Long-Term No-Till Impacts on Organic Carbon and Properties of Two Contrasting Soils and Corn Yields in Ohio

Sandeep Kumar*
Carbon Management and Sequestration Center
School of Environment and Natural Resources
Ohio State Univ.
2021 Coffey Road
Columbus, OH 43210-1085

Atsunobu Kadono
Tottori Univ. of Environmental Studies
Tottori, 689-1111, Japan

Rattan Lal
Carbon Management and Sequestration Center
School of Environment and Natural Resources
Ohio State Univ.
2021 Coffey Road
Columbus, OH 43210-1085

Warren Dick
School of Environment and Natural Resources
Ohio Agricultural Research and Development Center
Ohio State Univ.
1680 Madison Avenue
Wooster, OH 44691-4096

Tillage influence on soil properties and crop productivity depends on soil, crop, climate, and duration. Two long-term experimental sites with contrasting soils were selected to assess the influence of no-till (NT), minimum tillage (MT), and plow tillage (PT) under continuous corn (*Zea mays* L.) and corn–soybean [*Glycine max* (L.) Merr.] (CS) rotations on soil organic C (SOC) stock, bulk density (ρ_b), water-stable aggregation (WSA), aggregate tensile strength, penetration resistance, available water capacity (AWC), and corn yield. Experiments began in 1962 in northeast Ohio on a well-drained silt loam soil and in 1964 in northwest Ohio on a poorly drained clay loam soil. Results were compared with soil under an adjacent undisturbed woodlot (WL). The WL soils had the highest SOC content and stock. In the cultivated silt loam soil, stock was higher under NT (20.7 Mg ha^{-1}) followed by MT (17.3 Mg ha^{-1}) and PT (16.8 Mg ha^{-1}) for the 0- to 10-cm depth. Soil ρ_b for this depth was lower under NT by 8 and 3% than PT and MT, respectively. The percentage of total WSA >2000 μm in soil under NT (47%) was significantly higher than under MT (38%) or PT (34%). A similar trend was observed for the clay loam soil. Rotation also influenced soil properties. Corn yields were higher (3 yr) and lower (1 yr) during 5 yr for the silt loam soil under PT than NT and unaffected or slightly higher under NT for the clay loam soil. Long-term (47–49 yr) use of NT practices are highly sustainable and result in higher SOC and WSA, lower ρ_b, and greater AWC content than MT or PT.

Abbreviations: CC, continuous corn; CS, corn–soybean; AWC, available water capacity; MT, minimum tillage; MWD, mean weight diameter; NT, no-till; PT, plow tillage; SOC, soil organic carbon; SOM, soil organic matter; SPR, soil penetration resistance; TS, tensile strength; WSA, water-stable aggregation.

The choice of tillage and rotation practices suitable for an area depends on the climate, the type of soil, and the crop. These practices, when used in a favorable environment, help in improving soil properties and sustaining crop productivity by influencing, for example, SOC, aggregation and stability (Yang et al., 2007), and water retention of soils (Blanco-Canqui and Lal, 2008). Intensive tillage, however, disrupts the soil structure (Madari et al., 2005) and increases the oxidation of soil organic matter (SOM) because of increased aeration and microbial activity (Vance, 2000). Thus, it depletes the SOC stocks through erosion (Blanco-Canqui and Lal, 2008). It has been reported that conversion of natural systems to agroecosystems can deplete the SOC stock by as much as 40% for soils under forest to ~60% for those under grassland (Blanco-Canqui and Lal, 2008; West and Post, 2002). The NT system has been used in the Corn Belt soils of the U.S. Midwest for more than half a century (Wander et al., 1998) to enhance corn and soybean production. Therefore, this system is being promoted as an al-

---

Soil Sci. Soc. Am. J. 76:1798–1809
doi:10.2136/sssaj2012.0055
Received 16 Feb. 2012.
*Corresponding author (kumar.278@osu.edu).

ternative to more intensive tillage systems to restore SOC stocks and to improve soil properties (Blanco-Canqui et al., 2009).

Aggregate size and stability are strongly influenced by different tillage and cropping sequences. These structural attributes play a major role in providing adequate habitat and protection for soil organisms, supplying O_2 to roots, reducing the risks of accelerated soil erosion (Franzluebbers, 2002), and enhancing crop productivity. The NT systems result in more plant residues on the soil surface, which protect the soil from crusting and surface sealing (Lentz and Bjorneberg, 2003). Thus, macroaggregate formation and stability, due to increased microbial activity and production of binding agents, is enhanced (Golchin et al., 1994). Macroaggregates under NT soils protect fresh SOM from decomposition (Beare et al., 1994), whereas PT disrupts these aggregates, releases bound microaggregates and SOM contained within macroaggregates, and makes it more susceptible to decomposition (Six et al., 2000).

When soil is continuously tilled by heavy machinery, the bulk density (ρ_b) and soil penetration resistance (SPR) of these soils increases progressively, which decreases the water retention (Dao, 1996). In contrast, soils under NT remain undisturbed, and residues that remain in and on the soil from previous crops support the buildup of an elaborate subsurface channel network (Dao, 1996). Subsequently, the SOC stock under NT systems improves, which decreases the ρ_b and SPR and hence improves pore size distribution and AWC compared with those under reduced or full inversion PT (Blanco-Canqui and Lal, 2008). Furthermore, tillage also influences the tensile strength (TS) of aggregates, which is a sensitive indicator of the soil physical quality (Rahimi et al., 2000). Soils with higher SOC content generally have decreased TS of aggregates (Blanco-Canqui et al., 2005).

The effects of tillage and cropping systems on SOC, WSA, TS, ρ_b, and SPR vary spatially and temporally, yet most studies are limited to short durations and their results are mostly site specific (Kennedy and Schillinger, 2006). Conclusions drawn from short-term studies can be contradictory and misleading due to differences in prevailing climates and soil properties, antecedent conditions, crop rotations, etc., not yet reaching equilibrium conditions (Ferreras et al., 2000; Lal and Van Doren, 1990). Furthermore, long-term studies are needed to assess the effects of different cropping systems and management on soil productivity (Mrabet et al., 2001). Credible data based on long-term tillage and rotation systems on soil properties and crop yields in contrasting soil types are needed for identifying and implementing the best management practices for enhancing and sustaining productivity. Therefore, the specific objectives of this study were to assess the effects of long-term tillage and cropping systems on SOC, some soil properties, and corn yield and to compare the soil properties with those measured for undisturbed natural ecosystems.

MATERIALS AND METHODS

Long-Term Experimental Sites

The long-term experimental sites are located at the Ohio Agricultural Research and Development Center (Wooster, OH; 40°25′ N, 83°15′ W; Fig. 1) on a well-drained Wooster silt loam soil (a fine-loamy, mixed, active, mesic Oxyaquic Fragiudalf) and at the Northwestern Agricultural Research Station (Hoytville, OH; 41°29′ N, 84°9′ W; Fig. 1) on a poorly drained Hoytville clay loam soil (a fine, illitic, mesic Mollic Epiaqualf). The Wooster plots were established in 1962 (49 yr) and those at Hoytville in 1964 (47 yr). Treatments included three tillage systems—NT, MT, and PT—and two cropping sequences—CC and CS. Each crop in the CS rotation was planted every year. These two experiments were established to monitor the long-term effects of tillage and crop sequences on soil properties and agronomic productivity (Dick et al., 1991).

At the Wooster site, the PT system involved moldboard plowing to a depth of 20 to 25 cm in the spring of each season, followed by a 10-cm-deep secondary tillage (disking or field cultivator) before planting. The MT system involved chisel plowing, without soil inversion, to a depth of 20 to 25 cm in spring, followed by a single pass of a field cultivator to the 10-cm depth just before planting. The MT system retains crop residues on the soil surface but often less than the 30% normally required to qualify as a conservation tillage practice. The PT treatment incorporates almost 100% of the residues. The NT treatment involved complete elimination of pre-plant tillage operations, and seed was planted directly into soil that had residues remaining on the surface from the previous year's crop. Research plots were 22.3 by 4.3 m, with the long dimension up and down the slope (2–4%). Soils of this site are well drained and silt loam in texture. The mean annual temperature is 9.1°C, and mean annual precipitation is 905 mm (Dick et al., 1998).

