Evaluating the effect of tillage on soil structural properties using the pedostructure concept

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The pedostructure concept characterizes a soil based upon soil structural properties to predict soil–water behavior. The goal of this work was to determine the impact of land management on the measured pedostructure parameters, the quantitative soil structural properties used for modeling soil–water behavior. Soil samples (fine, illitic, mesic, Aquic Hapludalfs and fine, illitic, mesic, Eptic Epiaqualfs) were taken in May 2007 from DeKalb County in northeastern Indiana. The ideal pedostructure parameters were extracted from the continuously measured shrinkage and potential curves from the surface and diagnostic subsurface horizons of two soil series, differing slightly in drainage characteristics, one soil under no-tillage and the other under rotational tillage. Additionally, the pedostructure parameters were estimated from measured and estimated soil physical properties. Three of the seven pedostructure parameters: \( W_m \) (saturated micropore water content), \( K_{ss} \) (micropore linear shrinkage rate), and \( V_0 \) (soil specific volume at the oven-dry state) were significantly different due to the tillage treatment, while none of the parameters exhibited any significant differences due to depth. \( V_0 \) also showed a significant interaction between tillage and depth, as the rotational tillage subsurface samples had much lower values than other combinations of tillage and depth. Overall, no-tillage exhibits a larger amount of micropores, as evidenced by the higher \( W_m \) value, as well as a more strongly structured micropore system, as seen in the lower \( K_{ss} \) compared to rotational tillage. However, no significant differences exist when estimating the pedostructure parameters from measured and estimated soil physical properties. No significant differences were found for the macropore parameters. These results are unexpected, as it was believed that the no-tillage treatment would affect the macropore, and not the micropore, parameters.

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1. Introduction

As our knowledge of the intricate workings of the environment continues to grow, many see the need to reduce the amount and intensity of tillage operations to reduce erosion, improve soil structure, and ease flooding by increasing the infiltration of water into the soil. Bouma (1992) states that management-induced changes in the soil structure resulted in significantly different soil physical properties. The pedostructure concept allows for better modeling of the soil water system by quantitatively characterizing soil structural properties. No significant interaction between tillage and depth, as the rotational tillage subsurface samples had much lower values than other combinations of tillage and depth. Overall, no-tillage exhibits a larger amount of micropores, as evidenced by the higher \( W_m \) value, as well as a more strongly structured micropore system, as seen in the lower \( K_{ss} \) compared to rotational tillage. However, no significant differences exist when estimating the pedostructure parameters from measured and estimated soil physical properties. No significant differences were found for the macropore parameters. These results are unexpected, as it was believed that the no-tillage treatment would affect the macropore, and not the micropore, parameters.

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1.1. Description of the pedostructure concept

The pedostructure (PS) concept is a new paradigm of soil characterization that defines soil behavior based on its structure. There has been much discussion among researchers concerning the benefit of the inclusion of soil structural properties in soil water models. Timlin et al. (1999) reported that the current soil retention data has insufficient information regarding soil structure and the continuity of pores, which are important determinants of conductivity and other soil hydraulic properties. Pachepsky et al. (2006) hypothesized that though soil structural units (qualitative variables: grade, shape, and size) are observed at a coarser level than the pore size distribution index measured with water retention, there are possible similarities in spatial arrangements of these units at various scales, including soil horizon and finer. This development could allow for more accurate scaling of soil–water behaviors and interactions from fine scales (e.g. the pedon level) to coarser scales (e.g. watershed, or landscape levels). Pachepsky et al. (2006) observed that significant
differences in soil water retention values occur when comparing field values to laboratory derived values, especially in finer textured soils (sand content <50%). They indicate that the difference could be due to the effect of measuring the retention at different spatial scales between field and laboratory measurements.

According to Braudeau and Mohtar (2004, 2006), there are 15 unique pedostructure parameters (Table 1), inherent to every soil, to describe the pedostructure. These fifteen parameters are obtained using the continuously measured shrinkage, swelling, potential, and conductivity curves. Fig. 1 (Braudeau and Mohtar, 2006) shows a typical continuously measured soil shrinkage curve. Each letter represents an important point in distinguishing the four water pools described by Braudeau et al. (2004). At point F, all pores (macro and micro) are filled with water and the system is at a complete saturation. Upon drying, the pores between peds and the water inside peds begin to evaporate and the specific volume (in dm³ kg⁻¹) of the system becomes smaller. Since both the swelling and non-swelling water pools are draining from the macropore region, this is graphically displayed as the curvilinear section between F and E. At point E, all interpedal water has been drained and air entry into the macropores begins. This is exhibited by the lack of volume change as the water content decreases. At point D, the swelling water in the micropore system begins to evaporate. The shrinkage curve becomes curvilinear as the non-swelling water in the macropores and the swelling water in the micropores drain simultaneously. At point C, all macropore water has been drained and only the swelling macropore water is leaving the system, leading to a linear portion of the shrinkage curve. At point B, the non-swelling macropore water pool is removed from the system, beginning another section of the curvilinear drainage. At point A, only the non-swelling micropore water still exists in the system, known as the residual water content. Points N, M, and L represent points along the shrinkage curve corresponding to N′, M′, and L′. These points are the intersections between the tangent lines of the linear shrinkage sections of the shrinkage curve.

