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Effects of agricultural management systems on soil organic carbon in aggregates of Ustolls and Usterts

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Abstract

Soil erosion contributes to the removal and redistribution of soil organic C from cultivated fields. The soil organic C content of wind erodible and water unstable aggregates is an important factor in determining the amount of carbon loss occurring in erosion processes. The relative distribution of organic carbon among aggregate size fractions may also affect the response of soils to erosion. Soil organic C distribution is dependent on the chosen management system. The effects of no-till, till, and grassland management systems on organic C content of erodible and non-erodible aggregates were examined in six Ustolls and two Usterts of central South Dakota. Organic C contents were related to dry- and wet-sieving to represent the potential influence of wind and water erosion on C loss in the absence of vegetative cover. Loss of aggregate stability in cultivated soils was associated with organic C loss. Most structural characteristics developed under tilled systems persisted after 6–16 years of no-till. Changes in distribution of organic C due to management systems were most evident in Ustolls where cultivation resulted in net soil C losses. Soil organic C was not significantly increased by the no-tillage practices applied in this on-farm study (in Ustolls 49 Mg ha^{-1} in no-till versus 41 Mg ha^{-1} in till, for 0–0.20 m depth). Soil properties of Usterts were less affected by land use and management practices due to the high shrink swell action and self-mixing. In both soil orders the greater concentration of organic C in the wind erodible (<1 mm) dry aggregate size fraction implies a high potential for organic C loss by erosion in addition to organic C loss from mineralization after tillage. Grassland when compared to cultivated topsoil showed the largest amounts of organic carbon stored and the minimal potential for erosion loss of soil organic C.

Keywords: Soil organic C; Water erosion; Wind erosion; Soil management; No-till

1. Introduction

Organic C is a major component of the soil organic fraction and a variation of organic C content and location causes clear soil structural modifications. In general, soil organic C content declines with intensive management systems (Sparrow et al., 1999) and tends to decrease with increasing soil depth in relation to

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reductions in biological activity and root growth. Differences in depth distribution can be induced by different management systems. Organic C tends to be uniformly distributed within the tilled depth of moldboard plowed soils, and stratified in no-till soils with the highest concentration at the surface, where the first changes are usually observed after conversion from intensive tillage (Beare et al., 1997). Organic C content was found to be significantly different between management systems only in the top 0–0.05 m (Six et al., 1999, 2000).

There are few published data about organic C distribution in dry aggregate size fractions. Sometimes inferences have been made based on pre-moistened wet-sieved aggregates with discordant results (Angers and Carter, 1996). Puget et al. (1995, 2000) reported a reduction of organic C with decreasing aggregate sizes of dry-sieved aggregates. de Jonge et al. (1999) found a reduction of organic C with increasing aggregate size. Lado et al. (2004) did not find significant differences in organic matter content for different dry aggregate size fractions in a Humic Dystrudept containing >3% organic matter. In contrast, the organic matter was significantly greater in the 4–6 mm aggregate size fraction when the organic matter was <3% in a similar soil.

Wind erosion can result in considerable amounts of soil loss and deposition. Redistribution of soil implies redistribution of soil C. Soil C losses and gains from wind erosion depend on the C content of erodible particles and aggregates. Aggregates less than 1 mm in diameter are potentially erodible by wind (Woodruff and Siddoway, 1965). Particles and aggregates less than 0.1 mm in diameter are considered to be the most erodible (Skidmore and Powers, 1982). Su et al. (2004) attributed the major reduction in soil organic C found in the topsoil of a cultivated Entisol to the loss of particles and aggregates <0.1 mm in diameter by wind erosion. Potential losses of C from wind erosion are dependent on the proportion of erodible aggregates in the topsoil and in the C content of these aggregates.

Soil aggregate stability has been related to organic C content and localization in the architecture of the soil. Decreasing organic C contents are linked to decreasing wet aggregate stability and size of water stable aggregates (Puget et al., 2000). Less organic C in finer wet stable aggregate sizes was measured both in till and no-till soils (Beare et al., 1997). A linear relationship between macroaggregation and macroaggregate organic C content ($R^2 = 0.89$) was found by Shaver et al. (2003). A linear correlation was observed between organic C and wet stable aggregate size ($r = 0.90$) in soils of southeastern Scotland (Ball et al., 1996). The correlation coefficient was also significant ($r = 0.58$) in samples of an Inceptisol from New Zealand (Haynes and Swift, 1990). A significant linear relationship between C content and wet aggregate stability with $R^2 = 0.62$–0.67 ($n = 12$) was reported for Oxisols (Kouakoua et al., 1999). When air-dried aggregates are wet-sieved, stabilization by organic C may be more evident than in the case of pre-moistened aggregates not subjected to slaking stresses because stability to slaking is apparently a function of organic C (Chenu et al., 2000).