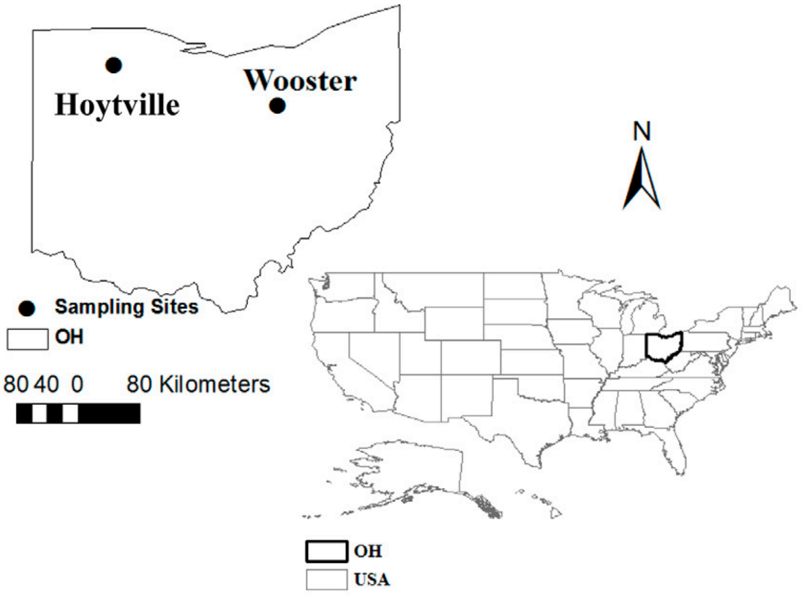

Fig. 1. Location of long-term sites for the Hoytville and Wooster soils in the state of Ohio and location of Ohio in the United States.

At the Hoytville site, tillage was performed in the fall every year. During the 6-yr interval before 1962 and 1963, this site was under a corn–oat (*Avena sativa* L.)–meadow rotation, with plowing and disking during 4 of the 6 yr. Soils at this site are nonsloping and have poor drainage when wet but cracks when dry. Research plots at this site were 27.4 by 6.1 m in size. At this site, tile drains have been installed at 17-m spacing. The mean annual temperature at Hoytville site is 9.9°C, and mean annual precipitation is 845 mm (Dick et al., 1998).

The WL areas at both sites included part of the remnants of a hardwood forest, which dominated the area before the land clearing that occurred in the 1930s and have no history of agricultural disturbances (Mishra et al., 2010). The experimental design at both sites was a factorial randomized block with three replications.

Treatments, Soil Sampling, and Analysis

Soil samples (n = 36 for each site) were collected with a shovel from both long-term sites (Wooster and Hoytville) during July 2011 from the three tillage (NT, MT, and PT) and two cropping systems (CC and CS) from all plots at the 0- to 10- and 10- to 20-cm depths. In addition, soil samples from these depths were also collected in triplicate (n = 6 for each site) from nearby natural undisturbed soils (WL). The soil samples from the WL sites were collected in three replicated areas at a distance of at least 2 m from the base of tree trunks. Intact soil cores (n = 72 for each tillage treatment and 12 samples from WL areas of each site) of 5.35-cm diameter and 6.0-cm length were also collected with a core sampler at four (0–10, 10–20, 20–30, and 30–40-cm) depths. At both sites, the long-term tillage plots and WL areas were next to each other, and hence, had similar soil and slope characteristics. Bulk soil samples were air dried and passed through 8- and 5-mm mesh screens to collect soil aggregates between the 5- and 8-mm sizes. Disturbed soil samples and intact soil cores were labeled, trimmed at both ends (for the intact core samples), sealed in plastic zip-lock bags, transported to the laboratory, and stored at 4°C pending analysis.

Soil Bulk Density and Organic Carbon Stock

Soil ρ_b for the 0- to 10-, 10- to 20-, 20- to 30-, and 30- to 40-cm depths was determined by the core method (Grossman and Reinsch, 2002). Soil cores were dried at 105°C until constant weight (about 48 h), and the oven-dry soil weight was divided by the core volume to calculate the ρ_b.

Soil samples were also collected using a metallic auger at the 0- to 10-, 10- to 20-, 20- to 30-, and 30- to 40-cm depths for determining the SOC concentration by the dry combustion method (900°C) using a vario Max CN elemental analyzer. The pH of the soils at both sites ranged from 5.3 to 5.5, and soil inorganic carbon (SIC) concentrations were $\leq$0.1%. Therefore, the SIC content was ignored and total C was considered to be SOC (e.g., Jagadamma and Lal, 2010). Furthermore, the SOC stocks were estimated based on an equivalent soil mass–depth basis to correct for differences in bulk density among the treatments (Ellert and Bettany, 1995). The SOC stock (Mg ha^{-1}) was computed by multiplying the SOC concentration by the ρ_b (Mg m^{-3}) and the equivalent soil depth d (m):

$$\text{SOC stock} = d\rho_b \text{SOC}_s \times 10{,}000\left(\text{m}^2\ \text{ha}^{-1}\right) \qquad [1]$$

where SOC$_s$ is the SOC concentration of the equivalent depth d (kg kg^{-1}).

Water-Stable Aggregation

The size distribution and amount of WSA were measured using the wet sieving method (Yoder, 1936). Six sieves of 6.375-, 3.375-, 1.5-, 0.75-, 0.375-, and 0.150-mm-diameter openings were nested and placed into a Yoder apparatus (Kemper and Rosenau, 1986) for the aggregate analysis. Air-dried aggregates (5–8 mm, 50 g) were slowly wetted by capillarity by adjusting the water level in the container so that the base of the top sieve just touched the water. The sieve nest was oscillated mechanically in the water at 60 oscillations min^{-1} for 30 min. Aggregates retained in the sieves were transferred to glass beakers. The weight of each of six fractions was measured after drying at 40°C for 2 to 3 d. The data from the six aggregate size fractions were grouped into four fractions: large macroaggregates (>2000 μm), small macroaggregates (>250–2000 μm), microaggregates (53–250 μm), and silt- and clay-sized microaggregates (<53 μm). The data were analyzed to compute WSA (Kemper and Rosenau, 1986) and the mean weight diameter (MWD) (Youker and McGuinness, 1957).

Tensile Strength of Aggregates

The TS of aggregates for all the tillage treatments and the WL areas at both sites was determined for the air-dry aggregates of 4.75- to 8.00-mm size from the 0- to 10- and 10- to 20-cm depths. A subsample of air-dry soil from each depth was gently broken and passed through sieves having 4.75- and 8-mm openings. The TS of these aggregates was determined by measuring the force required to crush an individual aggregate (Dexter and Watts, 2001). A total of 378 (n = 9 per depth for each plot including 54 from WL areas) aggregates from each site were used for the determination of the TS. The TS of aggregates was computed by (Rogowski et al., 1968)

$$\text{TS} = k\left(\frac{F}{D^2}\right) \qquad [2]$$

where F is the vertical force (N) applied to break the aggregate, D (m) is the mean aggregate diameter, and k is a dimensionless constant equal to 0.576. The diameter (d) of the aggregate was estimated as

$$d = \frac{s_1 + s_2}{2} \qquad [3]$$

where s_1 and s_2 are the openings of the upper and lower sieves used for that specific size class.

Soil Penetration Resistance

The SPR measurements were made for the 0- to 5- and 5- to 10-cm depths for all the tillage and cropping systems at both sites using an Eijkelkamp-type hand penetrometer (Herrick and Jones, 2002). Six SPR readings were made at each plot and the average value was used to represent the SPR of each plot. Soil water samples were also collected to confirm that any differences between the treatments were due to SPR and not to the water content. The SPR measurements were standardized for moisture changes using the following relationship developed by Busscher and Bauer (2003):

$$\mathrm{SPR_c} = \mathrm{SPR_o} \exp\left(\frac{x-0.1}{0.132}\right) \qquad [4]$$

where $\mathrm{SPR_c}$ is the adjusted penetration resistance (kPa), $\mathrm{SPR_o}$ is the measured penetration resistance, x is the water content (kg kg^{-1}), and 0.1 is the selected water content for standardization (0.1 kg kg^{-1}).

Available Water Capacity

Soil water retention at matric potentials of −33 and −1500 kPa was measured using a pressure plate apparatus (Soil Moisture Equipment Corp.) (Dane and Hopmans, 2002). The undisturbed soil cores were used for calculating the soil water retention at field capacity (−33 kPa), whereas disturbed sieved samples (<2-mm size) were used to determine the permanent wilting point (−1500 kPa). Volumetric values for water retention were calculated from the gravimetric data using the ρ_b. The AWC of the soil was calculated from the difference in volumetric moisture content at −33 and −1500 kPa. The AWC was computed for all treatments including the WL areas for the 0- to 10- and 10- to 20-cm soil depths.

Statistical Analysis

Soil samples collected from the randomized complete block design at two locations from three tillage and two crop rotations were analyzed separately with the PROC MIXED module of SAS (SAS Institute, 2007). Tillage, rotation, and depth were designated as fixed effects and replication was designated as a random effect in the model. A separate analysis was also performed to compare the treatments including WL using the PROC MIXED module of SAS. Estimates for the differences between treatments at different depths were obtained using the MIXED procedure in SAS. Statistical differences were declared significant at the $\alpha = 0.05$ level.

