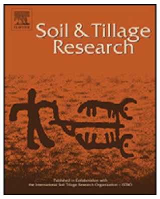
Soil & Tillage Research 121 (2012) 10–17

Contents lists available at SciVerse ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still



Long term effects of topsoil depth and amendments on particulate and non particulate carbon fractions in a Miamian soil of Central Ohio

V. Srinivasan *, H.P. Maheswarappa [1], R. Lal

Carbon Management and Sequestration Center, The Ohio State University, Columbus, OH, USA

ARTICLE INFO

Article history:
Received 18 July 2011
Received in revised form 18 January 2012
Accepted 22 January 2012

Keywords:
Simulated erosion
Amendments
Aggregate stability
Aggregate associated carbon
Stratification ratio

ABSTRACT

Topsoil removal to incremental depths (TSD) under field conditions is a useful technique to simulate erosion, and assess its on-site impacts on soil properties and agronomic productivity. As the sustained productivity of the soils of US Cornbelt is threatened by topsoil loss due to erosion, the artificial soil removal and addition methods can help in assessing the on-site impact of soil erosion under natural field conditions. Thus this study was conducted in an Alfisol at Waterman Farm of The Ohio State University, Columbus, Ohio with the objective to assess the impact of long-term (13 years) effects of TSD treatments (removal of 20 cm topsoil, undisturbed soil and addition of 20 cm of top soil) with two amendments (organic manures and synthetic fertilizer) on particulate C fractions, and C associated with different size fractions. Application of organic or inorganic amendments to the eroded soil improved bulk density (BD) (1.57 Mg m^3), water stable aggregates (WSA) (87%) and mean weight diameter (MWD) (3.18 mm) equivalent to undisturbed or soil addition treatments. However, the eroded soil had significantly lower total organic carbon (TOC) concentration (16.3 g kg^{-1}) compared to other treatments. A trend of higher TOC and nitrogen (TON) concentration was observed with manuring compared with the use of synthetic fertilizer. The lowest concentration (2.66 g kg^{-1}) of particulate organic carbon (POC) was measured in eroded soil, and it was 2.6 and 2.4 times lower than those of undisturbed and soil addition treatments, respectively. The sub-soil (15–30 cm) accumulated significantly lower POC (3.6 g kg^{-1}) compared to the topsoil (0–15 cm) (7.0 g kg^{-1}), with no difference among two amendments. The POC and N pools were also significantly lower in the eroded soil than in other treatments. The particulate organic C/N ratio was significantly larger in sub-soil (20.78) than surface soil (17.83), suggesting strong contribution of roots and root-derived products to POC. There was a positive correlation of macroaggregates C (>2 mm and 0.25–2 mm) with concentration of POC (0.58*, 0.41*) and PON (0.54**, 0.37*). The non particulate organic carbon (NPOC) pools increased with long term management, and were significantly correlated ($R^2 = 0.74^{**}$) with the TOC concentration. Higher stratification ratio for total and non particulate C and N was observed in undisturbed and soil addition treatments. Higher ratios (>2) of POC and PON in eroded treatments indicated the buildup of uncomplexed coarse organic residues of intermediate decomposition with higher turnover rate, and their positive impact on restoring the structural properties with the long-term use of amendments.

1. Introduction

Soil erosion is a geomorphic process comprising of the detachment, entrainment, transport and deposition of soil particles. It causes physical loss of topsoil with its constituent nutrients and soil organic matter (SOM), exposing the less fertile subsoil of a low structural stability and productivity. The global rate of soil erosion is ~75 billion Mg yr^{-1} (Pimentel et al., 1995) with an average erosion rate of 100 Mg ha^{-1} on severely eroded soils (Lal, 2003). Intensive tillage, residue removal and burning accelerate erosion and exacerbate soil degradation (Montgomery, 2007). Accelerated erosion adversely impacts ecosystem functions, soil quality, and soil organic carbon (SOC) concentration.

Whereas erosion depletes SOM on-site, sedimentation leads to its burial and net gain in SOC off-site making deposition site a sink of atmospheric CO$_2$ (Van Oost et al., 2007). The on-site depletion of SOC concentration reduces aggregation, increases susceptibility to crusting and erosion, and causes nutrient/elemental imbalance (Paustian et al., 1997; Grace et al., 1998) with adverse effects on soil quality and crop yield. Being an important component of

---

* Corresponding author. Permanent address: Indian Institute of Spices Research, Post Bag No. 1701, Marikunnu (PO), Calicut 673012, Kerala, India.
Fax: +91 495 2731187.
E-mail address: srisoilv@gmail.com (V. Srinivasan).
[1] Permanent address: Central Plantation Crops Research Institute (CPCRI), Kasaragod, Kerala, India.

0167-1987/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2012.01.014

the C cycle, SOC loss is also related to the accelerated greenhouse effect (Lal, 1998, 2003).

Despite changes in soil properties, it is difficult to assess the effects of erosion on crop productivity as the yield reduction occurs slowly, and the adoption of improved technology often masks the reduction in productivity (Bakker et al., 2004; Jagadamma et al., 2009). Thus, a range of indirect methods have been used to quantify the effects of erosion on productivity including those involving the effects of past erosion on yield compared with productivity of uneroded areas (Lal, 1981, 1998; Fahnestock et al., 1996), pot experiments with soils from different depths (Mielke and Schepers, 1986; Mbagwu, 1988), models to simulate the effects of erosion (Pierce et al., 1983) and artificial removal of topsoil to incremental depths (TSD) to simulate erosion and deposition at field levels (Larney et al., 2000; Oyedele and Aina, 2006; Jagadamma et al., 2009). Measurements of soil properties are made in TSD method after a long time (10–15 years) to minimize any overestimation of the total removal of topsoil in a single step in contrast to the gradual and selective removal by the natural erosion process. The strategy is to determine whether the adverse effects of topsoil removal are minimized by long-term adoption of recommended agricultural practices (RMPs) to ensure restoration of soil fertility. High crop yields can be sustained by applying extra doses of fertilizers and organic amendments to compensate the adverse effects of accelerated erosions (Lal, 1998, 2003; Salako et al., 2007). Erosion-induced changes in SOC concentration and soil properties such as aggregate stability can be used to assess its impact on soil quality and agronomic productivity.

