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Long-Term Tillage Impacts on Soil Aggregation and Carbon Dynamics under Wheat-Fallow in the Central Great Plains

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Long-term conservation tillage improves soil quality by enhancing soil structure, improving water availability, and reducing soil erosion. We investigated the effect of tillage intensity on soil organic carbon (SOC), organic carbon fractions, particulate organic matter (POM), and wet aggregate-size distribution after 39 yr of management. The data reported here were taken from a long-term tillage study initiated in 1967 near Akron, CO. Treatments sampled were conventional tillage (CT), moldboard plow (MP), no-tillage (NT), and reduced tillage (RT). In 2006, soil samples were collected from the 0- to 5-, 5- to 10-, 10- to 20-, 20- to 30-, and 30- to 60-cm depths in winter wheat (*Triticum aestivum* L.)–summer fallow (WF). Soils were fractionated for aggregate mass and POM–mineral-associated carbon (C) to evaluate the form and stability of SOC. On a fixed-depth basis, NT and RT had 21% more SOC, at the 0- to 30-cm depth than CT and MP. However, on equivalent mass basis (ESM), SOC was greater with NT, MP, and RT by 11% compared with CT. Conservation practices, NT and RT, had more macroaggregation and consequently greater soil stability compared with CT and MP. Tillage practices significantly impacted whole SOC distribution between POM-C and mineral-associated organic matter C (MAOM-C). The POM-C vs. MAOM-C component of the whole SOC was 23 vs. 77% at 0 to 5 cm and 10 vs. 90% at 5- to 20-cm depth. The POM-C associated with NT and RT, accounted for 17% of SOC where POM-C accounted for 12% of SOC with CT and MP at 0- to 20-cm depth. Redistribution and stratification of SOC, POM, and POM-C were observed especially with MP. Over all, we found the application of conservation tillage practices to be crucial for maintaining soil quality and soil C stock in the WF systems of the central Great Plains.

Abbreviations: CT, conventional tillage; ESM, equivalent soil mass; FD, fixed depth; MAOM, mineral-associated organic matter; MAOM-C, mineral-associated organic matter carbon; FD, fixed-depth; MP, moldboard plow; NT, no-tillage; POM, particulate organic matter; POM-C, particulate organic matter carbon; RT, reduced tillage; SIC, soil inorganic carbon; SOC, soil organic carbon; SOM, soil organic matter; WF, wheat-fallow rotation; WSA, water stable aggregate.

In the last two decades scientists have become aware of the importance of long-term studies to understand and evaluate the sustainability of specific agricultural practices (Brown, 1991). Since changes in soil parameters occur slowly, long-term field studies are particularly valuable for evaluating soil changes as influenced by different management practices (Peterson et al., 2012). Peterson et al. (2012) documented how long-term studies at the High Plains Agricultural Laboratory in

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western Nebraska improved our quantitative knowledge of soil sustainability and the long-term effects of soil management. In general, these long-term studies were initiated for a specific objective (Brown, 1991; Peterson et al., 2012), but through time they have become essential for assessing the impact of management decisions on soil quality and sustainability.

The WF system is the primary cropping system in the central Great Plains Region. Because of its low C input compared to continuous cropping systems, WF is susceptible to SOC loss and erosion (Smika, 1990; Halvorson et al., 2002; Mikha et al., 2010). In WF, conservation practices such as NT or RT can mitigate these risks (Cambardella and Elliott, 1992; Halvorson et al., 2002; Mikha et al., 2006, 2010) and provide additional soil water (Smika, 1990; Peterson et al., 1998). The study reported in this paper was originally initiated in 1967 to evaluate different tillage and weed control practices for water storage efficiency during the fallow period and to increase the productivity of the WF rotation (Smika, 1990; Halvorson et al., 1997). At the present time, this study site is considered as one of the long-term study sites across the United States and Canada. Since the initiation of this study, many researchers have reported on the influence of the tillage practices imposed on these plots. Previous studies found that the conservation tillage practices, NT and RT, increased available water (Elliott et al., 1984; Smika 1990), reduced erosion (Smika, 1990), enhanced aggregate stability (Blanco-Canqui et al., 2009), and increased soil C, N, and P, especially in the surface soil at the 0- to 2.5-cm depth (Halvorson et al., 1997). Halvorson et al. (2002) observed a reduction in SOC associated with MP tillage compared with NT, RT, and CT in the topsoil at the 0- to 15-cm depth. They also reported that surface crop residues decreased in order of NT > RT > CT > MP. Previous studies documented that tillage disturbed the surface soil, increased residue decomposition, destroyed soil macroaggregates, enhanced SOC decomposition, and increased soil erosion loss (Six et al., 2000; Blanco-Canqui et al., 2009). Tillage practices, especially MP, dramatically changed soil structure in the plowed layers because of the inversion and displacement of the surface soil due to burying crop residues in MP furrows (Staricka et al., 1991; Roger-Estrade et al., 2004). The MP practice deprives the soil surface of crop residues. It is these crop residues that protect the soil from wind erosion and increase soil organic matter, both of which affect soil aggregate quality (Blanco-Canqui et al., 2009). On the other hand, the lack of soil disturbance, in NT, resulted in a more homogeneous soil structure compared with MP (Oorts et al., 2007). Six et al. (2000) also observed that anthropogenic disturbances (namely tillage) could also decrease macroaggregate stability and shorten a macroaggregates' "life cycle." In their report, Six et al. (2000) found that tillage prevented the formation of new microaggregates within macroaggregates and that ultimately reduced POM-C stabilization within microaggregates. Macroaggregate stability (>250-μm diam.) are highly influenced by soil management practices. The loss of macroaggregate-occluded organic matter was found to be the main source of C lost because of tillage (Six et al., 2002a; Zibilske and Bradford, 2007).

Previous research (Cambardella and Elliott, 1992; Six et al., 1999; Fabrizzi et al., 2003; Paul et al., 2004) reported that evaluating SOC pools could better reflect changes in total SOC and soil aggregate dynamics as influenced by tillage management. Particulate organic matter was found to be the C pool that was most easily measured to change in magnitude (either lost or increased) because of changes in soil management (Cambardella and Elliott, 1992; Six et al., 2002a; Fabrizzi et al., 2003; Oorts et al., 2007; Mikha et al., 2006). As POM decomposes and breaks down to <53 μm, the POM becomes physically and/or chemically stabilized within the soil mineral components as mineral-associated organic matter (MAOM) by various mechanisms (Cambardella and Elliott, 1992; Jastrow, 1996; Six et al., 2002b; Lützow et al., 2006; Rumpel and Kögel-Knabner, 2011). The MAOM contributes to the formation and stabilization of (<250 μm) microaggregates (Oades and Waters, 1991; Six et al., 2000). The occlusion of POM-C within the microaggregates and/or with MAOM is an important mechanism for soil C protection and stabilization because this C becomes inaccessible to microbial decomposition (Six et al., 2002b; Lützow et al., 2006). The mineral-associated organic matter carbon (MAOM-C) has been reported to be the recalcitrant form of C (Six et al., 2002b; Jastrow, 1996; Lützow et al., 2006; Rumpel and Kögel-Knabner, 2011). Golchin et al. (1994) reported that the increase in MAOM-C coincided with the progression of organic matter decomposition.