1.2. Effects of tillage on soil properties

Organic matter in the vadose zone is an indicator of the amount of nutrients present in the soil. Givi et al. (2004) goes on to relate the importance of organic matter on soil physical properties in the upper horizons and the need to include organic matter as an input for PTFs estimating soil water content at −33 kPa and −1500 kPa. While experiments (Blevins et al., 1985; Dao, 1993; Franzluebbers et al., 1995; Hudson, 1994; Singh and Malhi, 2006) were conducted throughout the country, with a variety of climatic, topographic, and vegetation differences, a general pattern was observed. Higher organic matter content was observed in the upper horizons. Conventional tillage and other land management operations increase the decomposition rate of organic matter; therefore, after several successive years of such land management the organic matter content is seen to decrease (Blevins et al., 1985). The general trend among the articles is that no-till produces maximum organic matter, followed by conservation tillage, with conventional tillage having the lowest percentage of organic matter.

Bulk density is an indicator of the total porosity of the soil. The lower the bulk density, the higher the porosity, and the higher the amount of water that can infiltrate and be stored in the soil column. Different studies conducted in different regions of the country obtained different results. With the study conducted by Blevins et al. (1985), the results of no-tillage versus conventional tillage effect on bulk density were given for three states: Minnesota (1.25 g cm⁻³ no-till versus 1.12 g cm⁻³ conventional tillage), Virginia (1.48 g cm⁻³ no-till versus 1.43 g cm⁻³ conventional tillage), and Kentucky (1.25 g cm⁻³ no-till versus 1.29 g cm⁻³ conventional tillage). In the research conducted by Franzluebbers et al. (1995), the results stated that the soil density in the Brazos River floodplain in south-central Texas (Udifluventic Haplustept) was greater in no-tillage practices than in conventional till practice.

### Table 1

Pedostructure parameters and their definitions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Curve for extraction</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_0)</td>
<td>dm³ kg⁻¹</td>
<td>Shrinkage</td>
<td>Specific volume at non-swelling micropores (oven-dry) state</td>
</tr>
<tr>
<td>(W_1)</td>
<td>kg_water kg_soil</td>
<td>Shrinkage</td>
<td>Specific water content at saturation</td>
</tr>
<tr>
<td>(W_M)</td>
<td>kg_water kg_soil</td>
<td>Shrinkage</td>
<td>Specific water content at non-swelling micropores water level</td>
</tr>
<tr>
<td>(W_N)</td>
<td>kg_water kg_soil</td>
<td>Shrinkage</td>
<td>Specific water content at change of drying from macropores to micropores</td>
</tr>
<tr>
<td>(K_M)</td>
<td>kg_water kg_soil</td>
<td>Shrinkage</td>
<td>Constant of equilibrium (slope of shrinkage curve) between (W_{mn}) and (W_{w}) (swelling micropore water pool)</td>
</tr>
<tr>
<td>(K_{in})</td>
<td>kg_water dm³ sec⁻¹</td>
<td>Shrinkage</td>
<td>Constant of equilibrium (slope of shrinkage curve) between (W_{mn}) (swelling micropore water pool) and (W_{w}) (non-swelling micropore water pool) during drying</td>
</tr>
<tr>
<td>(E_{max})</td>
<td>J kg⁻¹</td>
<td>Potential</td>
<td>Potential energy of the external surface of primary peds</td>
</tr>
<tr>
<td>(E_{mi})</td>
<td>J kg⁻¹</td>
<td>Swelling</td>
<td>Potential energy of the internal surfaces of primary peds</td>
</tr>
<tr>
<td>(\alpha_L)</td>
<td>kg_water kg_soil</td>
<td>Conductivity</td>
<td>Constant of the exponential increase of macropore hydraulic conductivity</td>
</tr>
<tr>
<td>(\alpha^-)</td>
<td>kg_water kg_water</td>
<td>Conductivity</td>
<td>Constant of the exponential increase of macropore hydraulic conductivity</td>
</tr>
<tr>
<td>(K_{mx'})</td>
<td>dm s⁻¹</td>
<td>Conductivity</td>
<td>Hydraulic conductivity at the dry point of macroporosity</td>
</tr>
<tr>
<td>(K_{mx})</td>
<td>dm s⁻¹</td>
<td>Conductivity</td>
<td>Hydraulic conductivity at saturation</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>kg_water kg_soil</td>
<td>Potential</td>
<td>Skin water at the surface of primary peds</td>
</tr>
<tr>
<td>(T_{1/2})</td>
<td>min</td>
<td>Swelling</td>
<td>Time to half charge during swelling</td>
</tr>
</tbody>
</table>
with an average of 1.52 g cm$^{-3}$ among all the crops studied, versus under conventional tillage with an average of 1.42 mg m$^{-3}$. Likewise, the study conducted by Cassel and Nelson (1985) observed the trend of decreased bulk density with land management practices of plowing in the Piedmont region of North Carolina (2 Typic Hapludults). In contrast, an article of the research findings in Kentucky (Typic Paleudalf) of Thomas et al. (1996) concluded that bulk densities are lowest in no-till practices, intermediate with conservation tillage practices, and highest among conventional tillage practices, a direct opposition to the articles prior. The article went on to state that “compactability was negatively related to the amount of organic carbon in the sample”. According to Horn (2004), conservation tillage increases the mechanical strength of the soil by the formation of a higher percentage of finer pores over time. The results from Arshad et al. (1999) agree with this observation. Tillage creates more macropores in the upper horizon, thereby reducing the bulk density of the soil. While bulk density is a function of many factors, including soil texture, organic matter, time, etc., the general trend emerged that bulk density increases under conservation tillage, while increasing the continuity of macropores compared to mesopores (equivalent pore diameter 5 to 500 μm) and micropores in the surface horizon as compared to conventional tillage.

