Regional Assessment of Soil Compaction and Structural Properties under No-tillage Farming

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No-tillage (NT) farming is a proven technology for soil and water conservation, but its impacts on soil compaction and structure development are soil- and site-specific. We conducted a regional assessment of long-term (>5-yr) NT farming impacts on soil compaction, structure, and aggregate-associated soil organic carbon (SOC) concentration across 13 contrasting but representative soils in the eastern USA, each within a Major Land Resource Area (MLRA: 111C, 98, 114B, and 122 in Indiana; 111A, 111B, 111B2, 99, 111D, 124, and 126 in Ohio; and 147 and 127 in Pennsylvania). Each MLRA comprised NT, chisel plow (CP), and woodlot (WL) land uses. Impacts of NT management were moderate on soil compaction, small on soil structural properties, and nonsignificant on aggregate-associated SOC concentration. No-tillage soils had higher cone index (CI) and shear strength than CP in nine out of the 13 MLRAs, and they had the highest CI ($\sim$2 MPa) and shear strength (>180 kPa) within MLRAs 122 and 124. Bulk density (ρ_b) in NT was higher than in CP soils only in 111B (1.31 vs. 1.18 Mg m^{-3}) and 127 (1.37 vs. 1.17 Mg m^{-3}). No-tillage farming increased the mean weight diameter (MWD) of aggregates by a factor of 1.6 in MLRA 99, by 3.0 in 124, and by 5.3 in 111A, and reduced their tensile strength (TS) in 114B, 126, and 111B by a factor of $\sim$2.5. Macroaggregates (>1 mm) contained 15 to 100% more SOC than microaggregates. Woodlot soils had the lowest ρ_b and TS and the highest MWD and aggregate-associated SOC concentration. The MWD increased with increasing SOC concentration. Overall, the impacts of no-tillage farming on soil compaction and structure were small compared with plow tillage.

Abbreviations: CI; cone index; CP, chisel plow; MLRA, Major Land Resource Area; MWD, mean weight diameter; NT, no-tillage; SOC, soil organic carbon; TS, tensile strength; WL, woodlot.

SOIL & WATER MANAGEMENT & CONSERVATION

No-tillage agriculture is among the top options in the portfolio of technologies to reduce tillage costs, conserve soil and water, increase soil organic carbon (SOC) pools, and reduce net CO_2 emissions, which contribute to global warming. By eliminating intensive soil plowing and leaving crop residues on the soil surface, no-tillage (NT) agriculture generally improves soil properties, increases nutrient content and recycling, and moderates fluxes of water, air, and heat through the soil, resulting in improved agronomic productivity. Although the area under NT is, at present, only about 5% of the cultivated land (1379 Mha) in the world, NT technology is gaining wide acceptance, particularly in North and South America (Lal et al., 2004). In the USA, the area under NT, mostly in the Corn Belt region and Northern Plains, has increased from 5 Mha in the 1980s to about 22 Mha in 2000, which represents $\sim$18% of the total cultivated land area. No-tillage farming is expected to increase to about 75% in the USA by the year 2020 (Lal et al., 1998, p. 18–21). Adopting NT technology is advocated not only to meet the requirements of soil conservation programs but also to sustain crop production.

Despite their numerous benefits, however, various questions still remain about the potential of NT systems for improvement of soil physical quality (Blanco-Canqui et al., 2004) and long-term SOC sequestration (Baker et al., 2006). In fact, NT may not always improve the physical and mechanical properties of soils (Arshad et al., 2004), for example, its role in alleviating soil compaction is unclear. Soil compaction often increases with the conversion of plow tillage into NT systems from the lack of transient soil loosening by tillage operations (Drury et al., 2003; Seybold et al., 2003; Bueno et al., 2006). Machinery traffic during planting, harvesting, manuring, and weed and pest control can adversely affect soil strength properties, especially in soils under highly mechanized NT agriculture such as in the U.S. Corn Belt region. Excessive compaction in NT can retard root growth and reduce crop yields compared with chisel plow (CP) practices and create mixed reactions to NT adoption. This is the reason why some farmers, although NT advocates, favor occasional tillage (e.g., deep tillage) to ameliorate compaction problems in soils under NT that are susceptible to natural reconsolidation. In contrast, in some soils, NT management may not always increase soil compaction (Cassel et al., 1995; Arshad et al., 1999). Indeed, it can even decrease soil compaction due to the addition of organic amendments (e.g., animal manure) and enhanced biological processes (e.g., earthworm activity) (Logsdon and Karlen, 2004; Gregory et al., 2005; Blanco-Canqui et al., 2005a). The impacts of NT management on soil structural properties such as stability and strength of aggregates are also variable. Knowledge of properties of soil aggregates, structural units, is indispensable, but they have not

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been widely characterized to understand the macroscale structural behavior of NT soils (Horn, 1990). For example, quantification of aggregate-associated C distributions across contrasting NT management systems is necessary to determine the dynamics of aggregation and turnover rates of SOC. Moreover, the magnitude of soil compaction and structural parameters may (Blanco-Canqui et al., 2005a) or may not (Karlen et al., 1994) be affected by changes in SOC pools in long-term (>10-yr) NT systems.

The inconsistent response of soil compaction and structural properties to NT systems warrants further research. To date, most studies on soil physical quality in NT have been restricted to research on small plots or point measurements. A regional study involving a range of environments is required to gain a broader understanding of the impacts of NT technology by integrating information across a large geographic spectrum of NT management scenarios under contrasting soil types and topographic and management conditions. Research data from NT practices on farmers' fields would provide a better understanding of soil processes under real-world conditions. Information on a regional scale is especially needed when large areas of croplands are being gradually converted into long-term NT systems. A regional assessment, involving synthesis of data from contrasting soils, can lead to a broad generalization of changes in soil compaction and structural properties in relation to SOC pools.

