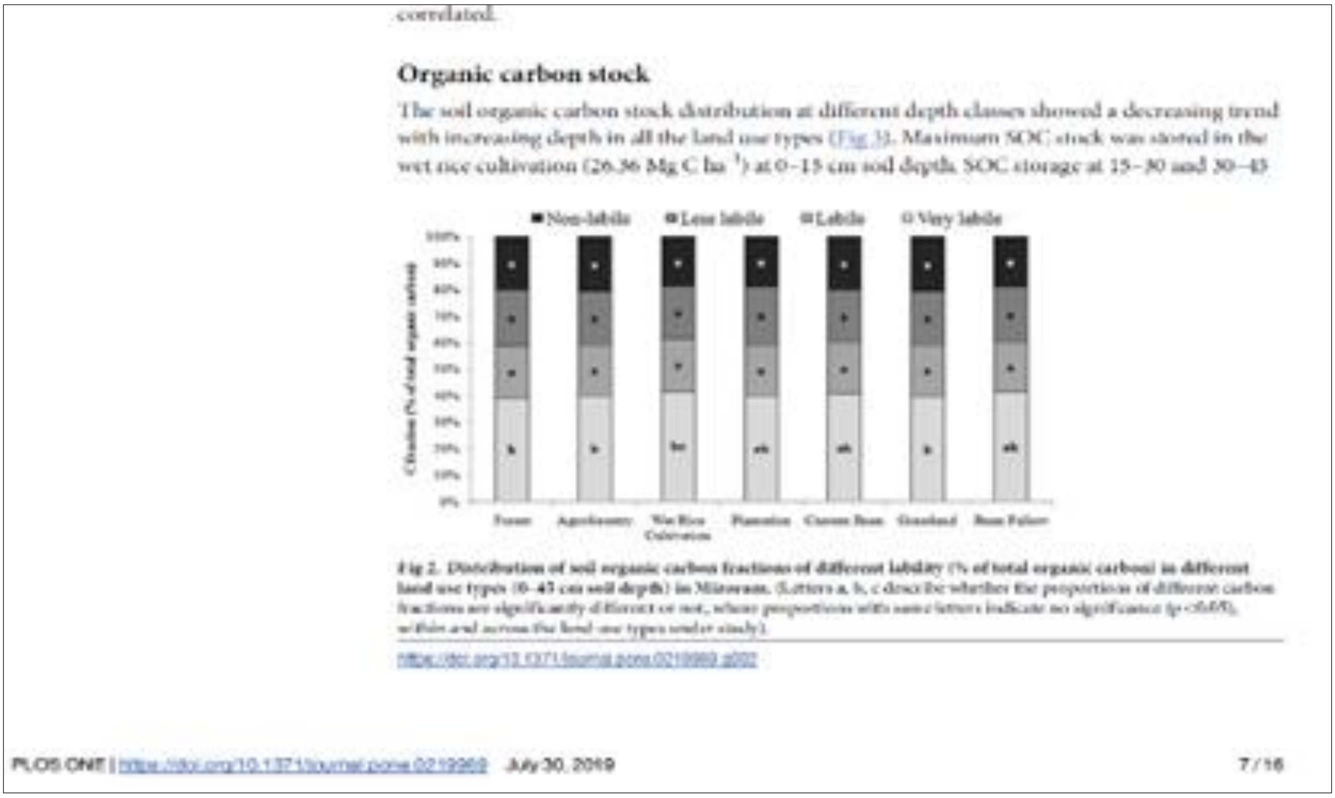
Fig 7a: Distribution of active and passive soil carbon at three soil depths in different land use systems [Source: Sahoo *et al.*, 2019] [37]



correlated.

Organic carbon stock

The soil organic carbon stock distribution at different depth classes showed a decreasing trend with increasing depth in all the land use types (Fig 3). Maximum SOC stock was stored in the wet rice cultivation (26.36 Mg C ha^{-1}) at 0–15 cm soil depth. SOC storage at 15–30 and 30–45

Fig 2. Distribution of soil organic carbon fractions of different lability (% of total organic carbon) **in different land use types (0–45 cm soil depth) in Mizoram.** (Letters a, b, c describe whether the proportions of different carbon fractions are significantly different or not, where proportions with same letters indicate no significance (p<0.05), within and across the land use types under study).

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Fig 7b: Distribution of soil organic carbon fractions of different lability (% of total organic carbon) in different land use types (0–45 cm soil depth) [Source: Sahoo *et al*., 2019] [37]

Conclusions

Review study showed the importance of a CA-based cropping system in improving soil quality in long run.

Minimal soil disturbance and residue retention improved the macro-aggregates, MWD and GMD of aggregates, and aggregation ratio). Both SOC concentration and stock improved considerably under a CA rice-wheat cropping system and thus established the role of CA in maintaining better soil health. Organic C was enriched in each aggregate class and no dependency of SOC was observed for aggregate diameter. The maximum contribution of macro-aggregates was to SOC stock. The process of aggregate formation was related to the fine mineral fraction of soil, and the proportion of macro-aggregates (>0.25 mm) increased with an increasing fine fraction in the soil.

The SOC, TN, POC and LOC contents of RP and CK in soil layer of 100–200 cm were higher than SC, especially for RP plot. Although the SOC, TN, POC and LOC stocks in soil layer of 100–200 cm were lower, there was more than 27.38–36.62%, 25.10–32.91%, 21.59–31.69% and 21.08–26.83% of SOC, TN, POC and LOC stocks were distributed in 100– 200 cm soil depth under RP, and CK. Meanwhile, the SR of SOC, TN, POC and LOC in the surface to lower depth ratio (i.e., 0–10:10–40 cm) was >2.0 in most of case. Changes in SOC concentration and composition occurred along with changes in structural stability to a depth of 15 cm, consistent with a reduced capacity for tilled soil to physically protect organic matter from decomposition. Although differences in stability were evident from 15–28 cm. SOC content in the surface soils under cropland (30 gkg^{-1}) was significantly lower than 45 gkg^{-1} under native vegetation land, as well as SON content (2.9 gkg^{-1} /4.4 gkg^{-1}), macro-aggregate proportion (63%/82%), and MWD (0.73 mm/0.94 mm). A significant effect of RT was sustained down to the 60–80 cm layer, while that of NT was sustained down to the 40–60 cm layer. This implies that conservation tillage can increase the SOC content in deep soil compared with CT. The RT treatment significantly increased the amount of small macro-aggregates in the layers from 10 to 100 cm, and the number of small macro-aggregates in the 0–100 cm layers under NT was higher than under CT.

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