Organic components can stabilize soil structure protecting the soil from erosion. At the same time the organic fraction can be stabilized by physical protection of mineral soil constituents and by chemical interactions with soil mineral surfaces. In particular, soil constituents with a large specific surface area are involved in these processes. Consequently, clay mineralogy and organic composition of the clay-size fraction can be factors determining soil structural characteristics. The ≥35% smectitic clay content of Vertisols produces soil cracking and self-mixing. Therefore, a uniform distribution of organic C is expected and horizons tend to be less differentiated in Vertisols than in other soil orders (Soil Survey Staff, 1999). Organic C concentration in wet stable macroaggregates appeared 1.65 times greater in macroaggregates than in microaggregates in soils with dominant 2:1 clay minerals consisting of illite and chlorite (Six et al., 2000). In these soils the concentration of organic C was similar in macroaggregates from all management systems, whereas it decreased from grasslands to no-till fields to tilled fields in microaggregates. Other soils with mixed clay mineralogy did not show any significant trend (Six et al., 2000). In a kaolinitic Ultisol organic C was higher in water stable microaggregates of 0.106–0.250 mm size than in smaller or larger aggregate size fractions in no-till soils, whereas similar concentrations of organic C among aggregate size fractions were measured in tilled soils (Beare et al., 1994).

The objective of this study was to examine the effect of management systems on organic C content of erodible and non-erodible aggregates. Organic C contents were related to dry and wet-sieving to represent the potential influence of wind and water erosion on C loss in the absence of vegetative cover. In addition, organic C was determined in each horizon through the soil profile in order to show how organic C changes with soil depth can be affected by management practices.

2. Methods and materials

2.1. Site description and experimental design

Eight locations were selected in the Upper Missouri River Basin. At each site no-till, conventional-till (till), and grasslands (grass) were present in fields in close proximity on the same soil series and with similar topography. Ustolls were present at six sites and Usterts were present at two sites. Seven soil series were considered in the study (Table 1). No-till management systems were in place for 6–16 years (average 10 years). Grasslands were typically used for hay or pasture and had no history of tillage. Dominant grass species were bromes (*Bromus* sp.), wheatgrasses (*Agropyrum* sp.) and Kentucky bluegrass (*Poa pratensis* L.). Conventional-till systems generally used chisel plowing and in a few cases field cultivation as primary tillage and tandem disking as secondary tillage. Depth of tillage varied between 0.07 and 0.20 m. Cropping systems included wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and soybean (*Glycine max* (L.) Merr.). The eight locations were used as replications with each of the three management systems compared as treatments.

2.2. Sampling

Four sampling areas with similar soil profiles and landscape positions were selected within each of the individual fields at each location. Each sampling area was marked using differential global positioning system (DGPS, Trimble Navigation Limited, 1998). A hydraulic 75 mm diameter soil probe was used to sample and compare soil profiles to 1–1.5 m depth according to standard procedures (Soil Survey Staff, 1998a). Soil cores were air-dried and stored for further analyses. Cores (0.05 m diameter) were taken from 0.02 to 0.07, 0.15 to 0.20 and 0.25 to 0.30 m depths for bulk density determination (Blake and Hartge, 1986).

Soil samples were collected from the topsoil (0–0.20 m depth) close to the cores with a spade for organic C distribution in aggregates of different sizes separated by dry and wet-sieving. Samples were thoroughly mixed and pooled by treatment at each location. Samples were air-dried at room temperature and stored until analysis without any pre-sieving, grinding or removing of organic particles. Additional bulk soil samples were separately taken with a spade to 0.20 m depth for organic C analysis without aggregate size separation.

2.3. Roots

Soils were morphologically described according to the Natural Resources Conservation Service protocol (Soil Survey Staff, 1998a). Scores were attributed to root quantities and sizes for assessing differences in hydraulic soil properties due to root differences. Ratings were based on the scale by Lin et al. (1999) and are reported in Table 2.

Table 1
Soil series sampled in the study (Soil Survey Staff, 1998b)

Soil series	Classification	Texture
Lowry	Coarse-silty, mixed, superactive, mesic Typic Haplustoll	Loam
Uly	Fine-silty, mixed, mesic Typic Haplustoll	Silt loam
Reeder	Fine-loamy, mixed, superactive, frigid Typic Argiustoll	Loam
Highmore	Fine-silty, mixed, superactive, mesic Typic Argiustoll	Silt loam
Williams	Fine-loamy, mixed, superactive, frigid Typic Argiustoll	Clay loam
Millboro	Fine, smectitic, mesic Typic Haplustert	Silty clay
Promise	Very-fine, smectitic, mesic Typic Haplustert	Clay

Table 2
Scores used for quantifying the morphological description of roots in the studied soils of central South Dakota (Lin et al., 1999)

Morphological feature	Class	Definition	Score
Root quantity	Few	<1 per unit area	1
	Common	1 to <5 per unit area	16
	Many	≥5 per unit area	25
Root size	Very fine, fine	<2 mm diameter, assessed on a unit area = 1 cm^2	43
	Medium, coarse	10–2 mm diameter, assessed on a unit area = 1 dm^2	13
	Very coarse	≥10 mm diameter, assessed on a unit area = 1 m^2	1

The soil area considered for root assessment varied with root size as defined (Soil Survey Staff, 1998a).

