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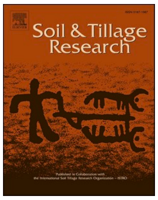

Cropping system partially offsets tillage-related degradation of soil organic carbon and aggregate properties in a 30-yr rainfed agroecosystem

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ABSTRACT

Soil tillage increases the susceptibility of agricultural soils to erosion and organic carbon losses, but tillage effects could be mitigated through other management practices such as crop rotation. Here, we evaluated the 30-year impacts of tillage intensity and cropping system on surface soil bulk density, nutrient availability, dry aggregate size distribution, and water-stable aggregation. This study was established in 1980 in eastern Nebraska USA, and included six tillage treatments of varying intensity (no-till, ridge till, disk till, subsoil rip, chisel plow, moldboard plow) and four crop rotation treatments (continuous soybean [*Glycine max* (L.) Merr.]; soybean-corn [*Zea mays* L.]; corn-soybean, continuous corn) in a randomized block design with six replicates. Surface soils were sampled in 2011 and soil aggregate properties assessed, including occluded particulate organic matter (oPOM) in micro/macroaggregates (0.053–0.5 mm) and mega-aggregates (>2.0 mm). Because of significant treatment differences in bulk density, soil properties were converted to an equivalent soil mass (ESM) basis to more accurately assess management effects. After 30 years, only the main effects of tillage and crop rotation were significant for most measured soil properties. Surface soil organic carbon (SOC) stocks (ESM for $\sim 0-30$ cm soil depth) decreased with tillage intensity, and stocks were higher when corn was included in the cropping system. Dry aggregate size distributions shifted towards smaller size classes as tillage intensity increased and whenever corn was included in the cropping system. As a result, aggregate mean weight diameter (mm) followed a similar trend. Soil stocks of water-stable mega-aggregates also decreased with increasing tillage intensity. In near-surface soils (0–7.5 cm), highly-erodible aggregate oPOM was highest in no-till soils and was more sensitive to tillage disturbance (56–69% loss) than mega-aggregate oPOM (5–35% loss). Even in no-till soils, highly-erodible aggregate oPOM concentrations decreased under continuous corn compared to rotated systems likely due to greater frequency of fertility management-related soil disturbances (i.e. fertilizer injection annually vs every two years). These results suggest that cropping systems that maximize plant carbon inputs can partially mitigate soil erosion risks due to long-term tillage, but that other crop management-related soil disturbances (i.e. method of fertilizer application) could limit the mitigating effect of cropping system.

1. Introduction

Tillage disrupts soil physical structure and can limit the capacity of agricultural soils to resist erosion (Blanco-Canqui and Ruis, 2018) and store soil organic carbon (SOC) (Tisdall and Oades, 1982; Six et al., 2000). Tillage practices impact the process of soil aggregation, which is key to minimizing wind and water erosion potential and stabilizing SOC for long-term storage (Golchin et al., 1994; Six et al., 1999; Denef et al., 2007). Specifically, the destruction of soil aggregates by tillage increases the abundance of smaller soil particles that are at higher risk of erosion while also exposing protected organic matter to decomposition which could lead to SOC losses (Balesdent et al., 2000; Mikha and Rice, 2004).

Soil aggregate formation and dynamics can vary by aggregate size class. Typically, micro-aggregates are defined as $<0.053-0.25$ mm, macroaggregates as 0.25–2.00 mm (Golchin et al., 1994), and mega-aggregates as >2.00 mm (Tiemann et al., 2015; Sarker et al., 2018). Micro-aggregates are expected to be less sensitive to external forces compared to macroaggregates (Tisdall and Oades, 1982; Six et al.,

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2000; Christensen, 2001; Mikha and Rice, 2004) because macroaggregates have greater dispersion and turnover rates under tillage (Beare et al., 1994; Six et al., 2000). When tillage exposes particulate organic matter occluded within aggregates (i.e. occluded POM, oPOM), decomposition of this newly available C source decreases the overall carbon content in tilled soil compared to no-till (Six et al., 2000). Because physically protected oPOM is more labile than POM not associated with aggregates (i.e. free POM) (Elliott, 1986; Ashman et al., 2003), oPOM is often more sensitive to management-related disturbances compared to either free POM or SOC (Beare et al., 1994; Marriott and Wander, 2006).

Tillage-induced stimulation of soil microbial activity could partially offset the physical disruption of aggregates by increasing the abundance of microbially-derived binding agents that serve as nucleation sites for aggregate formation, particularly macroaggregates (Golchin et al., 1994; Six et al., 1999; Bossuyt et al., 2002). Similarly, increasing the quantity or improving the quality of plant C inputs could stimulate microbial activity and subsequent aggregate development. Previous studies have found that higher crop residue inputs are associated with greater macroaggregate abundance (Yang and Wander, 1998; Six et al., 1999; Kahlon et al., 2013; Karlen et al., 2013). While higher plant inputs can occur under high-yielding monoculture cropping systems (i.e. continuous corn, *Zea mays* L.), other studies have found that increasing crop rotation complexity can improve soil physical properties and SOC compared to less diverse rotations (Munkholm et al., 2013; Tiemann et al., 2015; Blanco-Canqui and Ruis, 2018).

Statistically significant management impacts on soil properties can take years to be detected (Pikul et al., 2007; Jin et al., 2015), making long-term studies essential to quantify tillage and cropping system effects on soil properties involved in soil erosion and SOC storage. Here, we evaluate how 30 years of management under six different tillage intensities and three common cropping systems affected soil properties, including soil bulk density, soil chemical characteristics, dry aggregate size distribution, water-stable aggregation, and oPOM. Earlier studies at this site reported that tillage and cropping system affected various soil parameters (i.e. bulk density, SOC) in surface soils and deeper soil depths (Varvel and Wilhelm, 2010, 2011) but had little impact on near-surface soil hydraulic properties (Blanco-Canqui et al., 2017). None of the previous studies, however, assessed long-term tillage and cropping system effects on soil aggregation. Our objectives were to assess how long-term management has affected selected soil physical properties as well as extend previous findings on SOC stock changes at this site. Importantly, we examined the role of oPOM, a key organic carbon pool involved in both soil aggregation dynamics and in long-term soil carbon storage.

2. Materials and methods

2.1. Study site, experimental design, and management descriptions

This rainfed study was initially established in 1980 approximately 10 km east of Lincoln, NE (40°5′ N, 96°3′W; 370 m ASL) on silty clay loam soils of the Aksarben and Wymore series (fine, smectitic, mesic Typic Argiudoll; fine, smectitic, mesic Aquertic Argiudoll, respectively) (Varvel and Wilhelm, 2010; Sindelar et al., 2015). Mean annual precipitation and mean annual air temperature (1996–2011) at the site were 700 mm and 10.8 °C, respectively (USDA NRCS SCAN, Site 2001; https://www.wcc.nrcs.usda.gov/scan/). This site is representative of rainfed corn and soybean production levels in the region (Sindelar et al., 2015).