RESULTS AND DISCUSSION

Soil Organic Carbon

Data for SOC concentrations (g kg^{-1}) and stocks (Mg ha^{-1}) of the different treatments at the Wooster and Hoytville sites are presented in Table 1. The WL soils had the highest stocks compared with the cultivated soils. This was attributed to the incorporation of dead roots and faunal transport of residues in WL areas (Balesdent et al., 2000).

At the Wooster site, the SOC content and stocks were significantly higher under NT than the MT and PT systems for the 0- to 10- and 10- to 20-cm depths and remained unaffected beyond 20 cm. Mean SOC content ranged from 3.41 to 26.8 g kg^{-1}. The SOC content and stock values decreased with increasing depth. The stock values under NT were 20 and 7% higher for the 0- to 10- and 10- to 20-cm depths, respectively, compared with MT, and 23 and 39% compared with the PT treatment. Total SOC stocks for the 0- to 40-cm depth were 7% higher under NT (51.3 Mg ha^{-1}) than PT (47.8 Mg ha^{-1}), whereas SOC stocks were 2% lower under NT than MT (52.5 Mg ha^{-1}).

At the Hoytville site, the SOC content was influenced by tillage at the 0- to 10- and 10- to 20-cm depths, and a higher value was observed under NT (19.9 and 17.1 g kg^{-1}, respectively) than PT (15.1 and 12.8 g kg^{-1}, respectively). The SOC stock was also significantly different among the tillage systems for the 0- to 10-cm depth only, where it was 25% higher under NT than PT. The total SOC stock for the 0- to 40-cm depth was 4 and 13% higher under NT (64.4 Mg ha^{-1}) than MT (61.7 Mg ha^{-1}) and PT (57.2 Mg ha^{-1}), respectively. At both sites, in general, SOC content and stock values were higher for NT than MT and PT for the top 20-cm depth, and beyond this depth, the stock was almost the same. Rotation did not influence the contents or stocks at either site.

Soils at both sites had a history of tillage and crop rotation since 1962. Therefore, among cultivated soils, PT was considered to be a control, and NT and MT systems were compared with PT. Furthermore, cultivated soils were also compared with that of native vegetation (WL). Our data show that after using NT practice for more than four decades (47–49 yr), the SOC stock was improved compared with soils under PT. In general, the SOC stock was higher under CC than the CS rotation; however, differences were not significant. This was attributed to the higher residues added to the soil from corn under CC compared with soybean in the CS rotation.

In a 28-yr experiment involving continuous PT vs. NT on a Chalmers silty clay loam soil (a fine-silty, mixed, superactive, mesic Typic Endoaquoll), Gal et al. (2007) observed that NT resulted in an overall gain of 10 Mg ha^{-1} SOC to the 1-m depth. The SOC content was higher under NT up to 15 cm, there was no difference up to 30 to 50 cm, and NT had a reduced SOC content up to the 60-cm depth. These researchers also reported from the same experiment that CC stored slightly more SOC than a CS rotation; however, no substantial gain in SOC was observed with CC. Wander et al. (1998) conducted a study in central Illinois on a somewhat poorly drained Aquic Argiudoll silt loam and a poorly drained Typic Haplaquoll silty clay loam to compare the SOC between NT and PT systems. They observed that both systems adopted for a 19-yr duration had varied effects on the SOC depth distribution because of initial C contents and textures. The SOM-C was 25% higher for the 0-to 5-cm depth under the NT system compared with the PT system. The NT practice, however, is not always effective in SOC sequestration, especially in fine-textured soils, under cold and poorly drained

Table 1. Soil organic C (SOC) concentrations and stocks for the 0- to 10-, 10- to 20-, 20- to 30-, and 30- to 40-cm depths maintained under long-term tillage and crop rotations and woodlots for the Wooster and Hoytville sites.

Treatment†	SOC				SOC Stock			
	0–10 cm	10–20 cm	20–30 cm	30–40 cm	0–10 cm	10–20 cm	20–30 cm	30–40 cm
	g kg^{-1}				Mg ha^{-1}			
				Wooster				
Tillage								
PT	14.0 c‡	9.52 b	7.01 ab	5.05 b	16.8 c	13.2 b	10.2 ab	7.53 a
MT	15.1 c	12.7 a	7.61 ab	5.21 b	17.3 c	17.2 ab	10.4 ab	7.55 a
NT	18.8 b	14.0 a	5.43 b	3.41 b	20.7 b	18.4 a	7.41 b	4.83 a
WL	26.8 a	16.1 a	11.4 a	6.53 a	28.9 a	21.3 a	15.7 a	9.43 a
Rotation								
CC	16.2 a	12.4 a	6.22 a	4.53 a	18.0 a	16.8 a	9.38 a	6.71 a
CS	15.7 a	11.7 a	6.01 a	4.58 a	18.6 a	15.7 a	9.31 a	6.53 a
				Analysis of variance $P > F$				
Tillage	<0.01	0.01	0.34	0.30	0.03	0.03	0.34	0.28
Rotation	0.65	0.78	0.85	0.81	0.62	0.47	0.96	0.92
Tillage × rotation	0.07	0.13	0.11	0.76	0.05	0.09	0.18	0.98
				Hoytville				
Tillage								
PT	15.1 c	12.8 c	10.8 b	7.07 b	17.7 c	15.9 c	13.7 b	9.85 b
MT	17.9 b	15.5 bc	10.6 b	8.65 b	20.5 bc	17.9 bc	12.1 b	11.2 ab
NT	19.9 b	17.1 b	9.89 b	8.45 b	22.1 b	19.7 b	12.1 b	10.5 b
WL	56.5 a	38.9 a	22.5 a	16.2 a	62.6 a	33.4 a	27.0 a	19.8 a
Rotation								
CC	17.1 a	15.1 a	10.6 a	7.93 a	19.6 a	17.9 a	13.1 a	10.2 a
CS	18.1 a	15.4 a	10.3 a	8.41 a	20.7 a	17.7 a	12.1 a	10.8 a
				Analysis of variance $P > F$				
Tillage	<0.01	0.02	0.74	0.80	0.02	0.12	0.70	0.91
Rotation	0.28	0.85	0.72	0.91	0.33	0.95	0.73	0.79
Tillage × rotation	0.40	0.52	0.33	0.82	0.47	0.56	0.40	0.63

† PT, plow tillage; MT, minimum tillage; NT, no-till; CC, continuous corn; CS, corn–soybean rotation; WL, woodlot areas with undisturbed soil.
‡ Means followed by different letters within a column, treatment, and site are significantly different at $P < 0.05$.

conditions, and in soils with high antecedent SOC content (Yang and Wander, 1999). Therefore, it takes longer to observe the beneficial effects of NT practices on SOC stocks based on climate and soil properties (Miller et al., 2004). Higher SOC stocks in the 0- to 5-cm depth under NT adopted for 41 yr compared with that under PT in silt loam soils was also reported by Jarecki and Lal (2005); however, they did not observe any effect on SOC stock after 16 yr of NT compared with PT on Hoytville clayey soil.

Compared with NT, the PT practice enhances SOC and N mineralization by incorporating crop residues, disrupting soil aggregates, and increasing aeration, hence reducing the SOC and N contents (Balesdent et al., 1990). It was reported by West and Post (2002) from a global analysis of long-term agricultural management experiments that conversion of PT to NT can sequester 0.57 Mg C ha^{-1} yr^{-1} during 15 to 22 yr. For the present study, a total gain of 0.19 and 0.17 Mg ha^{-1} yr^{-1} was observed for the top 20-cm soil profile for NT practices adopted for 47 and 49 yr, respectively. The difference in total stock gain is attributed to climate and soil type. Long-term NT management has improved the SOC stock under NT compared with PT practices. The stock of the Hoytville soils was higher due to the formation of these soils in a poorly drained landscape and in fine-textured parent materials (Dick, 1983).