Previous research at this study site (1967–1997) mainly emphasized the impact of NT, CT, and RT on water availability, microbial activity, wheat yield, and SOC content (Elliott et al., 1984; Smika, 1990; Halvorson et al., 1997). After inclusion of the MP treatment in 1989, the emphasis of the research was on the impact of MP on SOC and plant productivity compared with NT, CT, and RT (Halvorson et al., 2002). Recently, the emphasis has been on evaluating tillage impacts on air-dried soil aggregate properties (Blanco-Canqui et al., 2009). More information is needed to evaluate the impact of long-term tillage in a WF system on water-stable aggregate and SOC dynamics in this region. The data presented in this paper is different than the historic data presented earlier for the following reasons: (i) the MP tillage depth was deepened in 1995 to 20 cm compared with the initiation of the MP tillage in 1989 to 1994 where the depth of tillage averaged between 10 and 15 cm as reported by Halvorson et al. (2002); (ii) in this paper, the overall depth studied for SOC mass is evaluated down to a 60 cm (the previous papers report C concentration (g/kg) but not total SOC mass as Mg/ha); (iii) to detect the influence of tillage practices on soil properties, the depth increments used in this study are smaller than what was presented previously by Halvorson et al. (1997, 2002); (iv) for the first time since the initiation of this study, we present a comparison of SOC mass when calculated using a fixed-depth approach versus SOC mass when calculated using the ESM basis approach; and (v) the soil C fractionations and sand-free water stable aggregates as influenced by different long-term tillage practices are evaluated.

Our aim was to examine the soil fractions most responsible for SOC changes within the tillage layer, down to a 20-cm depth, using soil aggregate mass, POM-C, and mineral-associated C. We hypothesized that the long-term application of conservation tillage practices such as NT and RT will conserve greater amounts of SOC compared with conventional tillage, CT, and MP. We also hypothesize that less soil disturbance will enhance soil aggregation and increase the accumulation of organic C in the POM pool compared with MAOM pool. Furthermore, we hypothesize that the type and depth of tillage will impact the redistribution of SOC and POM in the soil profile. The objectives of this study were (i) to evaluate changes in total SOC calculated at a fixed depth and with an equivalent soil mass basis, (ii) to evaluate aggregate-size distribution and SOC fractions in different soil POM size fractions as influenced by different tillage management in the WF system, and (iii) to assess changes in soil POM-C and MAOM-C fractions in relation to total SOC. This study uniquely measures changes in various soil quality parameters after 39 yr of different tillage management in the WF cropping system. Many of the measured soil quality parameters that are reported here have not been intensively evaluated in the central Great Plains Region.

MATERIALS AND METHODS

Site Description

The long-term (39 yr) tillage research plots are located at the USDA-ARS Central Great Plains Research station near Akron, CO. The elevation of the research study site is 1384 m above mean sea level. The study site is located at 40.15° N latitude and 103.15° W longitude. Temperature ranges from −2°C in January to 23°C in July with average daily temperature around 9°C. In this semiarid climate region, the 104 yr average total annual precipitation is 418 mm where approximately 80% of the annual precipitation occurs between April and September. At this study site, 29% of the annual precipitation is received as rain in July and August and about 30% as snow between October and May. The soil type is a Weld silt loam (fine, smectitic, mesic Aridic Paleustolls). Soil bulk density ranges from 1.2 to 1.48 Mg cm^{-3} in the 0- to 60-cm depth (Table 1). Soil texture, at the study plots, ranges from 27 to 32% sand, 43 to 50% silt, and 22 to 28% clay.

The long-term tillage plots were initiated in 1967 under various tillage practices in a WF rotation. In this study, each phase of the rotation is included each year. The experimental plots were established on land that had been farmed since 1907. Before 1907 the land was native short grass prairie. The experiment is arranged as a randomized complete block design with four replications, two replications for each tillage practices within the same rotation phase. However, after 39 yr, there were no statistically significant differences in any of the soil parameters studied between the rotation phases (W vs. F) within each tillage practice. Consequently, four replications of each tillage practice are considered for the statistical analysis for the data sets in this manuscript. Detailed descriptions of the site management history are reported by Elliott et al. (1984), Smika, (1990), and Halvorson et al. (1997, 2002). At the initiation of this study tillage practices consisted of NT, CT, and RT.

Table 1. Soil bulk density for each individual depth studied of the wheat-fallow conventional tillage (CT), moldboard plow (MP), no-tillage (NT), and reduced tillage (RT).

Tillage	Soil depth (cm) 0–5	5–10	10–20	20–30	30–60
			Mg m^{-3}		
CT	1.38 b†	1.36 b	1.45 a	1.40 b	1.45 a
MP	1.20 c	1.38 b	1.36 a	1.32 c	1.44 a
NT	1.43 a	1.48 a	1.46 a	1.49 a	1.45 a
RT	1.44 a	1.39 ab	1.48 a	1.45 ab	1.47 a
			PR > F		
Tillage	<0.0006	0.0462	0.0998	0.0005	0.4027

† Lowercase letter represents significant differences within each column for each individual depth.

However, in 1989 MP was introduced as an additional treatment. From 1989 to 1994 the MP was tilled at a 10- to 15-cm depth (Halvorson et al., 2002). Beginning in 1995 and continuing to the present time, the MP plots have been tilled deeper at approximately a 20-cm depth. Tillage treatments consist of (i) conventional tillage (CT; sweep tilled with three to six under-cutter V-blade sweep operations approximately 8 to 10 cm deep as needed for weed control during summer fallow); (ii) moldboard plow (MP; fall to late summer plowed at an average of 20-cm depth, followed by disking at approximately 8 to 12 cm deep, and then shallow sweep operations are included (8–10 cm) as needed to control weeds until wheat planting in the fall); (iii) no-tillage (NT) where all weeds are controlled with herbicides sprayed two to four times with glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] (depending on rainfall and the presence of weeds, there are as many as four herbicide applications in wet years and as few as two in dry years); and (iv) reduced tillage (RT). The RT treatment is a combination of herbicide and sweep tillage (two to three operations) as needed to control weeds during the fallow period (at 8- to 12-cm depth). With RT, herbicide (glyphosate) is used to control weeds just after wheat harvest in July through the fall and early spring of the following year. The RT maintains standing residue cover to trap snow and enhanced moisture conservation for the subsequent crop. Because of the standing residues, both RT and NT soils are generally moist the following spring. The moist spring soils provide a good environment for the effective use of herbicides to control weeds in the spring. As the summer progresses and the soils began to dry out herbicides are replaced with sweep-tillage in the RT plots to control weeds. Typically with RT, the fallow is sprayed once in fall, once in spring, and then tilled with V-blade sweeps approximately 8 to 10 cm deep once or twice before winter wheat planting. Winter wheat planting occurs in mid to late September of each year.

Plot size (10.8-m long by 30-m wide) and machinery widths are arranged to control field wheel traffic patterns. Wheat is planted with 0.19-m row spacing. Fertilizer N as ammonium nitrate (NH_4NO_3) was broadcasted at 34 kg ha^{-1} before planting each year up until 2007. After 2007 urea replaced ammonium nitrate as the N source and the N rate was increased to 50 kg ha^{-1}. A starter fertilizer of 11–52–0 is applied with the seed at planting at the rate of 7.3 kg P ha^{-1}.

Soil samples were taken in March 2006, 39 yr after research plot establishment. Composite soil samples, 2.5-cm diam. cores, were taken from the 0- to 5-, and 5- to 10-, 10- to 20-, 20- to 30-, and 30- to 60-cm depths of each tillage treatment using an Oakfield soil hydraulic probe. From each plot, three cores were taken at 0 to 60 cm and four cores were taken at the 0- to 20-cm depth. A total of six soil cores at 0 to 20 cm were divided into three increments and composited for various soil measurements (aggregate stability, SOC, and POM measurements), two cores at 30 to 60 cm were composited for SOC, and one core (0–60 cm) was used to evaluate bulk density. Soil bulk density was evaluated as described by Grossman and Reinsch (2002). Wheel-trafficked areas were purposely avoided during sampling, and soil samples were collected between the rows from each plot. Soil samples were placed in sterile polypropylene bags kept in coolers during field sampling and stored at 4°C after collection until processing. The field-moist soil samples were manually presieved with a 6-mm sieve to remove stones and coarse organic matter, to homogenize the soil sample, and to define the initial dimensions for the aggregates analysis. The presieved soil samples were air-dried before wet sieving for aggregates evaluation.

