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Crop Rotation and Tillage Effects on Soil Physical and Chemical Properties in Illinois

Stacy M. Zuber, Gevan D. Behnke, Emerson D. Nafziger, and Maria B. Villamil*

ABSTRACT

Recent increases in corn (*Zea mays* L.) production in the U.S. Corn Belt have necessitated the conversion of rotations to continuous corn, and an increase in the frequency of tillage. The objective of this study was to assess the effect of rotation and tillage on soil physical and chemical properties in soils typical of Illinois. Sequences of continuous corn (CCC), 2-yr corn–soybean [*Glycine max* (L.) Merr.] (CS) rotation, 3-yr corn–soybean–wheat (*Triticum aestivum* L.) (CSW) rotation, and continuous soybean (SSS) were split into conventional tillage (CT) and no-till (NT) subplots at two Illinois sites. After 15 yr, bulk density (BD) under NT was 2.4% greater than under CT. Water aggregate stability (WAS) was 0.84 kg kg^{-1} under NT compared to 0.81 kg kg^{-1} under CT. Similarly, soil organic carbon (SOC) and total nitrogen (TN) were greater under NT than under CT with SOC values for 0 to 60 cm of 96.0 and 91.0 Mg ha^{-1} and TN values of 8.87 and 8.40 Mg ha^{-1} for NT and CT, respectively. Rotations affected WAS, TN, and K levels with WAS being greatest for the CSW rotation at 0.87 kg kg^{-1}, decreasing with more soybean years (CS, 0.82 kg kg^{-1} and SSS, 0.79 kg kg^{-1}). A similar pattern was detected for TN and exchangeable K. Results indicated that while the use of NT improved soil quality, long-term implementation of continuous corn had similar soil quality parameters to those found under a corn–soybean rotation.

Increasing prices for corn in the United States have led to an increase in the area allocated to this crop at the expense of soybean area, and to a decline in the rate of no-till adoption around the Midwest region (USDA-ERS, 2013, 2014). This generates questions regarding the long-term effect of these management decisions on soil quality. Agricultural management practices, such as reduced tillage and crop rotations, have a direct effect on the quantity, quality, and rate of decomposition of the crop residues returned to the soil. In turn, these residues are directly related to the SOC content (Amézketa, 1999), which is a key indicator of soil health and quality (Varvel, 1994; West and Post, 2002). Soil organic C benefits soil by lowering BD, increasing nutrient availability, increasing cation exchange capacity (CEC) and improving water holding capacity; in addition, SOC increases WAS making soils less susceptible to erosion (West and Post, 2002; Varvel and Wilhelm, 2010).

A number of studies have reported greater SOC under no-till compared to conventional tillage (Karlen et al., 1994; West and Post, 2002; Kumar et al., 2012). Conventional tillage increases residue and soil organic matter decomposition by disrupting and aerating the soil, and exposing plant material and soil aggregates to the activity of soil microorganisms (Johnson and Hoyt, 1999; Balesdent et al., 2000). Although organic matter is added to the soil each year from these crop residues, tillage exposes previously protected interior soil aggregates accelerating the loss of SOC from the existing soil organic matter pool (Addiscott and Dexter, 1994; Balesdent et al., 2000). Similar results have been reported for N (Karlen et al., 1994; Needelman et al., 1999) and P (Karlen et al., 2013). Other studies have reported an accumulation of nutrients near the soil's surface under NT, but nutrient levels within the entire measured soil profile do not differ from (Franzluebbers and Hons, 1996; Needelman et al., 1999) or may even be less than (Wander et al., 1998) the soil profile under conventional tillage.

Likewise, soil physical parameters are also affected by tillage intensity, but data on this are inconsistent, reflecting the combined effects of duration of the experiments, timing of sampling, and initial soil conditions (Hussain et al., 1998; Al-Kaisi et al., 2005; Kumar et al., 2012). A number of studies have shown an increase in WAS with greater SOC under reduced tillage (Kladivko et al., 1986; Addiscott and Dexter, 1994; Karlen et al., 1994; Martens, 2000). While some studies have found that BD values are greater under NT than CT (Hill, 1990; Wander and Bollero, 1999; Halvorson et al., 2002),

Department of Crop Sciences, University of Illinois, Urbana, IL 61801.
Received 29 Aug. 2014. Accepted 17 Dec. 2014. *Corresponding author (villamil@illinois.edu).