The Midwest Regional Carbon Sequestration Partnership (MRCSP) initiative, established in 2003 as one of seven partnerships in the U.S. Department of Energy's Carbon Sequestration Program to assess the potential of C sequestration and strategies for mitigating CO_2 emissions, offers an excellent opportunity for a regional assessment of NT farming implications on soil physical quality in the eastern Corn Belt region. On-farm studies of soil processes within each Major Land Resource Area (MLRA) allow an elucidation of the uncertainties of NT impacts on soil compaction in relation to changes in SOC pools. Thus, the objectives of this study were to assess (i) the impacts of NT farming on soil compaction, soil structure development, and aggregate-associated SOC distributions compared with CP and forest management systems, and (ii) the relationships of soil compaction and structural parameters to management-induced changes in SOC, if any, across 13 selected MLRAs in the eastern USA.

MATERIALS AND METHODS

Description of the Study Sites

This study was conducted within the MRCSP framework, whose primary goal is to characterize the potential of terrestrial ecosystems for sequestering SOC and reducing CO_2 emissions. Paired fields under long-term (>5-yr) NT and CP systems were selected within 13 representative MLRAs across Indiana, Ohio, and Pennsylvania in the eastern USA (Table 1). The selected MLRAs were: 111C, 98, 114B, and 122 in Indiana; 111A, 111B, 111B2, 99, 111D, 124, and 126 in Ohio; and 147 and 127 in Pennsylvania (Fig. 1). These MLRAs were selected on the basis of their large area and high potential for SOC sequestration. A woodlot (WL) or forest site, adjacent to each paired cropped soil, was included in the study for comparison. Detailed information on soil and management for each selected site for the 13 MLRAs is presented in Table 1. Soil textural classes included sandy loam, silt loam, silty clay loam, and clay loam, with silt loam being the most common. Slope gradient ranged from 1 to 6% and the parent materials differed among the MLRAs. Soils in Indiana (111C, 122, 98, and 114B) and central and western Ohio (111A, 111B2, IIID, 99, and 111B) formed on lowland glacial deposits including dense and deep glacial till and lake sediments, whereas those in Pennsylvania (127 and 147) and eastern Ohio (124 and 126) are unglaciated and developed from weathered sedimentary deposits of shale, siltstone, and sandstone (NRCS, 2007). While the same land use and management systems were selected for all MLRAs, cropping systems and the duration of tillage management were not identical for all sites (Table 1). In a few MLRAs, NT and CP fields were not adjacent to each other but 0.16 to 8 km apart. Wooded sites were, however, always adjacent to either NT or CP farms. It was not always possible to locate adjoining NT and CP paired sites. Three soil strength parameters, cone index (CI), shear strength, and bulk density (ρ_b), were determined to evaluate the level of soil compaction, while two structural parameters, mean weight diameter (MWD) and tensile strength (TS) of aggregates, were quantified to discern differences in soil structural development among the three management and land use scenarios.

Determination of Soil Strength Properties

Cone index and shear strength were measured before harvest in fall 2006 for all MLRAs. Measurements were made at nine random points within NT, CP, and WL areas for the surface 5-cm depth. A relatively high number of replicated measurements was made to account for the within-field variability in soil strength parameters. Penetration resistance was measured using a static hand cone penetrometer (Eijkelkamp, Giesbeek, the Netherlands), and was converted to CI as a ratio of normal force to cone base area (Lowery and Morrison, 2002). The shear strength was measured by a hand shear vane tester (ELE International, Lake Bluff, IL) in kiloPascals (Lowery and Morrison, 2002). Soil cores in triplicate, using metal sleeves 5.4 cm in diameter by 6 cm deep, were collected from each field using a hammer-driven sampler for the surface 6-cm layer at the time of CI and shear strength measurements. These cores were used for the determination of gravimetric water content (θ_g) and ρ_b (Grossman and Reinsch, 2002). Volumetric water content (θ_v) for each treatment was computed as the product of θ_g and ρ_b.

Determination of Structural Properties and Aggregate-Associated Soil Carbon

A bulk soil sample of about 1 kg was collected from each field and MLRA in spring 2006 from the 0- to 5-cm depth for the determination of TS and stability of aggregates. The bulk samples were air dried at about 20°C for 72 h, gently crushed, and dry sieved to obtain aggregates in the 4.75- to 8-mm size range. Water-stable aggregates (WSA) were characterized by the wet-sieving procedure (Nimmo and Perkins, 2002). Fifty grams of 4.75- to 8-mm aggregates were saturated by capillarity on top of a nest of sieves of 4.75-, 2-, 1-, 0.5-, and 0.25-mm mesh, and vertically oscillated in water at 30 cycles min^{-1} for 30 min using a sieving device. Soil retained in each sieve was transferred to preweighed beakers, oven dried at 50°C, and weighed to compute the percentage of WSA and MWD of aggregates (Nimmo and Perkins, 2002). The soil fraction of <0.25 mm was obtained by collecting the sediment after decanting the water, and determining the oven-dry weight. Aggregate-size fractions between 0.25 and 8 mm were classified as macroaggregates and those <0.25 mm as microaggregates (Tisdall and Oades, 1982). The TS of the 4.75- to 8-mm aggregates was determined using the crushing method (Dexter and Watts, 2001). Nine aggregates per treatment were used for the TS tests to account for the expected high variability.

A portion of these samples dried at 50°C from each aggregate-size fraction was ground and passed through a 0.25-mm sieve for the determination of the aggregate-associated SOC concentration by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Americas, Mount Laurel, NJ) (Nelson and Sommers, 1996). In addition,

Table 1. Soil and management characteristics of each Major Land Resource Area (MLRA) by state.