Soil Bulk Density

Data on soil ρ_b for all the treatments at both sites are represented in Fig. 2. At the Wooster site, the tillage treatments significantly influenced the ρ_b in the 0- to 10- and 10- to 20-cm depths ($P < 0.01$). For these depths, ρ_b values in the NT soil (1.31 and 1.37 Mg m^{-3}, respectively) were significantly lower than those under PT (1.42 and 1.45 Mg m^{-3}, respectively) and MT treatments (1.35 and 1.41 Mg m^{-3}, respectively). Soil ρ_b for the 20- to 30-cm depth was different only between NT and PT treatments. The WL soils had the lowest ρ_b, but little differences in ρ_b were observed between WL and NT soils. Soil ρ_b increased with increasing depth up to 40 cm. Crop residue accumulation on the soil surface of NT soils improved the SOC stock and reduced the ρ_b. In contrast, mechanical tillage in PT plots increased the soil ρ_b compared with the NT and MT systems. For the 0- to 10- and 10- to 20-cm depths 8 and 6% higher values, respectively, for ρ_b were observed in PT compared with NT, and 5 and 3% higher values, respectively, compared with the MT system. Crop rotation also significantly affected the ρ_b but only for the 0- to 10-cm and 10- to 20-cm depths. The soil ρ_b under the CS rotation was

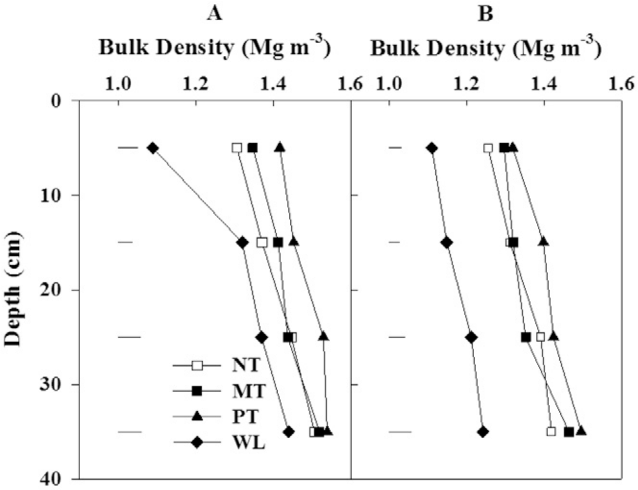

Fig. 2. Bulk density as influenced by no-till (NT), minimum tillage (MT), and plow tillage (PT), and in an adjacent woodlot (WL) area at different depths for the (A) Wooster and (B) Hoytville soils. Bars indicate the least significant difference (0.05) values and are presented at different depths when significant differences occurred among the treatments.

decreased by 3 and 2% in the 0- to 10- and 10- to 20-cm depths, respectively, compared with that under CC.

The soil ρ_b was also significantly affected by tillage at the Hoytville site ($P < 0.01$; Fig. 2) in the 0- to 10- and 10- to 20-cm depths. Among tillage systems, soils under NT had the lowest ρ_b followed by that under the MT and PT treatments up to the 20-cm depth. A significant decrease in ρ_b, from 1.32 Mg m^{-3} under PT to 1.30 Mg m^{-3} for MT and 1.26 Mg m^{-3} for NT, was observed only in the 0- to 10-cm depth. For the 10- to 20-cm depth, ρ_b was significantly lower (6%) only in soils under NT vs. PT. Crop rotation also influenced ρ_b; however, differences were significant only in the 0- to 10-cm depth ($P < 0.01$). Soil ρ_b was negatively correlated with SOC concentration with $r^2 = 0.54$ for Wooster and 0.43 for Hoytville. The lowest ρ_b was observed in soils under WL areas for all four depths compared with the cultivated soils. Similar trends were also reported by Mishra et al. (2010) and Murty et al. (2002). The tillage × rotation interaction for ρ_b was nonsignificant for both sites.

When NT is practiced continuously for a long duration, crop residue accumulates on the soil surface and promotes soil aggregation, which subsequently decreases the soil ρ_b (Blanco-Canqui and Lal, 2004). Furthermore, the reduction in soil ρ_b under NT compared with MT or PT can be attributed to better root growth, which can add additional SOM under NT. After 47 and 49 yr, the SOC stock improved and ρ_b was reduced under NT compared with PT systems established on both soils. Our findings are in accord with those reported previously for these sites (Dick et al., 1991, 1998). Roots of previous crops under NT plots remain undisturbed and build up an elaborate subsurface channel network (Dao, 1996), which decreases the soil ρ_b. In contrast, the surface soil under PT was crusted and compacted compared with that under NT and MT at both sites. In accord with the present data, significantly lower ρ_b values after 9 yr of NT compared with PT were reported by Dao (1996) for some silt loam soils. This is not always true when NT is used for such a short duration. In a calcic clay loam, Bescansa et al. (2006) reported higher ρ_b under NT than PT after 5 yr. Dick et al. (1991) also concluded that improvement in soil properties and crop yield are difficult to observe after a short duration (2–3 yr) of NT management, and beneficial effects become much more evident when observations are made at sites with long-term NT histories.

Differences in ρ_b values among sites are attributed to differences in soil type and climate. Soil ρ_b values for the Hoytville site were lower than those for the Wooster site partially because of a difference in soil texture between these sites. A higher clay content (Hoytville soil) stabilizes the soil SOC by adsorption, aggregation, and slow turnover (Alvarez and Lavado, 1998). Therefore, the Hoytville clay loam had a lower soil ρ_b than the Wooster silt loam. Continuous use of NT can improve soil quality.

Aggregate Stability and Mean Weight Diameter

The WSA and MWD data for the 0- to 10-cm and 10- to 20-cm depths under the different treatments are presented in Table 2. At the Wooster site, tillage significantly affected macroaggregates (>2000 μm) and silt- and clay-sized microaggregates (<53 μm) in the 0- to 10-cm depth and all the aggregate size fractions except the silt- and clay-sized microaggregates for the 10- to 20-cm depth ($P < 0.05$); however, most significant differences occurred between the NT vs. PT treatments. In the 0- to 10-cm depth, soils under NT (47%) had significantly more macroaggregates (>2000 μm) than those under MT (38%) or PT (34%). Retention of crop residues on the soil surface under NT significantly improved macroaggregate formation compared with PT (Lichter et al., 2008). Mechanical tillage contributes to the breakdown of soil macroaggregates in MT and PT systems.

The relative abundance of macroaggregates (>2000 μm) decreased with increasing depth for all tillage systems at the Wooster site. The soils under PT had higher amounts of microaggregates than those under NT and WL areas because of the disturbance created by cultivation in PT plots; however, differences were not significant among all aggregate size fractions. Rotation significantly influenced the macroaggregates in the 0- to 10-cm depth only. Soils under the CS rotation had 22% more WSA than soils under CC.

The MWD was significantly affected by tillage for the 0- to 10- and 10- to 20-cm depths at the Wooster site ($P < 0.01$; Table 2). The MWD ranged from 0.82 (PT) to 2.53 mm (WL) for the 0- to 10-cm depth and from 0.53 (PT) to 1.77 mm (WL) for the 10- to 20-cm depth. Among tillage systems, soils under NT had higher MWD than those under MT and PT treatments. Similar results of higher MWD for NT soils were also reported by Shukla and Lal (2005). Rotation also influenced the MWD for the 0- to 10-cm depth only.

For the cultivated soils at the Hoytville site, NT resulted in significantly more large macroaggregates than PT. The amount of macroaggregates in soils under NT was about 42 and 45% higher than those under MT and PT systems, respectively for the 0- to 10-cm depth and 24 and 47% higher, respectively, for the 10- to 20-cm depth. The MWD was also significantly higher

Table 2. Distribution of water-stable aggregates (WSA) and mean weight diameter (MWD) in the 0- to 10- and 10- to 20-cm soil depths maintained under long-term tillage and crop management and woodlots for the Wooster and Hoytville sites.

	0–10-cm depth					10–20-cm depth				
	WSA					WSA				
Treatment†	>2000 μm	250–2000 μm	53–250 μm	<53 μm	MWD	>2000 μm	250–2000 μm	53–250 μm	<53 μm	MWD
	%				mm	%				mm
					Wooster					
Tillage										
PT	34 c‡	26 b	16 a	24 a	0.82 c	23 c	41 a	19 a	17 b	0.53 d
MT	38 bc	32 a	14 a	16 b	1.50 b	27 bc	42 a	18 a	13 b	0.87 c
NT	47 a	28 ab	11 a	14 b	2.30 a	38 a	31 b	13 b	18 b	1.25 b
WL	43 ab	31 a	12 a	14 b	2.53 a	32 ab	28 b	14 b	26 ab	1.77 a
Rotation										
CC	36 b	30 a	13 a	21 a	1.25 b	29 a	37 a	18 a	16 a	0.81 a
CS	44 a	27 a	14 a	15 a	1.83 a	30 a	40 a	15 a	15 a	0.96 a
					Analysis of variance $P > F$					
Tillage	<0.01	0.07	0.22	0.02	<0.01	<0.01	0.03	0.05	0.70	<0.01
Rotation	0.01	0.10	0.88	0.06	<0.01	0.90	0.28	0.06	0.55	0.27
Tillage × rotation	0.01	0.05	0.55	0.20	0.43	0.09	0.22	0.01	0.91	0.11
					Hoytville					
Tillage										
PT	47 b	29 a	11 a	13 a	1.53 c	38 b	31 ab	13 a	18 a	1.58 c
MT	48 b	35 a	9 a	7 ab	2.46 b	45 ab	34 a	12 a	9 b	1.90 bc
NT	68 a	22 a	7 a	3 b	2.74 a	56 a	27 b	7b	10 ab	2.56 a
WL	67 a	23 a	8 a	2 b	2.84 a	54 a	23 b	11 ab	12 ab	2.35 ab
Rotation										
CC	49 a	33 a	9 a	9 a	2.04 b	45 a	32 a	11 a	12 a	1.89 a
CS	59 a	25 a	9 a	7 a	2.45 a	48 a	30 a	12 a	10 a	2.13 a
					Analysis of variance $P > F$					
Tillage	0.03	0.25	0.30	0.02	<0.01	0.01	0.27	0.13	0.01	0.04
Rotation	0.16	0.21	0.70	0.32	<0.01	0.72	0.55	0.85	0.10	0.41
Tillage × rotation	0.12	0.15	0.74	0.19	0.17	0.32	0.95	0.53	0.08	0.87

† PT, plow tillage; MT, minimum tillage; NT, no-till; CC, continuous corn; CS, corn–soybean rotation; WL, woodlot areas with undisturbed soil.