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Abbreviations: BD, bulk density; CCC, continuous corn; CS, corn–soybean; CSW, corn–soybean–wheat; CT, conventional tillage; NT, no-till; SOC, soil organic carbon; SSS, continuous soybean; TN, total nitrogen; WAS, water aggregate stability.

others have reported no effect of tillage on BD (Karlen et al., 1994; Hussain et al., 1998; Al-Kaisi et al., 2005; Huggins et al., 2007). The process of tillage loosens the soil and creates macropores which reduces soil BD; however, the lack of significant differences between NT and CT may be due to an increase in SOC and WAS and therefore a greater accumulation of less dense surface material to lower BD under NT (Hussain et al., 1998; Coulter et al., 2009). Other explanations for the discrepancy include length of the study (Dao, 1996; Hussain et al., 1998; Kumar et al., 2012) or the timing of soil sampling with fewer differences being found when sampled substantially later than tillage (Al-Kaisi et al., 2005).

While tillage primarily affects the rate of decomposition of crop residues, crop rotation affects the quantity and quality of crop residue. Much greater crop residue remains following corn than following wheat or soybean due to higher yields and only moderately greater harvest index of corn (Johnson et al., 2006). The amount of residue input to the soil has been found to be directly related to SOC (Havlin et al., 1990; Benjamin et al., 2010), and those greater SOC levels are also related to higher levels of N and P (Franzluebbers et al., 1994; Power et al., 1998). The rate of residue decomposition also varies among crops, primarily due to differences in quality (Ajwa and Tabatabai, 1994) and biochemical composition of the plant tissues (Martens, 2000). The ratio of C/N of the plant residues is an important contributor to the rate of decomposition as well as to the formation and stabilization of soil aggregates (Ajwa and Tabatabai, 1994). Decomposition of high C/N ratio residues, such as corn, occurs more slowly than for lower C/N ratios, but the soil aggregates formed from high C/N organic residues are more stable and resistant to degradation (Martens, 2000; Blanco-Canqui and Lal, 2004). The inclusion of soybean within a short crop rotation with corn has been found to lead to lower SOC values compared to a corn monoculture as a result of soybean's lower residue production and more rapid residue decomposition (Varvel, 1994; Coulter et al., 2009; Benjamin et al., 2010). Although SOC under CCC is typically greater than under CS rotation, more complex extended rotations can lead to greater SOC accumulation than either the monoculture or short rotation (West and Post, 2002; Karlen et al., 2006). A similar trend has been found for N (Varvel, 1994; Jagadamma et al., 2007).

As with SOC and N, the cropping systems can lead to changes to soil physical properties. The inclusion of soybean in a rotation with corn has been shown to reduce WAS compared to CCC (Kladivko et al., 1986; Jagadamma et al., 2008). The change in WAS may be due to reduced residue accumulation and soil organic matter depletion or a decrease in humic acids as a result of the biochemistry of soybean residue (Martens, 2000). The phenolic acid and lignin content of corn residue is greater than soybean; these substances are key to the long-term stabilization of soil aggregates (Martens, 2000; Blanco-Canqui and Lal, 2004). Rotations that generate greater SOC lead to a decrease in BD by incorporating a less dense material and increasing WAS (Reeves, 1994; Blanco-Canqui and Lal, 2004). Karlen et al. (2006) reported higher BD values for CCC and CS rotation compared to extended rotations that incorporated oat or pasture, and Coulter et al. (2009) reported 5% greater BD after 8 yr under a CS rotation compared to CCC due to a greater WAS from the addition of soil organic matter under CCC. However, a number of other studies report no effect on BD from the cropping system despite differences in SOC levels among rotations (Varvel, 1994; Huggins et al., 2007; Jagadamma et al., 2007).

While many researchers have examined the effects on soil properties of crop rotation and tillage independently, the interactive effect of crop rotation and tillage has been less frequently studied. Huggins et al. (2007) found tillage effects on SOC were greater in CCC than CS while tillage had no effect on SOC under SSS. Varvel and Wilhelm (2011) reported that after 20 yr, the highest levels of SOC and soil N were found under CCC with reduced tillage compared to other rotations and more intensive tillage. Kumar et al. (2012) found that tillage practices were much more influential on soil properties than cropping system, with greater SOC reported under NT, but no differences in SOC between CCC and CS rotation. This research on the effect of crop rotation and tillage practices on soils has yielded inconsistent results. Factors cited as contributing to this inconsistency include soil texture (Needelman et al., 1999), antecedent soil organic matter (Kumar et al., 2012) and the climatic region where the experiments are conducted (Wander et al., 1998). Campbell et al. (1996) found greater SOC differences between NT and conventional tillage in a clay soil compared to a silt loam and sandy loam. Fine-textured soils are more likely lead to a stratification of SOC under NT without changing the overall SOC in the soil (Needelman et al., 1999). The initial SOC content can also influence the results as soils with high initial SOC are more likely to be at equilibrium levels and be resistant to change (Kumar et al., 2012) and physical properties are also less likely to display differences due to more stable aggregates in these soils (Hill, 1990; Kumar et al., 2012). The duration of the management practices as well as differences in measurement timing and depth are also contributors to differing results (Dao, 1996; Al-Kaisi et al., 2005).

