# No-Tillage and Soil-Profile Carbon Sequestration: An On-Farm Assessment

**Humberto Blanco-Canqui***
**R. Lal**
Carbon Management and Sequestration Center
FAES/OARDC, School of Natural Resources
2021 Coffey Rd.
Ohio State Univ.
Columbus, OH 43210-1085

No-tillage (NT) farming is superior to intensive tillage for conserving soil and water, yet its potential for sequestering soil organic carbon (SOC) in all environments as well as its impacts on soil profile SOC distribution are not well understood. Thus, we assessed the impacts of long-term NT-based cropping systems on SOC sequestration for the whole soil profile (0–60-cm soil depth) across 11 Major Land Resource Areas (MLRAs: 121, 122, and 125 in Kentucky; 99, 124, 139A in Ohio; and 139B, 139C, 140, 147, and 148 in Pennsylvania) in the eastern United States. Soil was sampled in paired NT and plow tillage (PT) based cropping systems and an adjacent woodlot (WL). No-tillage farming impacts on SOC and N were soil specific. The SOC and N concentrations in NT soils were greater than those in PT soils in 5 out of 11 MLRAs (121, 122, 124, 139A, and 148), but only within the 0- to 10-cm depth. Below 10 cm, NT soils had lower SOC than PT soils in MLRA 124. The total SOC with NT for the whole soil profile (0–60 cm) did not differ from that with PT ($P > 0.10$) in accord with several previous studies. In fact, total soil profile SOC in PT soils was 50% higher in MLRA 125, 21% in MLRA 99, and 41% in MLRA 124 compared with that in NT soils. Overall, this study shows that NT farming increases SOC concentrations in the upper layers of some soils, but it does not store SOC more than PT soils for the whole soil profile.

Abbreviations: MLRA, Major Land Resource Area; NT, no-tillage; PT, plow tillage; SOC, soil organic carbon; WL, woodlot.

Intensive and continued tillage practices have caused enormous losses of SOC and N pools as greenhouse gases (e.g., $CO_2$, $CH_4$, $N_2O$) to the atmosphere. It is estimated that as much as 60% of SOC in temperate regions and 75% in the tropics has been depleted by PT, contributing about 23% of the total greenhouse gas concentration in the atmosphere (Intergovernmental Panel on Climate Change, 1996; Lal, 2004). As a consequence, NT farming is being promoted as an alternative to PT for restoring SOC as an ancillary benefit of NT farming. It is generally viewed that switching from PT to NT farming would restore the SOC pool that has been lost, thereby offsetting emissions by fossil fuel combustion and alleviating concerns of the projected global climate change (West and Post, 2002). The NT farming is being widely practiced in North and South America. In the United States, about 20% of the total cultivated area is under NT agriculture (Lal, 2004).

While NT farming is highly beneficial to soil and water conservation and reduction of production costs, its potential for sequestering SOC needs a critical and objective assessment (Angers et al., 1997; Puget and Lal, 2005). Indeed, Baker et al. (2007) argued that the higher SOC sequestration in NT systems reported in many studies may merely be due to sampling protocol that could have biased the results. The argument is that almost all the studies reporting higher SOC in NT soils relative to plowed soils have based their conclusions from samples collected within only a ≤30-cm soil depth (West and Post, 2002), and the few studies reporting SOC for the whole soil profile have found either no differences in SOC below the 30-cm depth or even lower SOC in NT than PT soils (Baker et al., 2007).

In most cases, SOC in NT soils appears to be concentrated near the soil surface. On an Alfisol in Nigeria, NT soils had higher SOC than PT in the 0- to 15-cm depth, but PT soils had greater SOC in the 15- to 30-cm depth, and total profile SOC was much greater under PT (Lal, 1997). The lower SOC in deeper NT layers may thus offset the greater SOC in the upper layers. As a result, the total profile SOC between NT and PT soil management may not significantly differ. The amount of SOC stored in deeper layers is the most important fraction for long-term SOC sequestration. Unlike SOC in the topsoil, which is prone to rapid perturbations and decomposition by the increased near-surface microbial activity and high fluctuations in soil temperature and moisture regimes, the SOC in subsoil is typically protected inside soil aggregates and has lower turnover rates (Lorenz and Lal, 2005).

Thus, further research is needed to clarify NT impacts on SOC sequestration for the entire soil profile. Previous studies have mostly focused on shallow surface soil (<30-cm depth) (West and Post, 2002). The limited information on soil profile SOC distribution is a hindrance to conclusive identification of the beneficial effects, if any, of NT farming on SOC sequestration in deeper layers. Assessment of SOC for the

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*Corresponding author (blanco.16@osu.edu).
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whole profile and comparison with previous studies for a wide range of soils under varying topographic and climatic conditions are warranted for a broader understanding of the performance of NT systems. This approach could also enhance our understanding of the dependence of SOC sequestration on soil intrinsic characteristics (e.g., soil texture, drainage, and topography). Several studies have shown that SOC concentrations in clayey and even in some silt loam soils may either change slowly or remain unaffected by conversion of PT to NT (Yang and Wander, 1999; Puget and Lal, 2005). Blanco-Canqui and Lal (2007a) reported that removal of corn (*Zea mays* L.) residue from long-term NT continuous corn systems rapidly decreased SOC in sloping and unglaciated silt loam soils, whereas its impacts on SOC in nearly level clayey soils were not detectable after 3 yr of residue management. Shifting from PT to NT practices may favor greater SOC storage in sloping soils and soils prone to accelerated erosion (VandenBygaart et al., 2003). Thus, further characterization of SOC under long-term NT practices for soils with contrasting properties and under contrasting landscape conditions is necessary to understand the soil-specific dynamics of SOC sequestration.

Most of the available information on SOC sequestration in NT systems has been collected from small research plots. Thus, little is known about the NT farming implications on SOC sequestration under on-farm conditions, particularly regarding the SOC distribution for the whole profile. Yet, this is precisely the information that is needed to discern the potential of NT farming in sequestering SOC at a large scale. Management practices in research plots, such as soil disturbance, cropping systems, planting and harvesting protocols, residue return rates, and weed and pest control, are delicately controlled. Moreover, research plots are often sited in uniform soils with gentle slopes managed with refined measures of erosion control to minimize the confounding effects of other natural factors. Such ideal conditions, while important to research, often contrast with the NT practices in growers' fields. As a consequence, NT farming performance under variable on-farm conditions may differ considerably from that on research plots.

Direct measurement of SOC on a regional basis covering a large geographic spectrum of NT farming scenarios in farmers' fields across contrasting soil, topographic, microclimate, and management conditions is uncommon. Expansion of the database of SOC in NT farming potential across a regional scale is urgently needed, especially now when large areas of cropland are being converted to long-term NT systems based on the premise, in part, that NT soils sequester SOC and may open economic opportunities in trading C for farmers through the Chicago Climate Exchange. Such a database on SOC dynamics is also needed as baseline information for modeling SOC sequestration in croplands at regional and national scales.