‡ Means followed by different letters within a column, treatment, and site are significantly different at $P < 0.05$.

for soils under NT than for those managed by the PT system for both depths. The MWD under NT was 11 and 79% higher than those under MT and PT treatments, respectively, in the 0-to 10-cm depth. Similar to the Wooster site, most of the significant differences in WSA and MWD values at both depths were observed between the NT and PT systems. At the Hoytville site, rotation influenced the MWD for the 0- to 10-cm depth only. The tillage × rotation interaction was nonsignificant for WSA and MWD.

The relative increase in the formation of larger macroaggregates in the soils under NT can partially be attributed to the increased amount of residues retained (Lichter et al., 2008). The conclusions from the literature, however, are contradictory. For example, under a semiarid Mediterranean climate, Hernanz et al. (2002) reported higher WSA in long-term PT and MT systems than under NT in a loamy soil. In contrast, Jagadamma and Lal (2010) reported that the size distribution pattern and MWD of aggregates under NT soils were higher than those under PT and MT for a site located in the U.S. Midwest. The present data from central and northwestern Ohio are in accord with those reported by Jagadamma and Lal (2010) for Illinois. The WSA and MWD values for the NT soil were similar or higher than those for soils under WL areas, implying that the use of NT for a long duration (47 and 49 yr) improved soil aggregation. Aggregate stability was higher for the Hoytville site than the Wooster soil; this trend was attributed to the clayey texture of the Hoytville soil.

Tensile Strength of Aggregates

The mean TS of aggregates for the three tillage treatments and the WL areas at both sites are presented in Table 3. Tillage significantly affected the aggregate TS for the 0- to 10- and 10- to 20-cm depths at Wooster and for the 0- to 10-cm depth at Hoytville. Soils under WL had the lowest aggregate TS compared with the cultivated soils.

At the Wooster site, NT (183 kPa) soils had 28 and 40% lower TS than those under MT (255 kPa) and PT (306 kPa), respectively, for the 0- to 10-cm depth. Significantly lower TS of aggregates was also observed in soils under NT (268 kPa) than those managed by MT (310 kPa) and PT (335 kPa) in the 10- to 20-cm depth. Tillage significantly increased the TS of aggregates in the soils. Crop rotation influenced the TS only for the 0- to 10-cm depth. Aggregates under the CS rotation had 7% lower TS than those under CC.

A trend similar to that of the Wooster soil was observed for the Hoytville site, where NT aggregates had lower TS than aggre-

Table 3. Mean tensile strength of aggregates (5–8 mm) in the 0- to 10- and 10- to 20-cm soil depths maintained under long-term tillage and crop management and woodlots for the Wooster and Hoytville sites.

Treatment†	Tensile strength 0–10 cm	 10–20 cm
	——— kPa ———	
	Wooster	
Tillage		
PT	306 a‡	335 a
MT	255 b	310 b
NT	183 c	268 c
WL	123 d	157 d
Rotation		
CC	286 a	304 a
CS	267 b	305 a
	Analysis of variance $P > F$	
Tillage	<0.01	<0.01
Rotation	<0.01	0.79
Tillage × rotation	0.73	0.12
	Hoytville	
Tillage		
PT	279 a	378 a
MT	224 b	391 a
NT	185 b	320 a
WL	122 c	150 b
Rotation		
CC	314 a	386 a
CS	278 a	338 a
	Analysis of variance $P > F$	
Tillage	<0.01	0.19
Rotation	0.28	0.14
Tillage × rotation	0.82	0.10

† PT, plow tillage; MT, minimum tillage; NT, no-till; CC, continuous corn; CS, corn–soybean rotation; WL, woodlot areas with undisturbed soil.

‡ Means followed by different letters within a column, treatment, and site are significantly different at $P < 0.05$.

Table 4. Soil penetration resistance (SPR) and gravimetric moisture content (*w*) in the 0- to 5- and 5- to 10-cm soil depths maintained under long-term tillage and crop management and woodlots for the Wooster and Hoytville sites.

Treatment†	0–5-cm depth SPR	 *w*	5–10-cm depth SPR	 *w*
	MPa	kg kg^{-1}	MPa	kg kg^{-1}
		Wooster		
Tillage				
PT	3.58 a‡	0.15 b	4.46 a	0.13 b
MT	3.30 a	0.15 b	4.41 a	0.14 b
NT	2.82 b	0.17 b	3.98 b	0.15 a
WL	0.94 c	0.22 a	1.84 c	0.16 a
Rotation				
CC	3.39 a	0.15 b	4.29 a	0.14 a
CS	3.07 b	0.16 a	4.27 a	0.15 a
		Analysis of variance $P > F$		
Tillage	<0.01	<0.06	0.03	0.02
Rotation	0.04	<0.01	0.88	0.07
Tillage × rotation	0.48	<0.01	0.11	0.22
		Hoytville		
Tillage				
PT	3.55 a	0.15 c	5.08 a	0.13 c
MT	2.74 b	0.16 b	4.03 b	0.15 b
NT	2.50 b	0.19 a	3.88 b	0.18 a
WL	1.02 c	0.20 a	1.36 c	0.18 a
Rotation				
CC	3.06 a	0.17 a	4.34 a	0.15a
CS	2.81 a	0.18 a	4.32 a	0.16 a
		Analysis of variance $P > F$		
Tillage	<0.01	<0.01	0.02	<0.01
Rotation	0.08	0.14	0.94	0.42
Tillage × rotation	0.79	0.81	0.48	0.11

† PT, plow tillage; MT, minimum tillage; NT, no-till; CC, continuous corn; CS, corn–soybean rotation; WL, woodlot areas with undisturbed soil.

‡ Means followed by different letters within a column, treatment, and site are significantly different at $P < 0.05$.

gates under MT and PT. In the 0- to 10-cm depth, the mean TS for NT aggregates was 185 kPa, compared with 224 and 279 kPa for MT and PT aggregates, respectively. The TS increased with increasing depth for all the treatments at both sites. The tillage × rotation interaction was nonsignificant for both sites.

The lower TS of aggregates in the NT soils of this study is in accord with data reported by Blanco-Canqui et al. (2005). The undisturbed soils of the WL areas for both sites had the lowest TS, probably because of a high proportion of macroaggregates loosely cemented by root hairs and fungal hyphae (Tisdall, 1991).

Soil Penetration Resistance

The SPR is strongly influenced by the soil moisture content (*w*) (Unger and Jones, 1998). Thus, both properties were determined at the same time. The SPR measurements were adjusted to *w* using Eq. [4] as given by Busscher and Bauer (2003); however, significant differences among the treatments in the adjusted SPR values were not observed. Therefore, analysis of SPR and *w* was done separately.

At the Wooster site, tillage had a significant effect on SPR in the 0- to 5- and 5- to 10-cm depths ($P < 0.05$) and *w* in the 5- to 10-cm depth (Table 4). Because *w* was nonsignificant for the 0- to 5-cm depth, differences in SPR values at this depth were due to tillage. Continuous use of inversion tillage for 49 yr increased the SPR under PT (3.58 MPa) by 27 and 8% compared with that under NT (2.82 MPa) and MT (3.30 MPa), respectively, for the 0- to 5-cm depth. Similarly, increases of 12 and 11% in SPR were observed under PT (4.46 MPa) and MT (4.41 MPa), respectively, compared with NT (3.98 MPa) for the 5- to 10-cm depth. In contrast, an opposite trend was observed in *w* for the 5- to 10-cm depth, where *w* in soils under NT (0.15 kg kg^{-1}) was about 13.4 and 13% higher than under PT (0.13 kg kg^{-1}) and MT (0.14 kg kg^{-1}), respectively. Therefore, differences in SPR among tillage systems for the 5- to 10-cm depth were probably because of *w*. The values of R^2 for SPR vs. *w* for the NT, MT, PT, and WL treatments were 0.59, 0.53, 0.48, and 0.47. Crop rotation also significantly influenced SPR and *w*; however, sig-

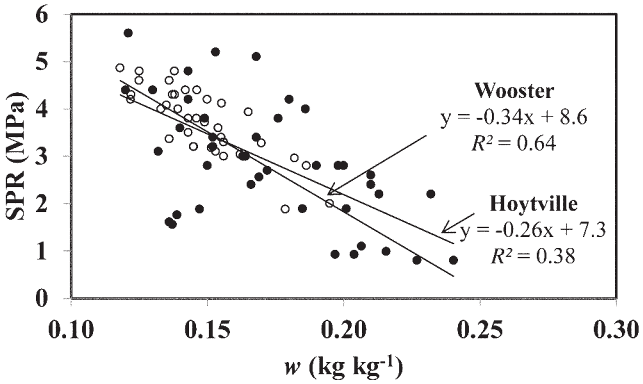

Fig. 3. Relationship between soil penetration resistance (SPR) and gravimetric moisture contents (n = 42) for the Wooster and Hoytville sites.

nificant differences were observed only for the 0- to 5-cm depth. On average, the SPR was lower under CS by 9% than under CC.