The management practices of crop rotation and tillage influence the soil properties, and understanding the long-term effect of these practices is essential to maintaining optimal soil properties. While a number of studies have reported on the effects of CS crop rotations on soil properties (Huggins et al., 2007; Jagadamma et al., 2007; Kumar et al., 2012), few have examined the effect of the addition of a small grain such as wheat to the short rotation. Due to the conflicting results of previous research and the specificity of results to soil type and climate, more work is needed to understand how crop rotations and tillage affect the soil. We hypothesized that both NT and use of a 3-yr crop rotation such as CSW will lead to improvement in soil properties compared to CT and monocultures or 2-yr crop rotations. Thus, the objective of this study was to determine the long-term effect on soil chemical and physical properties of tillage practices and crop rotations, which include monocultures, 2- and 3-yr rotations incorporating corn, soybean, and wheat. The results of this study will help develop further understanding of the impact of agricultural management practices on soil properties in the Midwest.

MATERIALS AND METHODS

Experimental Sites and Soil Characterization

This study was conducted at two locations in western Illinois: (i) at the Northwestern Illinois Agricultural Research and Demonstration Center (40°55′50″ N, 90°43′38″ W), approximately 8 km Northwest of Monmouth, IL; and (ii) at the Orr Agricultural Research and Demonstration Center (39°48′4″ N, 90°49′16″ W), approximately 8 km Northwest of Perry, IL. At Monmouth, the mean annual precipitation is 978 mm with a mean annual maximum temperature of 16°C (Illinois State Water Survey, 2010). The annual mean precipitation at Perry is 996 mm with a mean annual maximum temperature of 18°C (Illinois State Water Survey, 2010).

The experimental plots at Monmouth were located on Sable silty clay loam (fine-silty, mixed, mesic Typic Endoaquoll) and on Muscatune silt loam (fine-silty, mixed, mesic Aquic Argiudoll), with about 10% of the study area on Osco silt loam (fine-silty, mixed, mesic Typic Argiudoll). These soil series consist of dark colored, very deep soils with a slope of <2%, developed in loess 2 to 3 m thick over till under prairie vegetation. Sable soil is poorly drained, with moderate permeability. The potential for surface runoff is negligible. Muscatune is somewhat poorly drained with moderate permeability and low surface runoff potential. Osco soils are well drained with moderate permeability (Soil Survey Staff, 2014).

The majority of the study area at Perry was on Downsouth silt loam (fine-silty, mixed, mesic Mollic Oxyaquic Hapludalf) and Caseyville silt loam (fine-silty, mixed, mesic Aeric Endoaqualf) with slope of <2%. Both soil series consist of very deep, moderately well drained soils formed in 1 to 3 m loess over till under mixed prairie and forest vegetation. Permeability is moderate and surface runoff potential is low to medium (Soil Survey Staff, 2014). Textural analysis confirmed that the surface soil texture at both Monmouth and Perry sites were silt loam, with silty clay loam texture below 40 cm at Monmouth and below 20 cm at Perry.

The experimental plots were initiated in 1996, and were considered to be in place by 1998 following at least one full cycle of each rotation. They were laid out as a split-plot arrangement of four levels of rotation and two levels of tillage treatments in a randomized complete block design with four replications at each location with each phase of the rotations present each year. Crop rotation–CCC, CS, CSW, and SSS–were assigned to main plots. Only those phases with corn grown during the sampling year were sampled in the CS and CSW rotations. Subplot treatments were two levels of tillage: chisel tillage and no-till. Each main plot was 22 m long by 12 m wide, and subplots were 22 m long by 6 m wide.

At both sites, conventional tillage consisted of primary tillage with a chisel plow 20- to 25-cm deep in the fall after harvest, and secondary tillage with a field cultivator before planting in the spring. Corn and soybean were planted in April or May each year in 76- and 38-cm rows, respectively. Winter wheat was drilled in late September or early October with row spacing of 19 cm. Corn was planted at 75 to 85,000 seeds ha^{-1}, soybean at 340 to 350,000 seeds ha^{-1}, and wheat at 3,500,000 seeds ha^{-1}. Fertilizer and pest management decisions were based on best management practices for each location according to the Illinois Agronomy Handbook (Nafziger, 2009). Nitrogen fertilization of corn occurred in the spring at or before planting as incorporated urea ammonium nitrate at rates of 224 kg N ha^{-1} for corn at Perry, and at 202 kg N ha^{-1} for corn following soybean or wheat, and at 246 kg N ha^{-1} for corn following corn at Monmouth. Wheat was fertilized at Monmouth with 34 and 56 kg N ha^{-1} and at Perry with 49 and 90 kg N ha^{-1} at planting and as spring topdress, respectively. No N fertilizer was applied to soybean. Additional P and K fertilizer was applied as necessary based on soil test results.