Aggregate-Size Distributions

Water stable aggregates (WSA) were evaluated using the modified apparatus used by Mikha et al. (2005). The apparatus handles stacked sieves (12.7-cm diam.) and allows for complete recovery of different aggregate fractions from individual samples. Sand-free water stable aggregates and aggregate-size distribution were assessed using the procedure reported by Mikha and Rice (2004). Aggregates from each tillage treatment were fractionated into macroaggregate (>1000, 500–1000, 250–500 μm) and microaggregate (53–250 and 20–53 μm) size classes.

Particulate Organic Matter

The soil POM was evaluated using the procedure reported by Cambardella et al. (2001). Air-dried soil, 30 g, was dispersed in 90 mL of 5% sodium hexametaphosphate and shaken for 16 h on a reciprocal shaker. The dispersed soil was passed and washed through a set of nested sieves (mesh sizes of 250 and 53 μm). The sand and POM retained on each sieve was dried to a constant weight at 50°C and analyzed for total C. To evaluate the mass of POM (sand-free POM) associated with different tillage practices, the loss-on-ignition for POM was performed by mass differences after 4 h in a muffle furnace at 450°C. The POM fraction recovered in the 250- to 1000-μm size range represented the coarse POM (free light fraction + POM > 250 μm). The POM measured on sieves between 53 to 250 μm represented the fine POM size fractions. The sum of the two POM size fractions (total POM mass) was used to evaluate the effect of different tillage practices on soil POM content. The g POM per kg of soil was calculated as reported by Mikha et al. (2006):

$$\text{g POM kg}^{-1}\ \text{soil} = \frac{\begin{matrix}\text{initial mass} \\ \text{of the fraction}\end{matrix} - \begin{matrix}\text{mass of the fraction} \\ \text{after ignition}\end{matrix}}{\text{initial mass of the soil}} \times \frac{1000\ \text{g}}{\text{kg}} \qquad [1]$$

The MAOM was associated with the slurry that passed through 53-μm sieve. The mass of MAOM was determined by the difference between the mass of the soil used and the POM. The MAOM-C content was determined by the difference between total SOC and total POM-C (Fabrizzi et al., 2003).

Soil and Particulate Organic Matter Organic Carbon

After 39 yr of management the soil pH at the 0- to 30-cm depth averaged 6.0, which suggests an absence of soil carbonates at this soil depth (data not shown). The soil pH was evaluated using the electrometric measurement with a 1:1 of soil/water ratio outlined by Thomas (1996). Therefore, we assumed all C present within the 0- to 30-cm depth of soil to be organic C. Deeper in the soil (30- to 60-cm depth), the soil pH averaged between 7.5 and 7.7 indicating the presence of soil carbonates at this soil depth. Soil organic C at 30 to 60 cm was evaluated by the difference between soil total C and soil inorganic C (SIC). Soil total C was evaluated by direct combustion (950°C) using Leco CHN-2000 (Leco Co., St. Joseph, MI). Air-dried soils were ground to a fine powder using a roller mill, and about 0.2 g of grounded soil was used for C analysis. The SIC was measured using a modified pressure-calcimeter method reported by Sherrod et al. (2002). Briefly, 0.5 g of ground soil was acidified with 2-mL hydrochloric acid (HCl) in a sealed 20-mL Wheaton serum bottle (Wheaton Science Products, Millville, NJ). The reaction between the soil $CaCO_3$ and the acid was allowed to set for 6 h for the CO_2 pressure to build up inside the serum bottle before measurement. The oven-dried POM (50°C) samples were crushed to a fine powder using mortar and pestle to pass through a 20-μm sieve and approximately 0.2 g of ground soil and POM were analyzed for total C using direct combustion, as mention previously. The SOC was calculated on a fixed-depth and on an equivalent soil mass basis.

Expression of Soil Organic Carbon

The SOC was calculated on an ESM basis using the calculation method outlined by Ellert and Bettany (1995) and Lee et al. (2009). Briefly, soil masses for each depth increment were calculated on a fixed depth (FD) using soil depth increment and field measured bulk density. A specific soil mass measured in Mg ha^{-1} on a FD basis associated with a specific treatment, for each individual depth increment, was chosen as an ESM where all other soil masses were adjusted to the chosen mass. In this study, the chosen ESM was associated with CT at each individual depth studied (0- to 5-, 5- to 10-, 10- to 20-, and 20- to 30-cm depth). The CT soil masses were chosen as an ESM, for soil mass comparisons, because CT is a major traditional tillage system in the central Great Plains Region (Halvorson et al., 2002; Mikha et al., 2010) which would be critical to compare the other tillage practices to the traditional one. The baseline soil mass at each individual depth was 692.5 Mg ha^{-1} for 0- to 5-cm, 678.8 Mg ha^{-1} for 5- to 10- cm, 1455 Mg ha^{-1} for 10- to 20-cm, and 1397.5 Mg ha^{-1} for 20- to 30-cm depth for CT practices (Table 2). If the soil mass associated with other tillage practices was smaller than CT, at any depth increment, a specific

Table 2. Soil organic carbon (SOC) calculated on a fixed-depth basis and on an equivalent soil mass (ESM) basis of the wheat-fallow conventional tillage (CT) for each individual depth studied for moldboard plow (MP), no-tillage (NT), and reduced tillage (RT).

Tillage	Fixed soil depth (cm)							
	0–5	5–10	10–20	20–30	30–60	0–20	0–30	0–60
	SOC (Mg ha^{-1})							
CT	5.46 b†	4.86 a	7.20 c	9.07 a	27.82 a	17.52 b	26.58 b	54.40 b
MP	4.34 c	4.21 a	8.72 b	8.86 a	24.98 a	17.27 b	26.13 b	51.10 b
NT	6.96 a	5.01 a	10.00 a	10.12 a	29.82 a	21.97 a	32.08 a	61.90 a
RT	7.13 a	4.90 a	9.93 a	9.70 a	28.14 a	21.94 a	31.64 a	59.78 ab
	PR > F							
Tillage	0.0009	0.1037	0.0009	0.6404	0.1091	0.0018	0.0177	0.0115
	ESM soil depth (cm)							
Tillage	0 ± 5	5 ± 10	10 ± 20	20 ± 30		0 ± 20	0 ± 30	
	SOC (Mg ha^{-1})							
CT	5.46 b†	4.86 a	7.20 b	9.07 a		17.52 b	26.58 b	
MP	4.42 b	4.74 a	9.89 a	10.85 a		19.05 b	29.90 a	
NT	6.75 a	4.44 a	9.38 a	8.89 a		20.56 a	29.45 a	
RT	6.86 a	4.59 a	9.49 a	8.92 a		20.95 a	29.86 a	
	PR > F							
Tillage	0.0024	0.3834	<.0001	0.0919		0.0061	0.0540	
	ESM (Mg ha^{-1})							
Equivalent soil mass	692.5‡	678.8	1455	1397.5				

† Lowercase letter represents significant differences within each column at each calculation basis.
‡ Equivalent soil mass from CT practice used to adjust the other tillage treatments for 0 to 5, 5 to 10, 10 to 20, and 20 to 30 cm depth.