Minimizing the disturbance of the topsoil decreases SOC depletion and enhances aggregate formation and stabilization. In contrast, intense tillage exacerbates the depletion of SOC (Bajracharya, 2001). Quantity and quality of SOC fractions impacts aggregation (Lal, 2000) that in turn physically protect the C from degradation, increasing the mean residence time of C (Bajracharya et al., 1998). Being a heterogeneous mixture of organic substances, different fractions of SOC pool respond differently to management practices, and are sensitive indicator of the effects of management than TOC. Location of SOC within the matrix and its accessibility to decomposers leads to different C pools of varying physical stability and dynamics (Golchin et al., 1994a,b; Ladd et al., 1993). The relative amount of labile materials including free and intra aggregate particulate organic matter (POM) and the light fraction organic C (LFOC) (Vanyushina and Travnikova, 2003; Yang et al., 2005; Gregorich et al., 2006), and the degree to which they are protected determine the degradability of SOC (Rovira and Vallejo, 2002). Adverse effects of erosion on reduction of SOC and its restoration through management practices markedly affect the concentrations of free and occluded particulate and the mineral-associated SOM (Shi et al., 2010). The composition, stability and dynamics of these fractions affect soil aggregation (Tisdall and Oades, 1982; Elliott, 1986; Christensen, 2001; Six et al., 2000a,b, 2004) and are more responsive to changes in management systems, and can be used as early indicators of changes in soil quality (Cambardella and Elliott, 1992; Franzluebbers and Arshad, 1997; Franzluebbers and Stuedemann, 2002; Six et al., 1999; Chan et al., 2002; Wander, 2004; Wendling et al., 2010). In contrast, Leifeld and Kögel-Knabner (2005) suggested SOM associated with stable aggregates of $>20\ \mu m$ as an indicator of changes in different land uses.

The temporary (roots and fungal hyphae) and transient (polysaccharides) agents are labile and decomposable (Beare et al., 1994; Elliott and Coleman, 1988). In contrast, mineral associated C fraction contains more processed degraded plant- and microorganism-derived stable SOM (Hassink, 1995; Wander and Traina, 1996; Wiesenberg et al., 2010), is a major sink for C storage and contains little mineralizable C (Whalen et al., 2000; Dameni et al., 2010; Jagadamma and Lal, 2010).

When continued loss of top soil due to erosion in US Cornbelt is a threat (Jagadamma et al., 2009), regular addition of crop residues to soils (Oyedele et al., 1999) helps in increasing the SOC proportion. Organic manure addition may result first in the formation of SOM associations with clay and silt particles and with microaggregates ($<250\ \mu m$), and then with the formation of macroaggregate ($>250\ \mu m$) once the SOM binding capacity of the clay and silt fractions is saturated (Tisdall and Oades, 1982; Hassink, 1997). Thus, macroaggregates are the unique fractions affected by any change in land use and management (He et al., 2008). Both SOM and POM fractions are influenced by manure application (Yan et al., 2007). Addition of fertilizers and organic amendments increases the SOC associated with different particle size fractions, and alters the allocation of C among fractions (Wu et al., 2005). Manuring can also increase the SOC concentration in the heavy fraction in comparison with the use of mineral fertilizers which increase the uncomplexed organic C fraction. Banger et al. (2009) reported 53% and 30% increase in the light C fractions by application of NPK + FYM compared with inorganic fertilizers and control, respectively. Analyzing the impact of erosion on soil quality related to soil bulk density, TOC and SOC fractions and aggregate stability can provide a means to assess the impact of ameliorative management strategies and can aid in combating the impact of future erosion. As the aggregate protection of particulate or macro OM plays an important role in the equilibrium level of SOC pool, especially in fine-textured soils (Angers, 1998), a better understanding of the effect of soil management on the distribution and forms of SOC in different soil aggregate-size fractions and at different depths can improve the understanding of C dynamics and sequestration. Thus the present study was conducted with the objective of assessing the impact of simulated erosion and of using organic and synthetic amendments on augmentation of POC and NPOC fractions and associated C in different aggregate size fractions.

2. Materials and methods

2.1. Study area

The study was conducted in an on-going long-term experiment at the Waterman Farm of the Ohio State University, Columbus, Ohio. The overall goal of the study was to assess the impact of TSD levels and amendments on quality of an eroded soil. The soil type is deep, fine, mixed, active, mesic, Aeric Epiaqualf. It is developed on a level topography (0–2% slope), poorly drained loam derived from glacial till. The mean annual rainfall is 1016 mm and the mean annual air temperature is 11 °C (52 °F) (Jagadamma et al., 2009).

The treatments established to study the long term impact were, three TSD levels *viz.*: (1) removal of 20 cm of topsoil (eroded, TSD-1) (2) undisturbed soil (undisturbed, TSD-2) and (3) addition of 20 cm of topsoil (soil addition, TSD-3). There were two amendments *viz.*, synthetic N fertilizer and organic manure (Table 1). The ‘erosion’ was simulated once at the beginning of the experiment by physically removing the top 20 cm of soil layer by a landscape loader and depositing the removed topsoil onto another plot to create the ‘soil addition’ treatment. In amendments, 20 Mg ha^{-1} dry matter of compost was applied on the soil surface without mixing during each year in treatment receiving organic amendment and 150 kg N ha^{-1} as urea-ammonium nitrate (28% N) to that receiving synthetic N fertilizer treatment. The plots were laid out in a split plot arrangement with completely randomized blocks, with TSD levels as main plots and amendments as sub-plots. The 18 m × 9 m size main blocks were sub divided into 6 m × 4.5 m each sub plots, having three replications for each treatment combination. A border strip of 2.7 m was maintained between each

Table 1
Details of study area and treatments.

Location	Waterman Farm of the Ohio State University, Columbus, Ohio		
Soil type	Deep, fine, mixed, active, mesic, Aeric Epiaqualf		
Experiment duration	13 years		
Crop	Corn (*Zea mays* L.) from mid May–October each year		
Design	Split plot design		
Plot size	Main blocks – 18 m × 9 m with a border strip of 2.7 m	Sub plots – 6 m × 4.5 m	
Treatments			
Main blocks: topsoil removal to incremental depths (TSD)	Removal of 20 cm of topsoil once at the beginning of the experiment (eroded, TSD-1)	Undisturbed soil (undisturbed, TSD-2)	Addition of 20 cm of topsoil once at the beginning of the experiment (soil addition, TSD-3)
Sub plots: amendments addition	Synthetic N fertilizer (150 kg N ha^{-1} as urea-ammonium nitrate (28% N) every year)	Organic manure (20 Mg ha^{-1} dry matter of compost every year)	
Replications	Three		

main block. Corn (*Zea mays* L.) was grown in each year (mid May–October) without any major tillage disturbances, except that by seeding and harvesting. The crop residue after the harvest was left on the soil surface.

2.2. Soil sampling

Bulk soil and intact core (5 cm diameter and height) samples were taken during July 2010 from 0–15 and 15–30 cm depths. Field moist core samples, collected using a manually driven core sampler, were trimmed on both ends and weighed for calculating the wet bulk density. The dry bulk density (ρ_b) was calculated from the wet bulk density with a correction for soil moisture content, by drying a portion of trimmed core samples at 105 °C (Grossman and Reinsch, 2002). Bulk soil samples were air dried, extraneous roots removed, ground with wooden hammer and sieved through a set of 8, 4.75 and 2 mm sieves. The aggregates retained on the 4.75 mm sieve and the bulk soil passed through 2 mm sieve was stored in airtight poly bags for pending analyses.