Soil Sampling and Analyses

Soils were sampled in May 2011 at the Monmouth site and at Perry in May 2012; this followed at least five full cycles of the 3-yr rotation at both sites. At the Monmouth site, three soil cores with 3.1 cm diam. were taken with a hand-held split-core sampler in each subplot. Samples were cut in the field at depths of 0 to 10 cm, 10 to 20 cm, 20 to 40 cm, and 40 to 60 cm and stored in plastic bags in a refrigerator. For the Perry site, an Amity 4804 tractor mounted hydraulic probe (Amity Technology, Fargo, ND) was used to take three soil cores 4.3 cm in diameter in each subplot. The cores were transported and stored in plastic sleeves until cut to obtain 0- to 10-cm, 10- to 20-cm, 20- to 40-cm, and 40- to 60-cm subsamples in the laboratory. Samples were then stored and refrigerated in plastic bags until analysis.

Bulk density (Mg m^{-3}) values were determined using the core method (Blake and Hartge, 1986). The remaining soil samples were air-dried and sieved through 2-mm sieve, and the three replicated samples from each plot were composited to provide one sample per plot. Particle size analysis was completed using the hydrometer method to determine the percentage sand, silt, and clay-sized particles (Gee and Bauder, 1986).Three subsamples of the 1- to 2-mm soil fraction at 0- to 10- and 10- to 20-cm depths were used to determine WAS (kg kg^{-1}) with an Eijkelkamp wet sieving apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) using the procedure developed by Kemper and Rosenau (1986).

Soil pH was determined with 1:1 soil/H_2O solution. Soil pH indicated inorganic C content to be negligible so total C was assumed to be identical to SOC (Al-Kaisi et al., 2005). Soil organic C and TN were analyzed using dry combustion with a CHN Elemental Analyzer (Costech Analytical Technologies, Inc, Valencia, CA). Available P was determined by flow injection (Lachat Quickchem Analyzer, Lachat Instruments, Loveland, CO) following Bray-1 extraction. Potassium and other exchangeable cations were determined with an inductively coupled plasma mass spectrometer (PerkinElmer, Waltham, MA) following Mehlich III extraction. The CEC (cmol kg^{-1}) was determined by the summation method of exchangeable cations (Sumner and Miller, 1996). Results for element concentrations were converted to element mass per soil area using the soil layer thickness and bulk density and were expressed as Mg ha^{-1} (SOC, TN) or kg ha^{-1} (P, K). The measured values for 0- to 10- and 10- to 20-cm depths were combined for the soil chemical properties to obtain values for 0 to 20 cm so that all layers were of equivalent thickness.

Data were analyzed using the MIXED procedure of SAS software version 9.3 (SAS Institute, 2012). Tillage, rotation, and depth were considered fixed effects, while blocks and sites were considered random effects. Dependent variables measured at successive depths were analyzed using a repeated measures approach selecting the variance–covariance matrix of the residuals based on the Akaike's Information Criterion (Littell et al., 2006). Probability values associated with the analysis of variance and variance component estimates of the random effects and parameters of the variance–covariance matrix are presented in Table 1. The data for SOC, TN, and P exhibited heterogeneity of variances based on the plots of residuals vs. predicted values; thus a logarithmic transformation was selected based on the Box–Cox power transformation series (Box and Cox, 1964). Backtransformed means are presented for ease of interpretation. Least square means were separated using the PDIFF option of LSMEANS in SAS PROC MIXED; least significant differences (LSD) values are reported at a level (a) = 0.10. The CORR procedure of SAS (SAS Institute, 2012) was used to evaluate the relationship between SOC and WAS. Statistical model and SAS codes are available on request from the authors.