Therefore, this study was undertaken to assess the potential of long-term NT-based cropping systems on SOC sequestration compared with PT and forest sites across 11 selected MLRAs in the eastern United States. The specific objectives were to determine: (i) changes in SOC within the topsoil due to conversion to NT farming, and (ii) the depth distribution (0–60 cm) of SOC in NT soils compared with PT and forest soils. This study was conducted under the Midwest Regional Carbon Sequestration Partnership (MRCSP) program launched by the U.S. Department of Energy's Carbon Sequestration Program in 2003. The MRCSP initiative is specifically designed to underpin research into the many uncertainties and knowledge gaps concerning the potential of SOC sequestration in croplands on regional and national scales.

## MATERIALS AND METHODS

### Description of the Study Sites

Paired fields under long-term (>4 yr) NT and PT systems were selected within 11 representative MLRAs distributed in three states—Ohio, Kentucky, and Pennsylvania—in the eastern United States (Table 1). Three sites were in Kentucky, three in Ohio, and five in Pennsylvania, distributed in the following MLRAs: 121, 122, and 125 in Kentucky; 99, 124, and 139A in Ohio; and 139B, 139C, 140, 147, and 148 in Pennsylvania (Table 1). These MLRAs were selected on the basis of the abundance of long-term NT practices. An undisturbed site (control) under forest or woodlot (WL) adjacent to the paired NT and PT fields was included in the study for comparison purposes. Geographical coordinates and soil and management characteristics for each site studied are reported in Table 1. Soil textural classes included loam, silt loam, silty clay loam, and clay loam, with silt loam being the most common textural class. Slope gradient ranged from 1 to 6%.

At all sites, NT and PT fields were next to each other and thus had similar soil and slope characteristics. The duration of NT management across different MLRAs ranged from 4 to 30 yr. Cropping systems between NT and PT fields differed in some MLRAs, although corn–soybean [*Glycine max* (L.) Merr.] was the dominant rotation (Table 1). Some sites, such as those in MLRAs 121, 122, and 125 in Kentucky, were under complex crop rotations, but corn and soybean were always included in the rotations (Table 1). In some MLRAs, farmers use a combination of moldboard and chisel plows in PT because the use of a moldboard plow has decreased in recent years. These diverse and complex practices reflect the reality of farmers' fields. In some cases while still practicing the same tillage system in the same field, farmers often shifted crop rotations, fertilizer use, and amount of residue returned (e.g., corn silage) or introduced new practices including cover crops and perennial crops (e.g., legumes) depending on the market, weather conditions, and soil conservation needs. The complex management systems may affect the net changes in SOC as a result of adoption of NT farming. Identification of long-term and paired (adjacent) NT and PT fields managed under identical conditions of tillage and cropping systems for characterization of SOC under on-farm conditions was somewhat difficult. Thus, for the MLRAs in which cropping systems (e.g., crop rotations, residue return) differed between NT and PT (Table 1), this study reported the impacts of NT- and PT-based cropping systems on SOC rather than those of tillage alone. This study provided an inventory of SOC for the whole profile for on-farm NT and PT systems under both similar and differing scenarios of cropping systems reflecting the reality of farmers' fields (Table 1).

### Soil Sampling and Analyses

Intact soil cores, using metal sleeves 4.1 cm in diameter by 5 cm deep, were manually collected in triplicate from each field and MLRA using a hammer-driven sampler from depth intervals of 0 to 5, 5 to 10, 10 to 30, 30 to 50, and 50 to 60 cm in late March and early April 2007. The soil cores were used for the determination of bulk density ($\rho_b$) (Grossman and Reinsch, 2002). Bulk soil samples of approximately 2000 g were also obtained from the same five depth intervals at each sampling location. Soil samples were transported to the lab and air dried at 20°C for 72 h. A portion of the air-dried samples was gently ground and passed through a 0.25-mm sieve for the determination of SOC concentration by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Analysensysteme, Hanau, Germany; Nelson and Sommers, 1996). The mass of SOC on an area basis (Mg ha$^{-1}$) was computed by multiplying the SOC in grams per 100 g by the $\rho_b$ (Mg m$^{-3}$), depth of soil sampling (m), and soil area (10,000 m$^2$ ha$^{-1}$). The C/N ratio was computed by dividing the SOC by the N content in grams per 100 g.

## Statistical Analyses

The NT, PT, and WL systems were not field replicated. The three fields were, however, adjacent to each other and sited on a similar landscape position, slope, and soil (Table 1). Thus, the three sampling locations within each field were used as pseudo-replicates for the statistical analysis, and the analysis was treated as if it were a randomized experiment. While we recognize that this procedure may not fully separate the effects of inherent differences among fields, pseudo-replication is a common approach used to overcome the lack of replication in on-farm studies. A one-way ANOVA model was used to test whether differences in $\rho_b$, SOC, N, and C/N ratio among NT, PT, and WL treatments by MLRA were significant. Statistical analyses were performed using the SAS statistical software (SAS Institute, 2007), and significance is reported at the 0.05 probability level unless otherwise stated. Analyses of the measured data were conducted by MLRA and no comparisons among MLRAs were attempted owing to the high intrinsic variability among sites.

## Compilation of Published Studies

Previously published studies on SOC sequestration from long-term paired experiments across the globe were compiled to critically examine the results obtained in the present study. Because the focus of this study was to assess the total SOC for the entire soil profile, only those studies that have reported total SOC for >30-cm depth were compiled. The term *soil profile* refers to "a vertical section of the soil through all its horizons and extending into the C horizon" (SSSA, 2007). Some studies where soil was sampled only down to 40-cm depth were also included and were analyzed as if they had measured SOC for the whole soil profile, although this sampling depth of 40 cm may not have necessarily extended into the C horizon. Reports for SOC measurements between 0- and 30-cm soil depth have been extensively reviewed by other researchers (West and Post, 2002; VandenBygaart et al., 2003; Puget and Lal, 2005) and were thus not considered in this study. A total of 16 paired experiments were compiled and differences in SOC plus their statistical significance between NT and PT practices were reviewed.

# RESULTS

## Differences in Soil Organic Carbon by Depth Interval and the Whole Soil Profile

Data on soil $\rho_b$ required to express SOC concentration on an area basis (Mg ha$^{-1}$) are reported in Fig.