2.3. Aggregate fractionation

Aggregate fractionation was performed by the wet sieving method (Nimmo and Perkins, 2002). Fifty grams of air-dried aggregates of 4.75–8 mm size were placed on top of a nest of sieves of 4.75, 2, 1, 0.5 and 0.25 mm size, wetted by capillarity for 15 min and oscillated through a vertical distance of about 3 cm at 30 oscillations per minute in a water column for 30 min. The fractions retained in each sieve were washed into different beakers. The soil fraction of 0.05 mm was obtained by filtering the sediment in the collection tank after the sieving. The collected fractions were oven dried at 40 °C and weighed to compute the mean weight diameter (MWD), and percent water stable aggregates (WSA) calculated by the methods of Kemper and Rosenau (1986). Subsamples from each aggregate fraction were grouped and mixed together to represent three aggregate-size fractions (Tisdall and Oades, 1982): large macroaggregates (>2 mm), small macroaggregates (0.25–2 mm) and microaggregates (0.05–0.25 mm), ground using a mortar and pestle, sieved through 0.125 mm sieve and stored at room temperature for C analysis.

2.4. Particulate organic matter

The POM fraction (0.05–2.0 mm) was extracted with modifications to the method described by Cambardella and Elliott (1992). Briefly, 20 g of sieved (2 mm), air-dried soil was mixed with 60 cm^3 of hexametaphosphate solution (5 g L^{-1}) in a 250 ml bottle and shaken overnight (16 h) in an end to end floor shaker. The soil suspension was then washed through 0.05 mm sieve, rinsed several times with deionized water and washed into pre-weighed beakers and oven dried at 40 °C. The dried mass of this fraction was weighed and finely ground for dry combustion analysis of total C and N concentrations.

2.5. Soil organic carbon and nitrogen analysis

The total C and N concentrations in bulk soil, physical aggregate fractions and the POM were determined by the dry combustion method (Nelson and Sommers, 1996) using a NC 2100 soil analyzer (ThermoQuest CE Instruments, Milan, Italy). The SOC was assumed to be equal to the total C with negligible inorganic C concentration as the soil pH was below 7 (Jagadamma and Lal, 2010). The non particulate organic C (NPOC) and N (NPON), mostly associated with the mineral fractions, were computed by deducting the POC and PON fractions from the TOC and TON, respectively (Conant et al., 2003). The SOC and SON pools (Mg ha^{-1}) were calculated using ρ_b for the corresponding soil depth, as follows (Lal et al., 1998):

$$\begin{aligned}\text{SOC pool}_{(0-15,15-30)}\ (\text{Mg ha}^{-1}) = {} & [\text{C concentration}_{\text{layer}}\ (\text{kg Mg}^{-1}) \\ & \times (\text{Bulk density})_{\text{layer}}\ (\text{Mg m}^{-3}) \\ & \times \text{Depth (m)} \times 10^{-3}\ \text{Mg kg}^{-1} \\ & \times 10^{4}\ \text{m}^{2}\ \text{ha}^{-1}].\end{aligned}$$

2.6. Statistical analysis

The analysis of variance for testing the effects of different treatments was computed using GLM of PASW (SPSS) Statistics v18.0. The mean and interaction effects of treatment were separated using the *F*-protected least significant difference (LSD) test, at the probability level (p) of ≤0.05. Correlation and regression analyses were performed on selected variables at $p \leq 0.05$ using the same package.

3. Results and discussion

3.1. Soil physical characteristics

The soil ρ_b did not vary significantly among treatments and there were no interaction effects. Soil ρ_b ranged between 1.56 Mg m^{-3} and 1.59 Mg m^{-3}. In general, ρ_b in the organic

Table 2
Soil physical properties as affected by TSD levels and amendment types.

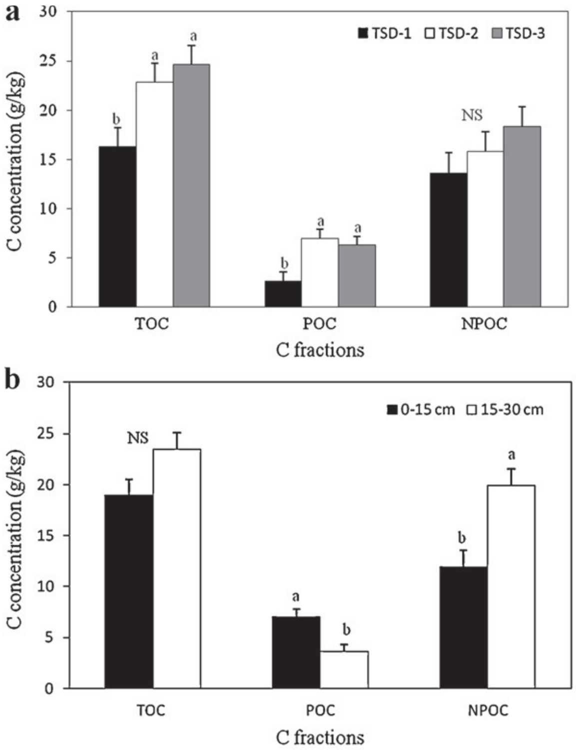
Treatments	BD (Mg/m^3)	WSA (%)	MWD (mm)
Topsoil depths[a]			
TSD-1	1.57	87.1	3.18
TSD-2	1.59	90.8	3.53
TSD-3	1.56	88.7	2.99
SE	0.04	1.2	0.22
Sig. ($p < 0.05$, 0.01)	NS	NS	NS
Amendments			
N fertilizer	1.59	89.7	3.25
Organic	1.56	88.1	3.11
SE	0.03	1.0	0.18
Sig. ($p < 0.05$, 0.01)	NS	NS	NS
Depths			
0–15 cm	1.57	88.4	3.49
15–30 cm	1.58	89.4	2.98
SE	0.03	1.0	0.18
Sig. ($p < 0.05$, 0.01)	NS	NS	NS

[a] TSD-1: topsoil removed; TSD-2: undisturbed soil; TSD-3: topsoil added.

manure addition was lower (1.56 Mg m^{-3}) compared to N fertilizer addition (1.59 Mg m^{-3}). There was no difference in ρ_b among soil depths (Table 2). Similar to ρ_b, there were also no significant differences in WSA either, among the main and sub plot treatments. Retention of crop residues uniformly over all the treatments might have increased the WSA in synthetic fertilizer amendment plots (89.6%) comparable to that of organic manure applied plots (88.1%). Any disruption of aggregates by sowing, etc. was compensated by retention of crop residues (Molope et al., 1987). Jagadamma et al. (2009) also observed higher WSA for N fertilized undisturbed soil.

