Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois

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Abstract

Interest in tillage impacts on sequestration of soil organic carbon (SOC) has increased greatly during recent years. The use of reduced and no-tillage (NT) practices generally increases the SOC concentration in surface few centimeters when compared to conventionally tilled soils. However, use of conservation tillage does not always result in increased SOC storage overall. The effects of sample handling and data expressions on the assessment of tillage-induced SOC sequestration were investigated using data collected from a tillage trial on a Thorp silt loam (US Taxonomy: fine-silty, mixed, mesic Argiaquic Argialboll; FAO: Orthic Greyzems). The tillage experiment was established in 1986 in Illinois, USA. The NT treatment used no soil disturbance except for planting. The disk tillage treatment included fall disking (7.5–10 cm deep) after corn (Zea mays L.) and spring field cultivation after soybean (Glycine max L.) production. The moldboard plowing treatment included fall moldboard plowing (20–25 cm deep) after corn, followed by spring disking (7.5–10 cm deep) and field cultivating; fall chisel plowing (30–35 cm) was done after soybean, followed by spring disking and field cultivation. Estimates of tillage impacts on SOC sequestration varied with the soil depth considered, time of sampling, and sample handling technique. Results indicated that tillage-induced changes in SOC occurred in the surface 30 cm. NT soil had greater C contents in the upper 30 cm when assessed on a concentration and volumetric basis. Although the use of NT practices did increase C content stored as surface residues and SOC concentrations in the top few cm of the soil, it did not increase SOC storage overall.

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1. Introduction

Accurate assessments of tillage effects on soil organic matter (SOC) sequestration are needed. A small difference in SOC contents can substantially change soil C storage estimates because the terrestrial carbon pool is so large. Changes in SOC contents have environmental ramifications, including contributions to or amelioration of greenhouse gases (CO₂ and CH₄) and ultimately global warming (Bouwman, 1989; Post et al., 1990). Changes in SOC storage are also closely related to soil quality and the long-term sustainability of agriculture (Doran and Parkin, 1994).

Tillage strongly influences SOC distribution and storage by physically mixing soil and by distributing
crop residues in the soil. Many studies have indicated that the use of reduced or no-tillage (NT) practices better protects the soil resource by increasing SOC as compared to moldboard plow (MP) practices (e.g., Doran, 1987; Mahboubi et al., 1993). Kern and Johnson (1993) and Paustian et al. (1997) concluded that the application of conservation tillage, in particular NT, generally leads to higher SOC levels than do conventional tillage. However, conservation tillage practices have limited ability to increase SOC in fine-textured and poorly-drained soils and in sites where cold climate constrains organic matter decay (Carter and Rennie, 1982; Angers et al., 1995; Angers et al., 1997; Paustian et al., 1997). In studies with three fine-textured poorly drained Illinois soils, Wander et al. (1998) found NT practices had increased SOC in surface soil (0–5 cm) at the expense of SOC stored at depth (5–17.5 cm), as compared to conventional tillage. In a study that included many soil types and climatic conditions in Illinois, Needelman et al. (Personal communication) confirmed that NT and MP practices have had different impacts on the vertical distribution but not the quantity of SOC. In a typic Argiudoll in Argentina, Alvarez et al. (1998) found that the use of NT would not significantly affect SOC pools in a region where erosion rates were low.

In most organic matter studies, SOC refers to organic matter within the soil. Residues accumulated on the soil, and sometimes within the soil, are typically removed before C is quantified. While in accord with the definition of soil organic matter, which is the organic fraction of the total soil exclusive of undecayed plant and animal residues, removal of residues may lead to incorrect and/or variable assessment of soil C storage potential. The amounts of residue in soil reflect disturbance and input patterns. Paustian et al. (1997) noted that the contribution of the surface residue to SOC buildup by NT was not fully accounted for by comparisons of plowed and NT systems where residues were removed. In such cases, the effect of NT on total carbon storage would be underestimated.