2.4. Dry-sieving

Dry-sieving was used to separate dry, stable aggregate sizes in the top 0–0.20 m of soil. A portable flat-sieve shaker (Model RX-24, Tyler CE Inc., Mentor, OH), equipped with a nest of two (20 cm diameter) sieves with openings 2.0 and 1.0 mm respectively was used for sieving. Air-dried soil samples of 200–300 g were gently broken by hand to pass a 25 mm sieve prior to shaking for 2 min. The soil retained on each sieve was weighed at 15 s intervals. Aggregates retained on the 1.0 mm sieve were removed and stored for C analysis. Subsequently, the residual 2–25 mm fraction was sieved again for a total of eight 15 s cycles. The remaining <1 mm material (wind erodible fraction) and 2–25 mm material (wind non-erodible fraction) were collected and stored for C analysis.

2.5. Wet-sieving

Air-dried 1–2 mm aggregates from 0 to 0.20 m depth were directly immersed in deionized water on a 0.25 mm screen at atmospheric pressure and room temperature. They were soaked for 3 min, and then shaken for 3 min according to the procedure of Kemper and Rosenau (1986). Water stable macro-aggregates (>0.25 mm) and the <0.25 mm fraction were oven-dried at 40 °C, weighed, and stored for C analysis. Wet stable aggregates included all organic and mineral particles and aggregates >0.25 mm after shaking.

2.6. Organic carbon

The fine earth of samples from each horizon of the cores was ground before C analysis. Also, the bulk topsoil samples and the aggregate fractions separated by dry and by wet-sieving were ground before C analysis, without any preliminary separation of coarse particulate organic matter (>2 mm). Organic C was determined by dry combustion of total C (Nelson and Sommers, 1982) followed by subtraction of inorganic C (Wagner et al., 1998). Organic C content was considered in reference both to the bulk soil (mass, volume, or equivalent mass; Ellert et al., 2001) and to the aggregate size fractions of the soil, separated either by dry or by wet-sieving. The organic C content of the aggregate size fractions stored in the bulk soil was calculated as follows:

$$\text{organicC}_{\text{soil fraction}} = \text{organicC}_{\text{aggregate}} \times \text{aggregate mass ratio} \qquad (1)$$

where organic $C_{\text{soil fraction}}$ is the organic C of the aggregate size fraction stored in the bulk soil (g C kg^{-1} soil), organic $C_{\text{aggregate}}$ the organic C concentration in the aggregate size fraction (g C kg^{-1} aggregates), and aggregate mass ratio is calculated as (aggregate mass)/(bulk soil mass) (kg aggregates kg^{-1} soil).

The total organic C in the bulk soil (organic C_{soil}) is the summation of all sieved aggregate fractions:

$$\text{organicC}_{\text{soil}} = \sum(\text{organicC}_{\text{soil fraction}}) \qquad (2)$$

2.7. Statistical analysis

Data were statistically analyzed using the SYSTAT 9 program (SPSS Inc., 1999). Relationships between measured soil properties were tested by regression analysis. Orthogonal contrasts were made between the grass and cultivated treatments and between the no-till and till treatments. Pairwise comparisons of aggregate means were made by Tukey tests. Data were separately analyzed for all sites (eight replications), for Ustolls (six replications) and for Usterts (two replications). Soil series within each soil order showed similar trends. Means of data grouped by soil order (and in some cases, by management system and aggregate size) were compared by *t*-tests. Results from data analysis were reported for all soils when Ustolls and Usterts showed similar response. Otherwise the response of two soil orders was separately discussed.

For the core samples, data of the four repeated measures per site and management system were averaged using horizons depths as weighing factors and analyzed by depth layer. Five depth increments were considered (0–0.05, 0.05–0.20, 0.20–0.40, 0.40–0.60 and 0.60–0.80 m). Weighted averages were also calculated for the top 0–0.20 m of soil for comparative purposes with analyses of spade samples. The top 0.20 m layer included the surface horizon (A or Ap) and part of the underlying horizon in pedons where the surface horizon was less thick.