soil mass and soil thickness with associated SOC were added to the treatment with the lower soil mass from the underlying depth to standardize the soil mass to the soil mass of the CT practice. The soil mass and soil thickness added were calculated as follows:

$$\mathrm{M_{add}} = \mathrm{ESM}_{\mathrm{layer}\ (i)} - \mathrm{M}_{\mathrm{soil\ layer}\ (i)} \qquad [2]$$

where $\mathrm{M_{add}}$ represents the additional soil mass (Mg ha^{-1}) needs to be added from the underlying depth (i+1), ESM $_{\mathrm{layer}\ (i)}$ represents the chosen equivalent soil mass (Mg ha^{-1}) of the CT at a specific increment (i), and $\mathrm{M}_{\mathrm{soil\ layer}\ (i)}$ represents soil mass on a FD basis (Mg ha^{-1}) of the same increment (i) for treatment with a soil mass less than CT. The soil thickness that corresponded to the $\mathrm{M_{add}}$ from the underlying depth (i+1) was calculated as follows:

$$T_{\mathrm{add}} = \frac{M_{\mathrm{add}}}{\rho_{b\ \mathrm{underlying}\ (i+1)}} \times 10^{-4} \qquad [3]$$

where T_{add} represents the additional soil thickness (m) added from the underlying depth increment (i+1), M_{add} represents the additional soil mass (Mg ha^{-1}) calculated using Eq. [2], $\rho_{\mathrm{b\ underlying}\ (i+1)}$ represents the bulk density (Mg m^{-3}) of the lower soil mass at lower soil increment (i+1), and 10^{-4} represents the conversion factors (ha m^{-2}). The M_{add} and T_{add} with SOC content became part of the soil layer (i) which was subtracted from the underlying increment (i+1). Consequently, the soil mass and soil thickness with SOC content in underlying increment (i+1) were reduced by the amount added to the above layer (i). Therefore, to adjust the soil mass at the underlying (i+1) to the soil mass of CT at the same depth increment, M_{add} and T_{add} with SOC content from the next underlying increment was added from the layer below. This type of calculation was applied to 0 to 5, 5 to 10, 10 to 20, and 20 to 30 cm of the MP treatment since the soil masses were less than CT soil masses at all depth studied.

However, if the soil masses associated with other tillage practices were greater than the CT soil mass at a specific depth, a specific soil mass and soil thickness with associated SOC were subtracted from the treatment with high soil mass. The soil mass and soil thickness subtracted were calculated as follows:

$$M_{\mathrm{sub}} = M_{\mathrm{soil\ layer}\ (i)} - \mathrm{ESM}_{\mathrm{layer}\ (i)} \qquad [4]$$

where M_{sub} represents the soil mass (Mg ha^{-1}) needed to be subtracted from layer (i), $M_{\mathrm{soil\ layer}\ (i)}$ represents soil mass on an FD basis (Mg ha^{-1}) of the same increment (i) for the higher soil mass treatment, and $\mathrm{ESM}_{\mathrm{layer}\ (i)}$ represents the chosen equivalent soil mass (Mg ha^{-1}) of the CT at a specific increment (i). The soil thickness that corresponded to the M_{sub} from the layer (i) was calculated as follows:

$$T_{\mathrm{sub}} = \frac{M_{\mathrm{sub}}}{\rho_{b\ \mathrm{layer}\ (i)}} \times 10^{-4} \qquad [5]$$

where T_{sub} represents the soil thickness (m) subtracted from a specific layer (i), M_{sub} represents the subtracted soil mass (Mg ha^{-1}) calculated using Eq. [4], $\rho_{\mathrm{b\ layer}\ (i)}$ represents the bulk density (Mg m^{-3}) of the higher soil mass at soil increment (i), and 10^{-4} represents the conversion factors (ha m^{-2}). The M_{sub} and T_{sub}

with SOC content became part of the soil layer (i+1) and were subtracted from the layer (i). Consequently, the soil mass and soil thickness with SOC content in underlying increment (i+1) were increased by the amount added from the above layer (i). This type of calculation was applied to 0 to 5, 5 to 10,10 to 20 and 20 to 30 cm of the NT and RT treatment since the soil masses were greater than CT soil masses at all depths studied.

Although SOC is being reported in this study at the 0- to 60-cm depth on a fixed-depth basis (Table 2), SOC calculated on an ESM is reported only down to a 30-cm depth. The lack of reported SOC data below the 30-cm depth on an ESM basis is due to the fact that SOC was not measured below the 60-cm depth. That is important because a specific soil mass and soil thickness with SOC content would need to be added from the depth below 60 cm to the 30- to 60-cm depth with MP tillage to normalize that treatment to the soil mass of the CT treatment at the 30- to 60-cm depth.

Statistical Analysis

The effect of tillage intensity on SOC, water stable macroaggregates, POM, and POM-C and MAOM-C was analyzed using ANOVA. The significant findings for each individual depth, 0 to 5, 5 to 10, 10 to 20, 20 to 30, and 30 to 60 cm were evaluated using the F-protected t test. For ANOVA and mean separation, PROC MIXED of SAS ver. 8 (SAS Institute, 1999) was used. Unless noted otherwise, all results were considered significantly different at $P < 0.05$. Simple linear regression and correlations between studied parameters were calculated across tillage practices for each individual depth.

RESULTS AND DISCUSSIONS

Soil Organic Carbon Stocks Using the Fixed-Depth Approach

Using the FD approach to determine changes in SOC mass, we observed that tillage depth influenced SOC distribution. This was especially true in the top 20 cm of the soil (Table 2). The amount of SOC in the 0- to 5-cm depth was greater in the CT than in the MP managed soils by an average of 26% ($P = 0.0009$). The lower C contents measured at the soil surface (0–5 cm) with MP were accompanied by an increase in C at the 10- to 20-cm depth ($P = 0.0009$). In the 0- to 20-cm depth, the amount of SOC measured in the NT and RT managed soils were greater by 26% than the MP and CT managed soils. The amount of SOC decreased in the order of NT = RT > MP = CT. Indeed, the same amount of SOC at the 0- to 20-cm depth (around 17.4 Mg C ha^{-1}) was associated with both CT and MP managed soils. However, the distribution of SOC among the depth intervals were influenced by the depth of tillage with CT and MP practices.

With CT in which the land is tilled at an 8- to 10-cm depth with undercutter V-blade sweeps, the surface 0 to 10 cm contained approximately 21% more SOC than MP. On the other hand, with the MP where the land is inverted at a 20-cm depth, there was more SOC found deeper at the 10- to 20-cm depth than in the CT managed soils (Table 2). These differences in C distribution within soil depth intervals in MP compared with CT are presumably a consequence of the differences in the mechanical nature of the two different tillage operations. With MP the land is inverted and that inversion buries surface crop residues deeper in the soil (10–20 cm depth). With CT the V-blade undercutter sweeps disturb the soil only shallowly with very little residue burial or inversion of topsoil. The intensive turnover of soil with the MP operation caused a redistribution of the surface crop residue C within the surface 20-cm depth. The MP operation forced a translocation of surface-rich soil C to the subsurface and the exposure of subsurface soil, low in soil C, to the surface. In this study, the MP operation was followed by a secondary disk operation at the soil surface 8- to 12-cm depth and then followed by approximately three sweep operations, 8 to 10 cm, during the fallow period. This frequent tillage caused a continuous soil disturbance at the soil surface that promoted a mechanical breakup of crop residues and enhanced soil organic matter oxidation at the surface layer of 0- to 5-cm depth. This data supported our hypothesis that the MP operation causes a redistribution of SOC within the soil. Although the MP operation occurred every other year for the last 17 yr, it still influenced the distribution of SOC within specific depths of the tillage layer. However, no differences in the total amount of SOC were observed between CT and MP for the whole 0- to 20-cm depth. In previous reports from this site, Halvorson et al. (2002) observed no differences in SOC between NT, CT, and RT at 0 to 7.5-cm and at 0- to 15.2-cm depths. However, SOC associated with MP was lower than all the tillage practices at 0 to 7.5 cm and only lower than CT at 0- to 15.2-cm depth. Halvorson et al. (2002) concluded that the reduction in SOC associated with MP practice in comparison to CT, at 0- to 15.2-cm depth, was a consequence of residue mixing and enhancing residue decomposition. In the current study and across the tillage practices in the top 20 cm of soil, SOC ranged between 17 and 22 Mg C ha^{-1} compared to 15 to 17 Mg C ha^{-1} at the first 15.2-cm depth reported by Halvorson et al. (2002) at the same study site. The 17-yr duration of MP practice in this study, versus the 5-yr reported by Halvorson et al. (2002), and the nature of the MP practice could have eliminated the differences between CT and MP that we currently observed at the 0- to 20-cm depth (Table 2).