The average MWD was 3.25 mm for treatment receiving chemical fertilizer compared with 3.11 mm for the manured plots. The MWD was 3.49 mm for 0–15 cm compared with 2.98 mm for 15–30 cm depth (Table 2). Long term addition of organic or inorganic amendments to the eroded soil has improved WSA and MWD from 81% and 2.0 mm in 2006 (Jagadamma et al., 2009) to 87% and 3.18 mm, respectively in 2010. These parameters are now equivalent to those for the undisturbed or soil addition sites, indicating the positive effect of amendments in restoring the structural properties.

3.2. Total soil organic carbon and nitrogen pools



(Note: The error bar represents SE values of different fractions and the bars with different letters in carbon fractions are significantly different; NS – statistically not significant).

Fig. 1. Effect of (a) topsoil depth treatments and (b) depths of sampling on distribution of different C fractions. *Note*: The error bar represents SE values of different fractions and the bars with different letters in carbon fractions are significantly different. NS: statistically not significant.

The total soil C was considered TOC as the soil pH values were below 7, and it showed considerable variation among the TSD treatments. The eroded soil recorded the lowest TOC concentration (16.3 g kg^{-1}) compared to 22.8 and 24.6 g kg^{-1} in undisturbed and soil addition treatments, respectively (Fig. 1a). The magnitude of reduction was 40–51% in the eroded compared with other treatments. Manuring increased the SOC to 22.7 g kg^{-1} but was similar to that of chemical fertilizer treatment. Long-term application of crop residue and N fertilizer addition causes build up of the TOC in both depths, and was comparable to that of the organic manure additions. This trend supports the hypothesis that use of organic and mineral fertilizers enhances SOC concentration and induces changes in ρ_b (Barzegar et al., 2002; Jarecki et al., 2005) (Fig. 1b). Higher access to the decomposition of added residues and amendments in the surface soil may have decreased the SOC

Table 3
Distribution of soil organic carbon pools as effected by TSD levels and amendment types at two depths.

Treatments	TOC (Mg/ha)	TON (Mg/ha)	C/N ratio	POC (Mg/ha)	PON (Mg/ha)	C/N ratio	NPOC (Mg/ha)	NPON (Mg/ha)	C/N ratio
Topsoil depths[a]									
TSD-1	38.28b	3.05b	11.98	6.29b	0.46b	17.86b	31.99	2.59b	12.5
TSD-2	54.08a	4.48a	12.17	16.64a	0.84a	20.16a	37.45	3.64ab	10.1
TSD-3	57.80a	4.73a	12.16	14.48a	0.73ab	19.90a	43.32	4.01a	10.5
SE	4.70	0.36	0.41	2.01	0.11	0.62	4.93	0.36	0.99
Sig. ($p < 0.05$, 0.01)	*	**	NS	**	*	*	NS	*	NS
Amendments									
N fertilizer	47.41	3.93	11.86	13.28	0.75	18.83	34.12	3.17	11.31
Organic	52.71	4.25	12.35	11.66	0.60	19.78	41.05	3.65	10.79
SE	3.83	0.29	0.34	1.64	0.09	0.50	4.03	0.29	0.81
Sig. ($p < 0.05$, 0.01)	NS	NS	NS	NS	NS	NS	NS	NS	NS
Depth									
0–15	44.50	3.67	11.80	16.30a	0.95a	17.83b	28.19b	2.72b	10.65
15–30	55.61	4.51	12.40	8.63b	0.41b	20.78a	46.98a	4.10a	11.45
SE	3.83	0.29	0.34	1.64	0.09	0.50	4.03	0.29	0.81
Sig. ($p < 0.05$, 0.01)	NS	NS	NS	**	**	**	**	**	NS

[a] TSD-1: topsoil removed; TSD-2: undisturbed soil; TSD-3: topsoil added. Values with different letters within a row are significantly different at $p \leq 0.05$, 0.01. * significant at $p \leq 0.05$; ** significant at $p \leq 0.01$; NS: statistically not significant.

concentration. The distribution of TON concentration followed a pattern similar to that of TOC. The undisturbed and added soils had somewhat higher N concentrations than eroded soil. But the mean difference was not statistically significant. Even though the organic manure addition (1.83 g kg^{-1}) and lower soil depths accumulated 21.8% more N concentration (1.90 g kg^{-1}), it was statistically on par to that of N fertilizer addition (1.63 g kg^{-1}) and surface soil (1.56 g kg^{-1}) concentrations. The interaction effect of the treatments did not significantly influence the total C and N concentrations. The C/N ratio of the soil pool was in the range of 11.9 (in eroded soil) to 12.2 (in undisturbed and soil addition) among the TSD treatments. Similar range was also observed for both depths in relation to amendments.

The bulk soil pool of SOC and SON also followed a trend similar to that of SOC and N concentrations among TSD, amendments, and depths (Table 3). The SOC and N pool were significantly lower for the eroded soil (38.3 and 3.05 Mg ha^{-1}) compared to undisturbed (54.1 and 4.48 Mg ha^{-1}) and soil addition (57.8 and 4.73 Mg ha^{-1}) treatments, respectively. Similar to SOC and N concentrations, TOC and TON pool did not differ among amendments or depths.

3.3. Particulate organic carbon

The POC is an important index of soil C dynamics in an ecosystem under different management practices (Wander and Bidart, 2000). The POC concentration differed significantly among the TSD levels, with the lowest concentration (2.66 g kg^{-1}) in eroded soil (Fig. 1a). The POC concentration ranged from 6.3 to 7.0 g kg^{-1} in other two TSD plots, and was about 26–31% of TOC. The POC concentrations in undisturbed and soil addition treatments were 2.6 and 2.4 times more than that in eroded plots. Even though the PON concentration did not differ significantly among the TSD treatments, eroded plot contained the lowest PON concentration (0.2 g kg^{-1}), which was 58–79% lower than that in the soil addition (0.32 g kg^{-1}) and undisturbed (0.36 g kg^{-1}) treatments. No significant differences were observed in POC concentration among amendments, and there was no interaction effect. The sub surface (15–30 cm) accumulated significantly less POC (3.6 g kg^{-1}) as compared to that in the surface layer (7.0 g kg^{-1}), and it constituted about 40% of the TOC. Continuous crop residue incorporation with no till (NT) activities and addition of fertilizer or manure amendments over years led to the accumulation of 49% more of POC, comprising mostly of roots, intermediary decomposition products of added organics, crop residues and fungal hyphae, in the top layer (Beare et al., 1994).