At establishment in 1980, the entire site was disk-tilled for uniformity, lime incorporated (4.9 Mg lime ha^{-1}), then planted to continuous corn (*Zea mays* L.). The main treatment of tillage began in fall 1981 (described below), and crop rotations were added as a split treatment in 1985. Continuous corn was retained, and continuous soybean (*Glycine max* (L.) Merr.) and corn-soybean rotations were added such that both phases of the rotation were present each year. Whole tillage plots are 18.3 m wide (24 0.76-m rows) x22.9 m long, and crop rotation subplots are 4.6 m wide (six 0.76-m rows) x22.9 m. The final treatment design is a randomized complete block design with six replications.

In general order of increasing tillage intensity, treatments were no-till, ridge-till (ridge), tandem disk (disk), subsoil tillage (subtill), chisel plow (chisel), and moldboard plow (plow). Corn stover was chopped each spring in no-till, ridge, and disk treatments for all treatment years, and in the fall after grain harvest for subtill, chisel, and plow treatments for 1986–1999 only. No-till soils did not have any soil management disturbances related to seedbed preparation or post-planting cultivation. The ridge-till treatment also did not include pre-plant soil tillage, but ridging was done at or within two weeks of cultivation in all cropping systems (V5-V8 for corn; V5 for soybean) using Buffalo row-crop cultivator (Fleischer Manufacturing Co., Columbus, NE). The disk treatment included two spring tillage events prior to planting. Subtill, chisel, and plow treatments were applied after grain was harvested, and included one disk-tillage event the following spring prior to planting plus an in-season cultivation event as described previously. The tillage depths for subtill was ~36 cm, and ~25 cm for chisel and plow. The subsoil tillage unit Blu-jet Subtiller (Thurston Manufacturing Co., Thurston, NE) was equipped with standard shanks and fall-till points with 76 cm spacing. The chisel plow had shanks equipped with straight points at 25 cm spacing. Moldboard plowing fully inverted soils.

Corn and soybean were planted at dates and seeding populations according to local recommendations. Glyphosate-resistant hybrids have been planted since 1998 and updated every four years to reflect farmer practice in this region. Both crops were planted in 76 cm rows with a planter equipped with double-disk openers as previously reported by Sindelar et al. (2015). Nitrogen fertilizer was applied to corn only as broadcast ammonium nitrate at the rate of 112 kg N ha^{-1} from 1986 to 2003, 168 kg N ha^{-1} from 2004 to 2006, then injected at 10–15 cm depth as granular urea from 2007 to present (168 kg N ha^{-1}). No N fertilizer has ever been applied to soybean crops. Crops were managed for weed control using a combination of pre- and post-emergence herbicides, cultivation, and hand weeding. Prior to 1998 when transgenic hybrids were planted, insecticide applications varied from year-to-year as needed and were applied based on label instructions.

2.2. Soil sampling, analyses, and stock calculations

Soils were sampled in November 2011 in each treatment subplot along a central transect where four, equally spaced locations were sampled and composited by depth. A hydraulic soil corer was used to collect deep cores which were split into 0–15, 15–30, 30–60, 60–90, 90–120, and 120–150 cm depths and composited by increment. Soil bulk density (Mg m^{-3}) was determined for each soil depth increment using core volumes, fresh soil mass, and corrected for moisture content measured in a subsample of oven-dried soil (dried at 105 °C). The remaining soils were air-dried, passed through a 2 mm sieve, and measured for soil pH and electrical conductivity (dS m^{-1}) in 1:1 water extracts; and soil organic carbon (SOC) and total N by dry combustion (g C or N kg^{-1} dry soil). No soil carbonates were present. Only 0–15 and 15–30 cm data are presented in this study.

Surface soils for soil aggregate analyses were sampled by hand immediately adjacent to deep coring locations using a flat-bladed spade to undercut and remove soils from 0 to 7.5, 7.5–15, and 15–30 cm depths. Surface soil samples were composited by depth increment, passed through an 8-mm sieve, and air dried. Dry aggregate size distribution was determined by passing 8-mm-sieved samples through nested sieves with a 1-min agitation time using a Ro-Tap Model B shaker (SoilTest, Inc.; Loveland, CO, USA). Resulting dry aggregate size classes were <0.053 mm, 0.053–0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm, and >2.0 mm. Individual aggregate size fractions were analyzed as gram (aggregates) per kilogram soil, and the overall size distribution was expressed as mean weight diameter (MWD) (Kemper and Rosenau, 1986; Wienhold et al., 2013).

Table 1

Management effects on selected soil properties by soil depth. Tukey-adjusted grouping shown for significant main effects (tillage, cropping system) for each depth increment.

[1]Tillage or cropping system	[2]Bulk density	Electrical conductivity	Soil pH	SOC	Total N
	Mg m^{-3}	dS m^{-1}	1:1 water	g kg^{-1}	
	0–15 cm depth				
No-till	1.23	0.25 b[3]	6.1 b	17.6 a	1.6 a
Ridge	1.22	0.27 ab	6.6 a	17.6 a	1.5 a
Disk	1.25	0.25 b	6.7 a	15.8 ab	1.4 b
Subtill	1.24	0.28 ab	6.6 a	15.6 bc	1.4 b
Chisel	1.25	0.29 a	6.8 a	16.5 bc	1.4 b
Plow	1.24	0.29 ab	6.5 a	14.8 c	1.4 b
Continuous soybean	1.30	0.28 A[4]	6.8 A	15.4 B	1.4 B
Soybean-corn	1.27	0.28 A	6.6 B	16.4 A	1.5 A
Corn-soybean	1.19	0.28 A	6.6 B	16.6 A	1.5 A
Continuous corn	1.19	0.25 B	6.1 C	16.9 A	1.5 A
	15 – 30 cm depth				
No-till	1.38	0.21 b	5.6 c	13.9 a	1.2 a
Ridge	1.37	0.23 ab	5.8 cb	13.3 a	1.2 ab
Disk	1.39	0.23 ab	5.9 cb	12.7 ab	1.1 cd
Subtill	1.33	0.25 ab	6.0 ba	12.3 abc	1.1 bc
Chisel	1.39	0.28 a	6.1 a	10.9 c	1.1 d
Plow	1.39	0.28 a	6.3 a	11.4 bc	1.1 cd
Continuous soybean	1.38	0.22 B	6.0 A	11.8 B	1.1 B
Soybean-corn	1.38	0.21 B	6.0 A	12.5 A	1.1 AB
Corn-soybean	1.37	0.26 AB	6.0 A	12.4 A	1.1 AB
Continuous corn	1.36	0.28 A	5.8 B	13.0 A	1.2 A

[1] For two-year rotations, the first crop phase listed was present when soils were sampled.

[2] Bulk density for 0−15 cm soils was affected by treatment interactions (see Fig. 1ab).