RESULTS AND DISCUSSION

Table 1 shows the results of the analysis of variance for the effects of rotation, tillage, and soil depth and their interactions on the studied soil properties across sites. The effect of rotation on BD varied by tillage and depth (Table 2). Bulk density under NT did not differ among rotations at any depth except for greater BD at 20 to 40 cm for SSS compared to the other rotations. This may be due to the loosening effect of corn's fibrous roots on the soil which was absent under the taproot system of SSS (Coulter et al., 2009). In contrast, BD under CT varied by crop rotation, but only at the surface (0–10 cm) depth. In this layer, BD values were the least for CCC (1.19 Mg m^{-3}) and the greatest for SSS (1.30 Mg m^{-3}); CSW and CS had intermediate values (Table 2). The results of Varvel and Wilhelm (2011) mirrored these results with no differences in BD among crop rotations under NT, but under chisel tillage, BD at the soil surface was lower under CCC and greatest under SSS. While our study detected differences among cropping systems under CT, Huggins et al. (2007) reported no differences in BD among CCC, CS, and SSS regardless of tillage practice. Coulter et al. (2009) reported lower BD under CCC compared to CS under chisel tillage at two Illinois locations on Mollisols with the differences found in the surface 0 to 15 cm at one location, but at 15- to 30-cm depth at the other; the opposite results were reported for a third Illinois location on an Inceptisol. In contrast, other studies have reported no differences between CCC and CS under chisel tillage, including Karlen et al. (2006) and Jagadamma et al. (2007) on the same Muscatune soil series at Monmouth.

Reduced BD in rotations with less frequent soybean (CCC and CSW) is likely related to greater aggregate stability due to greater residue accumulation from corn and wheat compared to soybean (Coulter et al., 2009). Tillage mechanically disrupts the soil, incorporating the crop residues throughout the surface. The less dense organic matter from the crop residues coupled with open pore spaces left behind by the tillage process would lead to reduced BD under CT; this reduction would be more pronounced for crop rotations with greater residue production. Without the incorporation of residue, soils under NT may have a layer of crop residues of varying thickness on the soil surface, but this carpet of residues does not affect BD. The lack of BD differences among cropping systems under NT may also be related to the clay content of the soil. Hill (1990) observed that the physical properties of soils with relatively

Table 1. Probability values associated with the analysis of variance of the effects of rotation, tillage, and depth and their interactions on the studied soil variables: bulk density (BD), water aggregate stability (WAS), soil organic carbon (SOC), total nitrogen (TN), available phosphorus (P), exchangeable potassium (K), and cation exchange capacity (CEC). For completion, we include variance component estimates of the random terms and the estimates of the variance-covariance matrix selected [AR(1), first-order autoregressive; ARH(1), first-order heterogeneous autoregressive; TOEP, toeplitz] in the repeated measures analysis for each model.

Source	BD	WAS	SOC	TN	P	K	CEC	pH
				Probability values				
Rotation (R)	0.421	0.039	0.185	0.041	0.319	0.109	0.923	0.006
Tillage (T)	0.040	0.013	0.037	0.016	0.322	0.975	0.794	0.072
R × T	0.824	0.300	0.206	0.359	0.333	0.931	0.657	0.256
Depth (D)	0.088	0.240	0.054	0.052	0.043	0.030	0.481	0.334
R × D	0.324	0.989	0.569	0.672	0.169	0.507	0.842	0.035
T × D	0.371	0.087	0.534	0.247	0.279	0.638	0.715	0.231
R × T × D	0.048	0.101	0.282	0.616	0.429	0.934	0.533	0.992
Random effect				Variance estimates				
Site	0.008	0.334	0.084	0.03	0.01	866.8	0	0.299
Block (site)	0.002	0.121	0.003	0.0002	0.001	102.2	3.83	0.038
R × Block (site)	0.0004	0.147	0.003	0.001	0.0007	21.2	0	0.009
Site × D	0.0007	0	0.004	0.003	0.006	734.4	22.48	0.048
Site × R × D	0	0	0	0	0	0	2.91	0.008
Site × T × D	0.0003	0	0	0	0	0	0	0
Repeated measures structure	AR(1)	AR(1)	AR(1)	ARH(1)	AR(1)	ARH(1)	ARH(1)	TOEP
AR(1)	0.272	0	0.145	–	0.168	–	–	–
TOEP (2)	–	–	–	–	–	–	–	0.016
TOEP (3)	–	–	–	–	–	–	–	0
Residual	0.004	0.596	0.004	–	0.011	–	–	0.076
Var (1)	–	–	–	0.001	–	10042	23.70	–
Var (2)	–	–	–	0.003	–	1339.6	5.01	–
Var (3)	–	–	–	0.006	–	2367.7	14.45	–
ARH(1)	–	–	–	0.05	–	0.409	0.115	–

Table 2. Bulk density across two sites as affected by tillage and rotation in the 0- to 10-, 10- to 20-, 20- to 40-, and 40- to 60-cm soil depths as well as averaged over 0 to 60 cm 15 yr following establishment.