Estimates of tillage effects on SOC storage differ because of variations in sampling and data expression. Ellert and Bettany (1995) questioned the validity of SOC expressed in simple concentration units or as the product of concentration and soil bulk density from the same soil thickness. To resolve this, the equivalent mass method was used to assess SOC sequestration (Powlson and Jenkinson, 1981; Ellert and Bettany, 1995). Ellert and Bettany (1995) found that calculation of mass of C, N, P, and S on an equivalent mass basis eliminated previously identified tillage-based differences in elemental contents.

Temporal changes in tillage effects on SOC storage are poorly understood. Several studies suggest that SOC contents increase rapidly during the first 10 years following conversion to NT practices and that this period is followed by slower SOC increases (Staley et al., 1988; Dick et al., 1991; Ismail et al., 1994). Generally, these decadal scale trends ignore within-year fluctuations in SOC contents and other properties that influence SOC storage estimates that could be large enough to mask tillage effects. Estimates of SOC sequestration may vary with time due to the dynamics of C contained in residue and shifts in soil bulk density (Markin et al., 1996). Both surface residues and bulk density are known to vary within-season (Markin et al., 1996). Failure to consider factors that vary in the short-term may compromise estimates of long-term trends.

Arbitrary and inconsistent approaches to estimating SOC sequestration can lead to variable results. Several factors must be taken into account when estimating SOC storage. Ignoring these factors can result in incomplete estimates of SOC storage. The objective of this study was to quantify tillage impacts on SOC storage in a silt loam in Illinois, USA, while considering the influences of soil depth, volume or mass considered, surface and soil incorporated residues, and date of sampling. Tillage effects were summarized using both concentration and equivalent mass-based assessments.

2. Materials and methods

2.1. Site description

Samples were collected from a tillage experiment established on the Agricultural Engineering Research Farm of the University of Illinois, at Urbana, IL. The tillage treatments were initiated in Fall 1986. The soil is a Thorp silt loam (US Taxonomy: fine-silty, mixed, mesic Argiaquic Argialboll; FAO classification: Orthic Greyzems) with a pH of 6.6–6.8. The experimental plots were laid out in a completely randomized
block with eight replicate plots. In this work, we characterized three of the eight treatments included in that tillage study. Samples were collected from NT, disking tillage (DT), and MP treatments. The NT treatment used no soil disturbance except for planting. The DT treatment included fall disking (7.5–10 cm deep) after corn (Zea mays L.) and spring field cultivation after soybean (Glycine max L.) production. The MP treatment included fall MP (20–25 cm deep) after corn, followed by spring disking (7.5–10 cm deep) and field cultivating; fall chisel plowing (30–35 cm) was done after soybean, followed by spring disking and field cultivation. Eight replicate plots for each main tillage treatment were further split into south and north fields in which corn and soybeans were rotated annually.

2.2. Soil sampling and handling

In 1994 and 1995, soil samples were collected after fall field operations. The samples were collected from the top 30 cm with a 4.9 cm diameter splittable soil core sampler (Forestry Supply, Jackson, MS) in mid-December. Three subsamples were collected from each plot. Cores were divided into 0–5, 5–15, and 15–30 cm increments. Samples were collected in similar fashion down to a 90 cm depth with the hydraulic probe before planting in April 1997. These samples were separated into eight intervals: 0–5, 5–10, 10–20, 20–30, 30–40, 40–50, 50–70, and 70–90 cm.

Samples collected on all dates were air dried and weighed. A subsample, dried at 105°C, was used to calculate water content; this value was used to calculate soil bulk density. Visibly identifiable crop residues were removed manually from the 1994 and 1995 samples. No residues were removed from the 1997 samples.

Soil total carbon content was determined with a LECO CNS-2000 (Leco, St. Joseph, MI). Total C was assumed to equal SOC because this soil contained no free carbonates.