[3] Different lowercase letters represent significant ($P \leq 0.05$) differences among tillage practices within each parameter studied in Tables 1–3.

[4] Different uppercase letters represent significant ($P \leq 0.05$) differences among cropping system within each parameter studied in Tables 1–3.

Water-stable aggregates were determined on subsamples of the three largest dry aggregate fractions (0.5–1.0 mm, 1.0–2.0 mm, >2.0 mm). Air-dried aggregates were saturated with deionized water by capillary wetting, then placed on 0.5, 1.0, and 2.0 mm sieves, respectively. Soils were agitated for 5 min on a wet-sieving apparatus (Five Star Scientific; Twin Falls, ID, USA). The fraction of water-stable aggregates was determined as the percentage of soil aggregate mass retained on each sieve, adjusted for sand content (Kemper and Rosenau, 1986). The abundance of sand-free water-stable aggregates (g kg^{-1} soil) in each size class was calculated as the abundance of dry aggregates in the whole soil multiplied by the fraction of sand-free water-stable aggregates.

Occluded particulate organic matter (oPOM) was determined in 0–7.5 and 7.5–15 cm soils for a subset of tillage treatments (no-till, chisel, disk) in soybean-corn, corn-soybean, and continuous corn systems only. Occluded POM was measured in two dry aggregate size classes, 0.053–0.5 mm and >2.0 mm. The 0.053–0.5 mm size class includes particle sizes most susceptible to water erosion (<0.10 mm) (Wischmeier et al., 1971) and wind erosion (<0.84 mm) (Hagen et al., 1999), so hereafter is referred to as “highly-erodible aggregates.” The >2.0 mm hereafter is referred to as “mega-aggregates.” Occluded POM was determined for these two size classes using methods by Cambardella et al. (2001) and Mikha et al. (2006). Briefly, a 30 g subsample of air-dried aggregates was dispersed in 90 mL of 5% sodium hexametaphosphate and shaken on a reciprocal shaker for 16 h. The dispersed soil was passed through (mesh size 0.053 mm) and washed. The POM + sand collected on each sieve was dried to a constant weight at 50 °C. Occluded sand-free POM mass was determined by loss-on-ignition using a muffle furnace at 450 °C for 4 h and reported as g oPOM kg^{-1} dry aggregate.

Due to treatment differences in soil bulk densities (described below), soil stocks of SOC, dry aggregates, and water-stable aggregates were calculated on an equivalent soil mass (ESM) basis for approximately the upper 0−15 cm soil depth (1197 Mg ha^{-1}) and 0-30 cm soil depth (2698 Mg ha^{-1}) (Lee et al., 2009). Equivalent soil mass stocks are referred to hereafter as “ESM15″ for the upper ~15 cm of soils and “ESM30″ for the upper ~30 cm of soils.

2.3. Statistical analyses

A mixed model analysis of variance (ANOVA) was used to analyze the main and interaction effects of tillage and crop rotation for each soil depth increment or by ESM. Block was considered a random effect in all analyses. Soil pH, electrical conductivity, and concentrations of SOC, total N, and oPOM were evaluated by soil depth increment. Stocks of SOC, total N, dry aggregate fractions, and water-stable aggregates were also evaluated for ESM15 and ESM30. Comparisons for significant main or interaction effects were assessed with Tukey-adjusted LSMEANS statements. Data were transformed for normality prior to analysis when necessary. All values are reported as non-transformed means and standard errors. Linear regressions were performed on treatment means to evaluate relationships between aggregate stocks and occluded POM over a range of tillage and cropping management practices. Treatment effects and correlations were considered significant at $P \leq 0.05$. All data used in this study are publicly available on-line through the USDA-ARS Agricultural Collaborative Research Outcomes System (AgCROS) platform (https://agcros-usdaars.opendata.arcgis.com/).

3. Results

3.1. Soil physical and chemical properties by soil depth

Soil bulk density was affected by management treatments (tillage and cropping system) in the 0−15 cm depth but not in 15−30 cm soils (Table 1; Fig. 1ab). In surface soils, cropping system differences occurred in only four of six tillage treatments (no-till, ridge, chisel, plow), where soils under continuous soybean had the highest bulk densities compared to other crop rotations in those four tillage treatments ($P_{till*crop} = 0.033$). Tillage differences within a specific cropping system occurred only under soybean-corn and continuous corn, where plowed soils had the lowest bulk density in the soybean-corn rotation but no-till and ridged soils had the lowest bulk densities in the continuous corn system (Fig. 1b).

Soil electrical conductivity (EC) and pH differed by only the main

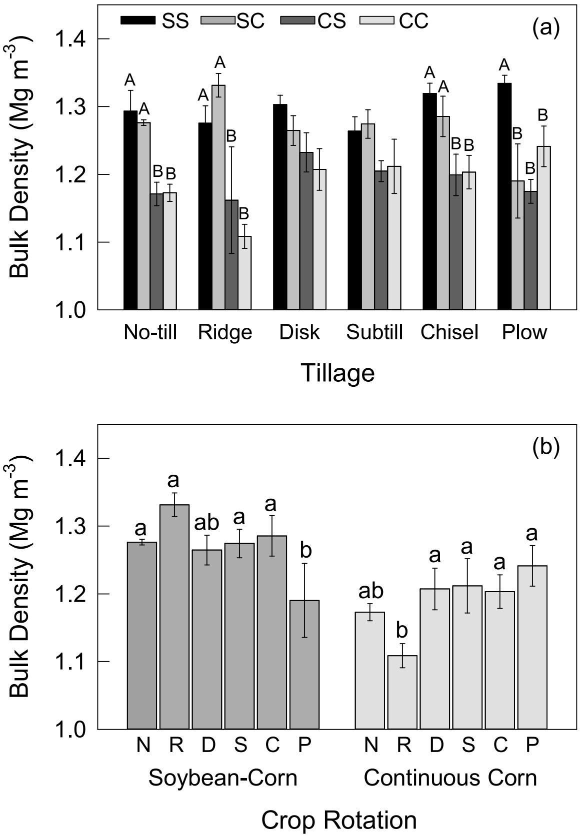

Fig. 1. Soil bulk density (0–15 cm) differed between crop rotation within tillage systems (a) and between tillage systems for two of four cropping systems (b). Different upper-case letters for each tillage system in panel (a) indicate significant Tukey-adjusted cropping system differences. Different lower-case letters for each cropping system in panel (b) indicate significant Tukey-adjusted tillage system differences. Crop rotations were continuous soybean (SS), soybean-corn (SC), corn-soybean (CS), and continuous corn (CC). Tillage treatments were no-till (N), ridge till (R), tandem disk (D), subsoil tillage (S), chisel plow (C), and moldboard plow (P). For two-year rotations, the first crop phase listed was present when soils were sampled.

effects of tillage and crop rotation in both 0−15 cm and 15−30 cm depth increments (Table 1). For both soil depths, EC tended to increase with tillage intensity. Soil EC was lowest in continuous corn in 0−15 cm, but highest in continuous corn for the 15−30 cm depth compared to other cropping systems. Soil pH was lowest under no-till and continuous corn in both soil depths compared to other tillage and cropping systems, with pH values decreasing by 0.3 to 0.8 units in deeper soil layers. Concentrations of total N and SOC were affected by main effects of tillage and crop rotation only in both soil depths (P_{till}, P_{crop} < 0.001). For both total N and SOC, concentrations in 0−15 cm soils were highest in no-till, ridge, and continuous corn treatments and lowest under plow and continuous soybean, with similar treatment trends in the deeper 15−30 cm increment.