**Table 1. Site information and soil and management characteristics of paired no-tillage (NT) and plow tillage (PT) fields per site within each selected Major Land Resource Area (MLRA) in Kentucky, Ohio, and Pennsylvania.**

| MLRA | Site location | Soil series (slope) | Taxonomic classification | Management |
|---|---|---|---|---|
| 121 | Georgetown, KY (38°13.1670´ N, 84°28.7651´ W) | Gilpin channery silt loam (6%) | fine-loamy, mixed, active, mesic Typic Hapludults | 8 yr NT sweet corn (*Zea mays* var. *rugosa*)–soybean–pumpkin (*Cucurbita maxima* L.) receiving 225 kg ha$^{-1}$ of N during pumpkin;<br>10 yr PT corn–soybean–vegetables (pepper [*Capsicum annuum* L.], bean [*Phaseolus vulgaris* L.], and tomato [*Lycopersicon esculentum* L.]) receiving 150 kg ha$^{-1}$ of N during corn |
| 122 | Glasgow, KY (37 0.1226´ N, 85°55.5832´ W) | Crider silt loam (3%) | fine-silty, mixed, active, mesic Typic Paleudalfs | 10 yr NT corn–soybean; 10 yr PT corn–soybean–tobacco receiving about 100 kg ha$^{-1}$ of N. |
| 125 | McKee, KY (37°25.8868´ N, 83°59.5938´ W) | Maury silt loam (5%) | fine, mixed, semiactive, mesic Typic Paleudalfs | 15 yr NT continuous corn silage receiving 140 kg ha$^{-1}$ of N and 112 kg ha$^{-1}$ of K; 10 yr PT continuous tobacco with wheat and rye cover crop receiving 105 kg ha$^{-1}$ N, 90 kg ha$^{-1}$ P, and 195 kg ha$^{-1}$ K |
| 99 | Fremont, OH (41°21.5594´ N, 83°5.2101´ W) | Lenawee silty clay loam (1%) | fine, mixed, semiactive, nonacid, mesic Mollic Epiaquepts | 15 yr NT and PT corn–soybean with residue returned, receiving 225 kg ha$^{-1}$ N, 84 kg ha$^{-1}$ P, and 135 kg ha$^{-1}$ K during corn |
| 124 | Jackson, OH (38°58.379´ N, 82°47.3865´ W) | Doles silt loam (1%) | fine-silty, mixed, active, mesic Aeric Fragiaqualfs | 12 yr NT corn–soybean–alfalfa and 20 yr PT continuous corn receiving 225 kg ha$^{-1}$ N and K, and 112 kg ha$^{-1}$ P during corn; ~7 Mg ha$^{-1}$ of lime was applied in 2002 |
| 139A | Canal Fulton, OH (40°52.7280´ N, 81°38.4214´ W) | Chili loam (4%) | fine-loamy, mixed, active, mesic Typic Hapludalfs | 30 yr NT and 15 yr PT corn–soybean receiving 120 kg ha$^{-1}$ N and 20 kg ha$^{-1}$ P and K during corn |
| 139B | Grove City, PA (41°13.2813´ N, 80°4.5554´ W) | Canfield silt loam (2%) | fine-loamy, mixed, active, mesic Aquic Fragiudalfs | 10 yr NT and 30 yr PT corn–soybean rotation with 135 kg ha$^{-1}$ N |
| 139C | Greenville, PA (41°21.1790´ N, 80°29.5330´ W) | Ravenna silt loam (1%) | fine-loamy, mixed, active, mesic Aeric Fragiaqualfs | 8 yr NT corn–soybean rotation and 3 yr PT receiving 25 L of liquid fertilizer with 9% N, 8% P, and 8% K, and 122 L of liquid fertilizer with 32%N during corn |
| 140 | Troy, PA (41°49.3611´ N, 76°51.7202´ W) | Morris channery loam (6%) | coarse-loamy, mixed, active, mesic Aeric Fragiaquepts | 20 yr NT and PT continuous corn receiving cattle manure at 50 Mg ha$^{-1}$ yr$^{-1}$ |
| 147 | Lewisburg, PA (40°57.9963´ N, 76°55.8258´ W) | Holly silt loam (3%) | fine-loamy, mixed, active, nonacid, mesic Fluvaquentic Endoaquepts | 5 yr NT and 4 yr PT corn–soybean with rye cover crop receiving 30.4 m$^3$ of liquid manure, 8 kg ha$^{-1}$ N, 24 kg ha$^{-1}$ P, 6 kg ha$^{-1}$ K, and 5 Mg ha$^{-1}$ lime |
| 148 | Lancaster, PA (40°6.1314´ N, 76°32.0274´ W) | Hagerstown clay loam (3%) | fine, mixed, semiactive, mesic Typic Hapludalfs | 4 yr NT corn–soybean and 10 yr PT continuous corn receiving 75 m$^3$ of liquid manure every other year |

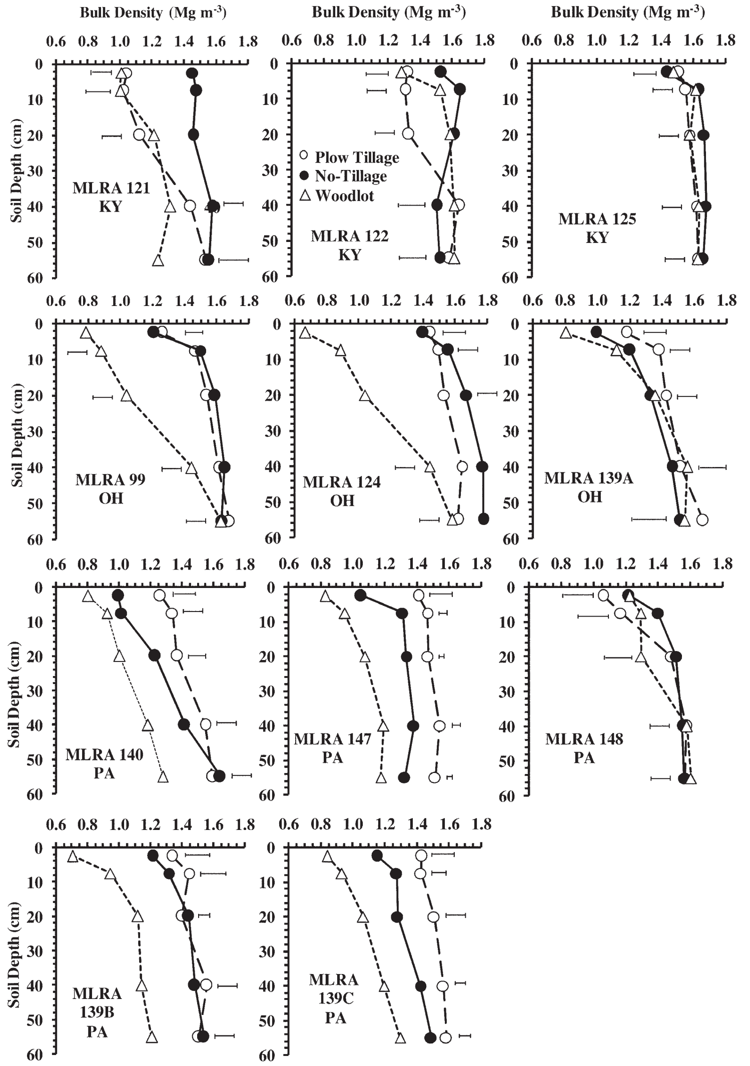

**Fig. 1. Mean soil bulk density by management for each Major Land Resource Area across Kentucky, Ohio, and Pennsylvania. Error bars are the LSD values for each depth interval.**

1. Conversion to NT farming increased, decreased, or had no effect on $\rho_b$, depending on the soil. It increased $\rho_b$ by 38% in MLRA 121 and by 21% in MLRA 122 across the 0- to 30-cm soil depth, whereas it decreased $\rho_b$ by 17% in MLRA 139A and by 30% in MLRA 140 in the 0- to 20-cm depth. The NT soil had lower $\rho_b$ than the PT soil in MLRA 147 for all depths and in MLRA 139C in the 0- to 50-cm depth. Soils under WL had significantly lower $\rho_b$ than cultivated soils in the surface layers in most MLRAs (Fig. 1).