We measured the percentage of the soil surface covered with crop residue shortly after planting on May 27, 1997. Amounts of crop residues were estimated using the following equation (Gilley et al., 1986):

\[
\text{Surface cover} = 100(1 - e^{-0.114 \text{ weight}}),
\]

where surface cover is given as a percentage and residue weight is measured in Mg ha\(^{-1}\). The SOC content of residues was calculated by multiplying residue mass by 0.40. This value (0.401) was confirmed by subsequent analysis of C in residues. Carbon concentration and soil bulk density data were used to compute SOC storage on a unit area basis to the depth of plowing (≈30 cm).

Treatment impacts on the sequestration of C in soil were based on values expressed in terms of equivalent mass. Briefly, the C concentrations of samples from each depth were multiplied by the corresponding bulk density and depth dimension values. The maximum average mass recovered from an individual plot sampled to a 30 or 90 cm depth was used as the basis for C sequestration comparisons. The values used (4375, 4450, and 12 276 ton ha\(^{-1}\)) were based upon NT samples collected from the 0–30 cm depth in Fall 1995 and Spring 1997, and from 0–90 cm in Spring 1997, respectively. The data collected in Fall 1994 were combined with the 1995 values because those data were analyzed together. The total quantities of SOC were then summed from the surface downward. Variable amounts of soil (and the associated SOC) were added to the less dense treatments from the deeper depth to bring all samples to an equivalent mass. The additional thickness of soil added to the DT and MP plots for purposes of SOC comparison were computed with the following equation:

\[
\text{Additional thickness} = (\text{Equivalent mass} - (BD_{(i, j)} \times TL_{(i, j)})/BD_{\text{bottom}, i}),
\]

where BD is soil bulk density, TL the thickness of depth \(l\), \(l\) is index of depths, and \(i\) refers to either DT or MP.

The bulk density and SOC concentration of the 15–30 cm depths were used to estimate SOC additions to the NT and MP treatments in Fall 1994 and 1995 samples. In Spring 1997, the density and C concentration of the 30–40 cm depths were used to compute SOC added by the additional thickness in the 30 cm equivalent mass. The density and SOC concentration of the 70–90 cm depths were used to compute SOC added by the additional thickness in the 90 cm equivalent mass. For more information about equivalent mass- or depth-based analyses, the reader is referred to Ellert and Bettany (1995).
2.3. Statistical analysis

Analysis of variance was performed using SAS PROC MIXED (SAS Institute, 1996) to assess treatment effects on SOC concentration, soil bulk density, and SOC storage. Since the sampling interval and handling procedures of Fall 1994 and 1995 samples differed from the 1997 samples, we analyzed those data separately. Tillage and depth were considered fixed effects. Block was considered a random effect. Year was considered a fixed effect for the analysis of the 1994 and 1995 bulk density and SOC storage, and as a random effect in all other analysis. Since depth was a repeated measure we used an unstructured covariance structure in the analysis. Least square means difference was used to compare the effects of treatment. Unless otherwise noted, significance was reported at the 5% probability level.

3. Results

3.1. Soil organic carbon concentration and storage in Fall 1994 and 1995 samples

Among the main effects, depth had the greatest impact on SOC concentration, soil bulk density, and SOC storage (Table 1). Comparisons of SOC concentration and bulk density averaged to 30 cm, and of SOC storage, considered on an aerial basis, are shown in Table 2. In general, the use of NT practices increased SOC concentrations in top few centimeters and soil bulk density in the top 30 cm as compared to the DT and MP treatments. When these data were combined to estimate SOC storage, the results suggest SOC storage was 25% greater in the NT than in the MP treatment. Differences among depths in SOC storage were due to differences in the soil volume compared, which increased from the top to the bottom depth. The sum of the C contained in the top and middle depths, which when combined had a volume equal to the bottom depth, exceeded the amount of C in the bottom depth. Based upon Table 2, NT and DT soils stored 25% and 15%, respectively, more SOC in the top 30 cm than did MP soils. The NT and DT soils were 17% and 13% denser than the MP soils. Therefore, most of the increase in SOC observed for NT and DT soils was associated with an increase in soil mass.