3.2. Soil physical and chemical properties by equivalent soil mass

Because of the significant management effects on bulk density (Fig. 1), soil stocks of SOC, total N, dry aggregate fractions, aggregate mean weight diameter, and sand-free water-stable aggregate fractions were calculated on an equivalent soil mass basis for approximately the upper 0−15 cm soil depth (ESM15; 1197 Mg dry soil ha^{-1}) and 0−30 cm soil depth (ESM30; 2698 Mg dry soil ha^{-1}) (Tables 2,3; Fig. 2). Management differences in ESM15 persisted in ESM30 comparisons, though differences were less clear when a higher mass of soil was considered.

Soil organic C and total N stocks in ESM15 soils were affected by main treatment effects only (P_{till}, P_{crop} < 0.001) (Fig. 2). Specifically, SOC and total N stocks were greatest under no-till, ridge, and disk and lowest in plowed soils, with intermediate values for other tillage systems. Stocks were lowest in continuous soybean soils. Stocks in ESM30 soils similarly were affected only by main treatment effects (P_{till}, P_{crop} < 0.05) where the same tillage effects described above persisted for this greater soil mass. Soil organic C and total N stocks under crop rotation, however, differed only between crop phases for the rotated cropping system, where stocks were higher during the soybean phase (soybean-corn) system compared with corn phase (corn-soybean) system.

Similar to SOC and total N stocks, the dry aggregate size fractions, MWDs, and water-stable aggregate fractions were influenced by main effects of tillage and crop rotation (P_{till}, P_{crop} < 0.05). Management trends were similar for both ESM15 and ESM30 soils, though some treatments that were significant in ESM15 did not persist in ESM30 (Tables 2,3; Fig. 2). For ESM15 soils (Table 2), increasing tillage intensity shifted dry aggregate distributions such that larger aggregates (>1 mm) decreased, with concomitant increases in the two smaller size classes (0.053–0.5 and 0.5–1.0 mm). The smallest size class (<0.053 mm) also decreased with increasing tillage intensity. In ESM30 soils (Table 3), similar tillage treatment patterns occurred, though the impact on tillage for the smallest dry aggregate size class (<0.053 mm) and mega-aggregates (>2.0 mm) were not significant. Crop rotation effects on dry aggregate size distributions were less clear, though there was a

Table 2
Mean management effects on soil stocks of five dry aggregate size classes and three water-stable aggregate size classes in the top ~15 cm of soil (equivalent soil mass of 1197 Mg ha^{-1}). Tukey-adjusted mean grouping shown for significant main effects.

[1]Tillage or cropping system		Dry aggregate size (mm)					Water-stable aggregate size (mm)		
		<0.053	0.053−0.5	0.5−1.0	1.0−2.0	>2.0	0.5−1.0	1.0−2.0	>2.0
				Mg ha^{-1}				Mg ha^{-1}	
No-till		37 a	178 b	182 c	229	570 a	162 c	167 a	406 a
Ridge		40 a	206 ab	185 c	192	573 a	158 c	130 b	393 a
Disk		38 a	246 a	227 ab	192	494 bc	197 ab	126 b	300 b
Subtill		35 ab	196 b	209 bc	217	541 ab	179 bc	149 ab	350 ab
Chisel		31 b	222 a	252 a	212	480 c	214 a	142 b	308 b
Plow		29 b	191 b	229 ab	216	532 ab	193 ab	136 b	310 b
Continuous soybean		37	216 AB	205 B	195	544 A	172 B	123 C	315 B
Soybean-corn		35	196 B	199 B	201	566 A	172 B	137 B	361 AB
Corn-soybean		34	222 A	236 A	216	488 B	205 A	150 AB	332 AB
Continuous corn		35	193 B	216 AB	224	529 AB	186 AB	156 A	371 A
Source of variation	*df*			*P-value*				*P-value*	
Tillage	5	**0.0005**	**0.0022**	**<.0001**	**<.0001**	**0.0036**	**<.0001**	**0.0002**	**0.0003**
Rotation	3	0.2276	**0.0031**	**0.0003**	**<.0001**	**0.0012**	**0.0004**	**<.0001**	**0.0008**
Tillage * Rotation	15	0.3660	0.4219	0.4844	**0.0131**	0.6439	0.8328	0.3319	0.4324

[1] For two-year rotations, the first crop phase listed was present when soils were sampled.

Table 3

Mean management effects on soil stocks of five dry aggregate size classes and three water-stable aggregate size classes in the top ~30 cm of soil (equivalent soil mass of 2698 Mg ha^{-1}). Tukey-adjusted mean grouping shown for significant main effects.

[1]Tillage or cropping system		Dry aggregate size (mm)					Water-stable aggregate size (mm)		
		<0.053	0.053–0.5	0.5–1.0	1.0–2.0	>2.0	0.5–1.0	1.0–2.0	>2.0
				Mg ha^{-1}				Mg ha^{-1}	
No-till		76	356 c	400 b	600 a	1656	356 bc	434 a	1153 ab
Ridge		78	384 bc	373 b	483 b	1717	319 c	333 b	1189 a
Disk		85	500 a	482 a	510 b	1588	417 a	343 b	1016 bc
Subtill		76	379 c	405 b	482 b	1697	347 c	335 b	1183 a
Chisel		74	455 ab	507 a	496 b	1635	429 a	334 b	1106 abc
Plow		72	424 abc	498 a	512 b	1591	419 ab	324 b	969 c
Continuous soybean		86 A	457 A	453 AB	522	1770 A	381 AB	335 B	1069 AB
Soybean-corn		81 A	406 B	418 B	495	1806 A	359 B	334 B	1203 A
Corn-soybean		71 B	431 AB	475 A	521	1461 B	414 A	368 A	1024 B
Continuous corn		70 B	372 B	429 AB	519	1556 B	369 AB	365 A	1117 AB
Source of variation	*df*			*P-value*				*P-value*	
Tillage	5	0.2520	**<.0001**	**<.0001**	**0.0018**	0.8527	**<.0001**	**0.0016**	**0.0435**
Rotation	3	**<.0001**	**0.0002**	**0.0223**	0.4276	**<.0001**	**0.0251**	0.0603	**0.0080**
Tillage * Rotation	15	0.2291	0.3547	0.2891	0.1361	0.6212	0.4197	0.3437	0.3315

[1] For two-year rotations, the first crop phase listed was present when soils were sampled.