The RT practice greatly conserved SOC compared with CT by an average of 17% at the 0- to 10-cm depth and by 25% at the overall 0- to 20-cm depths (Table 2). The SOC conserved with RT was a consequence of the combination of sweep tillage, two to three operations, and herbicide application compared with three to six sweep tillage operations associated with the CT practice. The reduction in the number of tillage operations, for weed control during the fallow period, associated with RT reduced soil disturbances and soil organic matter oxidation compared with CT management. There were no differences observed in SOC among the tillage practices at the 20- to 30- and 30- to 60-cm depths (Table 2). The lack of differences in these deeper soil samples could be a consequence of minimum disturbance and low SOC decomposition compared with the surface 20 cm. Nevertheless, SOC for the total depth sampled at the 0- to 30- and 0- to 60-cm depths was greater in the NT and RT managed soils than in the CT and MP managed soils. Over time, the continuous soil disturbances and enhanced surface residue decomposition in WF with the shallow sweep operations and MP reduced SOC at the 0 to 30 cm depth. Across NT and RT practices, measured SOC was greater by an average of 22% compared with SOC in CT and MP managed soils at the 0- to 30-cm depth. A similar trend in SOC was observed at 0 to 60 cm except that NT was greater than CT and MP by an average of 14% and 21%, respectively. The RT managed soils were intermediate in measured SOC, closer to NT, but not significantly different at $P < 0.05$ (Table 2). Regardless of tillage practice, the magnitude of SOC stock observed at the 30- to 60-cm depth was similar to the amount of SOC stock found in the top 30-cm depth (Table 2). This data agrees with the previous research that SOC below 30 cm is important in evaluating total soil C stocks as influenced by long-term management (VandenBygaart and Angers, 2006; Ellert et al., 2007; VandenBygaart et al., 2011). Similarly, VandenBygaart et al. (2011) observed that total SOC was greater if a deeper sample (0–30 cm) was compared to the top 0 to 15 cm. They also concluded that sampling below 30 cm is necessary to more accurately evaluate SOC storage. Overall, data from this long-term study revealed that RT and NT management, as conducted in this experiment, are better soil management practices for conserving SOC than CT or MP.

Soil Organic Carbon Stocks Using Equivalent Soil Mass Versus the Fixed-Depth Approach

On an ESM, the average CT soil mass for each individual soil depth was considered the base line for SOC calculation (Table 2). As previously mentioned, the soil masses associated with CT were chosen because CT in combination with WF represents a traditional tillage system in the central Great Plains Region (Halvorson et al., 2002; Mikha et al., 2010). In this study, since the chosen baseline at each individual depth was different than the soil masses associated with the other tillage practices, the measured mass for the 0- to 30-cm depth associated with CT corresponded to the soil mass at 0 to 34.5 cm for MP, 0 to 27.4 cm for NT, and 0 to 28.3 cm for RT. This indicated that the MP soil mass at any depth studied was smaller than the soil mass associated with CT. Thus a specific soil mass and soil thickness (cm) with SOC content were added to the value of the MP treatments to standardize soil mass to the CT mass. In contrast, the soil masses associated with NT and RT were larger than CT soil mass, thus a specific soil mass and soil thickness (cm) with SOC content were subtracted from NT and RT for each individual depth studied for the standardization procedure. Similarly, Oorts et al. (2007) observed changes in soil depths studied between CT and NT, as SOC was calculated on an equivalent mass basis. In this study, at the 0 to 5 cm depth, more SOC was associated with soil managed with NT and RT compared with those managed with CT and MP. At the surface 0 to 5 cm, the significant difference detected on an FD approach between CT and MP was partly due to differences in bulk density of that layer (Table 1). However, the difference disappears when corrected to the same mass of soil. Likewise, part of the difference between NT and RT detected in the 0- to 5-cm depth disappears when corrected to the same soil mass (Table 2). Similar to the FD approach, no differences in SOC were observed at the 5- to 10- and 20- to 30-cm depths (Table 2). An average across the whole 0 to 30 cm, SOC with CT was lower than NT, MP, and RT practices by an average of 11%. There were no differences in SOC between NT, MP, and RT with the ESM approach. This lack of measured statistical differences is a consequence of the accumulative effect of SOC associated with soil mass added to MP and subtracted from NT and RT for the standardization of soil masses to the CT mass at different depth intervals. The SOC stocks for the NT and RT managed soils were greater by 13.5% than the tilled MP and CT managed soils, at 0- to 20-cm depth. Comparing the two methods for calculating the total SOC mass (FD versus the ESM) we observed an increase in SOC measurement of 14.4% for MP with the ESM method over the FD method for the 0- to 30-cm depth (compare the 26.13 Mg C ha^{-1} with the FD approach to the 29.90 Mg C ha^{-1} with the ESM approach in Table 2). At the same depth, SOC with the ESM approach was 8.2% less for NT and 5.6% less for RT when compared with the FD calculation. This minimized the differences between treatments and eliminated the calculation of significant differences among the tillage practices at 0 to 30 cm (Table 2). For this data set, using either the ESM or the FD approach reveals that over the long term, MP causes a redistribution and stratification of SOC within the depth of tillage. In addition, MP apparently conserved some of SOC by burying crop residue below the surface.

Soil Aggregate Mass

Conservation management treatments, NT and RT, increased the mass of large macroaggregates compared to conventional management treatments, CT and MP, in all measured depths from 0- to 20-cm depth (Fig. 1). The CT and MP managed soils, had proportionally more microaggregates, indicating the loss of macroaggregate soil structure with tillage. These data are consistent with previous research (Mikha and Rice, 2004; Blanco-Canqui et al., 2009; Fabrizzi et al., 2009; Mikha et al., 2010) where they showed a greater increase in microaggregates associated with CT with a corresponding decrease in macroaggregates. Previously, greater erodible dry aggregates were found in the surface 0 to 5 cm of soil (Smika, 1990). Smika (1990) also reported greater amounts of erodible (>840 μm) dry aggregates associated with CT compared with NT and RT management for this study site. In general, our own data support our hypothesis that more soil macroaggregates were measured in NT and RT managed soils down to a to 20-cm depth than in the CT and MP managed soils. The analyses of these data indicate that both NT and RT are not only better management practices for maintaining SOC, but also better management for maintaining aggregate stability than either CT or MP for the soils at this study site.