3. Results and discussion

3.1. Organic C in bulk soil

Organic C decreased with depth in all soils (Fig. 1). Differences in organic C content between management systems were most evident in the top 0–0.20 m. In Ustolls organic C was higher in grass soil as compared to cultivated soils (till and no-till), either expressed on a mass basis (organic C_{soil} = 25.1 g kg^{-1} versus 16.7 g kg^{-1}), on an equivalent mass basis (67 Mg ha^{-1} versus 44 Mg ha^{-1}), or on a volume basis (58 Mg ha^{-1} versus 44 Mg ha^{-1}), although the bulk density in grass fields was lower than in cultivated fields (mean 1.16 Mg m^{-3} versus 1.33 Mg m^{-3}). In Ustolls organic C tended to decrease from no-till (49 Mg ha^{-1}) to till (41 Mg ha^{-1} with similar bulk density), but the difference was not significant ($P \leq 0.102$). In Usterts differences between management systems were not significant. Soil organic C distribution followed the root density pattern.

3.2. Roots

Root quantity scores were much greater under permanent grass than in annually cropped fields (Fig. 2). Dominant root size was fine in every treatment because of the herbaceous vegetation. Significantly more roots were present under grass than in the cultivated treatments at any measured depth. In Usterts differences in root quantity scores were significant only in the top 0.30 m. A sharp decrease of root quantity of grasslands was observed in Usterts at

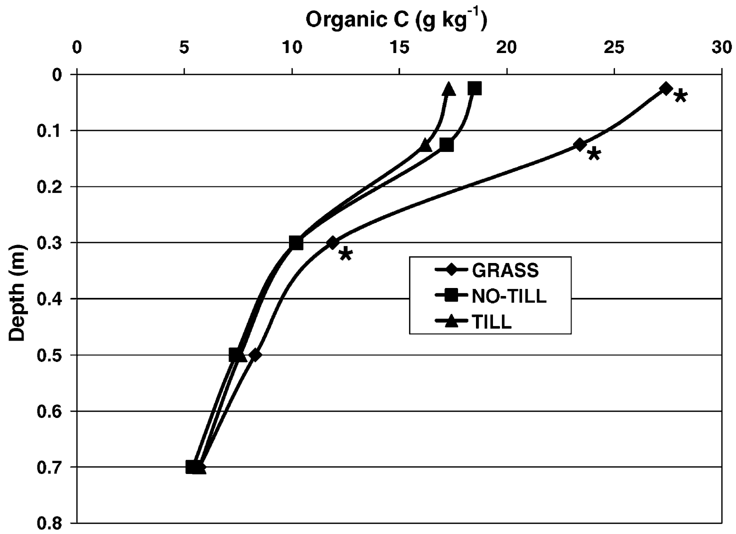

Fig. 1. Organic C content as a function of soil depth in prairie soils of central South Dakota (mean of eight sites). (*) A significant difference between grass and cultivated soils ($P < 0.05$).

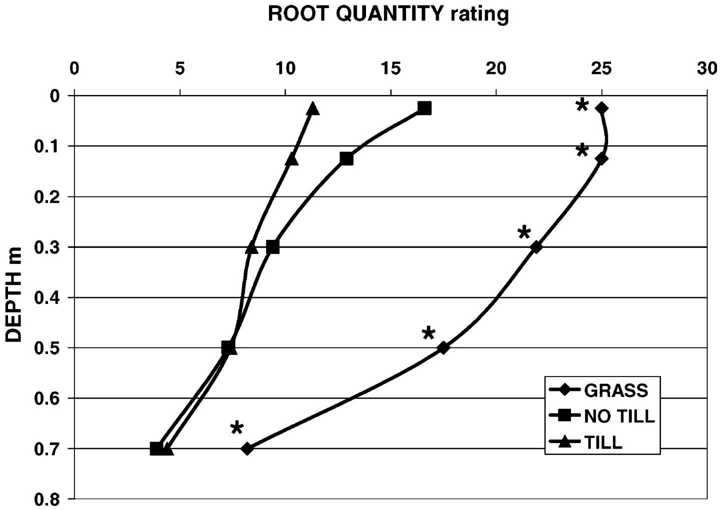

Fig. 2. Root quantity as a function of soil depth in prairie soils of central South Dakota (mean of eight sites). (*) A significant difference between grass and cultivated soils ($P < 0.05$).

0.30 m depth, probably due to problems of root growth related to intensive soil shrinking and swelling. When compared to till, no-till management systems did not significantly increase the root quantity or distribution.

