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Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils

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Abstract

Residue retention and reduced tillage are both conservation agricultural management options that may enhance soil organic carbon (SOC) stabilization in tropical soils. Therefore, we evaluated the effects of long-term tillage and residue management on SOC dynamics in a Chromic Luvisol (red clay soil) and Areni-Gleyic Luvisol (sandy soil) in Zimbabwe. At the time of sampling the soils had been under conventional tillage (CT), mulch ripping (MR), clean ripping (CR) and tied ridging (TR) for 9 years. Soil was fully dispersed and separated into 212–2000 μm (coarse sand), 53–212 μm (fine sand), 20–53 μm (coarse silt), 5–20 μm (fine silt) and 0–5 μm (clay) size fractions. The whole soil and size fractions were analyzed for C content. Conventional tillage treatments had the least amount of SOC, with 14.9 mg C g^{-1} soil and 4.2 mg C g^{-1} soil for the red clay and sandy soils, respectively. The highest SOC content was 6.8 mg C g^{-1} soil in the sandy soil under MR, whereas for the red clay soil, TR had the highest SOC content of 20.4 mg C g^{-1} soil. Organic C in the size fractions increased with decreasing size of the fractions. In both soils, the smallest response to management was observed in the clay size fractions, confirming that this size fraction is the most stable. The coarse sand-size fraction was most responsive to management in the sandy soil where MR had 42% more organic C than CR, suggesting that SOC contents of this fraction are predominantly controlled by amounts of C input. In contrast, the fine sand fraction was the most responsive fraction in the red clay soil with a 66% greater C content in the TR than CT. This result suggests that tillage disturbance is the dominant factor reducing C stabilization in a clayey soil, probably by reducing C stabilization within microaggregates. In conclusion, developing viable conservation agriculture practices to optimize SOC contents and long-term agroecosystem sustainability should prioritize the maintenance of C inputs (*e.g.* residue retention) to coarse textured soils, but should focus on the reduction of SOC decomposition (*e.g.* through reduced tillage) in fine textured soils.

Keywords: Particulate organic matter; Soil organic carbon; Tillage; Residue management; Conservation tillage; Tropical agro ecosystems

1. Introduction

Soil organic matter (SOM) is an important determinant of soil fertility, productivity and sustainability, and is a useful indicator of soil quality in tropical

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agricultural systems where nutrient poor and highly weathered soils are managed with little external input (Feller and Beare, 1997; Lal, 1997). The dynamics of SOM are influenced by agricultural management practices such as tillage, mulching, removal of crop residues and application of organic and mineral fertilizers.

Removal of crop residues from the fields is known to hasten soil organic carbon (SOC) decline especially when coupled with conventional tillage (Yang and Wander, 1999; Mann et al., 2002). This is a common practice in most communal areas of Zimbabwe, where crop residues are removed from the fields for use as fodder or grazed *in situ*. Mann et al. (2002) reviewed a number of studies where additions of stover resulted in greater increases in SOC than if stover was removed. They also found that the mean residence time of original SOC is substantially lengthened if stover is not harvested. Soil organic C decreased by 75% after 15 years of no-till maize cropping with residue removal on a Nigerian Alfisol following forest clearing while residue return had twice as much SOC than residue removal (Juo et al., 1996). When the effects of hoeing and ploughing were compared, with or without manure, greater soil organic C, C mineralization and crop yields were found when manure was applied, and with hoeing being superior to ploughing (Mando et al., 2005a). Their study also indicated that the use of manure can counter the negative effects of tillage. The use of grass mulch was also shown to reduce annual soil loss by up to 5 t ha^{-1} compared with no surface residue application in a study conducted in Zimbabwe on a clay loam (Hudson, 1957).

Tillage plays an important role in the manipulation of nutrient storage and release from SOM, with conventional tillage (CT) inducing rapid mineralization of SOM and potential loss of C and N from the soil. A global analysis of 67 long-term experiments indicated that on average a change from CT to no-till (NT) can sequester 57 ± 14 g C m^{-2} year^{-1} (excluding NT in wheat fallow systems) with peak sequestration rates being reached within 5–10 years after conversion (West and Post, 2002). By contrast, Six et al. (2002a,b) found a general increase in soil C contents of $\approx 325 \pm 113$ kg C ha^{-1} year^{-1} under NT compared with CT for both tropical and temperate systems. They also reported that, on average, C turnover was 1.5 times slower in NT compared with CT.