The POC and N pools observed trends similar to those of SOC and N concentrations, with significantly lower POC and PON pools in the eroded soil (Table 3). The PON pool was significantly more in undisturbed treatment (0.84 Mg ha^{-1}) and it was on par with soil addition treatment (0.73 Mg ha^{-1}). Significant accumulation of POC and N pools in 0–15 cm layer also occurred in accordance with their concentrations.

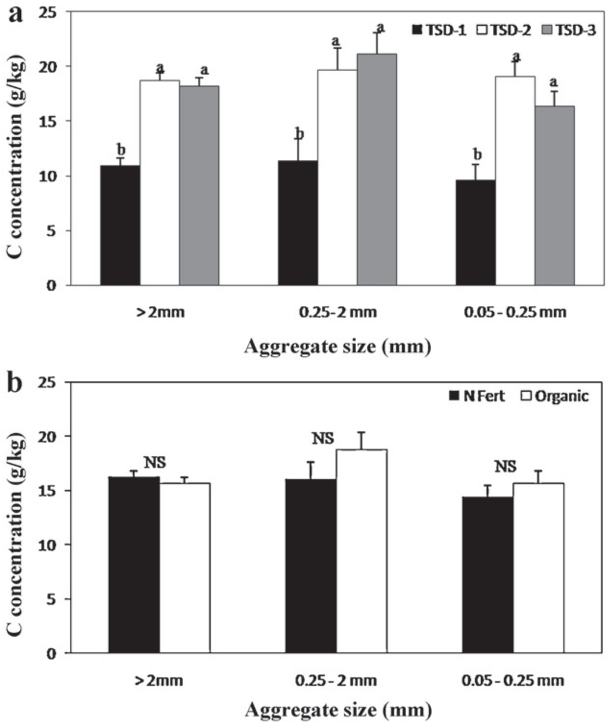
The POC/PON ratio observed a trend similar to that of POC concentration (Table 3). For examples, eroded soil had a significantly lower ratio (17.86) compared to undisturbed (20.16) and soil addition (19.9) treatments, with no differences among amendments. However, the ratio was significantly more in 15–30 cm than 0–15 cm depth, indicating that POC at lower depths is probably a reflection of root and root-derived decomposition products, since root C/N ratios are often as high as 29 in wheat (*Triticum aestivum*) (Jawson and Elliott, 1986) and 14–64 in corn (Mary et al., 1993). More POC at lower depths under forest land with larger, longer living roots than under cropland as observed by Franzluebbers and Stuedemann (2002) also support the hypothesis that POC pool is a reflection of the root-derived products. The POM with high C/N ratio, such as that observed at lower soil depths, may decompose at a slower rate than that with a low C/N ratio (Vigil and Kissel, 1991). However, when combined with more stable and favorable moisture and temperature regimes at lower depths this material may decompose equally or more rapidly than that in the surface layer.

3.4. Non particulate organic carbon

The NPOC that constituted about 68–72% of TOC ranged from 13.6 to 18.3 g kg^{-1} among the TSD levels, with the lowest concentration in eroded soils (TSD-1). Even though the organic amendment addition recorded 23% higher accumulation than the treatment receiving fertilizer addition, no statistical difference was observed among the TSD and amendment treatments (Fig. 1a). There was a significant accumulation of NPOC in 15–30 cm (19.9 g kg^{-1}) as compared to 0–15 cm (11.9 g kg^{-1}) layer (Fig. 1b). A similar trend was observed in the distribution of NPON concentration among treatments and depths, and constituted about 77–83% of the TON. The NPOC and NPON pools also observed a trend similar to that of their respective concentrations. The NPOC/NPON ratio was stabilized between 10.1 and 12.5 among treatments (Table 3). Because the NPOC fraction is mineral associated, resulting from the decomposition of POM and its subsequent protection by silt and clay particles (Álvaro-Fuentes et al., 2008), it serves as a major sink for C storage in soils. Due to the more humified nature of this C fraction, greater accumulation of NPOC implies the stabilization of SOC in the long term under undisturbed and soil addition treatments. Gong et al. (2009) also observed increase in the C concentration of the heavy fraction for the manure addition and light fraction C for mineral fertilizer treatments.

3.5. Aggregate associated SOC

The TOC concentration in different aggregate fractions was significantly highest in undisturbed and soil addition as compared



(Note: The error bar represents SE values of different aggregates; NS – statistically not significant).

Fig. 2. Effect of (a) topsoil depth treatments and (b) amendment types on soil organic carbon of aggregate fractions. *Note*: The error bar represents SE values of different aggregates. NS: statistically not significant.

Table 4
Correlation coefficients (significant at $p = 0.05$) between some soil properties and different soil organic carbon and nitrogen fractions.

	MWD	TOC	POC	PON	NPOC	NPON	>2 mm C	>0.25 mm C	>0.05 mm C	>2 mm N	>0.25 mm N	>0.05 mm N
WSA	0.623**	0.429**	–	0.443**	–	–	–	–	0.435**	–	–	–
MWD		–	0.384*	0.371*	–	–	–	–	–	–	–	–
TON		0.957**		–	0.830**	0.945**	–	–	0.360*	–	–	0.377*
TOC			–	–	0.890**	0.924**	–	–	0.384*	–	–	0.377*
POC				0.910**	−0.335*	–	0.578*	0.408*	–	0.545**	0.374*	–
PON					−0.428**	–	0.543**	0.314	–	0.531**	–	–
NPOC						0.937**	–	–	–	–	–	–
>2 mm C								0.416*	0.478**	0.980**	0.373*	0.421*
>0.25 mm C									0.681**	0.350*	0.992**	0.709**
>0.05 mm C										0.387*	0.634**	0.980**

[*] Significant at $p \leq 0.05$.
[**] Significant at $p \leq 0.01$.

to eroded treatment (Fig. 2a). The latter contained 70–85% lower SOC among different aggregate fractions. The interaction among treatments was significant only in large macroaggregates (>2 mm) for TSD × depths. Amendments or depth did not affect the aggregate associated SOC except that in the large macroaggregates (>2 mm) which showed significant accumulation in the 0–15 cm than in the 15–30 cm layer (Fig. 2b). The macroaggregates (both large and small, >0.25 mm) accumulated higher SOC than microaggregates (0.05–0.25 mm). Similar higher C accumulation in soil macroaggregates under reduced land use intensity situations was reported by Grandy and Robertson (2007). Puget et al. (1995) observed greater C accumulation in macroaggregates due to lower decomposable SOM associated with these aggregates and also direct contribution of SOM to the stability of macroaggregates resulting in C-rich macroaggregates capable of withstanding slaking.