MLRA	State	Soil series (slope)	Taxonomy	Management
98	IN	Maumee loamy sand (1%)	sandy, mixed, mesic Typic Endoaquolls	30-yr no-tillage (NT) corn–soybean rotation receiving 134 kg ha^{-1} N, 9 kg ha^{-1} P, and 280 kg ha^{-1} K for corn; 30-yr chisel-plow (CP) 2-yr corn and 1-yr soybean rotation receiving 50 kg ha^{-1} N and side-dressed with NH_3, 44 kg ha^{-1} P, and 93 kg ha^{-1} K for corn, and 118 kg ha^{-1} K for soybean
122	IN	Crider silt loam (2%)	fine-silty, mixed, active, mesic Typic Paleudalfs	15-yr NT corn–soybean rotation and >15-yr CP corn–wheat–soybean–soybean receiving 4.4 Mg ha^{-1} lime every 3 or 4 yr
111C	IN	Martinsville loam (<2%)	fine-loamy, mixed, active, mesic Typic Hapludalfs	10-yr NT and CP under 3-yr soybean and 2-yr corn rotation
114B	IN	Iva silt loam (3%)	fine-silty, mixed, superactive, mesic Aeric Endoaqualfs	23-yr NT and CP under corn–soybean rotation receiving 180 kg ha^{-1} of anhydrous NH_3 for corn
111B	OH	Milton silt loam (1%)	fine, mixed, active, mesic Typic Hapludalfs	20-yr NT and CP corn–soybean rotation with occasional wheat receiving 101 kg ha^{-1} N for corn and 57 kg ha^{-1} K for soybean
111D	OH	Fincastle silt loam (1%)/ Xenia silt loam (1%)	fine-silty, mixed, superactive, mesic Aeric Epiaqualfs/fine-silty, mixed, superactive, mesic Aquic Hapludalfs	5-yr NT and CP corn–soybean rotation with high use of wastewater
111A	OH	Kokomo silty clay loam (1%)/ Celina silt loam (2%)	fine, mixed, superactive, mesic Typic Argiaquolls/fine, mixed, active, mesic Aquic Hapludalfs	20-yr NT and CP corn–soybean rotation receiving 225 kg ha^{-1} lime, 76 kg ha^{-1} N, 333 kg ha^{-1} P, and 186 kg ha^{-1} K every other year
111B2	OH	Pewamo clay loam (1%)/ Blount silt loam (1%)	fine, mixed, active, mesic Typic Argiaquolls/Fine, illitic, mesic Aeric Epiaqualfs	25-yr NT corn–soybean rotation receiving 49 kg ha^{-1} N, 42 kg ha^{-1} P, and 90 kg ha^{-1} K, and >25-yr CP under corn–soybean rotation receiving 6.7 Mg ha^{-1} lime; NT was combined with strip tillage
99	OH	Hoytville clay loam (<1%)	fine, illitic, mesic Mollic Epiaqualfs	5-yr NT and CP under corn–soybean–wheat receiving 188 kg Mg ha^{-1}, 5.2 kg ha^{-1} Zn and S, 20 kg ha^{-1} N, 23 kg ha^{-1} P, and 7.2 kg ha^{-1} K
124	OH	Allegheny silt loam (5%)	fine-loamy, mixed, semiactive, mesic Typic Hapludults	35-yr NT 2-yr corn and 5–6-yr alfalfa; 35-yr CP continuous corn
126	OH	Otwell silt loam (6%)/Melvin silt loam (2%)	fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs/Fine-silty, mixed, active, nonacid, mesic Fluvaquentic Endoaquepts	15-yr NT corn–soybean–rye (cover crop) rotation receiving 29.9 m^3 of liquid manure; 15-yr CP corn–soybean rotation with occasional manuring
127	PA	Gilpin channery silt loam (4%)	fine-loamy, mixed, active, mesic Typic Hapludults	8-yr NT in 4-yr corn–alfalfa rotation receiving 33.3 m^3 liquid manure for corn and 2.2 Mg ha^{-1} lime in 2006; 8-yr CP in corn–alfalfa–nurse crop every 4 yr receiving 46.7 m^3 liquid manure for corn and lime for alfalfa
147	PA	Edom silty clay loam (5%)	fine, illitic, mesic Typic Hapludalfs	9-yr NT corn–soybean rotation receiving 74.5 m^3 of dairy manure; 9-yr CP with occasional moldboard plowing under corn–soybean rotation receiving 30 kg ha^{-1} N, 29 kg ha^{-1} P, and 56 kg ha^{-1} K

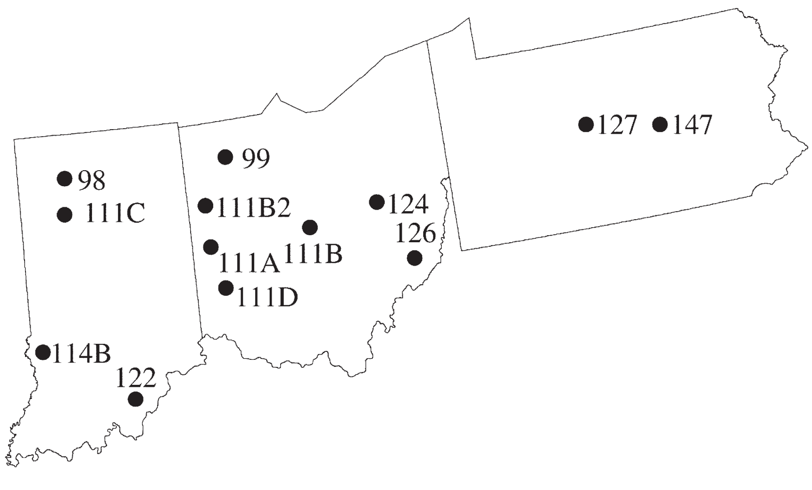

Fig. 1. Map of the three states (Indiana, Ohio, and Pennsylvania) showing the soil sampling points within each of the 13 Major Land Resource Areas.

total SOC concentration was determined on the bulk soil sampled in fall 2006. This study focuses only on soil physical properties, aggregate-associated SOC concentration, and relationships between SOC concentrations and soil physical properties. A one-way ANOVA model was used to test whether differences in soil physical properties and aggregate-associated SOC among the three land use and management systems by MLRA were significant. In this study, differences in soil properties among the three treatments were tested by site or MLRA to account for the high variability of soils among sites. Correlation analyses of SOC concentration vs. soil physical properties were performed with and without the WL data to assess relationships in both cropped soils and across all management systems, respectively. All statistical analyses were conducted using SAS software (SAS Institute, 2007).