There was an interaction between tillage and depth. Tillage effects on SOC contents varied among soil depths (Tables 1 and 3). Only in the surface (0–5 cm) were the SOC contents of the NT soil greater than in the DT and MP soils. The data based upon the same equivalent mass showed that the NT soils contained

| Table 1 |
|-----------------|-----------------|-----------------|
| | SOC content (g C kg⁻¹ soil) | Bulk density (Mg M⁻³) | SOC storage (Mg C ha⁻¹) |
| | F | P | F | P | F | P |
| Fall-collected samples (1994 and 1995) |
| Year | NS⁴ | 7.94 | 0.0051 | NS |
| Tillage | 7.49 | 0.0008 | 39.93 | 0.0001 | 21.68 | 0.0001 |
| Year × tillage | NS | D | D |
| Depth | 113.56 | 0.0001 | 54.58 | 0.0001 | 279.07 | 0.0001 |
| Year × depth | 3.27 | 0.0412 | 3.42 | 0.0358 | 2.00 | 0.1400 |
| Tillage × depth | 11.22 | 0.0001 | D | D |
| Tillage × depth × year | D⁵ | D | D |
| Spring-collected samples (1997) |
| Tillage | 2.22 | 0.1119 | NS | NS |
| Depth | 276.63 | 0.0001 | 7.97 | 0.0001 | 85.10 | 0.0001 |
| Tillage × depth | 2.95 | 0.0005 | 2.23 | 0.0086 | 116 | 0.0679 |

⁴ The data from Fall 1994 and 1995 are presented separately from spring 1997 data due to different depth intervals and methods used for preparing soil samples for organic carbon determination. Depth for 1994 and 1995 was 0–30 cm and for 1997 was 0–90 cm.

⁵ Effect was not significant at P = 10% level.

⁶ Terms dropped (D) from the model due to lack of statistical significance at P = 0.25.
2.5 (4.7%) and 4.7 (8.6%) Mg SOC ha\(^{-1}\) more SOC than did the DT and MP soils, respectively (Table 3). The DT soils contained 2.2 (3.5%) Mg SOC ha\(^{-1}\) more than the MP soils. Although the NT soils still contained more SOC than did the MP soils when storage was assessed on an equivalent mass basis, the difference was not statistically significant \((P > 0.10)\). The volume-based comparison of NT and CT soils (Mg C ha\(^{-1}\)), obtained by summing SOC concentrations to a 30 cm depth, underestimated C storage in the MP treatment by 8.1 Mg ha\(^{-1}\) (15%).

### 3.2. Soil organic carbon concentration and storage in Spring 1997 samples

To fully credit SOC sequestration by treatments, residues were not removed from the 1997 samples. Tillage alone had no impacts on SOC storage, bulk density, and SOC storage (Table 1). Tables 4 and 5 show that SOC concentration, soil bulk density, and SOC storage once again varied with depth. Soils in the 0–5 and 5–10 cm depths had the lowest, and highest, bulk density, respectively, in the entire 90 cm profile for NT and DT soils. The MP soil was denser in 30–40 cm layer too. The NT and DT soils had significantly higher SOC concentrations than the MP soils in the 0–5 cm depth (Table 4). The SOC contents sharply declined with depth in NT soils, and below 5 cm, NT SOC contents were generally equal to the values obtained for the DT and MP soils. The SOC contents of the 20–30 cm depth were greater in the MP than NT soils.

As was true for fall-collected samples, soil bulk density varied among tillage treatments in Spring 1997 (Table 5). The NT soils were denser than MP soils in the top 5–20 cm. Contrarily, MP soils were denser between 30–40 cm than were the NT and DT soils.
soils (Table 5). Changes in bulk density greatly influenced SOC storage within specific depth ranges when calculated on a volume basis (Table 6). Low SOC storage in the 0–5 cm of MP soil was associated with low SOC concentration in that depth (Table 4). Although soil bulk density was similar at the 20–30 cm depth in all plots, the higher SOC concentrations of the MP soil resulted in estimates of SOC storage that were 27% and 17% greater than estimates of SOC stored at that depth in the NT and DT soils. There were no significant differences in SOC storage among the three treatments in soil below the 30 cm depth.