Concentration of SON also observed a trend similar to that of SOC among the aggregate size fractions. All aggregate fractions had a smaller C/N ratio (10.7–12.0) suggesting a more humified and potentially larger degree of microbial origin associated with the fine-silt fraction which accounts for the largest proportion of small macro and micro aggregates (Six et al., 2001; Rodionov et al., 2000). There was a positive correlation of macroaggregates C (>2 mm and 0.25–2 mm) with POC (0.58*, 0.41*) and PON (0.55**, 0.37*) signifying the role of POM in aggregate formation (Table 4). The long-term application of corn straw and amendments could have helped in binding of microaggregates into macroaggregates as a result of secretion of mucilaginous substances, roots and fungal hyphae (Tisdall and Oades, 1982; Beare et al., 1994). The microaggregates C had a higher correlation with the TOC concentration (0.38*). The WSA was positively correlated with TOC (0.43**) and MWD (0.62**). Concentration of C in microaggregate was also positively correlated with large (0.48**) and small (0.68**) macroaggregate C. Further, NPOC was positively correlated with TOC (0.89**) and negatively with POC (−0.34*).

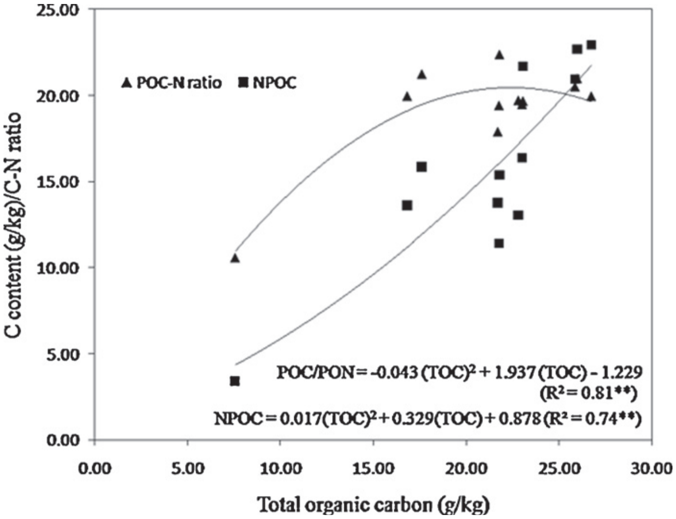


Fig. 3. Relationship of total organic carbon with non particulate organic carbon and particulate organic C–N ratio.

The NPOC pools increased with long-term management, and strongly correlated with TOC concentration ($R^2 = 0.74^{**}$). The magnitude of the POM pool, in the 0–15 cm layer depended upon the TOC concentration in soil, as POC/PON ratio increased with increase in TOC up to a threshold level of 25 g kg^{-1} (Fig. 3). At 15–30 cm depth, the NPOC fraction with low C/N ratio dominated the TOC concentration suggesting high N concentration which would enhance nutrient cycling and soil quality.

3.6. The stratification ratio

The stratification ratio as a soil quality indicator is influenced by the SOC concentration in the surface layer (Franzluebbers, 2002).

Table 5
Stratification ratio of soil organic carbon and nitrogen fractions as effected by TSD levels and amendment types.

Treatments	TOC	POC	NPOC	TON	PON	NPON
Topsoil depths[a]						
TSD-1	0.61	2.46	0.44	0.78	3.99a	0.60
TSD-2	0.95	2.34	0.68	0.89	2.75ab	0.71
TSD-3	0.98	1.80	0.83	0.98	1.86b	0.88
SE	0.184	0.36	0.21	0.22	0.50	0.23
Sig. ($p \leq 0.05, 0.01$)	NS	NS	NS	NS	*	NS
Amendments						
N fertilizer	0.79	2.11	0.57	0.79	3.26	0.61
Organic	0.91	2.30	0.74	0.97	2.47	0.85
SE	0.15	0.29	0.17	0.18	0.41	0.18
Sig. ($p \leq 0.05, 0.01$)	NS	NS	NS	NS	NS	NS

[a] TSD-1: topsoil removed; TSD-2: undisturbed soil; TSD-3: topsoil added. * significant at $p \leq 0.05$; NS: statistically not significant..

Stratification, in this context, is a soil property at the soil surface divided by the same property at a lower depth, such as the bottom of the tillage layer. High stratification ratio of SOC and SON pools reflects relatively undisturbed soil with high soil quality of the surface layer. High stratification of total and non particulate C and N was observed in undisturbed and soil addition treatments, and concentration of particulate C and N was high in the eroded treatment (Table 5). With the exception of PON, all other C and N pools were high in treatments with addition of organic amendments. The highest stratification ratios (>2) were obtained for POC and PON, although there were no differences among TSD or amendments. These high ratios of POC and PON are indicative of the buildup of coarse organic residues of intermediate turnover time (Cambardella and Elliott, 1992), and those which are improving with long-term management. Therefore, the impacts on these pools must be critically analyzed for their sustainability over time (Franzluebbers, 2002).

4. Summary

The SOM exists as a continuum in soil from strongly stabilized to non-protected particulate forms. Even though the C stored as POC would be temporary, it serves as an indicator of the potential of C storage in soil profiles, provided that the inputs of residues and improved management practices are continued. Long-term (13 yr) addition of organic or inorganic amendments to the eroded soil improved physical properties such as bulk density, aggregate stability and mean weight diameter comparable to that of undisturbed or soil addition treatment, indicating the positive effect of amendments in restoring the structural properties. Eroded soil recorded 40–51% reduced TOC and 2.4–2.6 times lower POC concentration compared to undisturbed and soil addition treatments. Continuous incorporation of crop residues with NT and addition of fertilizers or manure amendments over years led to accumulation of 49% or more POC as indicated by a positive correlation with macroaggregates (>2 mm and 0.25–2 mm) associated C. The NPOC constituted 68–72% of TOC, and its concentration was the lowest in eroded treatments. High stratification of total and non-particulate C and N was observed in undisturbed and soil addition treatments, and stratification of particulate C and N was also high in eroded treatments. These high ratios of POC indicated the buildup of coarse organic residues as more sensitive indicators of the management. This POC fraction with rapid turnover rate would provide a more readily accessible source of energy to soil organisms, and it can accentuate to nutrient cycling.

Acknowledgments

The authors are grateful to National Agricultural Innovation Project (NAIP), Indian Council of Agricultural Research (ICAR), New Delhi, India for the financial support to undertake the work at CMASC, Ohio State University. We thank Mr. Basant K Rimal for the technical help in analyzing the samples.

References

Álvaro-Fuentes, J., López, M.V., Cantero-Martinez, C., Arrúe, J.L., 2008. Tillage effects on soil organic carbon fractions in Mediterranean dryland agroecosystems. Soil Sci. Soc. Am. J. 72 (2), 541–547.