The amount of SOM loss due to tillage is dependent on the clay content of the soil. In general, greater SOM loss is observed in coarse textured than fine textured soils, primarily due to lack of physical protection of organic matter in sandy soils (Hassink, 1995; Feller and Beare, 1997). In fine textured soils, clay- and silt-sized particles with high surface activity may chemically stabilise SOM and form the building blocks for aggregates, thereby inducing physical protection of SOM by occlusion in aggregates, especially micro-aggregates (Six et al., 2000). Soil disturbance through tillage is a major cause of reduction in the number and stability of soil aggregates and subsequently organic matter depletion (Six et al., 2000). The greater part of the smallholder farming areas of Zimbabwe is dominated by coarse textured soils (Grant, 1981).

Type and length of tillage practice, and soil texture influence the amount of SOC present in the soil, the rate of SOC turnover, and its distribution among size fractions (Cambardella and Elliott, 1992; Six et al., 2002a,b; Feller and Beare, 1997). Tillage reduces SOM in all size fractions, but particulate organic matter (POM) is much more readily lost than other fractions (Cambardella and Elliott, 1992; Six et al., 1999). In continuously cultivated soils the decrease in SOC is primarily due to a loss of POM in sandy soils and of clay-associated C in clayey soils (Feller and Beare, 1997). Inputs of C also tend to increase SOC by mainly accumulating it as POM in the sand-size fraction in sandy soils whereas in clayey soils it accumulates both in the sand- and clay-size fractions (Feller and Beare, 1997). Silt-associated SOM is more stable and does not readily change with management (Christensen, 1992; Six et al., 2001).

The objective of this study was to assess the effects of disturbance (*i.e.* tillage) and C input (*i.e.* crop residue return) on SOC content and its distribution across size fractions in two soils differing in texture. We hypothesized that (i) SOC content would increase with decreasing tillage intensity in the order tied ridging (TR) > clean ripping (CR) > CT, (ii) returning crop residues would result in greater SOC contents than removing residues, and (iii) SOC dynamics are more responsive to tillage disturbance in the clay soil as aggregates are disrupted to release protected SOC, while in the sandy soil C input differences would result in bigger differences in SOC content.

2. Materials and methods

The two experiments used in this study were established in the 1988/1989 season at the Institute of Agricultural Engineering (IAE) in Harare (17°43′S; 31°06′E; 1500 m above sea level) and the Domboshawa Training Centre (DTC) (17°35′S; 31°10′E; 1550 m above sea level) approximately 30 km NE of Harare (Nyagumbo, 1997). The IAE site is on red clay soil (clay = 59%; silt = 20%; sand = 21%) derived from gabbro parent material and is classified as Chromic Luvisol (FAO classification) or Rhodic Paleustalf (USDA classification) or Harare 5E.2 (Zimbabwe classification) (Nehanda, 2000). The DTC site is on a sandy soil (clay = 4%; silt = 13%; sand = 83%) derived from granitic parent material classified as Areni-Gleyic Luvisol (FAO classification) or Udic Kandiustalf (USDA classification) or Harare 6G.3 (Zimbabwe classification) (Vogel, 1992). Both sites are found in Natural Region II (annual rainfall 800–1000 mm) with most of the rain (~90%) falling between November and March. Mean annual temperature for both sites is 22 °C.

The tillage treatments were conventional tillage (CT), clean ripping (CR) and tied ridging (TR) (Munyati, 1997; Nyagumbo, 1998). Conventional tillage involved annual ox ploughing (~20 cm depth), CR involved the use of a tine ripper to rip (~25 cm depth) between rows, and there were permanent crop ridges in the TR treatment. Crop residues were removed in the three tillage practices. A fourth treatment was mulch ripping (MR) which was similar to CR, but with crop residues being left on the surface (Munyati, 1997; Nyagumbo, 1998). Because there were no significant differences in yield between the different treatments at both sites (Munyati, 1997; Nyagumbo, 1998), the MR and CR treatments represent the comparison of C input treatments whereas the tillage treatments represent a gradient of disturbance (CT > CR > TR). The treatments were laid out in a completely randomized design at IAE and a complete randomized block design at DTC with 3 replicates at each site. All treatments received annual fertiliser additions of 114 kg N ha^{-1}, 22 kg P ha^{-1} and 25 kg N ha^{-1}. Maize (*Zea Mays* L.) was planted as the test crop continuously.