The impacts of NT farming on SOC concentration by depth were inconsistent and varied among MLRAs (Fig. 2 and 3). Trends in SOC concentration between tilled and NT soils on a mass (Fig. 2) and on an area (Fig. 3) basis were similar in seven MLRAs (99, 124, 125, 139A, 139B, 139C, and 148) and differed in four MLRAs (121, 122, 140, and 147). Tillage management affected the SOC concentration on a mass basis but not on an area basis in MLRAs 121 and 122.

The NT soil had greater SOC concentration on an area basis than PT soils in the 0- to 5-cm soil depth. On the contrary, in MLRAs 140 and 147, SOC concentration on a mass basis was significantly greater in NT systems but not on an area basis in the 0- to 5-cm soil depth. The SOC concentration on a mass basis in NT soils was 40% greater in MLRA 140 and 50% greater in MLRA 147 compared with that in PT soils.

The results for SOC concentration on an area basis were the following. The NT management increased SOC over PT in 5 out of 11 MLRAs, but these increases were only significant within the 0- to 10-cm soil depth. The SOC in NT soils was higher by 1.8 times in MLRA 121 and by 2.3 times in MLRAs 122, 139A, and 148 in the 0- to 10-cm depth. In MLRA 124, the SOC in the NT soil was greater by 1.5 times only in the 0- to 5-cm depth. Soils under WL consistently had the greatest SOC near the soil surface. Differences in SOC between wooded and NT soils were much smaller than those between wooded and tilled soils in most MLRAs in the 0- to 10-cm depth. In MLRAs 124, 125, and 148, while NT soil was greater than PT soil in the shallow layer (<10 cm), the PT soils had greater SOC below 10-cm depths. The greater SOC in NT soils in these three MLRAs was reversed at deeper depths. The SOC in NT soils was lower than that in PT soils by 1.4 times in the 10- to 30-cm depth, 1.8 times in the 30- to 60-cm depth, and 4.0 times in the 50- to 60-cm depth in MLRAs 124 and 125. In MLRA 148, the SOC in NT soils were lower than in PT soils by 1.3 times in the 30- to 40-cm depth and by 2.7 times in the 40- to 60-cm depth.

Differences in total SOC for the whole soil profile (0–60 cm) between tilled and NT soils were not significant (Fig. 4). Indeed, SOC in NT soils was lower than in PT soils in MLRAs 125, 99, and 124. The SOC in PT soils was 50% higher in MLRA 125, 21% in MLRA 99, and 41% in MLRA 124 compared with that in NT soils. These results are supported by the 16 previous paired experiments reviewed in this study (Table 2), where 88% of the pair studies reported no significant differences in SOC between tilled and NT soils for the entire soil profile, and only two paired studies reported higher SOC in NT soils. Table 2 also shows that 44% of previous studies found higher SOC in NT soils and 34% found higher SOC in PT soils but differences were not significant due to the high variability in the data.

## Soil Nitrogen and Carbon/Nitrogen Ratio

The trend of NT impacts on N was similar to that on SOC (Table 3). The NT management increased N in 5 out of 11 MLRAs ($P < 0.05$) in the 0- to 5-cm depth. Conversion to NT farming increased N by about 1.6 times in MLRAs 121 and 124, and by about 3.0 times in MLRAs 122, 139A, and 148. There were no significant differences in N between tilled and NT soils in the rest of the MLRAs in the 0- to 5-cm depth. At lower depths (>10 cm), NT soils had significantly higher N than PT soils in MLRA 124 by 49% in the 0- to 5-cm depth, equal in the 5- to 10-cm depth, and lower by 31% in the 10- to 30-cm depth and by about 66% in the 30- to 60-cm depth compared with PT. The NT soils had 28% lower N in the 10- to 30-cm depth in MLRA 99, about 70% lower N in MLRAs 122 and 125 in the 30- to 50-cm depth, and 130% lower N in MLRA 148 in the 50- to 60-cm depth compared with PT.

The C/N ratio was affected by management only in the surface layers. The NT soils had higher C/N ratios than PT soils only in MLRAs 121, 122, and 139B for the 0- to 5-cm depth (Table 4). Forest soils had generally higher N than PT soils in the 0- to 5-cm depth, but differences between wooded and NT soils were smaller. The C/N ratio in wooded soils was higher than in cultivated soils in 5 out of 11 MLRAs in the surface layer.

## DISCUSSION

Because calculations of SOC concentration on an area basis rather than on a mass basis are preferred (Ellert and Bettany, 1995), differences in SOC among treatments were analyzed based on SOC expressed on an area basis. Differences in bulk density between tilled and NT soils had a large influence on SOC concentration on an area basis. The lower bulk density with PT than with NT resulted in lower SOC concentrations in MLRAs 121 and 122, whereas the lower bulk density with NT in MLRAs 140 and 147 reduced differences in SOC concentration between tilled and NT soils (Fig. 1 and 3). Management impacts on soil bulk density were site specific. Time after tillage appeared to influence differences in bulk density in surface layers. The PT soils that were plowed in the fall, 5 mo before our sampling, and those in MLRAs 121 and 122 had significantly lower bulk density than NT management in silt loams. In contrast, the bulk density in soils plowed in the spring in 2006, 11 mo before soil sampling, was either higher or equal to that of NT soils. On a clayey soil in MLRA 99 in Ohio, bulk density values of PT soils plowed in the fall did not, however, significantly differ from those of NT soils, suggesting that clay soils rapidly consolidated following tillage. Similar results have been reported for other studies in clayey soils in the same region (Lal, 1999; Puget and Lal, 2005).