At the Hoytville site, the SPR and w values were significantly affected by tillage in the 0- to 5- and 5- to 10-cm depths ($P < 0.02$; Table 4). Rotation did not affect the SPR at this site. Soils under NT had 30 and 9% lower SPR than that under PT and MT, respectively, for the 0- to 5-cm depth. The differences in SPR values were nonsignificant, however, between the NT and MT systems. The R^2 for SPR vs. w for the NT, MT, PT, and WL treatments were 0.59, 0.52, 0.48, and 0.47.

Based on the results given for previous studies, tilled soils generally have more SPR values >1.5 MPa (Zou et al., 2001), with upper values of about 2 (Taylor and Ratliff, 1969) to 3 MPa (Boone and Veen, 1994). In our study, the SPR was >1.5 MPa for all tillage systems at both locations. It was visually observed at the time of sampling, however, that corn roots had already penetrated to below the sampling depths. Thus, root growth was not restricted by the dense soil as indicated by the high SPR. In addition, critical SPR limits are based on laboratory studies in a homogenized soil (Sinnett et al., 2006). Under field conditions, soils contain cracks or fissures that roots may exploit despite high SPR values (Sinnett et al., 2006). Also, SPR values are greatly influenced by w (Whalley et al., 2007). The SPR values in the present study are negatively correlated with w, having R^2 values ranging from 0.38 (Hoytville site, $P < 0.05$) to 0.64 (Wooster site, $P < 0.05$) (Fig. 3).

Available Water Capacity

Tillage significantly affected the AWC in the 0- to 10- and 10- to 20-cm depths at both sites ($P < 0.01$; Table 5). Soils under WL always had higher AWC than the cultivated soils. At the Wooster site, the AWC was significantly more under NT than under MT and PT. A larger difference in AWC among tillage treatments was observed for the 0- to 10-cm depth, where the AWC was 24 and 38% lower for the MT and PT soils, respectively, compared with those under NT. The AWC was significantly higher under the CS rotation than under CC.

At the Hoytville site, tillage also significantly affected the AWC at both depths. When comparing tillage systems in the 0- to 10-cm depth, the AWC was 39 and 95% higher under NT than MT and PT, respectively. A similar trend was observed for the 10- to 20-cm depth. Crop rotation also influenced the AWC ($P < 0.01$). The soils under the CS rotation had 12% higher AWC than the soils under CC at the 0- to 10-cm depth and 10% higher AWC at the 10- to 20-cm depth. The tillage × rotation interaction effects were significant only for the Wooster site at the 0- to 10-cm depth. Improved soil structure and higher SOC stocks increased the AWC of the soils under NT, meaning that these soils conserved more water and also increased the proportion of water available to the crop compared with the soils under PT.

Table 5. Available water capacity (AWC) in the 0- to 10- and 10- to 20-cm soil depths maintained under long-term tillage and crop management and woodlots for the Wooster and Hoytville sites.

	AWC	
Treatment†	0–10 cm	10–20 cm
	$m^3\ m^{-3}$	
	Wooster	
Tillage		
PT	8.30 d‡	6.40 d
MT	10.2 c	8.70 c
NT	13.4 b	10.1 b
WL	14.2 a	13.2 a
Rotation		
CC	8.90 b	7.90 b
CS	10.1 a	8.70 a
	Analysis of variance $P > F$	
Tillage	<0.01	<0.01
Rotation	<0.01	<0.01
Tillage × rotation	<0.01	0.67
	Hoytville	
Tillage		
PT	8.00 c	7.70 d
MT	11.2 b	8.70 c
NT	15.6 a	11.4 b
WL	15.8a	13.5 a
Rotation		
CC	9.80 b	8.70 b
CS	11.0 a	9.60 a
	Analysis of variance $P > F$	
Tillage	<0.01	<0.01
Rotation	<0.01	<0.01
Tillage × rotation	0.20	0.24

† PT, plow tillage; MT, minimum tillage; NT, no-till; CC, continuous corn; CS, corn–soybean rotation; WL, woodlot areas with undisturbed soil.

‡ Means followed by different letters within a column, treatment, and site are significantly different at $P < 0.05$.

Crop Yields

Corn yield data for the 2007 through 2011 growing seasons are presented in Table 6. For the well-drained soils at the Wooster site, there was a slight trend of a higher grain yield under MT than under the PT or NT systems for all years. For a PT vs. NT comparison, corn yield was significantly higher under PT for 2007, 2009, and 2010 but similar in 2008. For 2011, corn yield in the NT (13.3 Mg ha^{-1}) system was significantly higher

Table 6. Corn yield (2007–2011) under long-term tillage and crop management for the Wooster and Hoytville sites.

Treatment†	Corn yield					
	2007	2008	2009	2010	2011	Avg.‡
	Mg ha^{-1}					
	Wooster					
Tillage						
PT	10.5 a§	10.6 b	14.1 a	13.0 a	11.9 b	12.0 b
MT	10.7 a	12.3 a	14.4 a	13.5 a	14.1 a	13.0 a
NT	9.1 b	10.4 b	12.9 b	11.1 b	13.3 a	11.4 b
Rotation						
CC	10.1 a	10.8 a	13.9 a	11.8 b	13.6 a	12.1 a
CS	10.3 a	11.4 a	13.6 a	13.2 a	12.6 b	12.2 a
	Analysis of variance *P* > *F*					
Tillage	0.02	<0.01	<0.01	<0.01	<0.01	<0.01
Rotation	0.41	0.16	0.42	<0.01	0.04	0.52
Tillage × rotation	0.60	0.14	0.45	<0.01	0.24	0.04
	Hoytville					
Tillage						
PT	9.1 a	6.8 b	9.3 a	9.2 a	11.4 a	9.1 a
MT	8.7 a	6.6 b	9.2 a	9.8 a	11.5 a	9.2 a
NT	8.8 a	7.6 a	9.7 a	8.9 a	11.6 a	9.3 a
Rotation						
CC	8.8 a	6.9 a	9.5 a	8.9 b	11.3 a	9.1 a
CS	9.0 a	7.1 a	9.3 a	9.8 a	11.6 a	9.3 a
	Analysis of variance *P* > *F*					
Tillage	0.52	<0.01	0.11	0.13	0.89	0.61
Rotation	0.49	0.14	0.16	0.02	0.30	0.11
Tillage × rotation	0.42	<0.01	0.08	0.51	0.19	0.06

† PT, plow tillage; MT, minimum tillage; NT, no-till; CC, continuous corn; CS, corn–soybean rotation; WL, woodlot areas with undisturbed soil.

‡ Average of the corn yield from 2007 through 2011.

§ Means followed by different letters within a column, treatment, and site are significantly different at $P < 0.05$.

than that under PT (11.9 Mg ha^{-1}) ($P < 0.01$). Rotation influenced the corn yield only in 2010 and 2011 ($P < 0.05$). The tillage × rotation interaction on grain yield was significant only in 2010. Crop yield was significantly ($P < 0.01$) higher under the CS (13.2 Mg ha^{-1}) rotation than under CC (11.8 Mg ha^{-1}). At this site in 2010, there was a bigger difference between CC and CS for NT (44%) than for MT (6%), whereas yield under CS was 5% lower than that under the CC rotation for the PT treatment. Tillage also influenced the corn yield averaged across 5 yr (2007–2011). The average corn yield was significantly higher under MT than PT.

For the poorly drained soils at the Hoytville site, tillage influenced the corn yield only in 2008, when the yield was significantly higher under NT (7.63 Mg ha^{-1}) than under PT (6.75 Mg ha^{-1}) or MT (6.56 Mg ha^{-1}). Crop rotation influenced corn yield only in 2010, when it was higher under CS (9.77 Mg ha^{-1}) than under CC (8.86 Mg ha^{-1}). The tillage × rotation interaction on grain yield at this site was significant only in 2008. Corn yield for this year was always greater for the CS rotation under the NT and MT systems. Also, the yield was the highest for NT under the CS rotation compared with all other tillage treatments under either cropping system. The 5-yr average corn yield (2007–2011) was not influenced by tillage. The average yield was higher for the CS rotation than for CC; however, the difference was not significant.