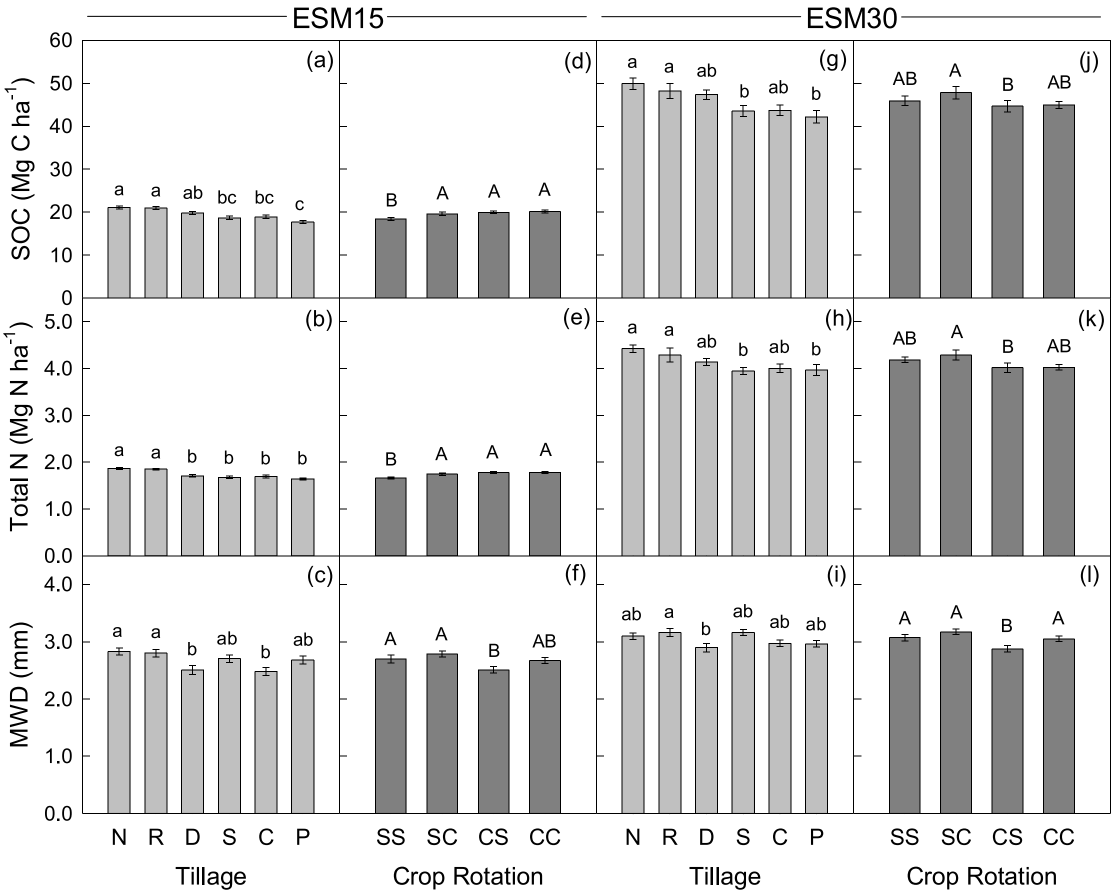

Fig. 2. Soil organic carbon (SOC), total nitrogen (N), and dry aggregate mean weight diameter (MWD) for equivalent soil masses for the upper ~15 cm (1197 Mg ha^{-1}) (a-f) and ~30 cm soil depth (2698 Mg ha^{-1}) (g-l). Different lower-case letters indicate significant Tukey-adjusted tillage system differences for each ESM15 and ESM30. Different upper-case letters indicate significant Tukey-adjusted cropping system differences for each ESM15 and ESM30. Tillage treatments were no-till (N), ridge till (R), tandem disk (D), subsoil tillage (S), chisel plow (C), and moldboard plow (P). Crop rotations were continuous soybean (SS), soybean-corn (SC), corn-soybean (CS), and continuous corn (CC). For two-year rotations, the first crop phase listed was present when soils were sampled.

tendency for corn-soybean soils to have higher aggregate fractions in smaller size classes while soybean-corn soils had higher aggregate fractions in the larger size classes. Only the 1.0–2.0 mm dry aggregate fraction in ESM15 soils was affected by an interaction between tillage and crop rotation ($P_{till*crop} = 0.013$), where this fraction was not affected by tillage under continuous corn but was greatest under no-till whenever soybeans were included in the cropping system. The MWDs resulting from treatment impacts in both ESM15 and ESM30 showed lowest

MWDs under disked soils and the highest MWDs under ridge or no-till, lowest MWDs in the corn-soybean system (Fig. 2f).

Water-stable aggregates >1.0 mm decreased as tillage intensity increased in both ESM15 and ESM30, with the lowest stocks of water-stable aggregates under plow or disk and the highest stocks under no-till. For the 0.5−1.0 mm size class, however, water-stable aggregates increased with tillage intensity. Generally, crop rotation effects on water-stable aggregation were more pronounced in ESM15 compared to ESM30 soils for all aggregate size classes, where the lowest stocks of water-stable aggregates were under continuous soybean and the highest stocks were under corn in corn-soybean or continuous corn system for all size classes.

3.3. Occluded POM and relationship to aggregate properties

Concentrations of oPOM within highly-erodible aggregates (0.053–0.5 mm) and mega-aggregates (>2.0 mm) were affected by a tillage*crop rotation interaction (Fig. 3) in both 0–7.5 cm and 7.5–15 cm depths (g oPOM kg^{-1} aggregate) ($P_{till*crop} < 0.001$). In near-surface soils (0–7.5 cm), highly-erodible aggregate oPOM was highest in no-till soils and under continuous corn, but any tillage resulted in oPOM losses of 56–69% across all cropping systems (Fig. 3a). Although near-surface mega-aggregate oPOM losses with tillage were less severe (5–35%), the use of continuous corn decreased oPOM compared to rotated cropping systems under no-till management (Fig. 3c). In 7.5–15 cm soils for both aggregate size classes, cropping system differences were most pronounced in no-till soils, where oPOM was highest under continuous corn (Fig. 3bd). In ESM15 soils, there was a marginally significant negative relationship between oPOM in highly-erodible aggregates with aggregate stocks ($R^2 = 0.33$, $P = 0.10$), where no-till soils and soils under chisel or disk were clearly separated (Fig. 4a). In contrast, total stocks of mega-aggregates and water-stable mega-aggregates were positively correlated to mega-aggregate oPOM ($R^2 = 0.49$, $P < 0.05$; $R^2 = 0.76$, $P < 0.01$, respectively) (Fig. 4bc). Separation between crop rotation systems were less clear within each tillage system. Mega-aggregates also showed clear separation between no-till vs tilled soils, where continuous corn further increased that separation in no-till soils (Fig. 4bc).