The movement of water into and throughout the soil is one of the most important soil properties. Blevins et al. (1985) concluded that the water was conserved in the upper soil profile in the no-tillage systems, regardless of soil type or location. It was also noted that infiltration capacity increased under no-tillage management in Ohio, due to a greater organic matter surface concentration. Other results found that an increase in organic matter (due to their continuous conservation tillage) resulted in a higher moisture content in the soil nearest the surface (Blevins et al., 1985). Franzluebbers et al. (1995) observed that the soil water content increased 3–12% among the crops under no-till practices, versus conventional tillage practices. They also observed that water-filled pore space was greater under no-till conditions compared to conventional tillage by 19–34%. Similarly, Thomas et al. (1996) concluded that better infiltration occurred under no-till conditions as compared to conventional tillage in their experiment conducted in Kentucky. Mahboubi et al. (1993) reported that no-till plots retained more water in the pore spaces than chisel plowing and moldboard plowing at suction of 0, 1, 3, 6, 30, and 1500 kPa. Arshad et al. (1999) also observed higher water retention in no-tillage as compared to conventional tillage along the soil matric pressure gradient, which was attributed to the higher volume fraction of micropores found in no-till. Diaz-Zorita et al. (2004) observed significantly higher gravimetric soil water content in no-till at 0.01 MPa of tension (0.265 g g$^{-1}$) compared to tillage for winter wheat (0.215 g g$^{-1}$). However, no significant differences were observed between the two tillage treatments at tensions above 1.5 MPa. Diaz-Zorita et al. (2004) reported that the proportion of meso-pores occurring in the upper 10 cm of soil was 23% higher in continuous no-till operations compared to soils tilled every two years for winter wheat planting (0.189 cm$^{-3}$ to 0.154 cm$^{-3}$). The authors conclude that greater water storage in no-till soils can be attributed to the larger percentages of meso-pores and macropore continuity.

Many researchers, however, observed results that are in conflict with those mentioned above. Fuentes et al. (2004) discovered that changes in the soil water characteristic curves in the top 3 cm of the soil were largest in conventional tillage, with less change occurring in no-till and natural prairie. The authors, however, go on to conclude that these changes are more associated with seasonal moisture levels at their field sites (eastern Washington state) as opposed to the tillage regime. Katsvairo et al. (2002) reported that the macro-porosity and total porosity did not differ significantly between moldboard plow, chisel, and ridge tillage systems on a silt loam soil near Aurora, NY. Similarly, a study conducted across several different soils in Kansas by McVay et al. (2006) concluded that the tillage choice had no effect on the water holding capacity of these soils. In regards to the land management effect on the soil water holding capacity there was no trend observed, indicating that soil–water relationships are also dependent on temporal, management, climatic, and biological factors.

According to the pedostructure concept, soil structure is a unique property for every soil and contributes to all the aforementioned properties. A soil with a higher strength of ped will have better defined channels between ped faces, allowing for better water movement and root growth. Blevins et al. (1985) observed that the effects of land management on soil structure depend greatly on soil type and climatic conditions. Blanco-Canqui and Lal (2007) reported that the differences in mean weight diameter of soil aggregates were, overall, small and site-specific when comparing no-tillage sites to chisel plow locations. However, they suggest that the duration of no-till management has a pronounced effect on soil structure. The researchers list that the aggregate size increased by a factor of 6 in a 35-year no-till plot, compared to chisel plow tillage, while a 5-year no-till field had no effect on the aggregate size compared with chisel plow tillage. Arshad et al. (1999) reported that the mean weight diameter of water-stable aggregates was greater under no-tillage compared to conventional tillage in the 0–75 cm depth range. Pagliai et al. (2004) reported that “storage pores”, with an equivalent pore diameter of 0.5 to 50 μm, vital as a water source for plants and microorganisms, were significantly higher in minimum tillage and ripper subsoiling applications compared to conventional deep plowing. Likewise, the “elongated transmission pores”, equivalent pore diameter of 50 to 500 μm, important in drainage and soil structure formation, occurred in significantly larger amounts in the conservation tillage schemes compared to conventional tillage. This could be attributed to the presence of continuous channels created by earthworms and other soil dwellers. Lipiec et al. (2006) observed more “storage pores” occurring in conservation tillage in the 0–20 cm depth, while the greatest frequency of “transmission pores” occurred with conventional tillage. In addition, the overall porosity was highest in conventional tillage, which resulted in higher infiltration rates.