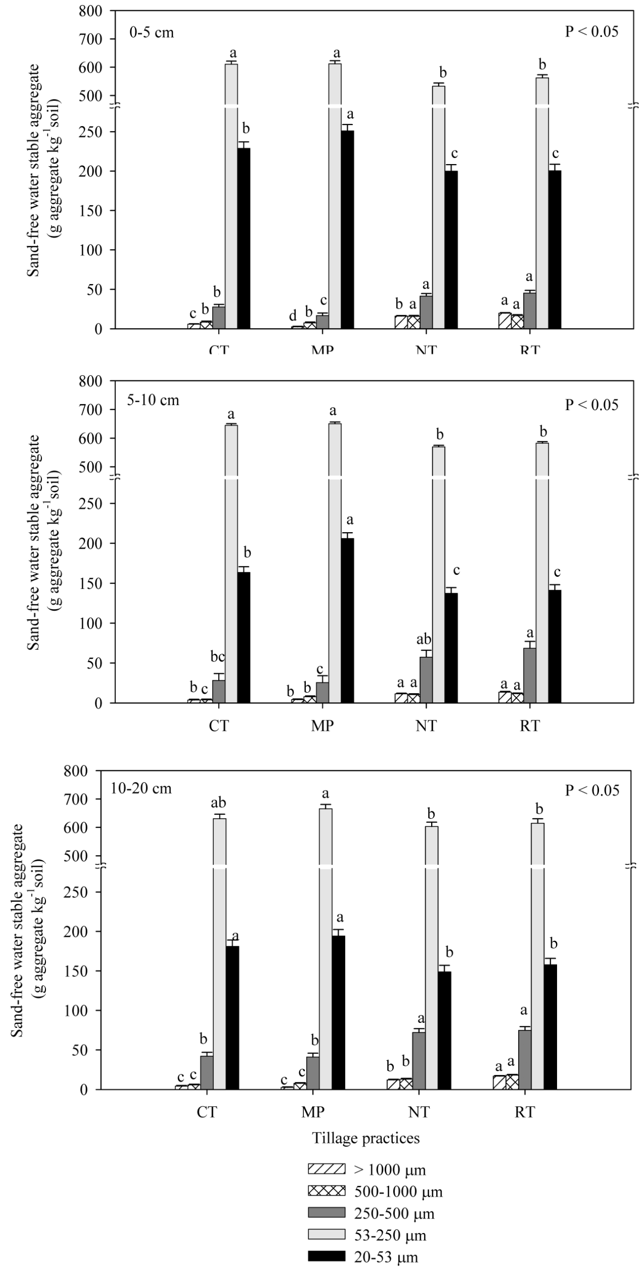

Fig. 1. Sand-free water stable aggregates (g aggregates kg^{-1} soil) at the 0- to 5-cm, 5- to 10-cm, and 10- to 20-cm depths as affected by conventional tillage (CT), moldboard plow (MP), no-tillage (NT), and reduced tillage (RT). Lowercase letters represent significant differences ($P \leq 0.05$) among tillage practices within the same aggregate size classes. The error bars represent standard errors of the mean.

Particulate Organic Matter

Particulate organic matter is considered a useful and sensitive indicator of management effects on soil quality and SOC dynamics (Cambardella and Elliott, 1992; Paul et al., 2004; Mikha et al., 2006). In this study, significantly more POM was measured in the surface 0 to 5 cm than at the other soil depths ($P < 0.0002$). The two-way interaction of tillage x depth was also statistically significant ($P = 0.002$). At the 0- to 5-cm depth, the POM mass measured in the NT plots were approximately 1.4-fold greater than in those managed with CT and 1.7-fold greater than POM measured in MP plots (Fig. 2). Similarly, the

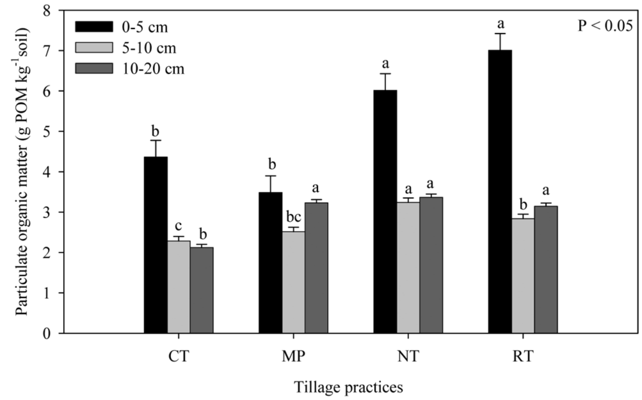

Fig. 2. Total particulate organic matter content (g POM kg^{-1} soil), at the 0- to 5-cm, 5- to10-cm, and 10- to 20-cm depth as affected by conventional tillage (CT), moldboard plow (MP), no-tillage (NT), and reduced tillage (RT). Soil total POM contents were calculated by the sum of the POM associated with different size classes. Lowercase letters represent significant differences ($P \leq 0.05$) among tillage practices within the same aggregate size classes. The error bars represent standard errors of the mean.

mass of POM was greater with RT compared with CT by an average of 1.6-fold and by an average of two-fold compared with MP. There was no significant difference in POM mass observed between NT and RT. Greater mass of POM was associated with NT, at the 5- to 10-cm depth, compared with CT, MP, and RT, by an average of 39, 28, and 14%, respectively. Considering that tillage practices did not influence crop biomass production (Halvorson et al., 2002), the analysis of our data suggests that POM conservation in this study is mostly a function of the elimination or reduction of soil disturbance caused by tillage. In three locations in the central Great Plains Region of the United States (Fargo, ND; Mandan, ND; and Sidney, MT), Mikha et al. (2006) observed an increase in POM mass with decreased tillage intensity and frequency (from Chisel plow and tandem disking to NT) and with fallow elimination. Regardless of tillage, greater POM mass was measured at the soil surface (0- to 5-cm depth) compared with the 5- to 10-cm depth. Similarly, Mikha et al. (2010) observed greater levels of soil POM at the soil surface compared to deeper layers with both NT and CT in WF on a Weld silt loam soil. The POM content, at the 5- to 10-cm depth, was greater in RT compared with CT, and no differences in POM mass were observed in MP compared with CT and RT (Fig. 2). The POM associated with MP, at the 10- to 20-cm depth, was greater than CT approximately by 52% (compare the 2.12 g POM kg^{-1} with CT to the 3.23 g POM kg^{-1} with NT in Fig. 2). Below 10 cm, there were no differences in POM with MP management compared with NT and RT practices. These findings match what we found with SOC and are thought to be a consequence of the soil surface being turned over and buried below 10 cm during the plowing operation. This inversion and burying of the surface organic matter with MP could help to protect POM from oxidation and reduce the decomposition rate. Overall, the conservation managed soils, NT and RT, had greater POM mass by an average of 33% compared with the CT and MP managed soils, at the 0 to 20 cm depth (Fig.

Table 3. Soil organic carbon (SOC), mineral-associated organic matter C (MAOM-C), particulate organic matter C (POM-C), and the percent POM-C and MAOM-C from total C in 250 to 1000 μm and 53 to 250 μm size fractions at 0 to 5, 5 to 10, and 10 to 20 cm depth under conventional tillage (CT), moldboard plow (MP), no-tillage (NT), and reduced tillage (RT).