RESULTS
Soil Compaction Parameters

There were no significant differences in θ_v between NT and CP practices at any of the MLRAs (Fig. 2A). Although NT soils tended to have greater θ_v than CP soils in eight out of 13 MLRAs, differences were not significant due to the high variability of θ_v values. Both NT and CP soils had, however, greater θ_v than wooded sites in the majority of MLRAs, and this is explained by the lower ρ_b of forest soils (Fig. 2B). While θ_g under WL management was typically higher than that for NT and CP systems, the opposite was true for θ_v.

Long-term NT management did not significantly affect ρ_b when compared with CP management except within two MLRAs (111B and 127) in which NT soils had significantly higher ρ_b ($P < 0.05$; Fig. 2B). The ρ_b was 1.31 ± 0.01 Mg m^{-3} (mean ± SD) under NT and 1.18 ± 0.06 Mg m^{-3} under CP for 111B, compared with 1.37 ± 0.04 Mg m^{-3} under NT and 1.17 ± 0.09 Mg m^{-3} under CP for 127, indicating that the ρ_b in NT soils was 17% higher in 111B and 11% higher in 127 than that in CP soils. The soil ρ_b values across NT and CP soils ranged from 1.14 ± 0.09 to 1.41 ± 0.07 Mg m^{-3} and were significantly greater than those in wooded sites, which ranged from 0.41 ± 0.09 to 1.12 ± 0.02 Mg m^{-3}, with the exception of 111C, which showed no significant differences. In comparison with the wooded control, mean ρ_b averaged across NT and CP soils was about 200% higher in MLRAs 98 and 127, 100% higher in 124 and 147, and 10 to 60% higher in the rest of the MLRAs.

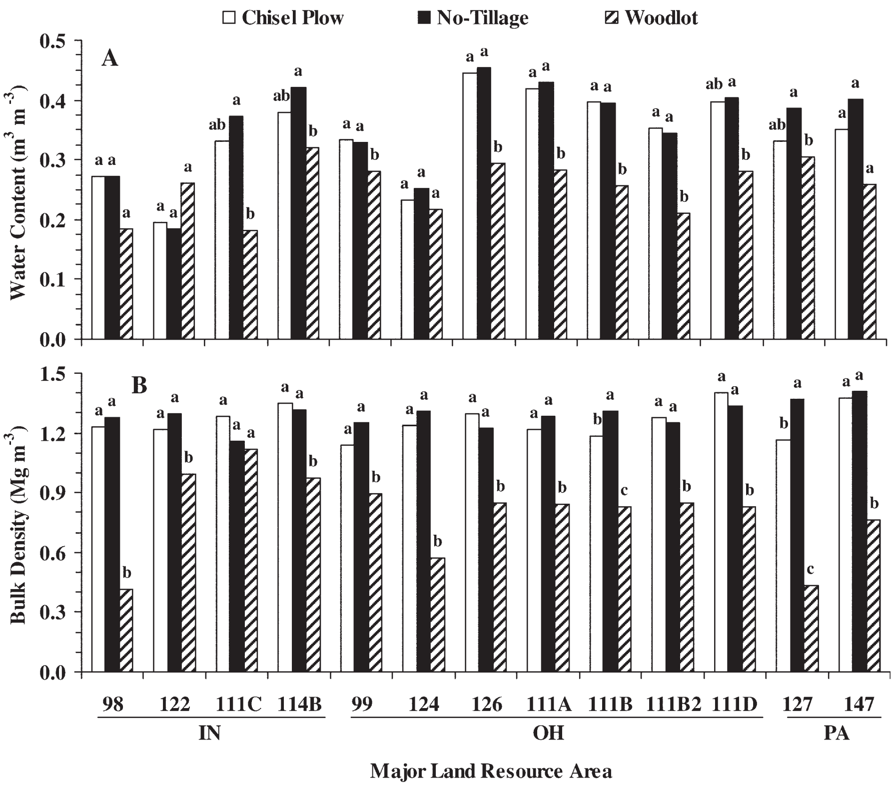

Fig. 2. Mean volumetric water content and bulk density by management for each Major Land Resource Area (MLRA) across Indiana, Ohio, and Pennsylvania. Bars with the same letters within each MLRA are not significantly different at the 0.05 probability level.

Differences in θ_g between CP and NT management were not significant for any of the sites and MLRAs. Moreover, regression fits between θ_g and CI and shear strength across all cultivated systems and MLRAs were not significant. Thus, no adjustment in measured CI and shear strength values to account for the possible confounding effect of θ_g on soil strength properties was performed (Busscher et al., 1997; Blanco-Canqui et al., 2005a). Differences in CI (Fig. 3A) and shear strength (Fig. 3B) between NT and CP management were more significant than differences in ρ_b. Similar trends in CI and shear strength under CP and NT soils indicated the strong interdependence between these parameters. Soils under NT had higher CI and shear strength than those under CP in nine out of the 13 MLRAs, and also had the highest values of CI (~2 MPa) and shear strength (>180 kPa) in two MLRAs (122 and 124). The CI in CP soils was consistently lower than that in NT soils except in 114B, where it was higher by 30%. The CI values across the whole region ranged from 0.44 to 2.13 MPa in NT soils and from 0.20 to 0.76 MPa in CP soils. In contrast, the shear strength values ranged from 12 to 54 kPa in NT soils and from 8 to 41 kPa in CP soils. Both CI and shear strength values were lower in WL soils than in NT soils but did not differ from those in CP soils except in MLRAs 98, 114B, 111B2, and 147.