Tillage	Depth	Rotation				Across rotations
		CCC†	CS	CSW	SSS	
	cm	Mg m^{-3}				
NT	0–10	1.29a‡§	1.28a	1.33a	1.30a	1.30
	10–20	1.40a	1.43a	1.43a	1.39a	1.41
	20–40	1.38b	1.39b	1.37b	1.44a	1.39
	40–60	1.37a	1.32a	1.37a	1.37a	1.36
CT	0–10	1.19c	1.25ab	1.24bc	1.30a	1.25
	10–20	1.35a	1.36a	1.34a	1.39a	1.36
	20–40	1.39a	1.37a	1.41a	1.39a	1.39
	40–60	1.34a	1.32a	1.36a	1.34a	1.34
NT	0–60	1.36	1.36	1.38	1.37	1.37A¶
CT		1.32	1.33	1.33	1.35	1.33B

† CCC, continuous corn; CS, corn–soybean; CSW, corn–soybean–wheat; SSS, continuous soybean; NT, no-till; CT, conventional tillage.

‡ Letters indicating significant differences are shown only for significant effects (α = 0.10).

§ Within rows, means at the same depth followed by the same lowercase letter are not significantly different by the Fisher's protected LSD test (α = 0.10).

¶ Within the column, means averaged across rotations followed by the same uppercase letter are not significantly different by the Fisher's protected LSD test (α = 0.10).

high clay content (about 21%), like the soils in our study, may be less likely to exhibit differences as a result of long-term management practices.

Bulk density was 2.4% greater under NT (1.37 Mg m^{-3}) than under CT (1.33 Mg m^{-3}) averaged across depths and rotations (Table 2). The increased BD under NT has been reported in a number of other studies, and is ascribed to the lack of mechanical fracturing of the soil under NT (Wander and Bollero, 1999; Balesdent et al., 2000; Halvorson et al., 2002). Across rotations and tillage treatments, the average BD was the smallest in the surface 0 to 10 cm (1.27 Mg m^{-3}). Despite the differences, all BD values are less than values considered root-inhibiting in silt loam and silty clay loam soils (Arshad et al., 1996).

No differences in SOC values were detected among rotations across the two sites (Tables 1 and 3) yet, significant differences were found in WAS among rotations (Tables 1 and 4). The formation and stability of soil aggregates is often related to the amount of SOC; therefore, WAS has been reported to increase with a corresponding increase in SOC (Martens, 2000). Water aggregate stability was the greatest for CSW rotation at 0.87 kg kg^{-1} while the smallest WAS values were detected in the CS and SSS rotations at 0.82 and 0.79 kg kg^{-1}, respectively; CCC had an intermediate value of 0.83 kg kg^{-1}. These differences among crop rotation were found over 0 to 20 cm in CT, but only at the 10- to 20-cm depth in NT, likely due to slower decomposition of crop residues in the surface of NT. While SOC was not significantly different among rotations, SOC was positively correlated with WAS (r = 0.49, $P \leq$ 0.0001), as expected. Significant differences in SOC among rotations were not detected and may be attributed to the high initial SOC levels in these soils, which would make them less sensitive to change (Kumar et al., 2012). Since WAS is related to the amount of SOC, greater C additions from more crop residues increase the formation of soil aggregates, but it is also the quality and biochemical characteristics of the residue that affect aggregate stability (Martens, 2000). The results indicate

Table 3. Effect of rotation and tillage on soil organic carbon (SOC) and total nitrogen (TN) at 0- to 20-, 20- to 40-, and 40- to 60-cm depths. Main effects of tillage and rotation (summation of 0–60-cm soil depths) and depth (averaged across treatments) are also shown.

Treatment	Soil depth				Soil depth			
	0–20 cm	20–40 cm	40–60 cm	0–60 cm	0–20 cm	20–40 cm	40–60 cm	0–60 cm
	SOC‡, Mg ha^{-1}				TN, Mg ha^{-1}			
Rotation								
CCC†	44.6	30.5	18.6	93.7	4.00	2.87	1.82	8.69ab§¶
CS	40.9	31.0	17.3	89.2	3.91	2.92	1.73	8.56b
CSW	47.1	33.5	21.3	101.9	4.22	3.02	2.03	9.27a
SSS	41.2	30.0	18.4	89.6	3.61	2.68	1.75	8.04b
Tillage								
NT	45.0	31.6	19.4	96.0a	4.09	2.89	1.89	8.87a
CT	41.8	30.9	18.3	91.0b	3.78	2.84	1.78	8.40b
Across all treatments	43.4A#	31.2B	18.8C		3.93A	2.87A	1.83B	

† CCC, continuous corn; CS, corn–soybean; CSW, corn–soybean–wheat; SSS, continuous soybean; NT, no-till; CT, conventional tillage

‡ Analyses for SOC and TN were performed on log-transformed data; results shown have been backtransformed.

§ Letters indicating significant differences are shown only for significant effects (α = 0.10).

¶ Means followed by the same lowercase letter within a column and treatment are not significantly different by the Fisher's protected LSD test (α = 0.10).