The objectives of this work were to compare the effect of different tillage treatments on the soil structural properties characterized by the pedostructure concept (Braudau and Mohtat, 2004, 2006, 2008; Braudeau et al., 2004). The hypothesis of this work is that the pedostructure parameters corresponding to the macropore structure will be significantly different between tillage methods, while the parameters corresponding to the micropore structure will not be significantly different.

2. Methods and materials

This study focuses on two field sites located within the Upper Cedar Creek Watershed (UCCW) in northeastern Indiana that are part of the USDA-ARS National Soil Erosion Research Laboratory’s environmental monitoring network. The area topography is low gradient and varies from rolling hills to nearly level plains with a maximum altitude above sea level of 326 m, and an average land surface slope of 3%. The average annual precipitation in the study area is approximately 900 mm. The average temperature during the growing season ranges from 10 °C to 23 °C. The area consists of soils formed from compacted glacial till and glacial fluvial materials. The majority of the soils in the UCCW are the Morley–Blount and Eel–Martinsville–Genesee associations. The Morley–Blount association usually occurs on the uplands and consists of shallow, moderately to well drained, sloping to steep, and loam to clay loam textured soils. The Eel–Martinsville–Genesee association consists of deep, moderately well drained, nearly level, and medium to moderately fine-textured soils on bottom lands and stream terraces. In 2007, the National Agricultural Statistics Service reported that 38.4% of the watershed area is agriculture, 25.3% pasture lands, 15.2% forested lands, and 13.3% urban (USDA-NASS 2007).
2.1. Field sites and soil sample collection

The no-tillage and rotational tillage subwatersheds are approximately 5 km northeast of Waterloo, Indiana, lying along Indiana State Highway 427, as shown in Fig. 2. The no-tillage subwatershed is 2.23 ha in area and its primary soil type is a Glynwood loam (fine, illitic, mesic, Aeric Epiaqualfs). The rotational tillage watershed, 2.71 ha in area, has a primary soil type of a Blount silt loam (fine, illitic, mesic, Aquic Hapludalfs) according to the NRCS Soil Survey (2008). The rotational tillage field is disk plowed when the farmer plants corn and is left in no-till when the farmer plants soybeans. Disk plowing disturbs the upper 10 cm of soil, leaving the remainder of the pedon intact. This tillage rotation has been in place since 2004. The rotational field was in no-till from 1990 to 2004. Four sets of cores (5 cm diameter) were taken from each site. From each core, representative 5 cm samples in depth were taken from both the surface Ap horizon (0–15 cm) and the diagnostic subsurface Bt horizon (15–45 cm), on which experiments, following the methodology described by Salahat (2006), were administered.

2.2. Laboratory procedures

The measurements began by completely saturating a sample through capillary action using a sand bath. It was then placed on a stand that has holes drilled into the sides and a coarse metal screen on top to allow for air drying on all sides. This stand was then placed on a scale to measure the mass change as the sample air dries. For the shrinkage curve analysis, a Linear Variable Displacement Transducer (LVDT) measured the height of the sample as it shrinks. A small square made of geotextile fabric was placed on top of the sample to prevent the LVDT rod from penetrating the soil sample. The sample’s mass and height were then measured and auto-recorded, using a virtual instrument created in LabView 9.2, into an Excel spreadsheet every minute during drying. Assuming isotropic shrinkage of the sample, the specific volume of the sample can be calculated to be:

\[ V = (H/H_0)^3 + V_0 \]  

where \( H \) is the measured height of the sample, \( H_0 \) is the height of the sample at oven-dry state, and \( V_0 \) is the volume of the sample at oven-dry state. When the change in height of the soil sample reached a rate of less than 0.0004 cm h\(^{-1}\), the test was concluded and the soil sample allowed to oven-dry for 48 h to determine the gravimetric water content. Additionally, the height and diameter of the oven-dried soil core were measured using a set of calipers to determine \( V_0 \). The specific volume of the soil sample was then graphed as a function of gravimetric water content.

For the potential curve measurements, a micro-tensiometer was inserted into the middle of a core, measuring soil water potential as the sample air dries. The sample’s mass and soil water potential were then recorded into an Excel spreadsheet. Once the soil water potential reached 1000 hPa, the test was concluded and the soil sample oven-dried to determine its oven-dry mass, so that the gravimetric water content could be computed. The methodology for obtaining both the shrinkage curve and the potential curve is described completely by Salahat (2006).

According to Salahat (2006), there are seven pedostructure (PS) parameters that can be extracted from the shrinkage and potential curves: \( W_L, W_M, \sigma, E_{ma}, K_{bs}, V_0, \) and \( K_M \). These parameters are described in detail in Braudeau et al. (2004) and Braudeau and Mohtar (2004, 2006). The potential curve was fitted to a third-order polynomial regression equation that uses the potential curve parameters \( W_L, W_M, \alpha, E_{ma}, \) and \( K_{bs} \), as variables, which are then optimized using Excel regression and solver tools (Salahat, 2006). In low-shrinking soils (which are prevalent in Indiana), the potential curve parameters \( W_L, W_M, \) and \( K_{bs} \) are used as initial values in an Excel solver, along with the measured shrinkage curve, to extract \( E_{ma} \) and \( V_0 \) by fitting a curve that uses the pedostructure parameters as its variables to the data and optimizing the mean square error (Salahat, 2006).