Soil Structural Parameters

Data on geometric mean TS and MWD of aggregates are shown in Fig. 4A and 4B. Effects of NT farming on soil structural properties (TS and MWD) were site specific, and the TS values within the same treatment were highly variable. The TS values were lower in NT than in CP soils in three MLRAs (114B, 126, and 111B) by a factor of about 2.5 (Fig. 4A). In contrast, mean TS was higher in NT (650 kPa) than in CP soils (141 kPa) only in MLRA 111A. The highest TS values were observed in MLRAs 99 (670 kPa), 111A (650 kPa), and 111B2 (630 kPa) and were measured under NT management. Sandy loam (MLRA 98), as expected, had the lowest TS (42 kPa). No-tillage soils had significantly higher MWD than those under CP only in three MLRAs (99, 124, and 111A). The MWD was higher by a factor of 1.6 in MLRA 99, by 3.0 in 124, and by 5.3 in 111A (Fig. 4B). The higher TS (650 kPa) under NT was in accord with the higher values of MWD (3.5 mm) in MLRA 111A. Wooded land use had the lowest TS of all treatments in seven MLRAs. Differences in MWD between NT and WL soils were smaller than those between CP and WL soils, showing that the intensive tillage in CP systems reduced aggregate size. The highest values of MWD were observed in soils under WL management followed by those under NT (Fig. 4B). The lower values of MWD in CP than in WL soils were observed in the following MLRAs: 98, 99, 124, 111A, 111B, 111B2, and 111D. Soils under WL management had lower ρ_b and TS but had higher MWD than cropped soils.

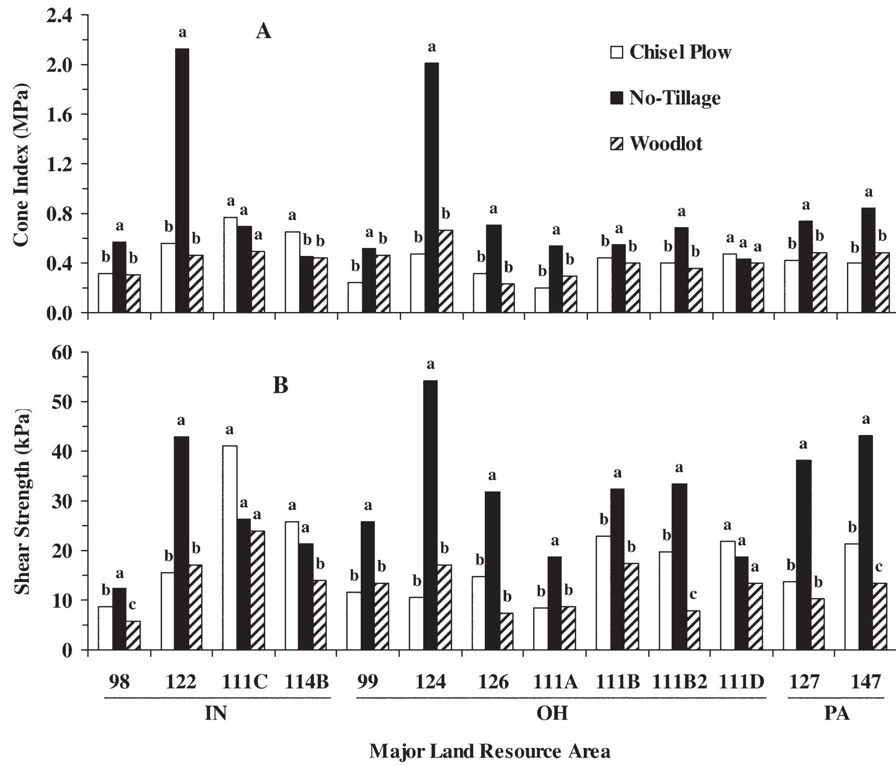

Fig. 3. Mean cone index and shear strength by management for each Major Land Resource Area (MLRA) across Indiana, Ohio, and Pennsylvania. Bars with the same letters within each MLRA are not significantly different at the 0.05 probability level.

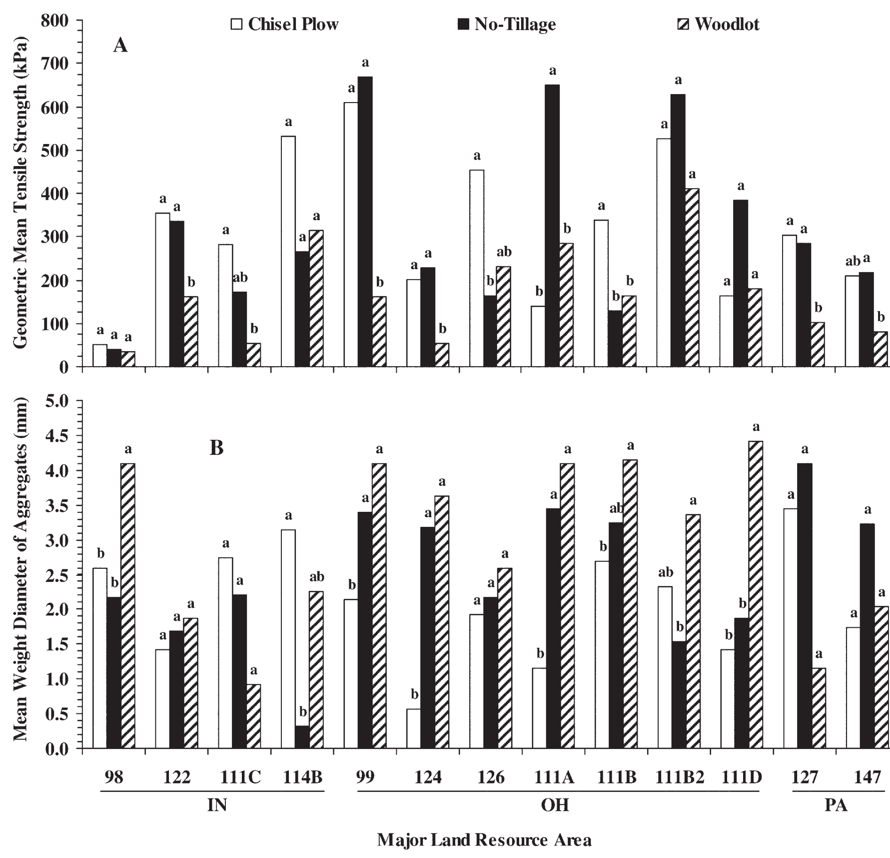

Fig. 4. Geometric mean tensile strength and mean weight diameter of soil aggregates under three management systems across 13 Major Land Resource Areas (MLRAs) in Indiana, Ohio, and Pennsylvania. Bars with the same letters within each MLRA are not significantly different at the 0.05 probability level.