Soil samples were collected in October 1998 from the top 30 cm using an auger of 5 cm diameter. A composite sample was made from six samples collected randomly from different parts of the plots, air-dried and passed through a 2 mm sieve except for rocks >2 mm. Fifty grams of soil was soaked in water for 24 h and then shaken overnight in 200 ml of 5 g L^{-1} sodium hexametaphosphate for 16 h. Soil was wet sieved to separate the 212–2000 μm, 53–212 μm, 20–53 μm fractions followed by separation of organic and mineral fractions in each size fraction by swirling and floating of the organic matter in water. The 0–5 μm and 5–20 μm fractions were separated by the sedimentation method but were not separated for organic and mineral fractions. Carbon in the organic matter fractions was analysed using a Leco Carbon-Sulphur Analyser (Leco C-S200H). Organic C was analysed in the floated SOM for the fractions greater than 20 μm while for the fractions less than 20 μm organic C was analysed in the whole fractions because organic and mineral fractions were not separated. Soil organic C was determined using the modified Walkley Black method (Anderson and Ingram, 1993).

2.1. Statistical analyses

The data were analysed as a completely randomized design for IAE and randomized complete block design for DTC, using the SAS statistical package for analysis of variance (PROC GLM). Significant differences were analysed using Tukey's test at $p < 0.05$. Tillage and residue management treatments were considered as fixed effects while replicates and blocks were considered as random effects ($n = 3$).

3. Results

3.1. Tillage effects on soil organic C and its distribution across particle size fractions

In this section, we only compare CT, CR and TR because we focus on the effect of disturbance independently from C input differences.

For the red clay soil, CT resulted in the greatest declines in SOM as is shown by the smallest amounts of soil organic C compared with the other tillage practices ($p < 0.05$) (Table 1). Total SOC increased with a decrease in intensity of soil disturbance in the red clay soil (Table 1). Tied ridging, having the least disruptive tillage practice, had the greatest amounts of soil organic C, 20.4 mg C g^{-1} soil for the red clay ($p < 0.05$) (Table 1). There were no significant differences in total SOC due to tillage for the sandy soil.

The amounts of organic matter in the different sand-sized fractions were highest in the TR treatment in the red clay soil but there were no differences between CT, CR and TR in the sandy soil (Table 2). Greater

Table 1
Management effects on soil organic carbon of a red clay soil at the Institute of Agricultural Engineering (IAE) and a sandy soil at the Domboshawa Training Centre (DTC) in Zimbabwe

Management treatment	Soil organic C (mg g^{-1} soil)	
	Red clay (IAE)	Sandy (DTC)
Conventional tillage	14.9^{a}	4.2^{a}
Clean ripping	16.8^{ab}	4.6^{a}
Mulch ripping	17.2^{b}	6.8^{b}
Tied ridging	20.4^{c}	4.8^{a}

Values followed by a different superscript letter (a–c) are significantly different across management treatments within a soil type.

Table 2
Management effects on amounts of soil organic matter in different size fractions of a red clay soil at the Institute of Agricultural Engineering (IAE) and a sandy soil at the Domboshawa Training Centre (DTC) in Zimbabwe

Management treatment	Amount (or mass) of organic matter in size fractions (mg g^{-1} soil)		
	Coarse sand (212–2000 μm)	Fine sand (53–212 μm)	Coarse silt (20–53 μm)
Red clay (IAE)			
Conventional tillage	2.68 ± 0.18^{a}	4.32 ± 0.82^{a}	7.98 ± 1.46^{a}
Clean ripping	2.78 ± 0.12^{a}	5.24 ± 0.36^{a}	10.18 ± 0.82^{a}
Mulch ripping	3.48 ± 0.22^{a}	6.34 ± 0.36^{a}	6.80 ± 1.12^{a}
Tied ridging	6.08 ± 0.26^{b}	12.66 ± 1.26^{b}	11.36 ± 0.62^{a}
Sandy (DTC)			
Conventional tillage	1.70 ± 0.04^{a}	1.48 ± 0.24^{a}	1.70 ± 0.26^{a}
Clean ripping	2.16 ± 0.06^{a}	1.86 ± 0.34^{a}	2.38 ± 0.24^{a}
Mulch ripping	3.42 ± 0.06^{b}	5.54 ± 0.42^{b}	3.56 ± 0.08^{a}
Tied ridging	2.98 ± 0.12^{a}	3.80 ± 0.64^{a}	2.12 ± 0.42^{a}