4. Discussion

Thirty years of continuous tillage and crop rotation practices affected both soil erosion potential and C storage, particularly in near-surface soils (0–7.5 cm). In contrast to expectations that tillage impacts are limited to the top 10 cm of soils (Blanco-Canqui and Ruis, 2018), results from this site indicate that location-specific responses to tillage and crop rotation can impact soils down to 30 cm (current study) and as far as 60 cm (Varvel and Wilhelm, 2011). There were few interactions between tillage and crop rotation treatments on most soil properties measured here, consistent with previous publications showing primarily main management effects on both soils (Varvel and Wilhelm, 2010, 2011) and crop yields (Sindelar et al., 2015).

4.1. Soil bulk density, electrical conductivity, and pH

Soil bulk density was among the few soil properties affected by the interaction of tillage and cropping system management, with the interaction limited to the top 0−15 cm soil depth. Overall, tillage and/or cropping system effects on surface soil bulk density or soil strength are highly variable, with reports of increases, decreases, or no change with management (Blanco-Canqui and Ruis, 2018). Much of the variable response could be attributed to soil moisture status at the time of sampling, time since tillage, and/or soil type differences (Mikha et al., 2006). Here, we found that soil bulk density was lowest when the corn phase was present at the time of soil sampling compared to soybean, consistent with previously published findings (Varvel and Wilhelm, 2010, 2011). Even for the same two-year rotation system, significant bulk density differences between the two crop phases likely reflected different soil moisture status due to crop-specific water uptake at the time of soil sampling (Nielsen and Calderón, 2011).

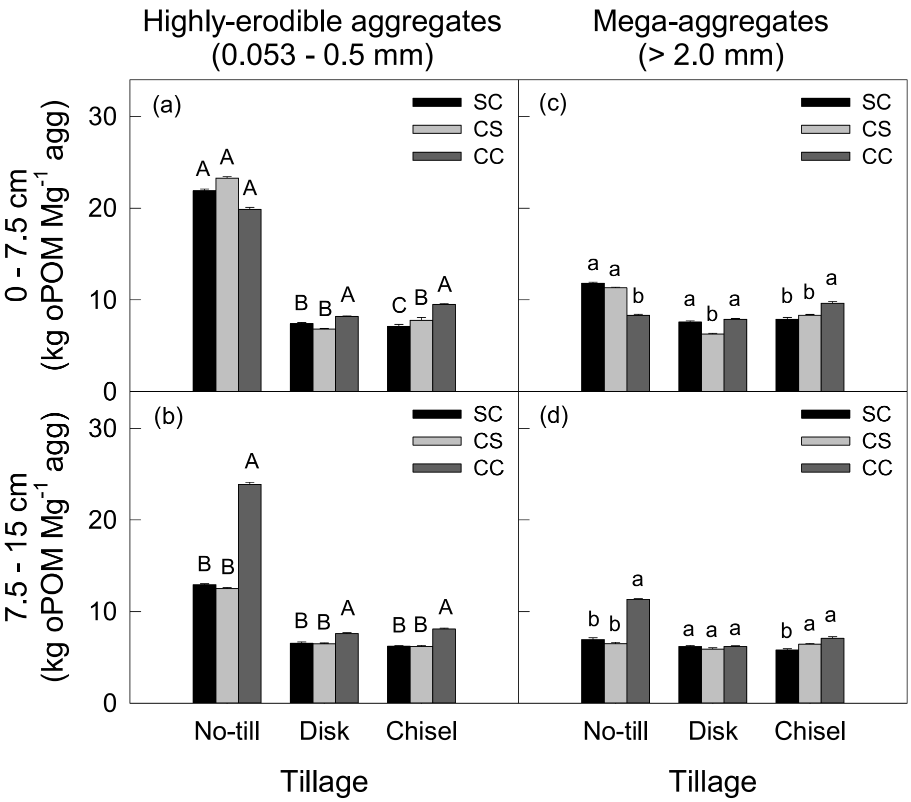

Fig. 3. Occluded particulate organic matter (oPOM) concentrations within highly-erodible aggregates (0.053–0.5 mm) (a, b) and mega-aggregates (>2.0 mm) (c, d). Upper-case letters show significant Tukey-adjusted crop rotation differences by tillage type for highly-erodible aggregates, lower-case letters for mega-aggregates. Crop rotations were soybean-corn (SC), corn-soybean (CS), and continuous corn (CC). For two-year rotations, the first crop phase listed was present when soils were sampled.

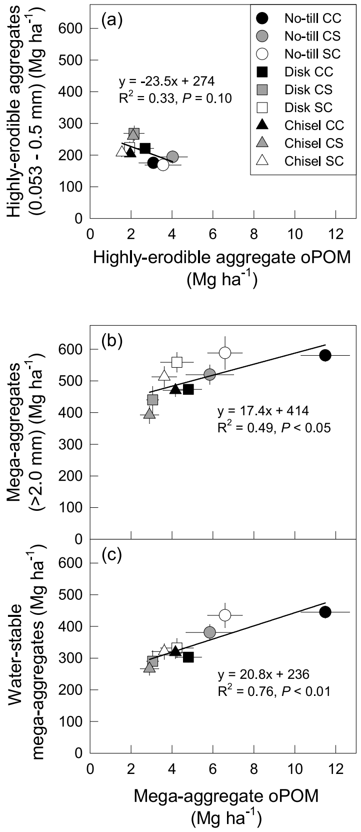

Fig. 4. Relationships between ESM15 soil stocks of occluded particulate organic matter (oPOM) in highly-erodible aggregates (0.053–0.5 mm) vs. highly-erodible aggregate stock (a); oPOM in mega-aggregates (>2.0 mm) vs. mega-aggregate stocks (b); and oPOM in mega-aggregates and water-stable mega-aggregates (c). Treatment means and standard errors shown for both axes (symbol size may be larger than error bars). CC = continuous corn, CS = corn-soybean, SC = soybean-corn. Linear regression equation, coefficient of determination (R^2), and p-value are shown in each panel.

The highest bulk densities were measured under continuous soybean in the majority of tillage treatments (four of six systems; Fig. 1a). Other long-term studies, however, have not found higher surface soil bulk densities under continuous soybean cropping compared to rotated or continuous corn (Wright and Hons, 2004; Huggins et al., 2007; Ashworth et al., 2020). Soybean production practices use fewer management operations than corn production (i.e. no fertilizer applied), but low crop residue inputs and subsequent decreases in soil organic matter under continuous soybean cropping can result in greater soil vulnerability to mechanical compaction (Hamza and Anderson, 2005; Shah et al., 2017; Ashworth et al., 2020). Both higher bulk density and less developed root systems compared to corn may limit deeper SOC storage in soybean soils, especially under no-till management (Jung et al., 2010). Further, longer fallow periods between soybean crops compared to continuous or rotated corn may exacerbate the effects of having less residue to physically protect the soil surface, prolonging soil exposure to wind and water erosion in the non-crop season and limiting the formation of larger, more stable soil aggregates (Nielsen and Calderón, 2011; Wienhold et al., 2013).