Soil Organic Carbon Distribution in Aggregates

Differences in SOC concentration between NT and CP systems were not significant for any aggregate size fraction ($P > 0.10$; Tables 2 and 3). While aggregate-associated SOC concentration was generally higher in WL than in cropped soils, differences were significant only in seven MLRAs. The SOC concentration was the highest in >4.75-mm macroaggregates, and it progressively and linearly decreased with decreasing size of aggregates except in soils for MLRAs 111B, 147, 111B2, and 111C. The concentration of SOC in >1-mm macroaggregates was 15 to 100% higher than that in microaggregates (<0.25 mm; $P < 0.05$). Differences in SOC concentration among macroaggregates were not generally significant, although aggregates with diameters between 0.25 and 0.5 mm had 10 to 40% lower SOC concentration than >1-mm macroaggregates in a few soils. The SOC concentration vs. aggregate size relationship was quadratic for NT soils in MLRA 114B and for WL soils in MLRA 98, indicating that macroaggregates with diameters between 0.5 and 2 mm had higher SOC concentration than either >4.75-mm macroaggregates or microaggregates.

Organic Carbon and Soil Compaction and Structure Relationships

The significance of correlations of SOC concentration with soil compaction and structural properties depended on management and MLRA (Table 1). The SOC concentration was more strongly correlated with soil physical properties when soils under WL management were included in the correlation analyses because of their low ρ_b, CI, and shear strength, and high MWD and aggregate-associated SOC concentration. Exclusion of WL soils from the analyses reduced the significant correlations to a few MLRAs. Across cropped soils, the CI significantly increased with decreasing SOC concentration in MLRAs 111B2, 127, and 98, whereas it decreased linearly with increasing SOC concentration in MLRAs 114B and 124. The ρ_b was not correlated with SOC concentration in cropped soils except for MLRAs 124 and 127, where the SOC concentration increased and decreased, respectively, with increasing ρ_b. The MWD was negatively correlated with SOC in MLRA 111C and positively with SOC concentration in MLRA 114B. Across the whole region, the SOC concentration was not correlated with CI, ρ_b, or TS, but it was positively correlated with MWD ($r = 0.49$, $P < 0.001$; Table 4). When analyses were conducted including WL soils, the SOC concentration was correlated with ρ_b for 12 MLRAs, MWD for eight, TS for seven, and CI for three. Across the whole region and all land use systems, the SOC concentration was negatively correlated with ρ_b, CI, and TS ($P < 0.001$), and positively with MWD ($P < 0.05$; Table 4).

Table 2. Soil organic C concentration as a function of aggregate size (4.75, 2, 1, 0.5, 0.25, and <0.25 mm) by soil and three management systems including chisel plow (CP), no-tillage (NT), and forest or woodlot (WL) in seven Major Land Resource Areas (MLRAs) in Ohio.

MLRA	Soil	Land use	Organic C within aggregate size class						
			8–4.75	4.75–2	2–1	1–0.5	0.5–0.25	<0.25	LSD
			g kg^{-1}						
124	Allegheny silt loam	CP	12	12	13	11	9	7	4
		NT	21	19	19	18	18	15	6
		WL	29	26	27	24	25	19	5
		LSD	15	6	11	7	8	6	
126	Otwell silt loam/ Melvin silt loam	CP	23	24	23	22	20	18	1
		NT	21	22	22	21	20	16	4
		WL	33	31	29	26	23	18	12
		LSD	14	7	7	12	11	12	
111A	Kokomo silty clay loam/Celina silt loam	CP	20	18	16	16	14	12	4
		NT	24	22	22	21	18	16	1
		WL	57	58	64	61	46	33	6
		LSD	26	35	40	35	31	33	
111B2	Pewamo clay loam/ Blount silt loam	CP	21	23	23	21	20	18	2
		NT	17	18	19	19	17	15	1
		WL	61	62	64	66	62	45	8
		LSD	7	10	6	11	10	17	
111D	Fincastle silt loam/ Xenia silt loam	CP	19	20	20	19	18	14	2
		NT	18	20	19	19	18	14	2
		WL	33	36	36	32	30	27	5
		LSD	25	7	4	5	6	9	
99	Hoytville clay loam	CP	22	21	21	20	15	16	2
		NT	23	23	25	23	25	17	1
		WL	80	74	79	86	52	46	22
		LSD	26	22	19	20	9	35	
111B	Milton silt loam	CP	16	16	15	15	14	12	1
		NT	13	14	13	13	13	11	3
		WL	26	26	26	25	23	20	4
		LSD	8	6	7	8	11	6	