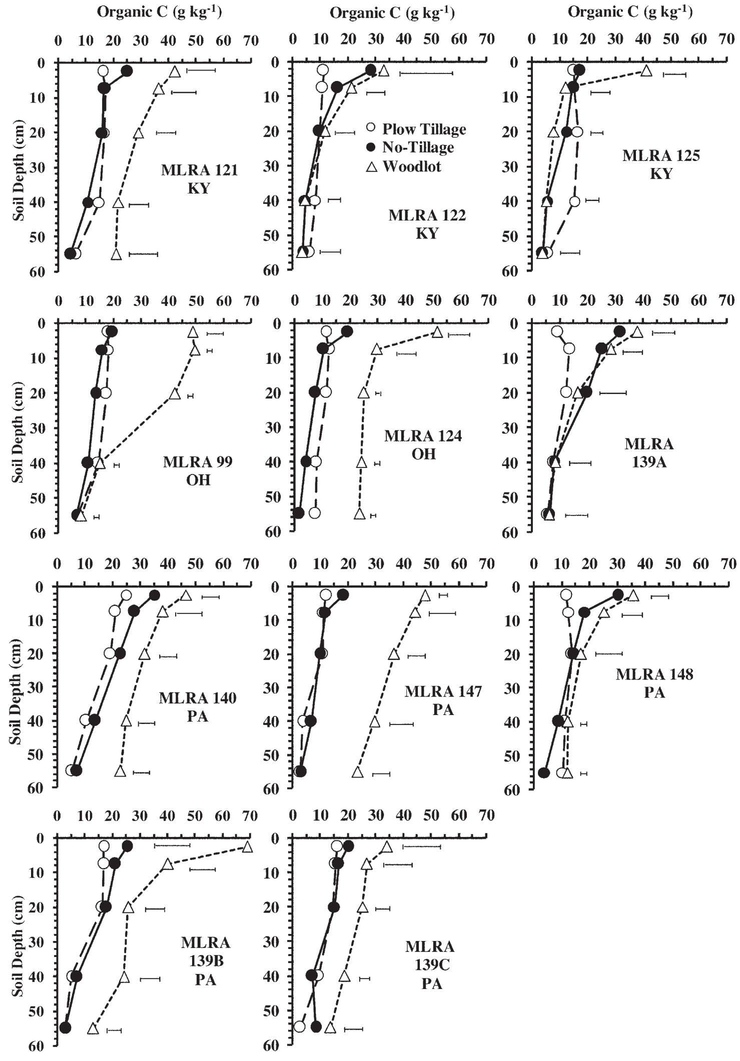

**Fig. 2. Mean soil organic C concentration on a mass basis by management for each Major Land Resource Area across Kentucky, Ohio, and Pennsylvania. Error bars are the LSD values for each depth interval.**

The impacts of 4 to 30 yr of NT farming on SOC and N were variable and soil specific (Tables 2, 3, and 4). Conversion of PT to NT farming increased SOC and N in a few soils but only in the surface layers (<10-cm depth). The strong stratification of SOC in the upper layers in NT soils, mainly attributed to surface residue mulching, is in accord with many other studies (Angers et al., 1997; West and Post, 2002). Blanco-Canqui and Lal (2007b) observed that soils under 10 yr of NT management receiving 8 and 16 Mg ha$^{-1}$ yr$^{-1}$ of wheat (*Triticum aestivum* L.) straw mulch developed a well-defined dark soil layer <5 cm near the soil surface and confined gains in SOC only to the 0- to 10-cm depth. The smaller differences in SOC and N between wooded and NT soils than those between wooded and tilled soils in the surface layers also corroborate the potential of NT soils for restoring some of the SOC lost and improving soil fertility in the surface soil. The influence of tillage on C/N was small, and the higher C/N ratio in NT soils in some MLRAs is attributed to the slower mineralization of surface residues (Torbert et al., 1997).

What is somewhat surprising is that total SOC for the whole profile was not only unaffected by NT farming but was actually lower in NT than in PT soils in three MLRAs (99, 124, and 125). The NT farming increased SOC in the surface layer (<10-cm depth) in 5 out of 11 MLRAs, but these beneficial effects abruptly dissipated with increasing soil depth. The lower SOC in NT farming in MLRAs 99, 124, and 125 suggests that SOC losses from some plowed topsoil may be compensated by SOC gains in deeper soil. The differences in SOC may have the following explanations. In MLRA 125, no surface residue was returned to the NT soil, as the field was under continual silage corn. Likewise, little or no residue was left in the PT soil, which was under tobacco (*Nicotiana tabacum* L.) (Table 1). Unlike the NT field, however, the PT field was under winter wheat and rye (*Secale cereale* L.) cover crops, which were plowed under every year. Thus, we hypothesize that the higher SOC with PT is due to the use of cover crops. In MLRA 124, the higher SOC with PT may have been due to the use of continuous corn, a high-biomass-producing crop, in contrast with the corn–soybean–alfalfa (*Medicago sativa* L.) rotation in the NT field. Annual burying of coarse corn residues in PT soils may have increased SOC at lower depths compared with the relatively low-biomass-producing rotation adopted in NT farming.

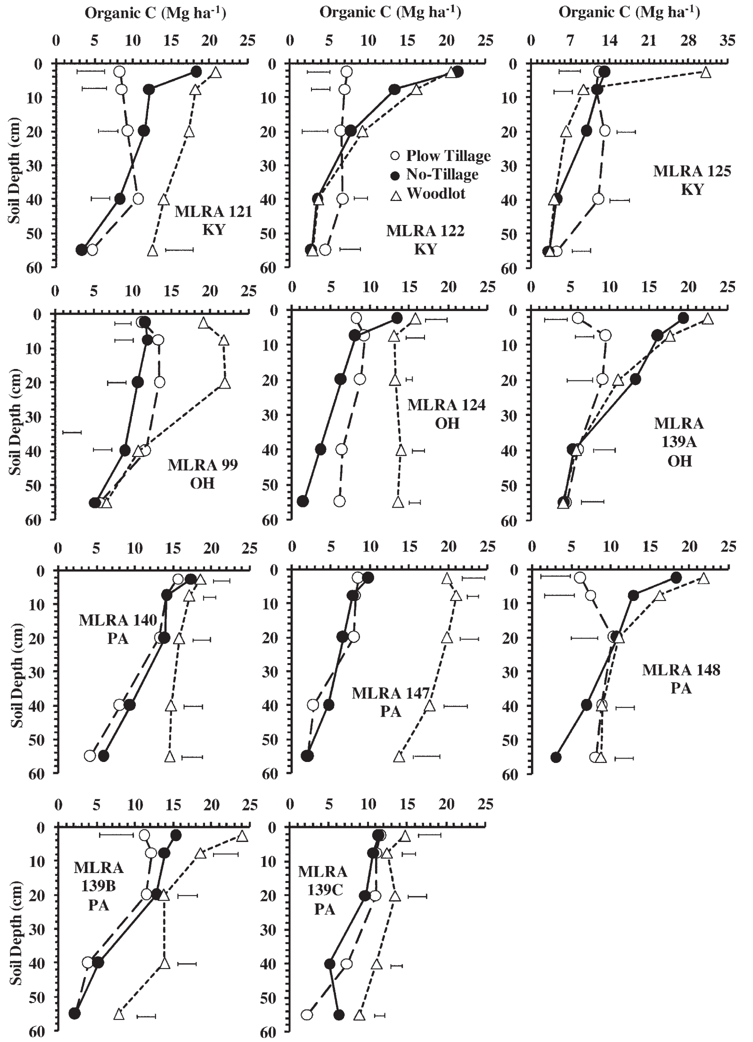

**Fig. 3. Mean soil organic C concentration on an area basis by management for 5-cm soil depth within each sampling depth interval (0–5, 5–10, 10–30, 30–50, and 50–60 cm) for each Major Land Resource Area across Kentucky, Ohio, and Pennsylvania. Error bars represent the LSD values for each depth interval.**

While the diverse cropping systems may have masked the true impacts of NT farming on SOC sequestration in MLRAs 124 and 125, the long-term (15-yr) paired NT and PT site in MLRA 99 was under identical cropping systems, yet NT soils stored less SOC than PT soils, implying that differences in SOC at this site are primarily due to the tillage system. The reasons for the lower SOC in NT soils may include the following.