Within a given cropping type, tillage influence on bulk density occurred only for the soybean-corn and continuous corn systems. Tillage differences tended to be small, with no-till soils in both systems having among the highest bulk density values compared to tilled soils (Fig. 1b). None of the bulk densities measured here, however, approached root-limiting values for silty clay loam soils ($\geq$ 1.50 Mg m^{-3}; Arshad et al., 1996). Greater bulk density under no-till compared to conventionally tilled soils was also noted in 39% of tillage studies in the last 10 years (Blanco-Canqui and Ruis, 2018). In addition, plowed soils in the soybean-corn system had the lowest bulk density, but plowed and other conventionally tilled soils under continuous corn had among the highest bulk density values. Varvel and Wilhelm (2011) noted that plowed soils under continuous corn had the lowest bulk density, contrasting with our current findings. Inconsistencies in management effects even at the same site over time, however, are commonly reported and likely reflect differences in sampling conditions (stated previously) as well as the observation that tillage treatment differences tend to decrease with management duration (Blanco-Canqui and Ruis, 2018).

In contrast to bulk density, soil electrical conductivity (EC) and pH values in both 0–15 and 15–30 cm soil depths were affected only by the main effects of tillage or cropping system (Table 1). For both soil depths, soil EC and pH tended to increase with greater tillage intensity such that values were relatively similar between the two soil depths as the degree of soil mixing increased. Conversely, no-till soils showed greater stratification of EC and pH values between depths in the absence of long-term tillage disturbance. At another nearby long-term tillage study, Kibet et al. (2016) also found soil pH increased with tillage intensity, with the lowest soil pH values under no-till. In humid environments, soil pH is expected to increase with soil depth due to the leaching of soluble base-forming cations (Bolan et al., 2005). Further, long-term applications of urea- and/or ammonia-based fertilizers are expected to significantly acidify agricultural soils (Bouman et al., 1995), particularly in the top 8 cm (Reeves and Liebig, 2016). In this study, the higher pH values in surface soils likely reflected the legacy effects of liming when the site was established three decades prior, similar to observations from other long-term tillage studies (Karlen et al., 2013; Kibet et al., 2016). Though management effects on soil EC and pH were statistically significant, the numerical differences were not considered large enough to impact crop emergence, growth, or productivity (Karlen et al., 2013).

4.2. Soil organic C and total N stocks

Because soil bulk densities differed by tillage and cropping system treatments, stocks of SOC, total N, dry aggregates, and water-stable aggregates were standardized to equivalent soil masses representing the upper ~0–15 cm (ESM15) and ~0–30 cm (ESM30) soil layers. After 30 years of management, SOC and total N stocks for both ESM15 and ESM30 were affected only by the main effects of tillage or crop rotation (Fig. 2). Management had stronger impacts on ESM15 than ESM30 soils, likely reflecting a dilution effect of added soil mass for the ESM30 responses. Management effects were consistent for both soil layers, with SOC and total N stocks generally decreasing with increasing tillage intensity. Tillage systems tended to group into less intensive (no-till, ridge, disk) and more intensive (subtill, chisel, plow) practices, with disk tillage and chisel tillage tending towards moderate intensity depending on soil layer. We also found that ESM15 stocks of SOC and N were lowest in continuous soybean and highest in rotated or continuous corn, with cropping system differences less clear for ESM30.

Our results are consistent with many studies reporting higher SOC in no-till vs tilled soils (Havlin et al., 1990; Angers et al., 1997; Balesdent et al., 2000; Six et al., 2000; Denef et al., 2007; Pikul et al., 2007; Jacobs et al., 2009; Samson et al., 2020), though other long-term studies have found little to no net C sequestration in no-till compared to conventionally tilled soils (Baker et al., 2007; Luo et al., 2010; Sanford et al., 2012; Sarker et al., 2018). Previous assessments at this site showed no-till and continuous corn systems had the highest SOC stocks (equivalent soil mass basis) and that these gains were observed as deep as 60 cm (Varvel and Wilhelm, 2010, 2011). Further, SOC stock changes between 1999 and 2004 indicated net C accrual in soils at this site (Varvel and Wilhelm, 2011). Using 2004 SOC concentrations from Varvel and Wilhelm (2010) and soil masses for ESM30 used in the present study, we estimated that all systems at this site gained SOC between 2004 and 2011 in the top 30 cm soil layer by 0.6 ± 0.1 Mg SOC ha^{-1} yr^{-1} across all management systems (range of 0.2 to 0.9 Mg SOC ha^{-1} yr^{-1}). Our findings contrast with another long-term management study that showed SOC losses after 20 years of best management practices even in systems that included perennial grasses, reflecting expected losses from these soils which were initially high in SOC content (Sanford et al., 2012). While a more precise evaluation of SOC changes over time is the subject of a separate report (Jin et al., *in prep*), the estimates calculated here indicated that the lowest accrual rates occurred under the most intensive tillage practices (subtill, plow), with higher gains occurring under no-till and less intensive tillage practices (ridge, disk, chisel).

For cropping systems, the lowest rates of SOC gain were estimated for continuous corn and highest under continuous soybean, even though standing stocks of SOC were larger in continuous corn than continuous soybean. Lower SOC stocks under continuous soybean have been attributed to less crop C input compared to continuous corn and because the lower C:N of soybean residues likely enhances the decomposition of native soil organic matter (Huggins et al., 2007). At this site, long-term dry matter production in both continuous corn and continuous soybean systems was relatively stable over time, with corn producing ~2.3 times more total aboveground biomass than soybean (Sindelar et al., 2015). Given higher C inputs and higher SOC stocks under continuous corn, the slower rates of SOC gain may reflect a greater degree of soil C saturation occurring under continuous corn vs. continuous soybean after 24–30 years of management at this site (Stewart et al., 2007).

4.3. *Dry aggregate distribution and water-stable aggregates*

Increasing tillage intensity shifted dry soil aggregate distributions towards a greater abundance of smaller aggregates and decreased aggregate mean weight diameters (MWDs), (Tables 2,3; Fig. 2). These results met expectations that greater tillage disturbance physically disrupts both the aggregates themselves as well as the protective barrier provided by unincorporated crop residues, leading to greater aggregate turnover (Tisdall and Oades, 1982). The stability of wet aggregates also decreased with tillage intensity, particularly for 1.0−2.0 mm macroaggregates. While these effects were apparent for both ESM15 and ESM30 soils, tillage differences were stronger in ESM15 soils, indicating an increased risk for wind and water erosion in intensively tilled soils. Similar negative impacts of long-term tillage on aggregate size and stability have also been reported (Hussain et al., 1999; Bossuyt et al., 2002; Pikul et al., 2007; Andruschkewitsch et al., 2014; Kahlon et al., 2013; Karlen et al., 2013; Kibet et al., 2016; Singh et al., 2020). Although recent reports (i.e. last 10 years) of tillage effects on dry aggregates are inconsistent, no-till practices in 75% of cases for medium-textured to clayey soils increased wet aggregate stability compared to reduced or conventional tillage, and it was positively correlated with management duration (Blanco-Canqui and Ruis, 2018).