3.3. Organic C in dry aggregate size fractions

More organic C was stored in the topsoil of Ustolls in the coarse aggregate fraction (2–25 mm) (mean organic $C_{soil\ fraction}$ 13.7 g kg^{-1}, $P < 0.001$) than in the other fractions separated by dry-sieving. Differences between 1 and 2 mm (mean organic $C_{soil\ fraction}$ 1.5 g kg^{-1}) and <1 mm (mean organic $C_{soil\ fraction}$ 3.3 g kg^{-1}) aggregate fractions were non-significant. C distribution among dry sizes can be mainly related to a large proportion of coarse aggregates stable to dry-sieving both in Usterts and in Ustolls. Grasslands of Ustolls tended to have more aggregates smaller than 2 mm since in soils under grass the soil mass was finely divided by roots (significant management × size interaction, $P \leq 0.006$).

The concentration of organic C per unit mass of aggregates (organic $C_{aggregate}$) was greater in 1–2 mm and <1 mm aggregates than in the coarse fraction of Ustolls (Table 3), without a significant management × size interaction ($P \leq 0.558$). The abrasion of aggregate coatings during dry-sieving and the accumulation of particulate organic matter from root

Table 3
Means (±standard errors) of organic C concentration (organic $C_{aggregate}$ = g of organic C kg^{-1} of dry aggregates) in dry aggregate fractions of Ustolls ($n = 6$) and Usterts ($n = 2$) in central South Dakota

Soil order	Size fraction (mm)	Grass (g kg^{-1})	No-till (g kg^{-1})	Till (g kg^{-1})
Ustolls	2–25	22.6 (±1.82) b	17.3 (±1.80) b	14.3 (±1.43) b
	1–2	26.7 (±2.17) a	19.1 (± 1.89) a	15.6 (±1.70) a
	<1	26.1 (±1.92) a	18.7 (±1.52) a	15.5 (±1.76) a
Usterts	2–25	23.5 (±1.05) a	19.7 (±3.40) a	23.5 (±0.35) a
	1–2	24.9 (±2.90) a	20.4 (±2.45) a	22.8 (±0.15) a
	<1	28.7 (±4.55) a	23.4 (±3.65) a	24.2 (±0.95) a

Means followed by the same letter in each column within a soil order are not significantly different ($P \leq 0.05$). The interaction between management and size was not significant in any soil order. The contrasts between grass and cultivated Ustolls and between till and no-till Ustolls were significant ($P < 0.001$). The contrast between grass and cultivated Usterts was significant ($P \leq 0.043$). The contrast between till and no-till Usterts was not significant ($P \leq 0.184$).

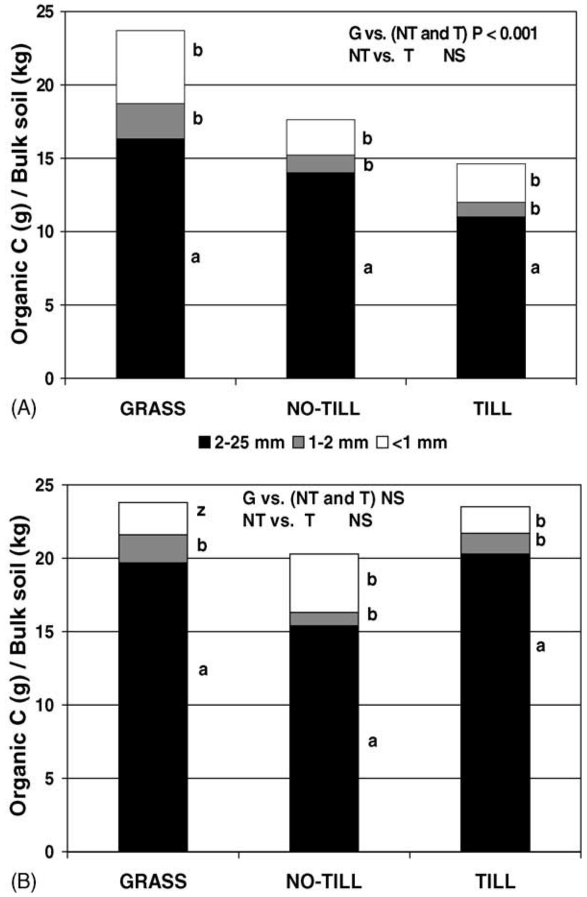

Fig. 3. Organic C in dry-sieved bulk soil (0–0.20 m depth) in Ustolls (A) and Usterts (B) of central South Dakota. For each soil order probability of differences of organic C of bulk topsoil between management systems are reported (G = grass, NT = no-till, T = till). Different letters adjacent to each bar indicate significant differences between aggregate sizes ($P < 0.05$).

systems holding soil particles and aggregates together can in part explain the enrichment of the finer sizes in organic C (Chenu et al., 2000). The process of saltation in wind erosion is also likely to create similar abrasive action resulting in detachment of particulate organic matter. In the procedure followed in this study no organic fragment at any stage of decomposition was discarded since root fragments and residues were present both within and between sieved aggregates. Other methods may give different results (Puget et al., 1995; Lado et al., 2004).