DISCUSSION

The data on this regional assessment show that long-term NT management systems caused moderate increases in soil compaction. Conversion to a NT system increased CI values by 0.3 to 1.6 MPa in nine out of 13 MLRAs. The increases in soil compaction were, however, relatively small and are not expected to adversely impact agronomic yield. Most of the CI values under NT were well below the critical values (>2 MPa) for silt loam, which has been shown to significantly limit seedling emergence, root development, plant growth, and crop yield (Siegel-Issem et al., 2005; Bueno et al., 2006). The high values of CI under NT compared with CP for MLRA 122 (2.13 vs. 0.56 MPa) and MLRA 124 (2.01 vs. 0.47 MPa) can be a concern, however, if NT-induced compaction persists or increases with time (Fig. 3A and 3B). Despite the high CI, the ρ_b values for these two MLRAs were relatively low (1.3 Mg m^{-3}), and differences between NT and CP systems were not significant. This contrasting response of related soil compaction parameters to NT management in these two MLRAs suggests the need for further monitoring of soil compaction parameters across time and space. Any future increase in compaction could negatively affect many dynamic soil processes and properties essential to plant growth. Excessive compaction can reduce macropores and their connectivity, thereby reducing aeration and inhibiting water movement (Siegel-Issem et al., 2005). While excessive compaction could lead to a decline in soil structure architecture with attendant degradation of soil physical, chemical, and biological properties, slight soil compaction in NT, as observed in the majority of MLRAs, can enhance crop growth. Indeed, minor soil compaction is beneficial to improving pore-size distribution, moderating air and water fluxes, increasing plant-available water retention, and reducing nutrient leaching in some coarse-textured soils (Mooney and Nipattasuk. 2003). It can also promote saturated and unsaturated flow through the soil matrix by reducing preferential or bypass flow. The larger difference in shear strength between NT and CP systems compared with the difference in CI indicates that shear strength may be a more sensitive indicator of management-induced changes in soil strength properties.

Increases in soil compaction by NT management relative to CP within each MLRA were not always correlated with changes in SOC concentration. The fact is that while adoption of NT practices consistently increased soil compaction, it did not increase SOC concentration for any aggregate size compared with CP practices at any of the MLRAs (Table 3). The higher CI and lower SOC concentration in NT soils compared with those in CP soils for MLRAs 111B2, 127, and 98 implies that a lower SOC concentration probably contributed to an increase in soil compaction levels in NT systems. In contrast, NT management had higher SOC concentration and soil compaction levels than CP in MLRA 124. These data show that relationships between SOC concentration and soil compaction parameters were soil specific.

Similar to the effects on soil compaction, the impacts of NT farming on soil structural properties were small and site specific (Fig. 4A and 4B). Soils under CP management reduced aggregate stability slightly compared with those under NT, but drastically when compared with those under WL management. This trend may be attributed to frequent disruption of aggregates by tillage in CP systems. The lack of disturbance in association with increased biological activity in NT and WL systems promotes aggregation (Shukla

Table 3. Soil organic C concentration as a function of aggregate size (4.75, 2, 1, 0.5, 0.25, and <0.25 mm) by soil and three management systems including chisel plow (CP), no-tillage (NT), and forest or woodlot (WL) in six Major Land Resource Areas (MLRAs) in Indiana and Pennsylvania.

MLRA	Soil	Land use	Organic C within aggregate size class						
			8–4.75	4.75–2	2–1	1–0.5	0.5–0.25	<0.25	LSD
			g kg^{-1}						
111C	Martinsville loam	CP	24	24	23	20	21	17	5
		NT	23	24	23	23	18	18	1
		WL	51	51	51	50	39	35	7
		LSD	32	28	29	29	32	21	
122	Crider silt loam	CP	11	13	13	12	11	9	2
		NT	12	12	11	11	10	8	2
		WL	34	32	26	20	15	11	6
		LSD	9	8	5	3	2	3	
98	Maumee loamy sand	CP	29	28	30	30	23	21	5
		NT	16	16	18	15	12	13	2
		WL	40	38	54	54	35	28	14
		LSD	8	12	31	31	12	4	
114B	Iva silt loam	CP	35	15	16	14	12	11	2
		NT	0	14	17	15	12	9	5
		WL	25	24	23	21	20	15	3
		LSD	10	9	2	2	2	1	
127	Gilpin silt loam	CP	31	30	26	28	28	23	3
		NT	26	24	24	26	24	21	3
		WL	42	41	37	35	32	24	8
		LSD	9	17	24	8	24	11	
147	Edom silty clay loam	CP	21	22	23	22	24	19	4
		NT	24	22	19	20	19	19	4
		WL	62	62	55	42	48	44	15
		LSD	45	45	35	23	30	24	

et al., 2003). The higher aggregate strength in CP than in NT soils for MLRAs 126 and 111B did not result in higher aggregate stability in CP soils because, during wet sieving, these aggregates slaked rapidly and differences in aggregate stability between CP and NT soils were not generally significant. These results are in accord with those reported from long-term cultivated watersheds by Shukla et al. (2003) and Blanco-Canqui et al. (2005b), who observed that CP soils had significantly higher aggregate strength but lower stability than long-term (>35-yr) NT on an unglaciated Rayne silt loam in Ohio. These trends are attributed to the fact that aggregates formed by organic binding agents, abundant in NT soils, are more water stable than those in soils under a CP system. The strong aggregate stability vs. SOC concentration relationship across the cropped soils indicates that increases in SOC concentration had an overall positive influence on macroaggregation, in accord with similar data reported for the region (Blanco-Canqui et al., 2006). The higher SOC concentration in macro- than in microaggregates indicates that the former are important to the sequestration and retention of SOC.

Aggregate-associated SOC concentration was not increased by the adoption of NT systems for any aggregate size at any of the MLRAs (Table 2). These results are not surprising, however, given that data from on-farm testing are affected by many interactive management factors compared with those from experimental research plots or small watersheds managed under controlled conditions. This on-farm study across a wide range of soil and management conditions shows that NT technology may not always increase SOC concentrations at the aggregate level relative to CP management. These findings have important implications for assessing the potential of NT farming for sequestering C and offsetting CO_2 emissions. We hypothesize that, in some soils, C gains in NT aggregates from higher input of biomass C may be offset by greater losses of C as greenhouse gases (e.g., CO_2 and CH_4) due to higher soil water content and favorable temperature in summer, thereby reducing any SOC gains in NT relative to CP systems (Baker et al., 2006; Venterea et al., 2006).