Values are expressed in amounts per total soil weight ($n = 3$; mean ± standard error). Values followed by a different superscript letter (a and b) are significantly different across management treatments within a fraction and soil type.

differences in amounts of organic matter were in the fine sand size fraction, with TR having 66% more organic matter than CT for the red clay soil ($p < 0.05$) (Table 2). There were no significant treatment differences in the coarse silt fractions (Table 2).

Organic C in the size fractions of the red clay followed a similar trend as total SOC and weight of organic matter in the size fractions. Tied ridging had the greatest C in all size fractions while CT had the least for the red clay but there were no significant differences due to tillage in the sandy soil, except for the coarse sand and coarse silt fractions where TR had higher organic C than CT (Table 3). For the red clay soil, organic C in the size fractions consistently (but not significant) increased with decrease in soil disruption from CT through CR to TR for all the size fractions, although the gradient of the differences was steeper in the coarser fractions (Table 3). In the red clay soil, tied ridging had about twice as much organic C in the coarse sand fraction than CT while in the fine sand fraction it was more than 2.5 times greater in the TR compared with CT ($p < 0.05$) (Table 3).

When organic C in the size fractions is expressed per unit of fraction, there was a decrease in organic C with decrease in fraction size for the red clay soil whereas for the sandy soil, organic C in the size fractions increased with decrease in fraction size (Table 4). Tied ridging had the greatest organic C while CT had the smallest concentrations for the red clay but there were no differences due to tillage in the sandy soil except in the coarse sand and coarse silt fractions (Table 4). In the red clay soil, the biggest differences in organic C were in

Table 3
Management effects on the amounts of organic carbon in the different size fractions of a red clay soil at the Institute of Agricultural Engineering (IAE) in Harare and a sandy soil from the Domboshawa Training Centre (DTC) in Zimbabwe

Management treatment	Amount (or mass) of soil organic C in the size fractions (mg C g^{-1} soil)					
	Coarse sand (212–2000 μm)	Fine sand (53–212 μm)	Coarse silt (20–53 μm)	Fine silt (5–20 μm)	Clay (0–5 μm)	Sum
Red clay (IAE)						
Conventional tillage	0.97 ± 0.07^{a}	0.95 ± 0.16^{a}	0.84 ± 0.06^{a}	1.69 ± 0.15^{a}	8.1 ± 0.16^{a}	12.6 ± 0.33
Clean ripping	1.05 ± 0.13^{a}	1.21 ± 0.02^{a}	0.96 ± 0.03^{a}	1.90 ± 0.14^{a}	8.7 ± 0.20^{ab}	13.8 ± 0.10
Mulch ripping	1.04 ± 0.09^{a}	1.34 ± 0.12^{a}	1.00 ± 0.10^{a}	2.09 ± 0.07^{a}	9.0 ± 0.10^{b}	14.5 ± 0.17
Tied ridging	1.93 ± 0.16^{b}	2.54 ± 0.17^{b}	1.47 ± 0.05^{b}	2.66 ± 0.08^{b}	10.1 ± 0.16^{c}	18.7 ± 0.12
Sandy (DTC)						
Conventional tillage	0.47 ± 0.01^{a}	0.35 ± 0.06^{a}	0.24 ± 0.04^{a}	0.24 ± 0.08^{a}	2.7 ± 0.89^{a}	4.0 ± 0.15
Clean ripping	0.53 ± 0.02^{ab}	0.37 ± 0.07^{a}	0.33 ± 0.11^{ab}	0.34 ± 0.12^{a}	3.0 ± 0.89^{a}	4.5 ± 0.23
Mulch ripping	0.92 ± 0.003^{c}	0.87 ± 0.09^{b}	0.60 ± 0.02^{c}	0.40 ± 0.05^{a}	3.89 ± 0.23^{b}	6.7 ± 0.50
Tied ridging	0.66 ± 0.22^{b}	0.37 ± 1.06^{a}	0.39 ± 0.13^{b}	0.30 ± 0.04^{a}	3.0 ± 0.26^{a}	4.7 ± 0.09

$n = 3$; mean ± standard error. Values followed by a different superscript letter (a–c) are significantly different across management treatments within a fraction and soil type.