To determine whether or not the pedostructure parameter values were significantly different due to either tillage or depth, a 2-way Analysis of Variance (ANOVA) test was performed for each of the seven pedostructure parameters. Each ANOVA test was implemented using SAS with class variables of tillage, depth, and the interaction term of tillage and depth with a significance level of 0.05.

3. Results and discussion

In this section, the measured shrinkage and potential curves, along with any significant differences due to the tillage method or depth, will be discussed. Each pedostructure parameter will then be analyzed to determine what differences, if any, occur in the parameter due to either the tillage method, depth, or both. Finally, the accuracy of estimation of each pedostructure parameter from measured and estimated soil properties will be discussed.

3.1. Shrinkage curves

The measured shrinkage curves for each tillage treatment can be seen in Figs. 3 and 4. Distinct water pools that can be easily seen in Fig. 1 are not discernable from these curves, indicating the low swelling ability of these soils. However, some qualitative results can be discerned. The soils with the no-tillage treatment exhibit a higher specific volume throughout the entire shrinkage curve in both the
surface (0–15 cm) and subsurface (15–45 cm) horizons compared to the rotational tillage. This is to be expected as results from the literature indicate that no-tillage increases the amount of meso-pores and micro-pores present in the soil horizon. This difference in the specific volume based upon the tillage method is more pronounced in the subsurface horizon than the surface horizon.

For the no-tillage treatment (Fig. 4), the subsurface horizon has a higher specific volume (and therefore, a lower bulk density) at high water contents than the surface horizon. As the soil reaches its dry state, the specific volume for both the surface and subsurface horizons becomes equal. The opposite trend is seen in the rotational tillage, with the surface horizons exhibiting higher specific volumes throughout the entire shrinkage curve compared to their subsurface counterparts. This could be due to the presence of a plow pan in the subsurface horizon caused by the repeated passage of tillage equipment at approximately the same depth resulting in a compacted soil layer. If this continues over several years the soil develops a very high bulk density and low infiltration rates, limiting water movement down the soil profile.

3.2. Potential curves

In low-swelling soils, the shrinkage curve is not pronounced enough to indicate pedostructure parameters in the macropore region. Salahat (2006) developed a methodology to use a soil’s continuously measured potential curve to obtain additional information about the macropore region of soil–water. Measured potential curves can be seen in Fig. 5. The equipment used for this experiment has an optimal working range of 0–100 kPa, which explains why the entire potential curve (0–1500 kPa) is not represented. As this work was only concerned with the macropore region of soil–water, this working range was sufficient. The results of this procedure were
mixed based on the tillage method, as can be seen in Fig. 5. The no-tillage subsurface horizon had the lowest water content throughout the procedure, while the no-tillage surface horizon had the highest water content above 200 hPa (20 kPa). The rotational tillage curves showed water content values for particular potentials in between the no-tillage values, with the exception being the rotational tillage surface horizon having the highest water content values for potentials below 200 hPa.

Differences between the potential curves based on horizon depth were more apparent, with the surface horizons of both the no-tillage and rotational tillage treatments having higher water contents for particular potentials than the subsurface horizons.

3.3. Variations in sigma due to tillage method

\( \sigma \) is an extracted parameter defining the skin water held at the surface of the primary peds. This water is held so rigidly by the primary peds that its behavior differs from that of free water molecules. This parameter also affects the angle of the inflection point on the potential curve as the shape of the curve changes from curvilinear to linear. Values (in kg\(_{\text{water}}\) kg\(_{\text{soil}}^{-1}\)) for \( \sigma \) for individual samples are shown in Table 2, with the average values based on the tillage treatment shown in Table 3. Values ranged from 0.001 to 0.0449 for all samples while the mean values based upon the tillage type, regardless of depth, were 0.0068 for no-tillage and 0.0163 for rotational tillage. While the rotational tillage average was higher, the difference was not statistically significant at the 0.05 level.

Looking at the measured pedostructure parameters (Table 4), rotational tillage does show a higher average value for \( \sigma \), especially in the surface horizon. The value of \( \sigma \) for the no-tillage surface horizon is 0.00819 and the value of \( \sigma \) for the rotational tillage surface horizon is 0.0242, as shown in Table 4. As tillage destroys the soil aggregates to create voids for air and water flow, a higher surface area of the primary peds is exposed in the voids. This allows for more water to adhere to the surface under the forces of adhesion and cohesion. However, the difference is not nearly as pronounced in the subsurface horizons. The value of \( \sigma \) for the no-tillage surface horizon is 0.00542 and \( \sigma \) for the rotational tillage subsurface horizon is 0.00698. The subsurface samples are never disturbed by tillage and therefore soil genesis is allowed to carry on under natural processes. Therefore, there is no significant difference due to the combination of tillage and depth. Differences in estimated values of \( \sigma \) from measured soil physical properties were minimal. The no-till subsurface horizon has an estimated \( \sigma \) of 0.0109 while the rotational tillage subsurface horizon had an estimated \( \sigma \) value of 0.0111. This small difference agrees with the conclusion with the measured pedostructure parameters, that the subsurface soil horizons are not disturbed by tillage and should exhibit little difference.