The yields for 2007 through 2011 show differences from the longer term yield averages reported by Dick et al. (1991). In the earlier years of maintaining the different tillage practices at the Wooster site, yields averaged higher under NT than PT. At the Hoytville site, the opposite was observed. Long-term maintenance of the different tillage practices on different soils is thought to have caused changes that result in corn yields also changing with time. For the well-drained Wooster soil, the early years of NT were more productive than PT in terms of corn grain yield, but these differences seem to have disappeared after 46 to 49 yr. For the Hoytville site, the early years were extremely negative when NT and CC were combined, but when comparing mean yields after 44 to 48 yr, the differences in yield between tillage systems and rotations had largely disappeared and the tillage × rotation interaction effect was only evident in 1 of the 5 yr. Crop rotation significantly affected the corn yields only for 2 of the 5 yr at Wooster and 1 out of 5 yr at Hoytville. When compared among tillage systems, the CS rotation provided a greater yield advantage for the NT system than CC.

DeFelice et al. (2006) reported that NT resulted in slightly lower corn yields than PT on poorly drained soils and higher yields on moderate to well-drained soils. They also reported that the CS rotation with NT provided a greater yield advantage than CC; however, the rotation effect on yield was minimal. Data from the present study show that yield was generally similar with NT compared with PT at the poorly drained Hoytville site. Weather (rainfall and temperature) and soil texture are major factors impacting crop yield response to tillage and crop rotation. Soil and water conservation technologies do not always result in increased crop yields (Hellin and Schrader, 2003). Colvin et al. (2001) reported that corn yield with the NT system and CC was 20% lower than with PT and 4% lower than with a CS rotation. Furthermore, only in 1 out of 5 yr was yield with NT numerically higher than with PT. In northeast Iowa on silty loam soils, Kanwar et al. (1997) concluded that tillage treatments (NT, PT, and MT) in a CS rotation produced significantly higher yields than those for CC. In contrast, a 3-yr study conducted by Tapela et al. (2002) indicated that corn yield under NT and PT with CC was nonsignificant for two of the years and lower in the other year. In southern Illinois on a silt loam soil, Kapusta et al. (1996) did not observe any differences in corn yield among NT, MT, and PT systems after 20 yr. DeFelice et al. (2006) concluded in their review that "corn and soybean producers in most of the United States may not suffer a yield disadvantage by shifting from PT systems to NT." It has been reported by Toliver et al. (2012) that soil and climate factors impact corn yields under different tillage systems and may be important factors for the adoption of NT practice by farmers. Production of corn under NT may be more economical than under PT because of reduced production costs. Furthermore, soil conservation and government incentives encourage farmers to adopt a NT system.

CONCLUSIONS

The influence of tillage and crop rotations on soil properties and corn yield are site specific and depend primarily on the duration of the tillage system that has been practiced on a particular soil type. The results from this study show that long-term (47 and 49 yr) and continuous use of NT practices on both soils is highly sustainable and influenced the soil properties. The NT system resulted in higher SOC stocks that improved or maintained soil tilth and enhanced the aggregate stability and AWC. In contrast, aggregates of soils under PT were less stable because of significantly lower SOC concentrations and stocks up to the 20-cm depth. Corn yield was higher under PT than NT for 3 out of 5 yr and lower for 1 out of 5 yr for the Wooster soil. It was unaffected for the Hoytville soils except for 1 yr (2008) when overall yields were below the long-term average and the yield under NT was significantly ($P < 0.05$) higher than that under PT and MT. It can be concluded from this study that the use of NT in well-drained and poorly drained soils for a long duration may be beneficial for the environment by sequestering more SOC than PT. Conversion of NT into PT or MT will lead to soil degradation and negatively impact the soil's physical quality.

ACKNOWLEDGMENTS

This research is part of a regional collaborative project supported by the USDA-NIFA, Award no. 2011-68002-30190, "Cropping Systems Coordinated Agricultural Project (CAP): Climate Change, Mitigation, and Adaptation in Corn-based Cropping Systems" (sustainablecorn.org).

REFERENCES

Alvarez, R., and R.S. Lavado. 1998. Climate, organic matter and clay content relationships in the Pampa and Chaco soils, Argentina. Geoderma 83:127–141. doi:10.1016/S0016-7061(97)00141-9

Balesdent, J., C. Chenu, and M. Balabane. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res. 53:215–230. doi:10.1016/S0167-1987(99)00107-5

Balesdent, J., A. Mariotti, and D. Boisgontier. 1990. Effect of tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields. J. Soil Sci. 41:587–596. doi:10.1111/j.1365-2389.1990.tb00228.x

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic-matter fractions in conventional-tillage and no-tillage soils. Soil Sci. Soc. Am. J. 58:777–786. doi:10.2136/sssaj1994.03615995005800030020x

Bescansa, P., M.J. Imaz, I. Virto, A. Enrique, and W.B. Hoogmoed. 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. Soil Tillage Res. 87:19–27. doi:10.1016/j.still.2005.02.028

Blanco-Canqui, H., and R. Lal. 2004. Mechanisms of carbon sequestration in soil aggregates. Crit. Rev. Plant Sci. 23:481–504. doi:10.1080/07352680490886842

Blanco-Canqui, H., and R. Lal. 2008. No-tillage and soil-profile carbon sequestration: An on-farm assessment. Soil Sci. Soc. Am. J. 72:693–701. doi:10.2136/sssaj2007.0233

Blanco-Canqui, H., R. Lal, and R. Lemus. 2005. Soil aggregate properties and organic carbon for switchgrass and traditional agricultural systems in the southeastern United States. Soil Sci. 170:998–1012. doi:10.1097/01.ss.0000187342.07331.a6

Blanco-Canqui, H., M.M. Mikha, J.G. Benjamin, L.R. Stone, A.J. Schlegel, D.J. Lyon, et al. 2009. Regional study of no-till impacts on near-surface aggregate properties that influence soil erodibility. Soil Sci. Soc. Am. J. 73:1361–1368. doi:10.2136/sssaj2008.0401

Boone, F.R., and B.W. Veen. 1994. Mechanisms of crop responses to soil compaction. In: B.D. Soane, and C. van Ouwerkerk, editors, Soil compaction in crop production. Dev. Agric. Eng. 11. Elsevier, Amsterdam. p. 237–264.

Busscher, W.J., and P.J. Bauer. 2003. Soil strength, cotton root growth and lint yield in a southeastern USA coastal loamy sand. Soil Tillage Res. 74:151–159. doi:10.1016/j.still.2003.06.002

Colvin, T.S., D.W. Meek, J.D. Cook, J.L. Baker, and R.M. Cruse. 2001. Analysis of long term tillage experiment record. In: Proceedings of the Sixth Agricultural Equipment Technology Conference, Louisville, KY. February 2001. Am. Soc. Agric. Eng., St. Joseph, MI. Pap. 01.

Dane, J.H., and J.H. Hopmans. 2002. Water retention and storage. In: J.H. Dane and G.C. Topp, editors, Methods of soil analysis. Part. 4. SSSA Book Ser. 5. SSSA, Madison, WI. p. 671–717.

Dao, T.H. 1996. Tillage system and crop residue effects on surface compaction of a Paleustoll. Agron. J. 88:141–148. doi:10.2134/agronj1996.00021962008800020005x

DeFelice, M.S., P.R. Carter, and S.B. Mitchell. 2006. Influence of tillage on corn and soybean yield in the United States and Canada. Crop Manage. June. doi:10.1094/CM-2006-0626-01-RS

Dexter, A.R., and C.W. Watts. 2001. Tensile strength and friability. In: K.A. Smith and C.E. Mullins, editors, Soil analysis: Physical methods. Marcel Dekker, New York. p. 405–433.

Dick, W.A. 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47:102–107. doi:10.2136/sssaj1983.03615995004700010021x

Dick, W.A., R.L. Blevins, W.W. Frye, S.E. Peters, D.R. Christenson, F.J. Pierce, and M.L. Vitosh. 1998. Impacts of agricultural management practices on C sequestration in forest-derived soils of the eastern Corn Belt. Soil Tillage Res. 47:235–244. doi:10.1016/S0167-1987(98)00112-3

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. Agron. J. 83:65–73. doi:10.2134/agronj1991.00021962008300010017x

Ellert, B.H., and J.R. Bettany. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529–538. doi:10.4141/cjss95-075

Ferreras, L.A., J.L. Costa, F.O. Garcia, and C. Pecorari. 2000. Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern "Pampa" of Argentina. Soil Tillage Res. 54:31–39. doi:10.1016/S0167-1987(99)00102-6

Franzluebbers, A.J. 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res. 66:95–106. doi:10.1016/S0167-1987(02)00018-1

Gal, A., T.J. Vyn, E. Micheli, E.J. Kladivko, and W.W. McFee. 2007. Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. Soil Tillage Res. 96:42–51. doi:10.1016/j.still.2007.02.007

Golchin, A., J.M. Oades, J.O. Skjemstad, and P. Clarke. 1994. Study of free and occluded particulate organic matter in soils by solid-state ^{13}C Cp/MAS NMR spectroscopy and scanning electron microscopy. Aust. J. Soil Res. 32:285–309. doi:10.1071/SR9940285

Grossman, R.B., and T.G. Reinsch. 2002. Bulk density and linear extensibility. In: J.H. Dane and G.C. Topp, editors, Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison WI. p. 201–228.