In Usterts there were no significant differences in organic C between management systems and between

Table 4
Significance of differences between Ustolls ($n = 6$) and Usterts ($n = 2$) of central South Dakota in organic C concentration means (organic $C_{aggregate}$ = g of organic C kg^{-1} of dry aggregates) in the top 0–0.20 m of soils under different management systems, based on the analysis on dry aggregate size fractions

Management	Ustolls (g kg^{-1})	Usterts (g kg^{-1})	Probability
Grass	25.1	25.7	$P \leq 0.797$
No-till	18.3	21.2	$P \leq 0.150$
Till	15.1	23.5	$P < 0.001$

aggregate sizes (Fig. 3; Table 3). Shrinking and swelling of smectitic clays redistribute organic C within aggregates. In contrast, in Ustolls, humified organic matter accumulates on the outer surfaces of the aggregates coating pores by illuviation (Soil Survey Staff, 1999). Therefore, larger differences were expected in Ustolls than in Usterts.

Topsoils of Usterts contained more organic C as an average over all the aggregate sizes than topsoils of Ustolls (23.5 g kg^{-1} versus 19.5 g kg^{-1} of organic $C_{aggregate}$, $P \leq 0.010$, for dry aggregate fraction measurements). All analyses confirmed this result, but differences between means grouped by management system were significant only in the case of tillage (Table 4). Tilled soils in Ustolls showed the maximum depletion of organic C as compared to grasslands. Limited loss of organic C in tilled Usterts may be due to greater stabilization of organic matter within aggregates in Usterts because of higher amounts of Ca saturated clay (Buol et al., 1997).

Although a majority of the soil organic C is contained in the non-erodible aggregate fraction the concentration of C in the erodible dry aggregate fraction is significantly higher (Fig. 3; Table 3). As a result soil organic C loss from wind erosion is likely to be greater than expected from calculations that are based on the bulk soil organic C content. The higher C content of the erodible fraction from the grass treatment could result in higher than expected rates of soil organic C loss from wind erosion during the first few years after conversion of grassland to clean-tilled (minimal residue cover) cropland in addition to C loss from mineralization. A linear decrease in soil organic C with loss of fine (<0.1 mm) soil fractions due to erosion in continuous conventionally tilled fields was observed in Haplustolls of Argentina (Hevia et al., 2003).

3.4. Organic C in size fractions separated by wet-sieving

In Ustolls under grass management systems water stable macroaggregates stored more organic C (organic $C_{soil\ fraction}$) than unstable materials (Fig. 4), whereas in cultivated soils similar organic C contents (organic $C_{soil\ fraction}$) were present in both size fractions separated by wet-sieving air-dried 1–2 mm aggregates (significant management × size interaction, $P < 0.001$).

In both wet-sieved size fractions of Ustolls differences in organic $C_{soil\ fraction}$ were significant between grasslands and cultivated treatments, but not between till and no-till soils (Fig. 4). This organic C distribution was due to a low proportion of water stable macroaggregates (wet aggregate stability) in cultivated soils (mean 33% versus 76% in grass, difference significant at $P < 0.001$) as well as to the organic C concentration in wet stable macroaggregates (Table 5). In Ustolls higher organic C concentrations per unit aggregates (organic $C_{aggregate}$) were found in grass than in till and no-till ($P < 0.001$) and higher in >0.25 mm than in <0.25 mm wet-sieved fractions in all management systems (non-significant management × size interaction).

Cultivated soils in eroding topographic positions are in greater danger of soil C depletion from water erosion than grassland soils since a greater proportion of soil C is in the unstable macroaggregate fraction in cultivated compared to grassland soils. This is due to a greater proportion of water stable macroaggregates and a higher concentration of organic C in macroaggregates from grassland compared to cultivated Ustolls. In the absence of vegetation and residue cover a greater proportion of C loss from soils are to be expected from the cultivated soils. In our study there would be little difference between no-till converted to tilled soil and continuously tilled soil in terms of the potential for C loss. Mineralization of C combined