First, PT management mixes and buries residue at deeper depths than NT farming, which leaves residues on the soil surface. Buried residues at the deepest boundaries of the plowed layer decompose at slower rates than surface residues because they are protected from microbial attack and erosion hazards, which favors SOC accumulation (VandenBygaart et al., 2003). While SOC in NT soils can also move to lower depths through earthworm burrows and leaching (Lorenz and Lal, 2005), the results of this study suggest that the amount transferred through such pathways may be modest in clayey soils compared with plowing of coarse residues.

Second, the crop rooting depth between NT and PT soils may differ. The NT soil may be unfavorable for the growth of roots (e.g., corn) into deeper layers. The relatively near-surface higher water content and favorable temperature of NT soils during the growing season (Blanco-Canqui and Lal, 2007a) may often concentrate roots near the surface, unlike in PT soils where roots may extend to lower depths due to the relatively loose plowed soil and high soil water content and favorable temperature at lower depths. Indeed, Qin et al. (2006) reported that the corn root length density in NT soils was higher than in PT soils in the 0- to 5-cm depth, but it was lower compared with that in PT soils at depths below 10 cm. Besides, corn plant roots often extend down to 50-cm depth (Qin et al., 2006), which is much deeper than the typical sampling depth for SOC in most studies (West and Post, 2002). The relatively higher soil strength, in some NT soils, can also limit the deeper distribution of roots (Hughes et al., 1992).While the soil profile final dry mass of roots between tilled and NT soils may not differ, NT management may reduce root length by 15 to 33% in deeper layers, and the greater root density in PT management in the subsoil could promote greater SOC storage under PT management in deeper soil (Braim et al., 1992).

Third, buried residues in PT soils are more closely associated with the soil matrix than surface residues in NT soils (Angers et al., 1997). The buried-residue-derived particulate organic matter could react with clay particles and organo-mineral complexes and favor formation of stable SOC. The SOC may then be physically entrapped and chemically adsorbed as recalcitrant compounds with lower turnover rates than surface SOC (Tisdall and Oades, 1982).

The lack of significant differences in SOC between tilled and NT soils for the whole profile in the majority (8 out of 11) of MLRAs with similar cropping systems has large implications and suggests that NT farming is no better than PT systems for storing SOC in the whole profile of the soils studied. These results are in accord with previously published

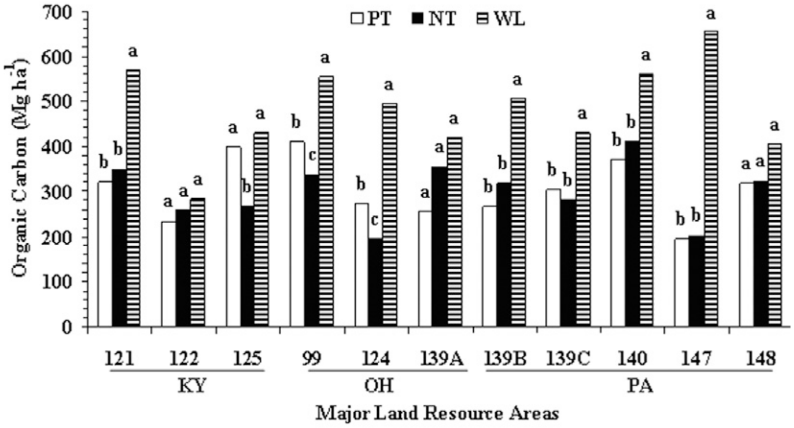

**Fig. 4. Mean soil organic C concentration on an area basis for the whole soil profile (0–60 cm) for no-tillage (NT), plow tillage (PT), and woodlot (WL) management within each selected Major Land Resource Area across Kentucky, Ohio, and Pennsylvania. Bars with the same lowercase letter within each MLRA are not significantly different.**

studies where 14 out of 16 pairs reported no significant differences in soil profile SOC between tilled and NT systems (Table 2). It also supports the recent discussions arguing that the reported higher SOC in NT soils is merely due to shallow sampling (Baker et al., 2007). Figures 3 and 4 show that conclusions regarding the NT management impacts on SOC sequestration depend on the depth to which the soil is sampled. If our samples had been collected only from shallow depths (<30 cm), this study could have reached completely different conclusions. Thus, based on the present results (Fig. 4) and in accord with Dolan et al. (2006), it is suggested that SOC must be assessed for the entire soil profile, while revisiting the current sampling scheme. The shallow sampling protocols (<30 cm) used in most previous studies not only have ignored accounting for SOC distribution in the whole soil profile but also have, surprisingly, overlooked the implications of the rooting depth of common crops and the depth of residue burial by plowing, which can easily reach depths below the typical sampling depth (<30 cm) (Dolan et al., 2006; Qin et al., 2006). Clearly more research involving intensive or multiyear quantification of SOC and dynamics including measurement of SOC losses through C emissions (e.g., $CO_2$, $CH_4$), erosion, and leaching in long-term paired NT and PT fields is necessary to fully discern the potential of NT farming. For now, based on the data available (Table 2), NT is no better than PT farming for SOC sequestration for the entire profile in the majority of soils. Data suggest that the potential of NT farming for favoring C storage is more complex than perceived, and thus caution must be exercised while generalizing the benefits of NT for SOC sequestration in all soils.

It is, however, important to point out that that while the SOC between PT and NT farming may not differ, the SOC under NT

**Table 2. Differences in soil organic C (SOC) between no-tillage (NT) and plow tillage (PT) for the whole soil profile across a range of soils.**