Angers, D.A., 1998. Water-stable aggregation of Quebec silty clay soils: some factors controlling its dynamics. Soil Till. Res. 47, 91–96.

Bajracharya, R.M., Lal, R., Kimble, J.M., 1998. Soil organic carbon distribution in aggregates and primary particle fractions as influenced by erosion phases and landscape position. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 353–367.

Bajracharya, R.M., 2001. Land preparation: an integral part of farming system in the mid-hills of Nepal. J. Sci. Technol. 3, 15–24.

Bakker, M.M., Govers, G., Rounsevell, M.D.A., 2004. The crop productivity–erosion relationship: an analysis based on experimental work. Catena 57 (1), 55–76.

Banger, K., Kukal, S.S., Toor, G., Sudhir, K., Hanumanthraju, T.H., 2009. Impact of long-term additions of chemical fertilizers and farm yard manure on carbon and nitrogen sequestration under rice–cowpea cropping system in semi-arid tropics. Plant Soil 318, 27–35.

Barzegar, A.R., Yousefi, A., Daryashenas, A., 2002. The effect of addition of different amounts and types of organic materials on soil physical proprieties and yield of wheat. Plant Soil 247, 295–301.

Beare, M.H., Hendrix, P.F., Coleman, D.C., 1994. Water stable aggregates and organic matter fractions in conventional and no tillage soils. Soil Sci. Soc. Am. J. 58 (3), 777–786.

Cambardella, C.A., Elliott, E.T., 1992. Particulate soil organic matter across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56, 777–783.

Chan, K.Y., Heenan, D.P., Oates, A., 2002. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. Soil Till. Res. 63, 133–139.

Christensen, B.T., 2001. Physical fractionation of soil and structural and functional complexity in organic matter turnover. Eur. J. Soil Sci. 52, 345–353.

Conant, R.T., Six, J., Paustian, K., 2003. Land use effects on soil carbon fractions in the Southeastern United States. I. Management-intensive versus extensive grazing. Biol. Fertil. Soils 38, 386–392.

Dameni, H., Wang, J., Qin, L., 2010. Soil aggregate and organic carbon stability under different land uses in the North China Plain. Commun. Soil Sci. Plant Anal. 1, 1144–1157.

Elliott, E.T., Coleman, D.C., 1988. Let the soil work for us. Ecol. Bull. 39, 23–32.

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorous in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633.

Fahnestock, P., Lal, R., Hall, G.F., 1996. Land use and erosional effects on two Ohio Alfisols. II. Crop yields. J. Sust. Agric. 7, 85–100.

Franzluebbers, A.J., Arshad, M.A., 1997. Soil microbial biomass and mineralizable C of water-stable aggregates. Soil Sci. Soc. Am. J. 61, 1090–1097.

Franzluebbers, A.J., Stuedemann, J.A., 2002. Particulate and non-particulate fractions of soil organic carbon under pastures in the Southern Piedmont USA. Environ. Pollut. 116, S53–S62.

Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Till. Res. 66, 95–106.

Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P., 1994a. Study of free and occluded particulate organic matter in soils by solid state ^{13}C CP/MAS NMR spectroscopy and scanning electron microscopy. Aust. J. Soil Res. 32, 285–309.

Golchin, A., Oades, J.M., Skjemstad, J.O., Clark, P., 1994b. Soil structure and carbon cycling. Aust. J. Soil Res. 32, 1043–1068.

Gong, W., Yan, X., Wang, J., Hu, T., Gong, Y., 2009. Long-term manure and fertilizer effects on soil organic matter fractions and microbes under a wheat–maize cropping system in northern China. Geoderma 149, 318–324.

Grace, P.R., Post, W.M., Godwin, D.C., Bryceson, K.P., Truscott, M.A., Hennessy, K.J., 1998. Soil carbon dynamics in relation to soil surface management and cropping systems in Australian agrosystems. In: Lal, R., et al. (Eds.), Management of Carbon Sequestration in Soil. Adv. Soil Sci. CRC Press, New York, pp. 175–194.

Grandy, A.S., Robertson, G.P., 2007. Land-use intensity effects on soil organic carbon accumulation rates and mechanisms. Ecosystems 10, 58–73.

Gregorich, E.G., Beare, M.H., McKim, U.F., Skjemstad, J.O., 2006. Chemical and biological characteristics of physically uncomplexed organic matter. Soil Sci. Soc. Am. J. 70, 975–985.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4: Physical Methods. SSSA Book Series, No. 5. ASA–CSSA–SSSA, Madison, WI, pp. 201–225.

Hassink, J., 1995. Density fractions of soil macroorganic matter and microbial biomass as predictors of C and N mineralization. Soil Biol. Biochem. 27, 1099–1108.

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soil 191, 77–87.

He, Y., Xu, Z., Chen, C., Burton, J., Ma, Q., Ge, Y., Xu, J., 2008. Using light fraction and macroaggregate associated organic matters as early indicators for management-induced changes in soil chemical and biological properties in adjacent native and plantation forests of subtropical Australia. Geoderma 147, 116–125.

Jagadamma, S., Lal, R., 2010. Distribution of organic carbon in physical fractions of soils as affected by agricultural management. Biol. Fertil. Soils 46, 543–554.

Jagadamma, S., Lal, R., Rimal, B.K., 2009. Effects of topsoil depth and soil amendments on corn yield and properties of two Alfisols in central Ohio. J. Soil Water Conserv. 64 (1), 70–80.

Jarecki, M.K., Lal, R., James, R., 2005. Crop management effects on soil carbon sequestration on selected farmers' fields in northeastern Ohio. Soil Till. Res. 81, 265–276.

Jawson, M.D., Elliott, L.F., 1986. Carbon and nitrogen transformations during wheat straw and root decomposition. Soil Biol. Biochem. 18 (1), 15–22.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. Soil Science Society of America, Inc., Madison, WI, USA, pp. 425–442.

Ladd, J.N., Foster, R.C., Skjemstad, J.O., 1993. Soil structure: carbon and nitrogen metabolism. Geoderma 56, 401–434.

Lal, R., 1981. Soil erosion problems on alfisols in western Nigeria. VI. Effects of erosion on experimental plots. Geoderma 25, 215–230.

Lal, R., 2000. Mulching effects on soil physical quality of an alfisol in western Nigeria. Land Degrad. Dev. 11, 383–392.

Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V., 1998. The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann. Arbor. Press, Chelsea, MI, p. 128.

Lal, R., 1998. Soil erosion impact on agronomic productivity and environment quality. Crit. Rev. Plant Sci. 17 (4), 319–464.

Lal, R., 2003. Soil erosion and the global carbon budget. Environ. Int. 29, 437–450.