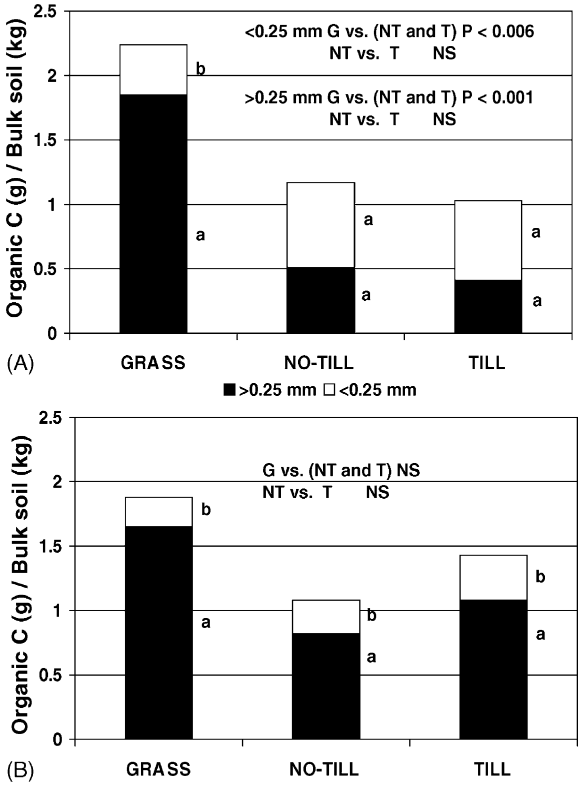

Fig. 4. Organic C in wet-sieved fractions from 1 to 2 mm dry aggregates from the topsoil (0–0.20 m) of Ustolls (A) and Usterts (B) in central South Dakota. In the top of each graph probability of differences of organic C between management systems are reported for each size fraction separated by wet-sieving (G = grass, NT = no-till, T = till). Different letters adjacent to each bar indicate significant differences between aggregate sizes ($P < 0.05$).

Table 5
Organic C concentration (organic $C_{aggregate}$ = g of organic C kg^{-1} of wet-sieved fraction) in wet-sieved fractions of Ustolls ($n = 6$) and Usterts ($n = 2$) of central South Dakota

Soil orders	Size fractions (mm)	Grass (g kg^{-1})	No-till (g kg^{-1})	Till (g kg^{-1})
Ustolls	>0.25	27.5 a	22.8 a	19.6 a
	<0.25	19.4 b	15.9 b	13.8 b
Usterts	>0.25	24.1 a	24.8 a	24.4 a
	<0.25	20.7 a	17.5 a	20.1 b

Means followed by the same letter in each column within soil orders are not significantly different ($P \leq 0.05$). The interaction between management and size was not significant in any soil order. The contrast between grass and cultivated Ustolls was significant ($P \leq 0.002$). No other comparison between management systems was significant

Table 6
Significance of differences between Ustolls ($n = 6$) and Usterts ($n = 2$) of central South Dakota in organic C means (organic C_{soil} = g of organic C kg^{-1} of soil) in the top 0–0.20 m of soils under different management systems, based on the analysis of wet-sieved stable macroaggregates (>0.25 mm size)

Management	Ustolls ($g\ kg^{-1}$)	Usterts ($g\ kg^{-1}$)	Probability
Grass	18.5	16.5	$P \leq 0.758$
No-till	5.1	8.2	$P \leq 0.028$
Till	4.1	10.8	$P \leq 0.008$

with reduced C input from root and residue biomass has a greater impact on loss of soil C immediately after conversion of grassland to cultivation. Soil erosion becomes increasingly important for C loss and redistribution in later years (Gregorich et al., 1998).

In contrast in Usterts there were no significant management × size interactions and more organic C was stored in the soil (organic $C_{soil\ fraction}$) as water stable macroaggregates than as fine materials (Fig. 4). In both Usterts and Ustolls the concentration of organic C (organic $C_{aggregate}$) appeared higher in >0.25 mm than in <0.25 mm wet-sieved fractions (Table 5), although in Usterts this difference was significant only in case of tilled soils.

Organic C concentrations in wet-sieved fractions (organic $C_{aggregate}$) were not significantly different between soil orders in any management system ($P > 0.05$). However, more organic C (organic $C_{soil\ fraction}$) was stored in stable macroaggregates in no-till and till in Usterts than in Ustolls (Table 6), as expected from higher wet aggregate stability in Usterts (70% versus 35% in no-till and 72% versus 31% in till).

3.5. Relationship between organic C and aggregate stability

No significant linear relationship was observed between total organic C content in the bulk topsoil and dry aggregate size fractions. Instead, organic C concentrations in wet-sieved aggregate fractions were linearly related to organic C content in the bulk topsoil ($R^2 = 0.62$, $P < 0.001$ for the >0.25 mm fraction; $R^2 = 0.83$, $P < 0.001$ for the <0.25 mm fraction). Similarly a direct relation ($r = 0.96$, $P < 0.01$) between water stable macroaggregate C content and bulk soil organic C content was shown in various soils of eastern Canada (Carter et al., 2003).