Table 4
Management effects on soil organic carbon concentrations in size fractions of a red clay soil from the Institute of Agricultural Engineering (IAE) in Harare and a sandy soil from the Domboshawa Training Centre (DTC) in Zimbabwe

Management treatment	Organic C in soil organic matter size fractions (mg C g^{-1} fraction)				
	Coarse sand (212–2000 μm)	Fine sand (53–212 μm)	Coarse silt (20–53 μm)	Fine silt (5–20 μm)	Clay (0–5 μm)
Red clay (IAE)					
Conventional tillage	18.9 ± 1.50a	14.3 ± 2.3a	12.7 ± 0.64a	11.9 ± 1.91a	12.1 ± 0.30a
Clean ripping	22.3 ± 5.10a	17.1 ± 0.33a	15.4 ± 0.93a	13.3 ± 0.50ab	12.8 ± 0.46ab
Mulch ripping	24.9 ± 4.05a	18.6 ± 2.45a	14.5 ± 2.60a	14.6 ± 0.67ab	13.2 ± 0.31b
Tied ridging	41.7 ± 4.52b	35.3 ± 0.82b	20.5 ± 1.20b	15.5 ± 0.82b	15.8 ± 0.31c
Sandy (DTC)					
Conventional tillage	0.8 ± 0.07a	1.3 ± 0.39a	4.8 ± 1.02a	9.6 ± 6.08a	40.4[a]
Clean ripping	0.9 ± 0.09ab	1.7 ± 0.79ab	6.3 ± 3.66ab	12.4 ± 6.67a	34.8 ± 23.10
Mulch ripping	1.8 ± 0.12c	3.0 ± 0.88b	9.9 ± 0.96c	12.1 ± 1.59a	40.0 ± 2.58
Tied ridging	1.1 ± 0.62b	1.8 ± 1.88ab	7.4 ± 4.26b	10.3 ± 2.00a	47.7 ± 2.15

$n = 3$; means ± standard error. Values followed by a different letter (a–c) are significantly different across management treatments within a fraction and soil type.

[a] The other two replications could not be analysed.

the fine sand fraction where TR had about 2.5 times more C than CT ($p < 0.05$) (Table 4). There was a general increase in organic C per gram of fraction with decrease in tillage intensity from CT to TR for all the size fractions of the red clay.

3.2. Residue management effects on soil organic C and its distribution in soil organic matter size fractions

In this section we describe the effect of C input by comparing MR with CR, which were subjected to the same degree of disturbance but differ in residue return: residues were returned to the soil under the MR treatment while under the CR treatment they were removed.

Mulch ripping had higher total SOC concentration, amounts of organic matter in the size fractions, and higher organic C concentration in the size fractions than CR ($p < 0.05$) (Tables 1–3) in the sandy soil but there were no significant differences in the red clay. In the sandy soil, MR had about 32% more whole soil SOC than CR ($p < 0.05$) (Table 1).

There were no differences in organic C in the coarse sand fraction of the red clay soil between the MR and CR treatments while in the sandy soil there was a difference of about 42% ($p < 0.05$) (Table 3). The magnitude of the differences in organic C in the size fractions between CR and MR treatments decreased with decrease in fraction size for the sandy soil whereas there were consistently no differences across the size fractions of the clay soil (Table 3). When organic C was expressed per gram of fraction, MR still had higher organic C than CR in the sandy soil but not in the clay soil (Table 4). Differences in organic C per gram of fraction between CR and MR in the sandy soil were more pronounced in the coarse sand fraction where MR had twice as much organic C than CR (Table 4).