Larney, F.J., Olson, B.M., Janzen, H.H., Lindwall, C.W., 2000. Early impacts of topsoil removal and soil amendments on crop productivity. Agron. J. 92 (5), 948–956.

Leifeld, J., Kögel-Knabner, I., 2005. Soil organic matter fractions as early indicators for carbon stock changes under different land-use? Geoderma 124, 143–155.

Mary, B., Fresneau, C., Morel, J.L., Mariotti, A., 1993. C and N cycling during decomposition of root mucilage, roots and glucose in soil. Soil Biol. Biochem. 25 (8), 1005–1014.

Mbagwu, J.S.C., 1988. Physico-chemical properties of and productivity of an ultisol in Nigeria as affected by long term erosion. Pedology 38, 137–154.

Mielke, L.N., Schepers, J.S., 1986. Plant response to topsoil thickness on an eroded loess soil. J. Soil Water Conserv. 41 (1), 59–63.

Molope, M.B., Grieve, I.C., Page, E.R., 1987. Contributions of fungi, bacteria to aggregate stability of cultivated soils. J. Soil Sci. 38, 71–77.

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. PNAS 104, 13268–13272.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis: Chemical Methods. Part 3. SSSA, Madison, WI, pp. 61–1010.

Nimmo, J.R., Perkins, K.S., 2002. Aggregate stability and size distribution. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4: Physical Methods. SSSA Book Series No. 5. SSSA, Madison, pp. 317–328.

Oyedele, D.J., Schjønning, P., Sibbesen, E., Debosz, K., 1999. Aggregation and organic matter fractions of three Nigerian soils as affected by soil disturbance and incorporation of plant material. Soil Till. Res. 50, 105–114.

Oyedele, D.J., Aina, P.O., 2006. Response of soil properties and maize yield to simulated erosion by artificial topsoil removal. Plant Soil 284, 375–384.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls of soil carbon. In: Paul, E.A., et al. (Eds.), Soil Organic Matter in Temperate Agroecosystems: Long Term Experiments in North America. CRC Press, Boca Raton, FL, pp. 15–49.

Pierce, F.J., Larson, W.E., Dowdy, R.H., Graham, W.A.P., 1983. Productivity of soils: assessing long term changes due to erosion. J. Soil Water Conserv. 38 (1), 39–44.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123.

Puget, P., Chenu, C., Balesdent, J., 1995. Total and young organic matter distributions in aggregates of silty cultivated soils. Eur. J. Soil Sci. 46, 449–459.

Rodionov, A., Amelung, W., Urusevskaja, I., Zech, W., 2000. Carbon and nitrogen in the enriched labile fraction along a climosequence of zonal steppe soils in Russia. Soil Sci. Soc. Am. J. 64, 1467–1473.

Rovira, P., Vallejo, V.R., 2002. Labile and recalcitrant pools of carbon and nitrogen in organic matter decomposing at different depths in soil: an acid hydrolysis approach. Geoderma 107, 109–141.

Salako, F.K., Dada, P.O., Adejuyigbe, C.O., Adedire, M.O., Martins, O., Akwuebu, C.A., Williams, O.E., 2007. Soil strength and maize yield after topsoil removal and application of nutrient amendments on a gravelly Alfisol toposequence. Soil Till. Res. 94 (1), 21–35.

Shi, X.M., Li, X.G., Long, R.J., Singh, B.P., Li, Z.T., Li, F.M., 2010. Dynamics of soil organic carbon and nitrogen associated with physically separated fractions in a grassland-cultivation sequence in the Qinghai-Tibetan plateau. Biol. Fertil. Soils 46, 103–111.

Six, J., Elliott, E.T., Paustian, K., 2000a. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000b. Soil structure and organic matter. I. Distribution of aggregate-size classes and aggregate associated carbon. Soil Sci. Soc. Am. J. 64, 681–689.

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Till. Res. 79, 7–31.

Six, J., Guggenberger, G., Paustian, K., Haumaier, L., Elliott, E.T., Zech, W., 2001. Sources and composition of soil organic matter fractions between and within soil aggregates. Eur. J. Soil Sci. 52, 607–618.

Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63, 1350–1358.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water stable aggregates in soil. J. Soil Sci. 33, 141–163.

Van Oost, K., Quine, T.A., Govers, G., De Gryze, S., Six, J., Harden, J.W., Ritchie, J.C., McCarty, G.W., Heckrath, G., Kosmas, C., Giraldez, J.V., Marques da Silva, J.R., Merckx, R., 2007. The impact of agricultural soil erosion on the global carbon cycle. Science 318, 626–629.

Vanyushina, A.Y., Travnikova, L.S., 2003. Organic–mineral interactions in soils: a review. Eurasian Soil Sci. 36 (4), 379–387.

Vigil, M.F., Kissel, D.E., 1991. Equations for estimating the amount of nitrogen mineralized from crop residues. Soil Sci. Soc. Am. J. 55 (3), 757–761.

Wander, M.M., Bidart, M.G., 2000. Tillage practice influences on the physical protection, bioavailability and composition of particulate organic matter. Biol. Fertil. Soils 32, 360–367.

Wander, M.M., Traina, S.J., 1996. Organic matter fractions from organically and conventionally managed soils. 1. Carbon and nitrogen distribution. Soil Sci. Soc. Am. J. 60, 1081–1087.

Wander, M.M., 2004. Soil organic matter fractions and their relevance to soil function. In: Magdoff, F., Weil, R. (Eds.), Advances in Agroecology. CRC, pp. 67–102.

Wendling, B., Jucksch, I., Mendonça, E.S., Alvarenga, R.C., 2010. Organic-matter pools of soil under pines and annual cultures. Commun. Soil Sci. Plant Anal. 41, 1707–1722.

Whalen, J., Peter, K., David, J., Myrold, B.D., 2000. Carbon and nitrogen mineralization from light- and heavy-fraction additions to soil. Soil Biol. Biochem. 32, 1345–1352.

Wiesenberg, G.L.B., Dorodnikov, M., Kuzyakov, Y., 2010. Source determination of lipids in bulk soil and soil density fractions after four years of wheat cropping. Geoderma 156, 267–277.

Wu, T., Schoenau, J.J., Li, F., Qian, P., Malhi, S.S., Shi, Y., 2005. Influence of fertilization and organic amendments on organic carbon fractions in Heilu soil on the loess plateau of china. J. Plant Nutr. Soil Sci. 168, 100–107.

Yan, D., Wang, D., Yang, L., 2007. Long-term effect of chemical fertilizer, straw, and manure on labile organic matter fractions in a paddy soil. Biol. Fertil. Soils 44, 93–101.

Yang, C., Yang, L., Ouyang, Z., 2005. Organic carbon and its fractions in paddy soil as affected by different nutrient and water regimes. Geoderma 124, 133–142.