Total organic C content of the topsoil explained 65% of the variation in wet aggregate stability. The relationship between these two variables was linear and very highly significant ($P < 0.001$). When grouping the data by management system, a linear regression between organic C and wet aggregate stability appeared significant only in case of tillage

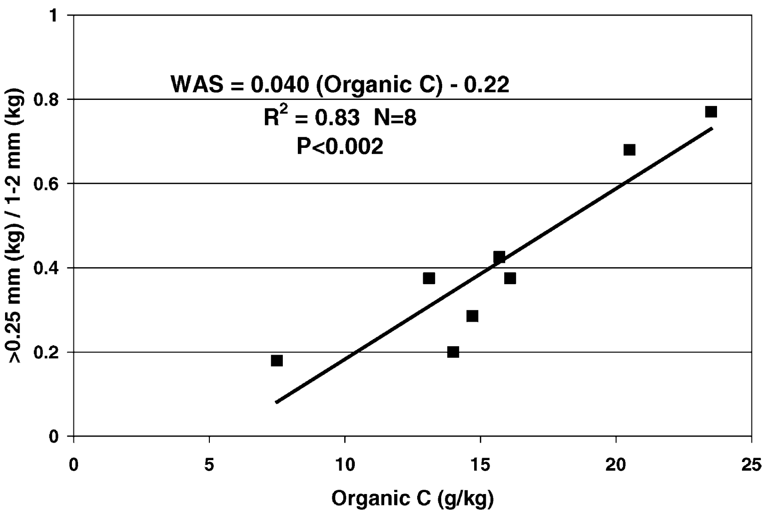

Fig. 5. Wet aggregate stability (WAS) as a function of organic C content in the bulk topsoil (0–0.20 m depth) of all tilled soils studied in central South Dakota. The linear regression is reported in the top left corner.

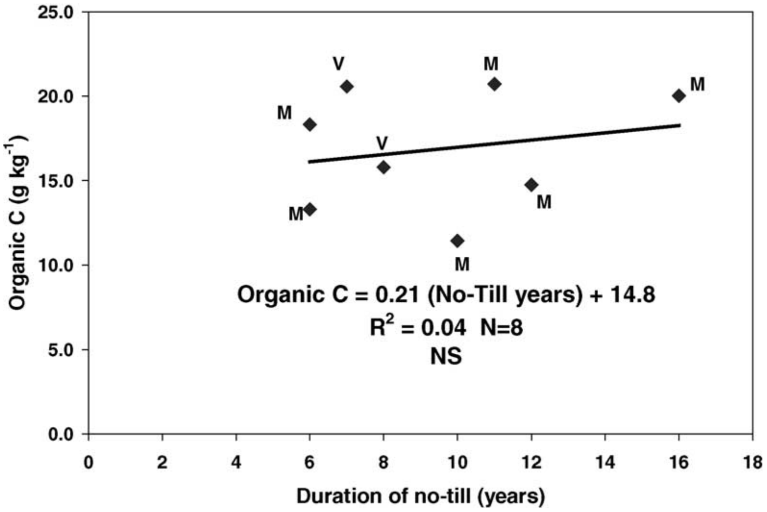

Fig. 6. Organic C content in the bulk topsoil (0–0.20 m) as a function of years of no-tillage after long-term intensive conventional tillage in all studied soils of central South Dakota (M = Ustolls; V = Usterts). The linear regression is not significant ($P > 0.05$).

($P \leq 0.002$). In the studied tilled topsoils, total organic C explained 83% of the variation in aggregate stability (Fig. 5). In grasslands aggregate stability was probably not limited by organic C content in the topsoil ($\geq$2%). The variation in duration (6–16 years) of no-tillage practices may have obscured simple relationships between aggregate stability and organic C content in no-till soils. However, there was no linear relationship between years in no-till and soil organic C content (Fig. 6).

4. Conclusions

In soils of central South Dakota cultivation decreased organic C as compared to grasslands. The reduction was evident especially in the top 0–0.20 m of soil, where no-till systems did not significantly increase organic C or root quantity relative to conventional tillage. Most organic C was stored in the soil as coarse aggregates due to a large proportion of >2 mm aggregates. Maximum concentrations of organic C per unit aggregates were measured in 0.25–2 mm wet stable aggregates. A linear relationship was found between organic C content in the soil and wet aggregate stability, especially in tilled soils where organic C loss by cultivation was most evident in the case of Ustolls. Ustolls appeared more affected by organic C loss consequent to tillage than Usterts.

In both soil orders the high concentration of organic C in the wind erodible (<1 mm) dry aggregate size fraction implies a high potential for organic C loss by erosion in addition to organic C loss from mineralization after tillage. Cultivated Ustolls showed a greater proportion of organic carbon in the wet unstable macroaggregate fraction with consequent greater potential organic carbon loss by water erosion relative to grasslands. Inclusion and expansion of grass in management systems appeared the best means of maintaining soil organic C in the soil and minimizing losses and redistribution of C from wind, water, and tillage erosion.

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