Tillage	SOC	MAOM-C	POM-C		POM-C/SOC		MAOM-C/SOC
			250–1000 μm	53–250 μm	250–1000 μm	53–250 μm	
	g kg^{-1}				%		
0–5 cm							
CT	7.89 b†	6.32 a	0.76 b	0.81 b	9.63 b	10.27 b	80.10 a
MP	7.21 b	6.05 a	0.56 b	0.61 b	7.77 b	8.46 b	83.77 a
NT	9.75 a	6.97 a	1.22 a	1.56 a	12.51 a	15.99 a	71.49 b
RT	9.90 a	7.09 a	1.31 a	1.51 a	13.23 a	15.25 a	71.52 b
	PR > F						
Tillage	0.0113	0.5385	0.0010	0.0002	0.0007	0.0127	0.0022
5–10 cm							
CT	7.17 a	6.45 a	0.15 c	0.57 b	2.09 c	7.95 b	89.96 a
MP	6.11 a	5.49 a	0.13 c	0.50 b	2.13 c	8.18 b	89.85 a
NT	6.75 a	5.73 a	0.27 a	0.75 a	4.00 a	11.11 a	84.89 b
RT	7.03 a	6.20 a	0.21 b	0.62 ab	2.99 b	8.82 b	88.19 a
	PR > F						
Tillage	0.0714	0.0758	<0.0001	0.0177	0.0002	0.0267	0.0032
10–20 cm							
CT	4.96 b	4.62 b	0.07 c	0.27 c	1.41 b	5.44 b	93.15 a
MP	6.43 a	5.97 a	0.08 c	0.37 b	1.24 b	5.75 b	92.85 a
NT	6.85 a	6.10 a	0.17 a	0.59 a	2.48 a	8.61 a	89.05 b
RT	6.73 a	6.16 a	0.12 b	0.45 b	1.78 b	6.69 b	91.53 a
	PR > F						
Tillage	0.0002	0.0005	<0.0001	0.0002	0.0019	0.0040	0.0021

† Lowercase letter represents significant differences within each column at each individual depth.

2). The POM mass redistribution was evident with MP having the least POM in the surface and as much as the conservation treatments, NT and RT, in the 10- to 20-cm depth. Similar to SOC, this finding also supports our previous hypothesis that long-term MP could causes redistribution and stratification of POM within the plowed layer.

Particulate Organic Matter Carbon and Mineral-Associated Organic Matter Carbon

The amount and distribution of SOC among coarse POM-C, fine POM-C, and MAOM-C was influenced by tillage practices and depth studied. Several studies documented that changes in SOC associated with certain soil fractions could reflect changes in soil management (Cambardella and Elliott, 1992; Six et al., 1999; Fabrizzi et al., 2003; Paul et al., 2004). In this study, tillage practices influenced coarse POM-C (250–1000 μm), fine POM-C (53–250 μm), and MAOM-C concentrations at all depths studied (Table 3). In the surface 0 to 5 cm, the coarse POM-C associated with NT and RT was greater than coarse POM-C associated with CT and MP. Deeper in the soil at 5- to 10- and at the 10- to 20-cm depth, coarse POM-C increased in the order of NT > RT > CT = MP. Greater macroaggregates stability (Fig. 2) contributed to greater concentrations of coarse POM-C associated with NT and RT where POM-C was protected from rapid decomposition compared with CT and MP. At the surface (0–5 cm), fine POM-C concentration associated with NT and RT was twice the amount measured in the CT and MP managed soils. Similar patterns were observed at lower depths with less magnitude (Table 3). Higher amounts of coarse and fine POM-C associated with NT and RT is a consequence of POM-C conservation within macroaggregates due to less soil disturbance in NT and RT compared with CT and MP. According to Six et al. (1999, 2000), continuous soil disturbance with tillage practices promotes macroaggregates turnover, enhances coarse POM-C decomposition to fine POM-C, and reduces the formation and stabilization of fine POM-C within the macroaggregates.

The coarse and fine POM-C fractions associated with NT and RT represent a greater proportion of the total SOC measured in those soils compared to POM-C measured in CT and MP managed soils at 0- to 5-cm depth (Table 3). At deeper depth, 10 to 20 cm, the percentage of coarse POM-C (1.7-fold) and fine POM-C (1.4-fold) of total SOC were higher with NT compared with other tillage practices. The percentage of coarse POM-C to the total SOC was lower than the percentage of fine POM-C to the total SOC at all depths except for the surface 0 to 5 cm. There were no differences between coarse and fine POM-C, as a percentage of the total SOC, observed at the surface 5 cm due to continuous replenishment of C at the surface as crop residues. The total POM-C (coarse + fine) fraction accounted for a greater percent (an average of 28%) of the SOC concentration for NT and RT compared with CT and MP (an average of 18%) at the soil surface (0–5 cm). At the subsurface, the total POM-C with NT accounted for a greater percentage of

SOC concentration, approximately 15% at 5 to 10 cm and 11% at 10 to 20 cm, compared with CT, RT, and MP (an average of 11 and 7% for 5 to 10 cm and 10- to 20-cm depths, respectively). This data suggested that total POM-C fractions accounted for a greater percentage of SOC concentration at the soil surface compared with layers below the surface. The magnitude of this association between POM-C and total SOC decreased with depth (Table 3). Wander et al. (1998) also observed that NT associated POM-C was higher in the surface 5 cm of soil than below that layer as more plant residues tend to accumulates in undisturbed soils relative to tilled soils. After 39 yr of different tillage practices, total POM-C in NT comprised an average of 18% of the total SOC at the 0- to 20-cm depth. At the same 0- to 20-cm depth the CT, MP, and RT practices significantly reduced POM-C by an average of 12, 11, and 16% of the total SOC, respectively. Since there were no differences in wheat residue input observed among tillage practices (Halvorson et al., 2002), the reduction in POM-C signified the rapid residue decomposition with CT, MP, and RT compared with NT management. Similar to the previous research (Cambardella and Elliott, 1992; Wander et al., 1998; Chan et al., 2002; Fabrizzi et al., 2003), our data indicated that POM-C is the form of soil C that can be lost due to different tillage practices.

Previous studies (Six et al., 2002b; Lützow et al., 2006) concluded that POM-C further decomposed to be occluded within MAOM and became inaccessible for microbial decomposition which increased C stability and protection. In this study, the MAOM-C was not influenced by tillage practices except at the 10- to 20-cm depth (Table 3). The MAOM-C concentration was lower with CT than any other tillage practices at 10 to 20 cm depth. The MAOM-C at the 10- to 20-cm depth with MP was not different in relation to NT which could be due to redistribution and stratification of soil C influenced by MP tillage. Nevertheless, at the soil surface, MAOM-C accounted for an average of 72% for NT and RT of the total SOC concentration (Table 3) which was lower than CT and MP, an average of 82%. The percentage of total SOC that was associated with MAOM-C increased with depth, but it remained lower with NT than any other tillage practices. Overall, a greater percentage of total SOC was associated with MAOM-C, by an average of 71 to 93%, compared with total POM-C, which averaged 7 to 28%, (Table 3). According to Oorts et al. (2007), the elimination and/or reduction in tillage practices can impact the relative distribution of soil organic matter between POM and MAOM by protecting POM within soil aggregates from further decomposition. Jastrow (1996) also suggested that soil POM-C was quickly decomposed by microbial activity and converted to MAOM-C with tillage disturbances. Previous studies (Six et al., 2002b; Lützow et al., 2006; Rumpel and Kögel-Knabner, 2011), also concluded that the association between SOC and MAOM provide stability and protection due to inaccessibility of SOC to microbial decomposition. Our findings support our hypothesis that (i) NT soil management, in comparisons to CT, MP, and RT management conserves a higher percentage of SOC in less degraded forms (coarse and fine POM fractions) and (ii) the percent SOC distribution between POM-C and MAOM-C is also greatly influenced by tillage practices and tillage depth.