For the main effect of depth, means averaged across all treatments followed by the same uppercase letter are not significantly different by the Fisher's protected LSD test (α = 0.10).

Table 4. Water aggregate stability across two sites as affected by tillage and rotation in the 0- to 10- and 10- to 20-cm soil depths as well as averaged over 0 to 20 cm 15 yr following establishment.

Tillage	Depth	Rotation				Across rotations
		CCC†	CS	CSW	SSS	
	cm	kg kg^{-1}				
NT	0–10	0.93a‡§	0.86a	0.89a	0.83a	0.85
	10–20	0.88a	0.83ab	0.86a	0.76b	0.83
CT	0–10	0.85ab	0.80bc	0.87a	0.77c	0.82
	10–20	0.77b	0.78ab	0.86a	0.81ab	0.80
NT	0–20	0.84	0.83	0.88	0.80	0.84A¶
CT		0.81	0.81	0.86	0.78	0.81B
Across tillage		0.83ab	0.82b	0.87a	0.79b	

† CCC, continuous corn; CS, corn–soybean; CSW, corn–soybean–wheat; SSS, continuous soybean; NT, no-till; CT, conventional tillage.

‡ Letters indicating significant differences are shown only for significant effects (α = 0.10).

§ Within rows, means at the same depth or averaged across tillage followed by the same lowercase letter are not significantly different by the Fisher's protected LSD test (α = 0.10).

¶ Within the column, means averaged across rotations followed by the same uppercase letter are not significantly different by the Fisher's protected LSD test (α = 0.10).

that WAS decreases with increasing frequency of soybean in the rotation; similar results were found by Gantzer et al. (1987) and Martens (2000), who reported soil under soybean had a less stable structure than soil under corn. This has been credited to lower phenolic acid content, a precursor of soil humic substances, in soybean residue (Martens, 2000). It may also be related to the rapid decomposition of soybean residue due to the relatively lower C/N ratio of the legume, which can lead to the formation of aggregates that are more susceptible to degradation (Blanco-Canqui and Lal, 2004).

Rotations with soybean incorporated more frequently (SSS and CS) had lower TN compared to CSW; CCC had intermediate values (Table 3). Jagadamma et al. (2007) also reported greater TN under CCC than a CS rotation, but only in the surface 20 cm at Monmouth, whereas our results indicate differences between the two rotations over the full 60 cm measured soil profile. As a result of N fertilization of corn and wheat, the CSW and CCC rotations have greater inputs of N compared to the CS and SSS. However, greater N inputs do not necessarily lead to greater TN compared to other cropping systems with less N fertilization; losses of N in the form of leaching of nitrates and denitrification gaseous losses can offset the addition of N to the soil. The return of greater crop residue from corn and wheat compared to soybean is an important factor in the greater TN under rotations that incorporate these crops more frequently.

Table 5. Effect of rotation and tillage on soil pH at 0–20, 20–40, and 40–60 cm depths. Main effects of tillage and rotation (averaged over 0–60 cm soil depths) and depth (averaged across treatments) are also shown.

Treatment	Soil depth			
	0–20 cm	20–40 cm	40–60 cm	0–60 cm
	Soil pH			
Rotation				
CCC†	5.3c‡§	6.1a	6.1a	5.9c
CS	5.7b	6.3a	6.2a	6.1b
CSW	5.7b	6.3a	6.2a	6.0b
SSS	6.4a	6.3a	6.1a	6.3a
Tillage				
NT	5.7	6.2	6.2	6.0b
CT	5.9	6.3	6.1	6.1a
Across all treatments	5.6	6.3	6.1	

† CCC, continuous corn; CS, corn–soybean; CSW, corn–soybean–wheat; SSS, continuous soybean; NT, no-till; CT, conventional tillage.

‡ Letters indicating significant differences are shown only for significant effects (α = 0.10).

§ Means followed by the same lowercase letter are not significantly different by Fisher's protected LSD test (α = 0.10).

While no differences were detected among rotations for available P or CEC across sites, there were differences for K (Table 1). Potassium levels were lowest in SSS with 312 Mg ha^{-1} total in 0 to 60 cm compared to 351 Mg ha^{-1} and 343 Mg ha^{-1} in CSW and CCC, respectively; CS was intermediate with 325 Mg ha^{-1}. The lower K levels in the soil under SSS are likely due to a greater uptake of K by soybean compared to the corn as reported by Russell et al. (2006) and Jagadamma et al. (2008). Both P and K were greater in the surface 20 cm across all treatments compared to the soil below with P values of 69.6, 25.3, and 23.3 kg ha^{-1} and K values of 525, 232, and 240 kg ha^{-1} for 0 to 20 cm, 20 to 40 cm, and 40 to 60 cm, respectively; CEC did not differ among treatments or depth (Table 1). The differences in the pH of the soil were related to the frequency of corn in the rotation; soil under CCC was the most acidic followed by CSW and CS, with the greatest pH under continuous soybean (Table 5). The three rotations that contain corn had more acidic soil at the surface 20 cm compared to the soil below, but the soil pH under SSS was greater at the surface and remained relatively constant through greater soil depths. Acidification of the soil is related to surface or near-surface applications of N fertilizer, which occur more frequently in CCC than in the other rotations, and never in SSS. Reduced acidification under rotations with more frequent soybean and therefore less N fertilization has been previously reported by Divito et al. (2011). Karlen et al. (1991) similarly found lower pH under continuous corn compared to other crop rotations.