| Site | Soil | Cropping system | Duration of NT | Total depth of sampling | ΔSOC† | Statistical significance (NT vs. PT)‡ | Reference |
|---|---|---|---|---|---|---|---|
| | | | yr | cm | Mg $ha^{-1}$ $yr^{-1}$ | | |
| Londrina, Brazil | clayey | soybean–winter wheat and corn–soybean–cotton | 21 | 40 | | NS | Machado et al. (2003) |
| Harrington, QC, Canada | fine sandy loam | wheat–barley (*Hordeum vulgare* L.)/barley–soybean | 8 | 60 | −0.99 | NS | Angers et al. (1997) |
| La Pocatière, QC, Canada | clay | continuous barley | 6 | 60 | −3.38 | NS | Angers et al. (1997) |
| Normandin-2, QC, Canada | silty clay | continuous barley | 3 | 60 | 0.90 | NS | Angers et al. (1997) |
| Ottawa, ON, Canada | sandy loam | continuous corn | 5 | 60 | 1.20 | NS | Angers et al. (1997) |
| Ottawa, ON, Canada | sandy loam | continuous wheat | 5 | 60 | 2.97 | NS | Angers et al. (1997) |
| Delhi, ON, Canada | sandy loam | continuous corn | 4 | 60 | −0.77 | NS | Angers et al. (1997) |
| Harrow, ON, Canada | clay loam | continuous corn | 11 | 60 | −0.08 | NS | Angers et al. (1997) |
| Ponta Grossa, Brazil | clay | wheat–soybean/black oat (*Avena strigosa* Schreb.) soybean/black oat–corn | 22 | 40 | 0.86 | S | Sa et al. (2001) |
| Prince Edward Island, Canada | fine sandy loam | soybean–barley | 16 | 60 | −0.20 (estimate) | NS | Carter (2005) |
| Waseca, MN | clay loam | continuous corn | 14 | 45 | 1.9 | S | Huggins et al. (2007) |
| Waseca, MN | clay loam | continuous soybean | 14 | 45 | 0.85 | NS | Huggins et al. (2007) |
| Waseca, MN | clay loam | corn–soybean | 14 | 45 | 0.76 | NS | Huggins et al. (2007) |
| Rosemount, MN | silt loam | corn–soybean with corn stover removed | 23 | 45 | 0 | NS | Dolan et al. (2006) |
| Rosemount, MN | silt loam | corn–soybean with corn stover returned | 23 | 45 | −0.48 | NS | Dolan et al. (2006) |
| Ontario, Canada | silt loam | continuous corn | 29 | 50 | −0.04 | NS | Wanniarachchi et al. (1999) |
| MLRA 121 (Georgetown, KY) | silt loam | sweet corn–soybean–pumpkin and corn–soybean–vegetables | 8 | 60 | 3.74 | NS | this study |
| MLRA 122 (Glasgow, KY) | silt loam | corn–soybean and corn–soybean–tobacco | 10 | 60 | 2.63 | NS | this study |
| MLRA 125 (McKee, KY) | silt loam | continuous corn silage and continuous tobacco and wheat and rye cover crop | 15 | 60 | −6.65 | S | this study |
| MLRA 99 (Fremont, OH) | silty clay loam | corn–soybean | 15 | 60 | −4.76 | S | this study |
| MLRA 124 (Jackson, OH) | silt loam | corn–soybean–alfalfa and continuous corn | 12 | 60 | −6.63 | S | this study |
| MLRA 139A (Canal Fulton, OH) | loam | corn–soybean | 30 | 60 | 3.34 | NS | this study |
| MLRA 139B (Grove City, PA) | silt loam | corn–soybean | 10 | 60 | 4.94 | NS | this study |
| MLRA 139C (Greenville, PA) | silt loam | corn–soybean | 8 | 60 | −2.65 | NS | this study |
| MLRA 140 (Troy, PA) | loam | continuous corn | 20 | 60 | 1.98 | NS | this study |
| MLRA 147 (Lewisburg, PA) | silt loam | corn–soybean | 5 | 60 | 1.62 | NS | this study |
| MLRA 148 (Mount Joy, PA) | clay loam | corn–soybean–alfalfa and continuous corn | 4 | 60 | 1.32 | NS | this study |

† ΔSOC = SOC in NT minus SOC in PT.

‡ NS, nonsignificant; S, significant.

**Table 3. Mean soil N for no-tillage (NT), plow tillage (PT), and woodlot (WL) management for five soil depth intervals within each selected Major Land Resource Area (MLRA) in Kentucky, Ohio, and Pennsylvania.**

| Soil depth | | | | | Soil N | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | PT | NT | WL | PT | NT | WL | PT | NT | WL |
| cm | | | | | Mg ha$^{-1}$ | | | | |
| | | MLRA 121 (KY) | | | MLRA 122 (KY) | | | MLRA 125 (KY) | |
| 0–5 | 1.14 b† | 1.90 a | 2.03 a | 0.83 b | 2.09 a | 1.88 a | 1.18 b | 1.33 b | 2.61 a |
| 5–10 | 1.17 b | 1.44 ab | 1.81 a | 0.80 a | 1.46 a | 1.57 a | 1.16 a | 1.26 a | 1.23 a |
| 10–30 | 1.39 a | 1.37 a | 1.78 a | 0.76 b | 0.95 ab | 1.01 a | 1.26 a | 1.04 a | 1.24 a |
| 30–50 | 1.35 a | 1.04 a | 1.49 a | 0.82 a | 0.54 b | 0.50 b | 1.12 a | 0.62 b | 1.18 a |
| 50–60 | 0.84 ab | 0.54 b | 1.31 a | 0.67 a | 0.49 ab | 0.43 b | 0.58 ab | 0.49 b | 1.26 a |
| | | MLRA 99 (OH) | | | MLRA 124 (OH) | | | MLRA 139A (OH) | |
| 0–5 | 1.12 b | 1.12 b | 1.85 a | 0.82 b | 1.22 a | 1.40 a | 0.65 b | 2.04 a | 1.67 ab |
| 5–10 | 1.35 b | 1.21 b | 2.13 a | 0.94 ab | 0.83 b | 1.26 a | 0.97 b | 1.71 a | 1.43 a |
| 10–30 | 1.38 b | 1.08 c | 2.04 a | 0.89 b | 0.68 c | 1.29 a | 0.94 a | 1.43 a | 1.04 a |
| 30–50 | 1.26 a | 0.91 a | 1.23 a | 0.66 b | 0.40 c | 1.46 a | 0.67 a | 0.57 a | 0.53 a |
| 50–60 | 0.80 a | 0.58 a | 1.12 a | 0.64 b | 0.24 c | 1.36 a | 0.52 a | 0.48 a | 0.43 a |
| | | MLRA 139B (PA) | | | MLRA 139C (PA) | | | MLRA 140 (PA) | |
| 0–5 | 1.25 b | 1.47 ab | 1.98 a | 1.15 a | 1.15 a | 1.24 a | 1.69 a | 1.78 a | 1.69 a |
| 5–10 | 1.26 a | 1.38 a | 1.67 a | 1.09 a | 1.09 a | 1.08 a | 1.47 a | 1.47 a | 1.55 a |
| 10–30 | 1.18 b | 1.31 a | 1.27 ab | 1.12 a | 0.99 a | 1.19 a | 1.35 a | 1.44 a | 1.43 a |
| 30–50 | 0.50 b | 0.63 b | 1.27 a | 0.75 a | 0.56 a | 1.01 a | 0.87 a | 1.01 a | 1.32 a |
| 50–60 | 0.33 b | 0.34 b | 0.77 a | 0.34 b | 0.68 a | 0.86 a | 0.54 b | 0.72 b | 1.23 a |
| | | MLRA 147 (PA) | | | MLRA 148 (PA) | | | | |
| 0–5 | 0.90 b | 0.89 b | 1.68 a | 0.66 b | 2.07 a | 2.01 a | | | |
| 5–10 | 0.87 b | 0.80 b | 1.82 a | 0.83 b | 1.40 ab | 1.61 a | | | |
| 10–30 | 0.86 b | 0.71 b | 1.75 a | 1.15 a | 1.21 a | 1.17 a | | | |
| 30–50 | 0.35 b | 0.56 b | 1.66 a | 1.00 a | 0.79 a | 0.98 a | | | |
| 50–60 | 0.31 b | 0.32 b | 1.33 a | 0.93 a | 0.41 b | 0.92 a | | | |