The inconsistent changes in soil physical properties and their relationships with SOC concentration with NT farming within each MLRA may be explained by differences in (i) soil attributes, (ii) management duration, (iii) cropping systems, and (iv) crop residue management. Within a generic NT system, farmers used a wide range of practices. Unlike in studies on small research plots, in this study factors such as slope gradient and cropping systems between NT and CP fields were not always identical in each MLRA. For example, soil textural and topographic characteristics varied among the 13 MLRAs (Table 1). The soils were developed under different parent materials and textural classes ranging from sand loam to clay. These differences probably influenced the magnitude of NT farming impacts on soil physical quality and aggregate-associated SOC concentration. For example, in a clayey soil (MLRA 99) in Ohio, the relationship between SOC concentration and soil physical properties was not significant, whereas in silt loams (MLRAs 114B and 124) the correlations were strong ($P < 0.01$). In some MLRAs, slope gradient significantly differed even within the same soil series for NT and CP systems.

The duration of NT and CP management also differed among all MLRAs. The NT management duration ranged between 5 and 30 yr. Improvements in soil structure and increases in SOC pools are a function of the duration of the NT system. The 35-yr NT management in MLRA 124 increased aggregate size by a factor of 6, whereas the 5-yr NT management in MLRA 111D did not have any effect on aggregate size when compared with the CP system. The 35-yr NT management compacted soil more than the 5-yr NT management, contrasting with the perception that long-term NT management often ameliorates compaction problems as the soil structure restores from initial stresses toward a steady-state equilibrium with time (Wilkins et al., 2002).

While some of the NT farms received a complete return of crop residues after harvest, others, for example under corn (*Zea mays*

Table 4. Coefficients of the correlations between soil organic C concentration and soil compaction and structural parameters across 13 Major Land Resource Areas (MLRAs) in the eastern USA.

MLRA	Across croplands				Across croplands and forest			
	Cone index	Bulk density	Tensile strength	Mean weight diameter	Cone index	Bulk density	Tensile strength	Mean weight diameter
111A	0.54 NS	0.59 NS	0.07 NS	0.78*	–0.13 NS	–0.89**	–0.35 NS	0.72*
111B	–0.52 NS	–0.61 NS	0.80*	–0.65 NS	–0.71*	–0.87**	–0.12 NS	0.66*
111B2	–0.78*	–0.13 NS	–0.96**	0.85*	–0.64*	–0.92***	–0.73*	0.91***
111C	–0.12 NS	0.35 NS	0.76*	–0.96**	–0.50 NS	–0.37 NS	0.52 NS	0.89**
114B	0.96***	0.66 NS	0.94**	0.99***	0.01 NS	–0.80*	0.38 NS	0.66*
122	0.37 NS	0.29 NS	0.76*	–0.35 NS	–0.47 NS	–0.67*	–0.68*	0.05 NS
124	0.94**	0.77*	–0.30 NS	0.59 NS	0.16 NS	–0.72*	–0.86**	0.69*
126	–0.36 NS	0.63 NS	0.68 NS	0.37 NS	–0.56 NS	–0.65*	–0.18 NS	0.56 NS
127	–0.97***	–0.85*	0.94**	–0.41 NS	–0.57 NS	–0.98***	–0.76*	–0.91***
147	0.26 NS	–0.01 NS	–0.74*	0.72 NS	–0.29 NS	–0.87**	–0.80**	0.02 NS
98	–0.95**	–0.44 NS	0.33 NS	0.22 NS	–0.86**	–0.84**	–0.21 NS	0.65*
99	–0.17 NS	–0.42 NS	–0.24 NS	0.07 NS	0.28 NS	–0.84**	–0.87**	0.49 NS
111D	0.27 NS	0.66 NS	0.58 NS	–0.60 NS	–0.26 NS	–0.93***	–0.75*	0.97***
All	–0.10 NS	–0.12 NS	0.05 NS	0.49***	–0.21*	–0.56***	–0.25*	0.32***

* Significant at the 0.05 probability level; NS = not significant.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

L.) for silage, received only partial or none. Complete residue return is vital to buffer wheel traffic and raindrop impacts, reduce soil compaction, and increase both aggregate stability and aggregate-associated SOC concentration in NT systems. Some of the fields received animal manure, which often has positive effects on soil physical quality and SOC pools (Mosaddeghi et al., 2000). Blanco-Canqui et al. (2005a) reported that CI and shear strength in cultivated watersheds under NT soils without manure were about twice as high as those in NT with manure. In this study, soil compaction parameters increased in MLRAs 126 and 127 in spite of frequent manure application. Cropping systems and the length of crop rotations also differed with MLRAs and tillage management. While a corn–soybean [*Glycine max* (L.) Merr.] rotation was the dominant system, there were other rotations such as corn–alfalfa (*Medicago sativa* L.) (MLRAs 124 and 127) and corn–soybean–wheat (*Triticum aestivum* L.) (MLRA 99). Soil aggregates were more stable and the aggregate-associated SOC concentration was relatively higher in NT under a corn–alfalfa rotation than in CP continuous corn in MLRA 124.

Cropping (CP and NT) increased soil compaction and reduced soil structural stability and aggregate-associated C in all aggregates size fractions compared with soils under WL management, which were less compact, more stable, and had higher aggregate-associated SOC concentrations than cropped soils. Inclusion of soils under WL in the correlation analyses greatly increased the significance of correlation coefficients between SOC concentration and soil physical properties.

CONCLUSIONS

The data presented show that NT management induced moderate changes in compaction across a broad range of soils in the eastern USA. The moderate compaction is not likely to adversely impact crop production because the values are below the high thresholds levels of compaction. The impacts of NT on soil structural properties are similarly small and site specific. Chisel-plowed soils reduced aggregate stability moderately compared with those under NT systems and drastically compared with wooded land. No-tillage farming appeared not to increase soil aggregate-associated SOC concentration compared with plow tillage in any of the soils studied. Differences in soil attributes, NT duration, cropping systems, and management of crop residues among the soils studied may explain the variable impacts of NT on soil properties. On a regional basis, improvement in aggregate stability is positively correlated with increases in SOC concentration. Cropping compacted and degraded soil structure and reduced aggregate-associated SOC concentration compared with wooded land. Further monitoring of spatial and temporal changes of the measured soil physical properties and aggregate-associated soil organic C concentration across these and other representative NT soils on a regional scale is recommended to make comparisons based on multiyear data.

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