Inclusion of residues formerly removed from 1994 and 1995 samples revealed that the NT soil did not contain significantly more SOC than the MP soil (Table 6). When SOC sequestration was assessed on an equivalent mass basis using either the bulk density and SOC contents above the added thickness or the data associated with the actual thickness added, produced different estimates of SOC storage. Use of data obtained from above the added thickness resulted in over-estimation of SOC contained in an equivalent mass of the tilled plots (Table 7) because of higher SOC concentration than beneath soil. Even though the carbon contained in surface residues varied with tillage practices (Table 8); tillage impacts on overall SOC storage remained insignificant when all residues were accounted for (Table 6).

4. Discussion

Use of NT practices has not resulted in significant accumulation of SOC during the first decade after NT adoption at this site. This may be due, at least in part, to the fact that erosion is not as significant a factor in central as it is in southern Illinois, where use of NT
practices has been shown to increase SOC conservation (Hussian, 1997), and to the relative short period of time.

The most apparent difference among the three treatments was the vertical distribution of SOC. The SOC was concentrated at the surface of the NT and DT soils and was more evenly distributed within the MP soil. The SOC concentrations declined rapidly in both DT and NT soil with increasing depth. Wander et al. (1998) and Needelman et al. (Personal communication) have reported similar results for Illinois soils. Our data are consistent with other work in the Midwest (Dick et al., 1991; Karlen and Cambardella, 1996), that indicates that the use of NT practices alter the vertical distribution of SOC in these non-erosion prone soils.

The inclusion of surface residues in the 1997 samples affected sample ranking in SOC storage (DT > MP > NT with buried residue only, and DT > NT > MP with surface and buried residue) for the surface 30 cm soils. Samples containing no residues (1994 and 1995) were ranked (NT > DT > MP). This suggests that the DT soils contained more residues than the other two treatments and that the MP soil contains more residues than the NT soils. In general, MP incorporate the most, and NT practices the least, amount of residues into the soil (Carter and Rennie, 1982; Doran, 1987; Collins et al., 1992; Tindall and Crabtree, 1980; Stott, 1991). Accordingly, the nearly identical SOC content of all three treatments of 1994 and 1995 subsurface soils, which residues were removed, suggests that SOC decay rates were fastest in the MP, intermediate in the DT, and slowest in the NT soil.

Estimates of tillage impacts on SOC sequestration depended upon several factors. Results based on a shallow sampling depth and volume-based comparisons positively credit the ability of NT practices to sequester SOC (Fleige and Baumer, 1974; Granatstein et al., 1987; Campbell et al., 1989). Our fall-collected data suggested that NT soil had higher SOC concentrations than DT soil, which in turn, had higher SOC concentrations than MP soil. These concentration-based results did not reflect differences in the density of the soil volume compared. Volume-based estimates of SOC indicated NT soils contained more SOC than MP soils. Such volume-based comparisons have been rightly challenged because they consider

<table>
<thead>
<tr>
<th>Table 7</th>
<th>A comparison of two methods (A and B) used to compute the length and SOC of the additional thickness of soil used to determine SOC sequestration with the equivalent mass based method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No tillage</td>
</tr>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Additional thickness (cm)</td>
<td>0</td>
</tr>
<tr>
<td>Associated SOC (Mg C ha⁻¹)</td>
<td>0</td>
</tr>
</tbody>
</table>

* The values followed by different letters in the same tillage are significantly different at P < 0.05.
* NT values are used as the basis for comparison, equal 100%.
* Values were computed based on bulk density and SOC content data collected to a 30 cm depth.
* Values were computed based on bulk density and SOC content data collected to a 40 cm depth.