### Table 2: Experimentally determined pedostructure parameters.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Parameter</th>
<th>sigma</th>
<th>( E_{\text{max}} )</th>
<th>( K_m )</th>
<th>( W_m )</th>
<th>( W_l )</th>
<th>( K_{\text{in}} )</th>
<th>( V_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Units</td>
<td>kg(<em>{\text{water}}) kg(</em>{\text{soil}})</td>
<td>J kg(_{\text{soil}})</td>
<td>kg(<em>{\text{soil}}) kg(</em>{\text{water}})</td>
<td>kg(<em>{\text{soil}}) dm(</em>{\text{soil}})</td>
<td>dm(^3) kg(_{\text{soil}})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-tillage 1</td>
<td>5–10</td>
<td>7.7E–3</td>
<td>20.00</td>
<td>–31.41</td>
<td>0.28</td>
<td>0.33</td>
<td>0.91</td>
<td>0.60</td>
</tr>
<tr>
<td>No-tillage 1</td>
<td>20–25</td>
<td>6.0E–3</td>
<td>4.15</td>
<td>–156.02</td>
<td>0.26</td>
<td>0.38</td>
<td>0.62</td>
<td>0.60</td>
</tr>
<tr>
<td>No-tillage 2</td>
<td>0–5</td>
<td>1.6E–3</td>
<td>7.82</td>
<td>–84.35</td>
<td>0.16</td>
<td>0.30</td>
<td>0.56</td>
<td>0.61</td>
</tr>
<tr>
<td>No-tillage 2</td>
<td>18–23</td>
<td>9.2E–3</td>
<td>15.57</td>
<td>–94.88</td>
<td>0.25</td>
<td>0.32</td>
<td>0.97</td>
<td>0.63</td>
</tr>
<tr>
<td>No-tillage 3</td>
<td>0–5</td>
<td>1.0E–3</td>
<td>3.28</td>
<td>–276.57</td>
<td>0.18</td>
<td>0.29</td>
<td>1.01</td>
<td>0.60</td>
</tr>
<tr>
<td>No-tillage 3</td>
<td>18–23</td>
<td>1.1E–3</td>
<td>1.12</td>
<td>–31.02</td>
<td>0.29</td>
<td>0.30</td>
<td>0.99</td>
<td>0.67</td>
</tr>
<tr>
<td>Rotational tillage 1</td>
<td>10–15</td>
<td>1.2E–3</td>
<td>6.03</td>
<td>–71.11</td>
<td>0.20</td>
<td>0.36</td>
<td>1.40</td>
<td>0.59</td>
</tr>
<tr>
<td>Rotational tillage 1</td>
<td>30–35</td>
<td>1.0E–3</td>
<td>53.26</td>
<td>–330.02</td>
<td>0.09</td>
<td>0.22</td>
<td>1.27</td>
<td>0.53</td>
</tr>
<tr>
<td>Rotational tillage 2</td>
<td>5–10</td>
<td>2.0E–3</td>
<td>50.08</td>
<td>–14.41</td>
<td>0.22</td>
<td>0.29</td>
<td>1.02</td>
<td>0.59</td>
</tr>
<tr>
<td>Rotational tillage 2</td>
<td>30–35</td>
<td>1.0E–3</td>
<td>9.30</td>
<td>–123.19</td>
<td>0.14</td>
<td>0.28</td>
<td>1.04</td>
<td>0.53</td>
</tr>
<tr>
<td>Rotational tillage 3</td>
<td>10–15</td>
<td>4.5E–3</td>
<td>17.60</td>
<td>–425.05</td>
<td>0.16</td>
<td>0.21</td>
<td>1.13</td>
<td>0.60</td>
</tr>
<tr>
<td>Rotational tillage 3</td>
<td>20–25</td>
<td>1.9E–3</td>
<td>23.28</td>
<td>–39.22</td>
<td>0.21</td>
<td>0.41</td>
<td>1.17</td>
<td>0.53</td>
</tr>
</tbody>
</table>
estimated soil physical properties were negative, which is impossible in real world applications as this parameter can never be less than 0.

3.4. Variations in $E_{ma}$ based on tillage method

The potential energy on the external surface of the primary peds, and therefore the macropore water content, is labeled as $E_{ma}$. It is a measure of the specific energy (in $J kg_{soil}^{-1}$) needed to remove the water from the external surface of the primary peds. Table 2 shows the values of $E_{ma}$ for all samples tested with the means listed in Table 3. The range of values was 1.20 to 53.27 with the averages being 8.67 for the no-tillage treatment and 26.59 for the rotational tillage treatment, regardless of the horizon depth. However, due to large variations between replicates at the same factor levels, the statistical analysis determined that this difference in the means was not significant at the 0.05 level.

As with $\sigma$, the rotational tillage exposes more of the surface of the primary peds due to the destruction of soil aggregates. This allows more water to be stored on these sites. With more water to remove, more energy is needed to remove the water from the surface of the primary peds. The value for $E_{ma}$ for the surface horizon of no-tillage is 9.28 and the value of $E_{ma}$ for the surface horizon of the rotational tillage is 23.12. The difference in $E_{ma}$ between tillage treatments in the subsurface horizon is even greater (6.98 for no-tillage versus 28.61 for rotational), which is difficult to explain given the small difference in $\sigma$ in the subsurface horizon.