Cropping systems using rotated or continuous corn had the highest abundance of larger and more stable aggregates, which we attributed to greater biomass inputs in these cropping systems compared to continuous soybean. In a different 28 year tillage study which used the same crop rotation systems as the current study, Nouwakpo et al. (2018) found higher wet aggregate stability under no-till than chisel tillage to 30 cm depth, and higher stability in systems with corn residues compared to soybean residues. Further, greater crop inputs can lead to a higher abundance of soil fungi, which can also improve aggregate stability (Simpson et al., 2004; Tiemann et al., 2015). Other long-term studies have also found that higher crop litter inputs are associated with a greater abundance of larger soil aggregates (Yang and Wander, 1998; Six et al., 1999; Kahlon et al., 2013; Karlen et al., 2013), though this relationship can be soil-specific (Sarker et al., 2018). Sediment losses have been found to be up to 20 times greater under conventionally tilled soybean compared to corn (Nouwakpo et al., 2018), highlighting how both tillage and cropping system management interact to impact erosion risks.

4.4. *Relationships between occluded POM and aggregate properties*

In a subset of the most common management systems for our region, we measured oPOM concentrations in highly-erodible aggregates (0.053−0.5 mm) and mega-aggregates (>2 mm) in two near-surface soil layers (0–7.5 cm and 7.5−15 cm) as an indicator of tillage (no-till, disk, chisel) and cropping system (continuous corn, corn-soybean, soybean-corn). For both depth increments and size classes, we found the highest oPOM concentrations under no-till management, where oPOM concentrations were higher in micro/macroaggregates than in mega-aggregates (Fig. 3). While the magnitude of cropping system effects within tillage treatments were smaller than differences between tillage treatments, oPOM tended to be higher under continuous corn. Other studies have reported similar results, where higher biomass C inputs from continuous corn compared to rotated corn led to greater soil POM (Coulter et al., 2009), and could approximate POM levels in perennialized systems (Cates et al., 2016). Tillage markedly decreased highly-erodible aggregate oPOM concentrations by 56–69% across all cropping systems in the 0–7.5 cm soil layer, with mega-aggregate oPOM losses less severe (5–35%). This relative decrease in oPOM content is within the range reported in other studies for oPOM or POM (Beare et al., 1994; Six et al., 1999; Simpson et al., 2004; Pikul et al., 2007), though no changes in oPOM due to tillage have been reported elsewhere (Jacobs et al., 2009). In another long-term study near the current study site, total POM followed a similar pattern, where total POM was greatest in no-till, followed by disk, then chisel after 33 yrs of management (Kibet et al., 2016).

While our size class here combines the standard micro- and macroaggregate size classes into a single category, other studies generally have reported higher oPOM concentrations in smaller vs larger aggregates (Elliott, 1986; Beare et al., 1994; Sarker et al., 2018; Singh et al., 2020), while another reported greater oPOM concentrations in macroaggregates (Mikha and Rice, 2004). Notably, we found that for mega-aggregates in no-till soils, continuous corn management decreased oPOM content in the 0–7.5 cm increment but increased oPOM in the 7.5−15 cm increment compared to rotated corn. A similar dynamic of lower magnitude occurred for highly-erodible aggregate oPOM in the 7.5−15 cm increment, suggesting that C in mega-aggregates was more labile (i.e. vulnerable to loss) than C in smaller aggregates (Tiemann et al., 2015). One major management difference in continuous vs. rotated corn systems is the frequency of N application (annually vs every 2 years, respectively). Because fertilizer application to corn changed from surface broadcast to subsurface banding at 10−15 cm depth several years prior to the 2011 sampling event, the added soil disturbance related to fertilizer management may have stimulated oPOM losses in near-surface soils. It is unclear whether higher oPOM contents in the next soil layer was due to the physical redistribution of crop residues or near-surface aggregates/oPOM to deeper depths, or due to greater formation of aggregates themselves related to residue incorporation and fertilizer placement.

Despite differences in aggregate dynamics noted for the 0–7.5 and 7.5−15 cm layers, calculating oPOM stocks on an ESM15 basis tended to decrease or eliminate the management impacts measured for the smaller component depth increments. Overall, ESM15 highly-erodible aggregate oPOM stocks were smaller than mega-aggregate-associated oPOM stocks, largely due to the difference in aggregate abundance (Fig. 4). Slower turnover of macro-aggregates is presumed to allow the formation of more stable micro-aggregates involved in long-term SOC stabilization (Angers et al., 1997; Balesdent et al., 2000; Six et al., 2000; Denef et al., 2007). In this study, significant losses of oPOM in highly-erodible aggregates with tillage are consistent with the loss of SOC after decades of intensive tillage management.

For both aggregate size classes, the ESM15 relationships between oPOM and other soil physical properties (i.e., stocks of aggregate abundance and water-stable aggregates) clearly separated between no-till and tilled soils, with much smaller cropping system differences in tilled soils overall (Fig. 4). Our finding that tillage was the primary driver of oPOM dynamics is consistent with another long-term tillage study where 39 years of no-till management had a stronger impact than crop rotation choice on SOC storage (Singh et al., 2020). For no-till soils, the largest cropping system differences occurred in mega-aggregates between continuous and rotated corn, where oPOM stocks under continuous corn were the highest of all management systems. These differences were more marked for oPOM compared to SOC or other measured parameters, demonstrating that oPOM was a more sensitive indicator of management impacts compared to SOC (Beare et al., 1994; Marriott and Wander, 2006; Tiemann et al., 2015).

5. Conclusions

After 30 years of a range of management practices, we found that management affected soil physical properties and C storage, especially in near-surface soils. Specifically, tillage management was the primary driver of physical soil responses, though cropping system impacted soil properties via differences in biomass input amounts previously reported in Sindelar et al. (2015). Because both tillage and cropping system treatments affected soil bulk density, accurate assessments of management impacts on soil physical properties required the use of equivalent soil mass. Tillage intensity was positively correlated with SOC loss and degradation of soil aggregate properties. Further, we found that oPOM was more management-sensitive in smaller than larger sized aggregates, and that oPOM overall was a more sensitive indicator than SOC in evaluating management effects on soils. While maximizing plant C inputs via cropping system type partially mitigated the negative effects of tillage, soil disturbance from other crop management practices (i.e. N management) can potentially limit the mitigating effects of cropping system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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