Table 8:
Residue percent coverage and C contents after planting 1997

<table>
<thead>
<tr>
<th>Crop (Summer 1996)</th>
<th>No tillage</th>
<th>Dish tillage</th>
<th>Moldboard plow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cover (%)</td>
<td>C (Mg ha⁻¹)</td>
<td>Cover (%)</td>
</tr>
<tr>
<td>Soybean</td>
<td>40</td>
<td>4.48b</td>
<td>35</td>
</tr>
<tr>
<td>Corn</td>
<td>18</td>
<td>1.74</td>
<td>7</td>
</tr>
<tr>
<td>Mean</td>
<td>26</td>
<td>2.64</td>
<td>21</td>
</tr>
</tbody>
</table>

* Percentage of surface covered with residues was determined using the string intercept method.
* SOC contained in residues was computed with following equation: Surface cover = 100 × (1 - e⁻⁰·¹¹⁴ weight) (Gilley et al., 1986). The above ground residues contained 40% carbon.
unequal soil masses (Ellert and Bettany, 1995). When our data were assessed using the equivalent mass method, tillage effects on SOC storage were not found significant. The form in which data was expressed determined the conclusions drawn about tillage impacts on SOC sequestration.

We found that SOC concentration and bulk density varied within the plow layer. We suggested that a reasonable comparison of SOC storage should include, at minimum, the entire rooting zone. Differences in bulk density and SOC concentration observed below this depth suggest that inclusion of deeper depths may be warranted. The MP soils had a denser plow pan at 30–40 cm, which coincided with an area of relatively lower SOC concentration. According to Mann (1985), inclusion of deeper soil depths reduces the variability of estimates of SOC sequestration.

There were significant differences in the bulk density of samples collected on different dates even though there were no changes in the corresponding SOC concentrations. Markin et al. (1996) also reported that soil bulk density varied with time. Clearly, bulk density can influence estimates of SOC sequestration expressed on a volumetric or equivalent mass basis. Even though changing bulk density did alter our results in absolute terms, they did not affect assessment of general treatment effects on SOC sequestration. We found that within-season variability in bulk density had a minimal impact on our results when equivalent masses of soil were compared.

There is controversy over how to deal with residues when estimating SOC storage. Removal of surface residues may discount the effect of NT practices on SOC sequestration (Paustian et al., 1997) because NT practices frequently lead to the accumulation of surface residues (Tindall and Crabtree, 1980; Stott, 1991). In our study, the inclusion of C in surface residue did not significantly alter conclusions about differences between MP and NT soils; it did, however, change estimates of absolute C contents. In addition, inclusion of residues buried within soils, which are also removed by sieving, influenced our results. By including buried residues, we noted significantly higher SOC concentration in the 20–30 cm depths of the MP soils than in the NT soils. When residues were removed, there were no differences in the SOC concentrations of the CT and NT soils at this depth. When buried residues were included in estimates of SOC storage within the top 30 cm, the three treatments were found to be nearly identical. These findings show both surface and buried residues contribute to SOC storage, and both types of residues should be assessed in studies of SOC sequestration.

We found the equivalent mass-based method provides a more accurate way to assess tillage impacts on SOC (or other elements) storage than do concentration and volume-based measures. However, assumptions and data handling affect the results regardless of the means of data expression selected. When, in keeping with the recommendations of Ellert and Bettany (1995), the bulk density and SOC concentration of the 15–30 depth were used to estimate C stored in the thickness of soil added, results differed from the estimates obtained using values collected from the deeper depth. Detailed sampling at small depth increments beyond the depth of tillage will further diminish errors.

5. Conclusions

Except for the accumulation of surface residues and SOC in the top few centimeters, the use of NT practices did not increase C storage at this site. Tillage-induced changes in SOC concentrations and soil bulk density were concentrated in the top 30 cm. Estimates of tillage impacts on SOC sequestration varied with the soil depth considered, sampling time, sample handling, and the methods used to quantify SOC storage. Use of concentration- or volume-based comparisons produced erroneous and misleading results. The equivalent mass-based method provided a means to assess C sequestration that can be adapted to accurately compare the effects of different tillage systems on C storage. In order to obtain accurate estimates of C sequestration and compare tillage practices, the C contents of surface and subsurface residues and of subsoil should be considered.

References