Estimated values of $E_{ma}$ from measured and estimated soil physical properties showed little difference between tillage practices (Table 4). Using estimations from the measured soil properties, no-till has a value of 14.80 and rotational tillage a value of 15.04. Using estimations from the estimated soil properties, no-till has a value of 21.74 and rotational tillage a value of 23.12. This once again indicates that the tillage technique has little effect on the properties that occur on the surface of the primary peds. The subsurface horizons could not be compared due to the lack of information on the rotational tillage subsurface horizon soil physical properties. However, since the subsurface horizon is not disturbed by tillage, little to no change between the two sites would be expected.

### Table 3
Pedostructure parameter averages based upon tillage method for the entire profile.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Rotational tillage</th>
<th>No-tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>(kg$<em>{soil}$ kg$</em>{-}^{-1}$H$_2$O)</td>
<td>0.016*</td>
<td>0.0089*</td>
</tr>
<tr>
<td>$E_{ma}$</td>
<td>(kg$<em>{soil}$ kg$</em>{-}^{-1}$H$_2$O)</td>
<td>26.59*</td>
<td>8.67*</td>
</tr>
<tr>
<td>$K_m$</td>
<td>(kg$<em>{soil}$ kg$</em>{-}^{-1}$H$_2$O)</td>
<td>$-167.83^*$</td>
<td>$-112.38^*$</td>
</tr>
<tr>
<td>$W_m$</td>
<td>(kg$<em>{soil}$ kg$</em>{-}^{-1}$H$_2$O)</td>
<td>0.17*</td>
<td>0.24*</td>
</tr>
<tr>
<td>$K_w$</td>
<td>(kg$<em>{soil}$ kg$</em>{-}^{-1}$H$_2$O)</td>
<td>0.32*</td>
<td>0.24*</td>
</tr>
<tr>
<td>$V_m$</td>
<td>(dm$^3$ kg$_{-}^{-1}$H$_2$O)</td>
<td>1.11*</td>
<td>0.84*</td>
</tr>
<tr>
<td>$V_w$</td>
<td>(dm$^3$ kg$_{-}^{-1}$H$_2$O)</td>
<td>0.53*</td>
<td>0.02b</td>
</tr>
</tbody>
</table>

Values with the same letter are not significantly different at the 0.05 level.

*The interaction term of tillage and depth was significant for $V_m$, however no other parameter exhibited a significant interaction term.

### Table 4
Pedostructure parameter means for each tillage and depth combination.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No-till surf</th>
<th>No-till sub</th>
<th>Rotational surf</th>
<th>Rotational sub</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>8.2E−3</td>
<td>5.4E−3</td>
<td>2.4E−2</td>
<td>7.0E−3</td>
</tr>
<tr>
<td>$E_{ma}$</td>
<td>9.28</td>
<td>6.98</td>
<td>23.11</td>
<td>28.61</td>
</tr>
<tr>
<td>$K_m$</td>
<td>$-130.78$</td>
<td>$-93.978$</td>
<td>$-148.94$</td>
<td>$-164.14$</td>
</tr>
<tr>
<td>$W_m$</td>
<td>0.21</td>
<td>0.27</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>$W_l$</td>
<td>0.31</td>
<td>0.33</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>$K_w$</td>
<td>0.83</td>
<td>0.86</td>
<td>1.14</td>
<td>1.16</td>
</tr>
<tr>
<td>$V_m$</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Surface samples collected from 0 to 15 cm depth and subsurface samples collected from the 15 to 45 cm depth.

### 3.5. Variations in $K_m$ based on tillage method

$K_m$ represents the equilibrium constant as the shrinkage curve transitions from the structural water pool (non-swelling macropore water) to the basic water pool (swelling micropore water). As the number of macropore sites available for water removal from the system decreases exponentially, an equal exponential increase in the number of micropore sites draining is seen to keep the entire soil–water system at thermodynamic equilibrium (Braudeau et al., 2004). According to Braudeau et al. (2004a), $K_m$ can be related to water contents along the shrinkage curve by:

$$K_m = \ln(2) \cdot 4.8 / (W_m - W_d)$$

where $W_m$ is the water content at point M along the shrinkage curve (more detail below) and $W_d$ is the water content at point D (Fig. 1), the water content at which the first micropores begin to drain. As $W_d$ is always larger than $W_m$, values for $K_m$ are negative. Using data from the potential curves, $K_m$ values (in kg$_{soil}$ kg$_{-}^{-1}$H$_2$O) for individual samples are listed in Table 2, with the means based upon the tillage method shown in Table 3. Individual sample values, regardless of tillage treatment, ranged from $-429.05$ to $-14.41$. The no-tillage average was $-112.38$, and the rotational tillage average was $-167.83$. While the no-tillage treatment has a higher value than the rotational tillage, the large variations between samples indicated these averages were not significantly different at the 0.05 level.