† Rows with the same lowercase letter are not significantly different.

soils may be more stable with less turnover time and less susceptibility to seasonal changes than that under PT soils, which could still favor the higher sink capacity of NT soils (Six et al., 1998). Thus, more research on the mechanisms of SOC stabilization and residence time in tilled and NT soils is warranted. It is also hypothesized that occasional plowing of NT soils may be necessary to bury crop residues for enhancing SOC sequestration while ameliorating soil compaction, especially in clayey

**Table 4. Mean C/N ratio for no-tillage (NT), plow tillage (PT), and woodlot (WL) management for five soil depth intervals within each selected Major Land Resource Area (MLRA) in Kentucky, Ohio, and Pennsylvania.**

| Soil depth | | | | | C/N ratio | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | PT | NT | WL | PT | NT | WL | PT | NT | WL |
| cm | | | | | | | | | |
| | | MLRA 121 (KY) | | | MLRA 122 (KY) | | | MLRA 125 (KY) | |
| 0–5 | 7.53 b† | 9.56 a | 10.19 a | 8.90 b | 10.26 a | 10.97 a | 10.14 b | 9.93 b | 11.72 a |
| 5–10 | 7.50 b | 8.49 ab | 9.98 a | 8.83 a | 9.12 a | 10.17 a | 10.05 a | 9.58 a | 7.54 a |
| 10–30 | 7.06 b | 8.44 ab | 9.75 a | 8.73 b | 8.27 b | 9.17 a | 10.36 a | 9.43 a | 5.54 b |
| 30–50 | 8.04 b | 7.80 b | 9.38 a | 8.10 a | 6.53 a | 8.10 a | 10.75 a | 7.14 ab | 3.89 b |
| 50–60 | 5.95 b | 6.36 b | 9.47 a | 6.91 a | 5.74 a | 6.86 a | 7.84 a | 6.57 ab | 2.75 b |
| | | MLRA 99 (OH) | | | MLRA 124 (OH) | | | MLRA 139A (OH) | |
| 0–5 | 10.12 a | 10.32 a | 10.50 a | 9.97 a | 11.02 a | 11.30 a | 9.30 b | 9.49 b | 14.39 a |
| 5–10 | 9.59 a | 9.81 a | 10.26 a | 9.97 b | 9.83 b | 10.37 a | 9.90 b | 9.41 b | 12.24 a |
| 10–30 | 9.71 a | 9.98 a | 10.78 a | 9.99 ab | 9.33 b | 10.22 a | 9.53 a | 9.29 a | 10.54 a |
| 30–50 | 9.26 a | 9.92 a | 9.34 a | 9.82 a | 9.03 b | 9.56 b | 8.42 b | 9.53 ab | 10.63 a |
| 50–60 | 7.47 a | 8.73 a | 8.10 a | 9.62 a | 6.38 b | 10.01 a | 7.99 a | 8.72 a | 9.42 a |
| | | MLRA 139B (PA) | | | MLRA 139C (PA) | | | MLRA 140 (PA) | |
| 0–5 | 8.94 c | 10.37 b | 12.08 a | 10.09 b | 9.92 b | 11.80 a | 9.27 c | 9.81 b | 11.02 a |
| 5–10 | 9.68 b | 10.05 ab | 11.17 a | 10.17 b | 9.84 b | 11.50 a | 9.59 b | 9.61 b | 11.09 a |
| 10–30 | 9.68 b | 9.71 b | 10.87 a | 9.87 b | 9.80 b | 11.37 a | 9.80 b | 9.64 b | 11.07 a |
| 30–50 | 7.85 b | 8.23 b | 10.90 a | 9.81 ab | 8.88 b | 10.99 a | 8.77 b | 9.25 ab | 11.21 a |
| 50–60 | 6.65 b | 6.45 b | 10.19 a | 6.94 b | 9.10 ab | 10.36 a | 7.62 b | 8.11 b | 11.83 a |
| | | MLRA 147 (PA) | | | MLRA 148 (PA) | | | | |
| 0–5 | 9.56 a | 10.99 a | 11.83 a | 9.27 a | 9.05 a | 10.87 a | | | |
| 5–10 | 9.38 b | 9.81 ab | 11.63 a | 8.80 b | 9.12 b | 10.09 a | | | |
| 10–30 | 9.25 b | 9.39 b | 11.32 a | 8.84 a | 8.96 a | 9.45 a | | | |
| 30–50 | 8.07 b | 8.33 b | 10.63 a | 8.87 a | 8.64 a | 9.05 a | | | |
| 50–60 | 6.72 b | 6.64 b | 10.36 a | 8.67 a | 7.29 b | 9.58 a | | | |

† Rows with the same lowercase letter are not significantly different.

soils. It is further suggested that the use of improved practices such as manure application, cover crops, high biomass producing crops, complete residue return, and complex crop rotations with perennial grasses may be the strategies for increasing SOC in NT over PT soils.

## CONCLUSIONS

This regional study shows that NT farming impacts on SOC and N are highly variable and soil specific. In MLRAs where NT soils have greater SOC than tilled soils, the gains in SOC are limited solely to the surface soil layers (<10 cm). The net effect of NT on SOC sequestration for the whole soil profile (0–60 cm) is not significantly different from that of plow tillage. Indeed, the soil profile organic C, in a few cases, may be higher in plowed than in NT soils. The reasons for the lower SOC under NT warrant a careful analysis. We hypothesize that the main causes for the greater SOC under PT are deep burial of crop residues and deeper root growth.

Based on the data on soil profile C distribution from previous reports and this regional study, the view that NT farming would increase SOC over PT is questionable. These results have enormous implications in a time when NT technology is receiving increased attention as a potential means for SOC sequestration. The data from this study suggest that the results of many previous studies that reported significant differences in SOC between NT and PT systems based on shallow sampling be reevaluated for the whole soil profile. Furthermore, we recommend that future studies in SOC sequestration consider the whole soil profile and not only the surface layers. Had we evaluated the SOC concentration in the surface layers (<30-cm depth) only, we would have reached completely different conclusions. Results from this study warrant a reexamination of the actual potential of NT farming for storing C based on soil profile C storage and dynamics.

No tillage farming is an important technology to improving soil processes, controlling soil erosion, and reducing tillage costs, and these are sufficient reasons to promote the conversion of plow tillage to no-tillage framing , but the idea that no-tillage would also enhance soil organic carbon sequestration as an additional benefit of no-tillage technology needs a careful reexamination.

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