4. Discussion

4.1. Tillage effects on soil organic C and its distribution in soil organic matter size fractions

In general, reduced tillage practices have been found to result in enhanced stabilization of SOC within temperate and (sub)tropical soils (*e.g.* Six et al., 2002a; West and Post, 2002) and have been related to the formation and stabilization of aggregates (Six et al., 2002a). However, we found no difference in SOC between CT and TR in the sandy soil. The lack of differences due to tillage in the sandy soil was probably because of the low clay content which is essential for the physical protection of SOM by mineral association (Feller and Beare, 1997) and aggregate formation (Six et al., 2002a). Sandy soils have a small capacity for longer-term SOM storage, reducing the importance of increased decomposition through disturbance. Few or no aggregates are stable in this soil type because of the low clay content resulting in a fast turnover of added organic matter even without disturbing the soil. Sandy soils have large pores which cannot protect SOM against microbial decomposition. Mtambanengwe et al. (2004) observed that pore diameters of <75 μm were responsible for the protection of organic substrates against microbial decomposition in soil. They also noted that C mineralization decreased with increasing clay content. There was a 3-week delay in N mineralization associated with minimum tillage following improved fallows in a sandy loam soil in Zimbabwe, but the delay was not long enough to significantly improve synchrony of mineral N availability and crop demand (Chikowo et al., 2004a). In the same experiments Chikowo et al. (2004b) also observed that CT resulted in higher yields than minimum tillage over two seasons. As a result, tillage operations seem to have little effect on SOC decomposition in sandy soils and hence reduced tillage will not likely easily raise C in the sandy soils. It has been noted that for some soils, especially those with coarse texture and in arid areas, conversion to NT following long-term cultivation may have little effect on SOC content (Lal, 1997). In a study conducted in Mali TR had higher crop yields than open ridges mainly in the finer textured loamy soil compared with a sandy soil (Kouyate et al., 2000).

The high clay content of the red clay soil, on the other hand, provides potential for the stabilization of SOC by association of organic materials with clay minerals and the formation and stabilization of organic materials within aggregates (Six et al., 2002b). However, CT practices will reduce the stabilization of SOC within aggregates compared with TR practices by enhancing soil structural degradation and aggregate breakdown. Indeed, we found that TR had about 26% more soil organic C than CT in the red clay soil. This is consistent with Beare et al. (1994a) who found in a kaolinitic Ultisol that NT soil had 18% larger standing stock of organic C than CT after 13 years of continuous treatment, and Sa et al. (2001) found that NT had 52.8 g C kg^{-1} soil compared with 30.1 g C kg^{-1} soil under CT after 22 years of continuous treatment. Also, organic C was decreased by 23.4% and 47.8% after 11 years under NT and CT, respectively, compared with an adjacent non-cultivated soil in an oxisol in Brazil (Machado and Silva, 2001). Beare et al. (1994b) also showed that the largest stable aggregates were more abundant in the surface samples of kaolinitic soil under no-tillage management and that these aggregates were more stable and contained higher concentrations of C and N than did water stable aggregates under CT. The proportion of large macroaggregates (>2000 μm) was higher under NT than CT but there were no differences in C and N content across aggregate-size classes indicating that 1:1 clay dominated soils do not express aggregate hierarchy (Zotarelli et al., 2005), and this might be the case with the red clay soil in this study.

In the red clay soil, we observed the biggest differences in SOC due to tillage in the fine sand organic matter fractions probably as a result of physical disintegration of soil aggregates (Tiessen and Stewart, 1983; Six et al., 1999). Coarse sand organic matter is found in soils as free coarse particulate organic matter (POM) or within large macroaggregates which have a fast turnover in soils (Six et al., 1999). Fine sand organic matter, on the other hand, is predominantly found as fine POM within microaggregates occluded in macroaggregates (Six et al., 2000) and is exposed upon tillage with subsequent decomposition and loss from the soil (Six et al., 1999, 2000; Denef et al., 2004). More specifically, the turnover of macroaggregates in CT is fast, providing less opportunity for the stabilization of fine POM (or fine sand organic matter) within stable microaggregates formed within macroaggregates (Six et al., 2000). In contrast, reduced tillage practices allow for a slow macroaggregate turnover resulting in the formation of stable microaggregates in which C is stabilized (Six et al., 2000). Nyagumbo (1998) and Munyati (1997) working at both sites, observed higher runoff losses under CT while TR had the least runoff losses. This is an indication that some of the organic C losses could have been associated with runoff which would be more under CT. These results imply that CT causes faster soil degradation with increased SOM decline, nutrient losses and susceptibility to soil erosion, faster soil fertility decline and lower crop yields in the long-term (Doran et al., 1987; Feller and Beare, 1997). Huxley (1981) noted however, that the key to the success of minimum tillage in the tropics lies in the concomitant use of plant residues.