Soil organic carbon and TN over the full 0- to 60-cm depth were greater under NT than CT averaged over rotations (Table 3). A number of studies have reported similar results (West and Post, 2002; Kumar et al., 2012). Under conventional tillage, crop residues and soil organic matter are mechanically disturbed and exposed to soil microorganisms. This stimulates decomposition and can lead to depletion of organic matter and

SOC as previously protected C within the soil organic matter mineralizes (Balesdent et al., 2000). In contrast, no-till soils are undisturbed and can accumulate crop residues, especially at the soil surface while previously existing stable soil organic matter is protected. Since aggregate stability is often related to increases in SOC (Martens, 2000), it is not surprising that greater WAS was also found in NT than CT (Table 4). Water aggregate stability under NT was 0.84 kg kg^{-1} compared to 0.81 kg kg^{-1} found under CT; under NT, WAS differed among the crop rotations only at the 10- to 20-cm soil depth. It is interesting to note that while SOC was not significantly different among crop rotations, there were differences in WAS. In contrast, the effect of tillage was significant for both SOC and WAS (Table 1). No differences between tillage treatments were detected for P, K, or CEC values throughout the profile (Table 1). The soil pH was 6.1 under CT and 6.0 under NT over 0- to 60-cm soil profile, which differs from the results of many studies that report lower pH only in the surface soil under NT as a result of having acidification of the soil from N fertilization remain stratified with NT (Crozier et al., 1999; Divito et al., 2011).

This study set out to examine the interactive effects of rotations and tillage, but the lack of significant rotation × tillage interaction effects except for the three-way rotation × tillage × depth interaction for BD and WAS indicate that the rotations affected soil chemical properties similarly regardless of tillage practices. A similar lack of interaction between rotation and tillage was reported by Kumar et al. (2012) and Varvel and Wilhelm (2011). It is surprising that a similar trend was not found for the chemical properties as for BD where rotations varied under CT, but there were no differences under NT. Since the rotations primarily differ by the quantity and quality of crop residues, the effect of tillage on the rate of decomposition might be expected to affect the amount of C and N stored within the soil.

While SOC, WAS, and TN under CCC were intermediate and did not differ from either CSW or CS, yields of CCC over 15 yr at these two sites were 17% lower than for corn rotated with soybean, and no-till yielded 8% less than tilled plots in CCC compared to CS (Nafziger, unpublished data, 2014). While the lower yield of CCC should lead to lower residue production each year in CCC compared to the corn in CS and CSW, the accumulated organic matter from growing corn every year maintains SOC and TN to the same level. This also suggests that factors beyond the soil properties measured in this study are affecting crop yields at these two sites.

CONCLUSIONS

Tillage was more influential on SOC than crop rotations after 15 yr since establishment. Greater levels of SOC, TN, and higher BD and WAS were found under NT compared to CT. Potassium levels were greater in CSW and CCC compared to SSS, and despite no differences in SOC among rotations, WAS, and TN were greater under the 3-yr CSW rotation and CCC than in CS or SSS rotations. The latter two variables were apparently more sensitive to the differential inputs of the various cropping systems. The two most common crop rotations, CCC and CS, were similar at storing N and protecting soil aggregates. The addition of wheat to a corn–soybean rotation may be beneficial to soil quality, but extended CSW rotation affected the soil in the same way as the far more common CCC monoculture. We suspect that the study of certain biological properties such as changes in the microbial communities within these soils and their effects on nutrient cycling might be more sensitive to crop rotations than the standard properties evaluated here yet need further investigation.

Our results suggest the shift toward continuous corn in the Midwest related to increasing corn prices has not been detrimental to soil quality; however, high initial SOC levels and finer soil textures may make it difficult to detect changes even after 15 yr of management. Of more concern, however, is the more selective use of no-till as producers shift toward including more corn in their rotations. While the greater production of corn is not detrimental to soils in the U.S. Corn Belt, the corresponding shift in tillage practices may have a greater impact on soil quality.

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