Hellin, J., and K. Schrader. 2003. The case against direct incentives and the search for alternative approaches to better land management in Central America. Agric. Ecosyst. Environ. 99:61–81. doi:10.1016/S0167-8809(03)00149-X

Hernanz, J.L., R. Lopez, L. Navarrete, and V. Sanchez-Giron. 2002. Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. Soil Tillage Res. 66:129–141. doi:10.1016/S0167-1987(02)00021-1

Herrick, J.E., and T.L. Jones. 2002. A dynamic cone penetrometer for measuring soil penetration resistance. Soil Sci. Soc. Am. J. 66:1320–1324. doi:10.2136/sssaj2002.1320

Jagadamma, S., and R. Lal. 2010. Distribution of organic carbon in physical fractions of soils as affected by agricultural management. Biol. Fertil. Soils 46:543–554. doi:10.1007/s00374-010-0459-7

Jarecki, M.K., and R. Lal. 2005. Soil organic carbon sequestration rates in two long-term no-till experiments in Ohio. Soil Sci. 170:280–291. doi:10.1097/00010694-200504000-00005

Kanwar, R.S., T.S. Colvin, and D.L. Karlen. 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. J. Prod. Agric. 10:227–234.

Kapusta, G., R.F. Krausz, and J.L. Matthews. 1996. Corn yield is equal in conventional, reduced, and no tillage after 20 years. Agron. J. 88:812–817. doi:10.2134/agronj1996.00021962008800050021x

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. In: A. Klute, editor, Methods of soil analysis. Part 1. Agron. Monogr. 9. ASA and SSSA, Madison, WI. p. 425–442.

Kennedy, A.C., and W.F. Schillinger. 2006. Soil quality and water intake in traditional-till vs. no-till paired farms in Washington's Palouse region. Soil Sci. Soc. Am. J. 70:940–949. doi:10.2136/sssaj2005.0160

Lal, R., and D.M. Vandoren, Jr. 1990. Influence of 25 years of continuous corn production by three tillage methods on water infiltration for two soils in Ohio. Soil Tillage Res. 16:71–84. doi:10.1016/0167-1987(90)90022-6

Lentz, R.D., and D.L. Bjorneberg. 2003. Polyacrylamide and straw residue effects on irrigation furrow erosion and infiltration. J. Soil Water Conserv. 58:312–319.

Lichter, K., B. Govaerts, J. Six, K.D. Sayre, J. Deckers, and L. Dendooven. 2008. Aggregation and C and N contents of soil organic matter fractions in a permanent raised-bed planting system in the Highlands of Central Mexico. Plant Soil 305:237–252. doi:10.1007/s11104-008-9557-9

Madari, B.E., J.B. Reeves III, M.R. Coelho, P.L.O.A. Machado, H. De-Polli, R.M. Coelho, et al. 2005. Mid- and near-infrared spectroscopic determination of carbon in a diverse set of soils from the Brazilian National Soil Collection. Spectrosc. Lett. 38:721–740. doi:10.1080/00387010500315876

Miller, J.O., J.M. Galbraith, and W.L. Daniels. 2004. Soil organic carbon content in frigid southern Appalachian Mountain soils. Soil Sci. Soc. Am. J. 68:194–203. doi:10.2136/sssaj2004.0194

Mishra, U., D.A.N. Ussiri, and R. Lal. 2010. Tillage effects on soil organic carbon storage and dynamics in Corn Belt of Ohio USA. Soil Tillage Res. 107:88–96. doi:10.1016/j.still.2010.02.005

Mrabet, R., N. Saber, A. El-Brahli, S. Lahlou, and F. Bessam. 2001. Total, particulate organic matter and structural stability of a Calcixeroll soil under different wheat rotations and tillage systems in a semiarid area of Morocco. Soil Tillage Res. 57:225–235. doi:10.1016/S0167-1987(00)00180-X

Murty, D., M.U.F. Kirschbaum, R.E. McMurtrie, and A. McGilvray. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Global Change Biol. 8:105–123. doi:10.1046/j.1354-1013.2001.00459.x

Rahimi, H., E. Pazira, and F. Tajik. 2000. Effect of soil organic matter, electrical conductivity and sodium adsorption ratio on tensile strength of aggregates. Soil Tillage Res. 54:145–153. doi:10.1016/S0167-1987(00)00086-6

Rogowski, A.S., W.C. Moldenhauer, and D. Kirkham. 1968. Rupture parameters of soil aggregates. Soil Sci. Soc. Am. Proc. 32:720–724. doi:10.2136/sssaj1968.03615995003200050037x

SAS Institute. 2007. SAS user's guide: Statistics. SAS Inst., Cary, NC.

Shukla, M.K., and R. Lal. 2005. Erosional effects on soil physical properties in an on-farm study on Alfisols in west central Ohio. Soil Sci. 170:445–456. doi:10.1097/01.ss.0000171667.60883.f2

Sinnett, D., J. Poole, and T.R. Hutchings. 2006. The efficacy of three techniques to alleviate soil compaction at a restored sand and gravel quarry. Soil Use Manage. 22:362–371. doi:10.1111/j.1475-2743.2006.00053.x

Six, J., E.T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:2099–2103. doi:10.1016/S0038-0717(00)00179-6

Tapela, M., T.S. Colvin, and D.L. Karlen. 2002. Spatial and temporal variability in corn yield grown with different tillage systems. In: P.C. Robert et al., editors, Proceedings of the 6th International Conference on Precision Agriculture and Other Precision Resources Management, Minneapolis, MN. 14–17 July 2002. ASA, CSSA, and SSSA, Madison, WI. p. 473–482.

Taylor, H.M., and L.F. Ratliff. 1969. Root growth pressures of cotton, peas, and peanuts. Agron. J. 61:398–402. doi:10.2134/agronj1969.00021962006100030020x

Tisdall, J.M. 1991. Fungal hyphae and structural stability of soil. Aust. J. Soil Res. 29:729–743. doi:10.1071/SR9910729

Toliver, D.K., J.A. Larson, R.K. Roberts, B.C. English, D.G. de la T. Ugarte, and T.O. West. 2012. Effects of no-till on yields as influenced by crop and environmental factors. Agron. J. 104:530–541. doi:10.2134/agronj2011.0291

Unger, P.W., and O.R. Jones. 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. Soil Tillage Res. 45:39–57. doi:10.1016/S0167-1987(97)00068-8

Vance, E.D. 2000. Agricultural site productivity: Principles derived from long-term experiments and their implications for intensively managed forests. For. Ecol. Manage. 138:369–396. doi:10.1016/S0378-1127(00)00425-4

Wander, M.M., M.G. Bidart, and S. Aref. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci. Soc. Am. J. 62:1704–1711. doi:10.2136/sssaj1998.03615995006200060031x

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66:1930–1946. doi:10.2136/sssaj2002.1930

Whalley, W.R., J. To, B.D. Kay, and A.P. Whitmore. 2007. Prediction of the penetrometer resistance of soils with models with few parameters. Geoderma 137:370–377. doi:10.1016/j.geoderma.2006.08.029

Yang, X.M., and M.M. Wander. 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. Soil Tillage Res. 52:1–9. doi:10.1016/S0167-1987(99)00051-3

Yang, Y.H., A. Mohammat, J.M. Feng, R. Zhou, and J.Y. Fang. 2007. Storage, patterns and environmental controls of soil organic carbon in China. Biogeochemistry 84:131–141. doi:10.1007/s10533-007-9109-z

Yoder, R.E. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28:337–351. doi:10.2134/agronj1936.00021962002800050001x

Youker, R.E., and J.L. McGuinness. 1957. A short method of obtaining mean weight-diameter values of aggregate analyses of soils. Soil Sci. 83:291–294. doi:10.1097/00010694-195704000-00004

Zou, C., C. Penfold, R. Sands, R.K. Misra, and I. Hudson. 2001. Effects of soil air-filled porosity, soil matric potential and soil strength on primary root growth of radiata pine seedlings. Plant Soil 236:105–115. doi:10.1023/A:1011994615014