4.2. Residue management effects on soil organic C and its distribution in soil organic matter size fractions

Higher soil organic C contents under MR compared with CR were mostly a result of residue retention under the MR treatment. In a study conducted on soil fertility gradients across 120 farms located on granitic derived sandy soils in three agroecological regions of Zimbabwe, SOC was consistently higher in most productive than least productive fields within farm (Mtambanengwe and Mapfumo, 2005). In addition Zingore et al. (2005) observed that there was a faster decline of SOC when woodland soils were cleared for arable cropping in the smallholder farming sector compared to the commercial farms because of the intensive use of mineral fertilizers and incorporation of residues in the latter. Such differences were attributed to cumulative effects of substantial amounts of organic matter addition to the most productive fields on a regular basis. In Nigeria on an Alfisol under continuous maize cropping with stover removed, SOC was 36% lower than with stover returned 11 years after forest clearing (Juo et al., 1995). A study conducted on a ferric Lixisol in Burkina Faso indicated that the addition of manure resulted in an increase in the POM fraction due to incorporation of manure and increased sorghum residues (Mando et al., 2005b). Dalal et al. (1991) observed that in the surface soil layers, the interactive effects of zero tillage and returning residues resulted in higher organic C contents compared with CT and zero tillage with residue burning. Kushwaha et al. (2001) also found that the combined effect of tillage reduction and residue retention on SOC and total N was greater than the effects of either tillage reduction or residue retention alone in a sandy loam soil under tropical dryland agriculture. Kang and Yunusa (1977) noted a marked increase in root density in the surface soil with minimum tillage compared with conventional tillage and this they attributed to the mulching effect of crop residue to stimulate root activity, in southern Nigeria.

There were, however, no differences in organic C for the MR and CR treatments on the red clay. In contrast, organic C was greater in the coarse fractions of the sandy soil under MR than CR because the increased C input results in increased macro-organic matter, especially in the short-term (Feller and Beare, 1997). Feller et al. (1996) also observed that in coarse textured soils a large part of SOC variations was mainly due to variations in the plant debris fraction. Coarse organic matter is usually found in free form in sandy soils and is readily attacked by microorganisms, especially in tropical soils where conditions are favourable for microbial activity. Thus, the maintenance of this pool that turns over rapidly will only be accomplished through management options that ensure a sufficiently large input to compensate for the high losses. In conclusion, greater differences in SOC contents of the sandy soil were only observed in the coarse sand fraction with organic matter inputs predominantly controlling the size of this fraction.

The greater parts of the smallholder farms of Zimbabwe are dominated by coarse granitic sands (Nyamapfene, 1991), and hence MR would be a more appropriate option for improving SOC contents. Availability of organic resources in these sectors is, however, limited as residues are usually fed to livestock, as in many parts of Africa (Huxley, 1977). Moreover, in these semi-arid environments termites attack crop residues left in the field, reducing amounts returned for the following crop and in some instances disease prevalence will force farmers to burn or remove crop residues from field. In addition, returning cereal residues was not found to be sufficient on improving crop growth and yield in a study conducted over 8 years in Mali (Kouyate et al., 2000). This brings a significant challenge for the effective adoption and practice of conservation agriculture.

The lack of interactive effects of tillage and residue management on SOC in this study is consistent with findings from other studies. In a study conducted in the sub-arctic region on a silt loam, reduced tillage had higher SOC and total N in the upper 10 cm depth of the mineral soil while crop residue management had no effect on SOC and total N (Sparrow et al., 2006). Duiker and Lal (1999) also observed a linear increase in organic C with increasing rates of residue applied while within each rate of residue application there were no differences across tillage treatments. In another study however, both tillage and residue management had an influence on SOC with more SOC under reduced tillage compared with moldboard plowing while returning residues increased SOC (Dolan et al., 2006).