Relation between Soil Organic Carbon, Particulate Organic Matter Carbon, and Mineral-Associated Organic Matter Carbon

The correlation between SOC and soil POM-C was affected by depth (Fig. 3) and it was separated into two groups. The first group was represented by the surface soil (0–5 cm) and the second group comprised the deeper soil layers, (5–10 and 10–20 cm). There was a positive and significant linear correlation between SOC and POM-C concentrations within each of the depth groups. The r^2 of 0.86 for regression of POM-C and SOC at the soil surface (0- to 5-cm depth) was higher than that r^2 of 0.58 fitted to the soil in the deeper layers (5- to 10- and 10- to 20-cm depths). This indicates that POM-C is closely related to SOC amounts and the relationship is stronger at the soil surface than in the deeper soil. Also, increased POM-C in relation to SOC (slope = 0.43) at the soil surface (0–5 cm), was greater ($P < 0.0001$) than those at 5 to 10 and 10 to 20 cm (slope = 0.12). The slope of the regression lines suggested that POM-C accounted for 43% of SOC at surface layer and only 12% of SOC in subsurface layers. Previously, Paul et al. (2004) reported that POM-C accounted for 47% of SOC averaged across different study sites. This

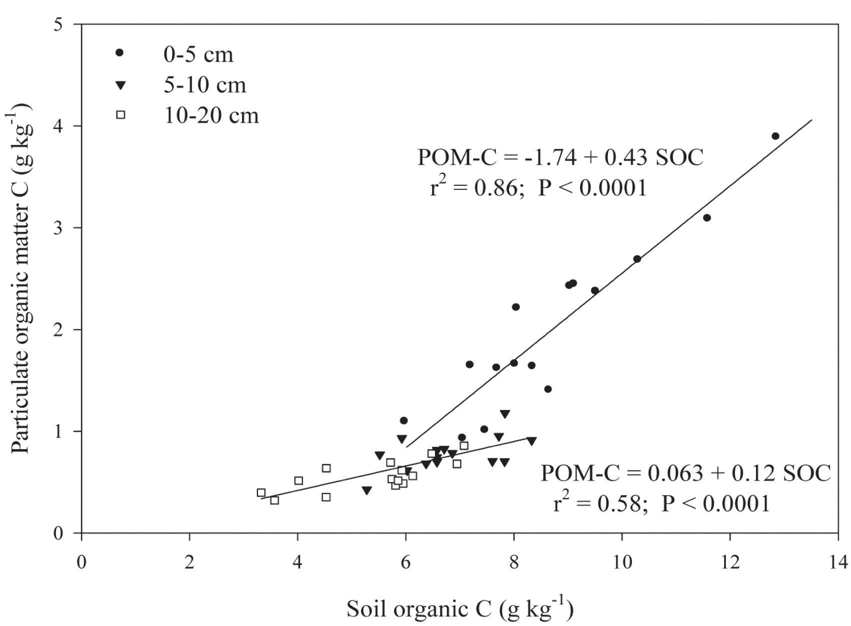

Fig. 3. Relationship between particulate organic matter carbon (POM-C) concentration (g POM-C kg^{-1} soil) and soil organic C (SOC) concentration (g C kg^{-1}) at the 0- to 5-cm, 5- to 10-cm, and 10- to 20-cm depth.

data also supported our hypothesis that after 39 yr of different tillage practices, SOC associated with POM-C was substantially influenced by depth studied.

The relationship between SOC and MAOM-C was also affected by the depths studied (Fig. 4) and could also be separated into two groups, surface layer, 0 to 5 cm, and subsurface layer 5 to 10 and 10 to 20 cm. A significant and positive relationship was observed at 0 to 5 cm depth, and at the 5 to 10 and 10 to 20 cm depths with r^2 values of 0.93 and 0.98, respectively. The correlation between SOC and MAOM-C did not follow what we observed previously between SOC and POM-C (Fig. 4). The increase in MAOM-C in relation to SOC (slope = 0.65) at the surface layer, 0 to 5 cm, was smaller ($P < 0.0025$) than the subsurface layers 5 to 10 and 10 to 20 cm (slope = 0.98). This suggested that the MAOM-C accounted for 65% of SOC at the surface layer and for 98% of SOC at the subsurface layer. The correlation between SOC, POM-C, and MAOM-C supported our hypothesis that SOC distribution in different soil C fractions was influenced by depth studied.

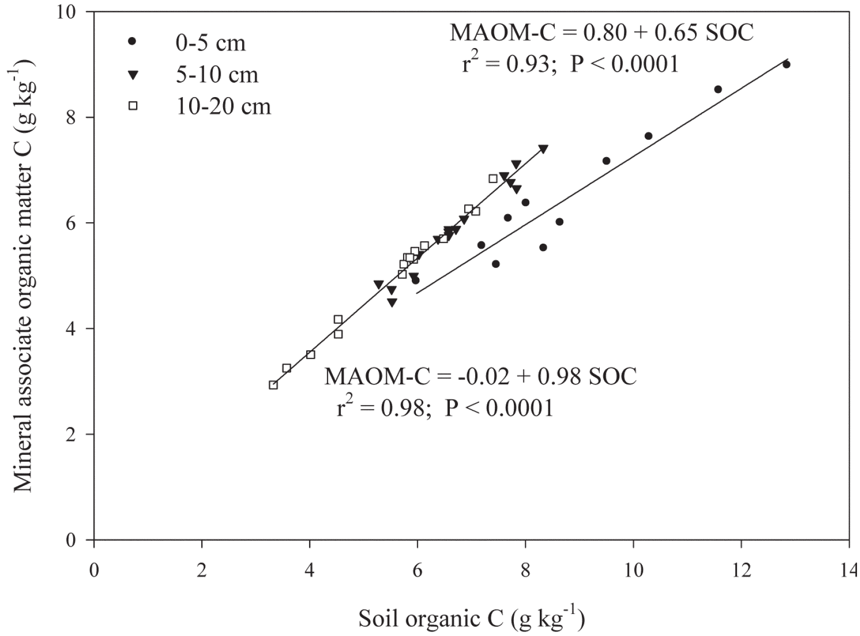

Fig. 4. Relationship between mineral-associated organic matter carbon (MAOM-C) concentration (g kg^{-1} soil) and soil organic C (SOC) concentration (g C kg^{-1}) at the 0- to 5-cm, 5- to 10-cm, and 10- to 20-cm depth.

CONCLUSION

The long-term SOC pools, soil aggregation, and soil POM measured in this study indicated that RT and NT are better management practices for the WF system than CT primarily because of a reduction in tillage intensity or frequency. Thirty-nine years of NT and RT soil management increased SOC levels, enhanced soil aggregate stability, and conserved the labile fraction of SOC at different depths. With any SOC mass calculation approach, either on a fixed-depth basis or using an equivalent mass basis, SOC was highly influenced by tillage practices. This data also demonstrated that SOC below 30-cm depth was important in evaluating soil C stock as influenced by long-term managements. At all study depths, NT and RT management maintained soil structure by conserving macroaggregates compared with soils managed with tillage, CT, and MP. The long-term use of MP management caused a redistribution and stratification of SOC and soil POM-C below the soil surface which reduced C loss compared with CT practices. The soils managed with NT had more SOC conserved in POM fractions and less SOC conserved in MAOM compared with CT, MP, and RT practices. The percent SOC distribution between POM and MAOM was greatly influenced by tillage practices and depth studied. The POM-C and MAOM-C relationships with SOC were influenced by the depths studied. In general, long-term conservation management in the central Great Plains under low-input WF systems are important in maintaining soil structure stability and conserving SOC from rapid decomposition.

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