4.3. Effects of interactions of soil texture and management on soil organic matter

It is evident from our results that there is an interactive effect between management practice and soil texture on SOC stabilization. Namely, there were greater differences in total SOC between the tillage treatments with the strongest (CT) and least (TR) degree of soil disturbance under the red clay soil while there were no significant tillage effects in the sandy soil (Table 1). In the sandy soil, on the other hand, MR had greater SOC contents than CR (Table 1). Consequently, residue management is of greater importance for increasing SOC in coarse textured soils with tillage management playing a lesser role (Fig. 1a). Carbon input predominantly controls SOC by influencing the size of the coarse sand fraction (Table 3). Hence, this coarse sand fraction should be the focus of future studies attempting to understand and control SOM dynamics in sandy soils. In contrast, tillage strongly influences SOC accumulation in finer textured soils while organic matter input is of lesser importance (Fig. 1b). This is attributed to the disruption of aggregates with tillage, exposing the coarse sand fraction to decomposition and therefore limiting the transfer of C from the coarse sand pool to the fine sand pool. Consequently, a stabilization of the fine sand fraction is diminished (Table 3). In conclusion, the fine sand fraction is mostly affected by tillage disturbances and determines SOC accumulation *versus* losses in clay soils (Fig. 1b). Therefore, in future studies, the fine sand fraction can function as a diagnostic fraction for detecting tillage effects on SOC in clay soils.

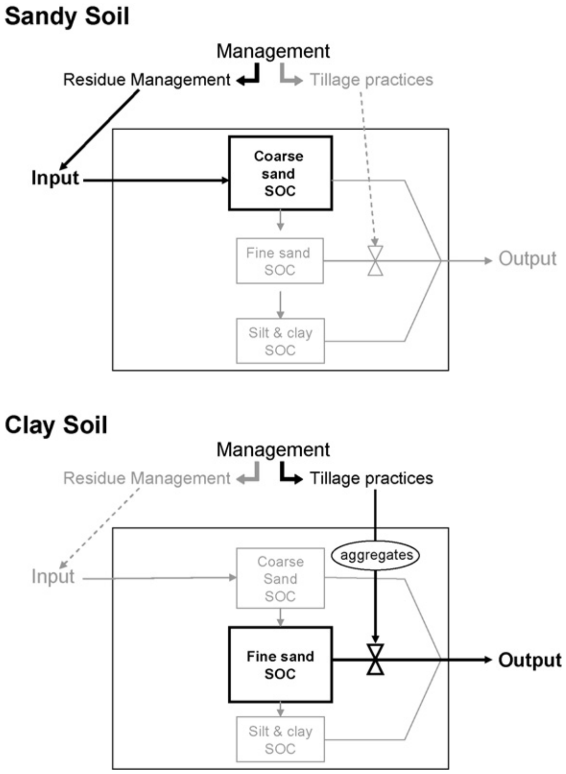

Fig. 1. Conceptual representation of the interactive effects between management and soil texture on soil organic C (SOC) stabilization. (a) In sandy soils organic matter inputs improve SOC contents and especially increase SOC in the coarse sand fraction. (b) Tillage plays a lesser role in controlling SOC content in coarse textured soils. In clay soils soil disturbance regulates SOC storage where high tillage intensity results in greater losses of SOM. This occurs mainly in the fine sand and coarse silt fractions, which are strongly affected by aggregate turnover that tends to be faster in heavily tilled systems.

5. Conclusion

Results from this study indicate that the conversion of current management practices in Zimbabwe from CT with residue removal to conservation agriculture practices on clay soils can improve SOM storage and longer-term sustainability. In clay soils, organic C accumulation, primarily within the fine sand fraction, can be enhanced by reducing disturbance due to tillage. In contrast, soil organic C build up in sandy soils is hardly affected by reduced tillage practices and can only be accomplished by manipulating the coarse SOM fractions through additions of organic inputs.

The importance of residue management in the sandy soils is pertinent because the greater parts of the smallholder farming areas of Zimbabwe are covered by coarse granitic sands. This means that for SOM build up in these soils, more emphasis should be placed on addition of organic resources than reducing tillage disturbance. Crop residues, are usually removed from the fields and fed to livestock making the MR treatment where residues are returned to the soil not a practical option. Crop fields are used as communal grazing lands during off season, such that even farmers without livestock have difficulties managing their residues. Coupled with the prevailing poor productivity of cropping in these sandy soils, where yields are limited due to sparse use of mineral fertilizers and manure, the challenge remains to find alternative organic residues that can be added to the soil for SOM build up.

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