Results for each tillage and depth combination are shown in Table 4. The no-tillage surface horizon has a value of $-130.77$, while the rotational tillage surface horizon has a value of $-148.94$. For the subsurface horizon of both tillage treatments, the no-tillage value was $-93.978$ and the rotational tillage value was $-164.14$. No-tillage has lower $K_m$ values across both depths compared to rotational tillage. A lower $K_m$ value for no-tillage compared to rotational tillage indicates that the quantity ($W_m - W_d$) is a smaller negative expression than for the rotational tillage. Therefore, $W_m$ and $W_d$ are closer in value to one another, indicating a higher percentage of micropores in the no-tillage treatment. No-tillage leaves the soil undisturbed, allowing micropores to form through repeated wetting/drying cycles. Also, each tillage treatment has a lower $K_m$ value for the subsurface horizon compared to the surface horizon, indicating higher water content in the micropores for both tillage treatments in the subsurface horizon compared to the surface horizon. Looking at estimated values of $K_m$, differences between the surface horizons of the two tillage treatments were not substantially different. Using the estimations from the measured soil property values, no-till had a value of $-125.06$ and rotational tillage a value of $-124.51$. Using the estimations from the measured soil properties, no-till had a value of $-68.74$ and rotational tillage a value of $-55.91$.

### 3.6. Variations in $W_m$ based on tillage method

$W_m$ represents the water content at which the extension of the linear shrinkage phases of the structural and basic water pools intersect one another (see Fig. 1). All but the smallest macropores have been drained of water and the loss of water comes primarily from the swelling micropore water (basic water pool). Values for all samples are listed in Table 2 with the averages presented in Table 3. Values for $W_m$ ranged from 0.09 to 0.29. The averages for $W_m$ were: 0.24 for no-tillage and 0.17 for rotational tillage. The 2-way ANOVA test indicated that this difference is significant, meaning that the no-tillage treatment, regardless of depth has higher water contents in its micropore structure compared to rotational tillage. This agrees with the results of Diaz-Zorita et al. (2004).

Looking deeper at $W_m$ in the surface horizon, no-tillage has a water content of 0.21 and rotational tillage has a value of 0.20 (Table 4). This difference indicates that the different tillage treatments have a small
effect on the amount of micropores present in the surface. However, when looking at the subsurface horizon, no-tillage has a value of 0.27 and rotational tillage a value of 0.15. Therefore, there is much more water present in the micropores of no-tillage below the surface. The subsurface horizon of the no-tillage treatment has not been disturbed in over twenty years. Therefore, many more wetting/drying and freeze/thaw cycles have occurred, changing the pore size distribution of the smallest pores slightly with each cycle. Micropores are seen as the primary pores for water storage (Pagliai et al., 2004). Therefore, according to these results, plants grown in no-till fields have better access to water, especially in drier conditions when water in the macropores is no longer present.

The estimated values of $W_m$ from the measured soil properties were not significantly different (Table 4). The surface horizon of the no-till treatment had a value of 0.20 and the rotational tillage surface horizon had a value of 0.20. There was a substantial difference in $W_m$ values estimated from estimated soil properties (no-till, 0.21; conventional, 0.12), but with the additional error included by using estimated soil properties, this difference may not be accurate. Further investigation is needed to have a definitive conclusion.

3.7. Variations in $W_l$ based on tillage method

$W_l$ represents the total water content of the soil at saturation, when all pores are completely filled with water. Values for individual samples ranged from 0.21 to 0.41, as presented in Table 2, with the averages for the two tillage treatments shown in Table 3. The averages for the two tillage treatments, regardless of depth were: no-tillage, 0.32, and rotational tillage 0.30. The difference was not statistically significant at the 0.05 level. As seen above, the water content in the micropores ($W_m$) is significantly higher in the no-tillage treatment. Therefore, if the total water content for each soil is approximately the same, then the rotational tillage has a higher percentage of macropores present for water infiltration. Tillage breaks up the soil aggregates to create macropores to improve water infiltration and encourage root growth.

Table 4 shows the individual mean for $W_l$ for each tillage and depth combination. Looking at the extracted pedostructure parameters (Table 4), the surface horizon of the no-tillage treatment has a value of 0.31, while the $W_l$ for the surface horizon of the rotational tillage treatment is 0.30. A similar trend can be found when comparing the two tillage treatments at the subsurface horizon level. The no-tillage has a value of 0.33 and the rotational tillage has a value of 0.30. Little difference in $W_l$ values occur when looking at estimated values from soil properties. Using the estimations from the measured soil properties, the no-till surface horizon has a value of 0.27 and the rotational tillage surface horizon a value of 0.27. Using the estimations from the estimated soil properties, the no-till surface horizon had a value of 0.37 and the rotational tillage surface horizon had a value of 0.37. No estimations of $W_l$ were done with the rotational tillage subsurface horizon due to the lack of soil property data for this horizon.

3.8. Variations in $K_{bs}$ based on tillage method

$K_{bs}$ measures the slope of the shrinkage line as the basic water pool dries (Fig. 1). Salahat (2006) described the parameter as representing the volume change ratio between the soil aggregates and primary ped. This parameter represents the amount of shrinkage occurring in the soil–water system as the shrinking micropore water is removed from the system. Table 2 lists the values for each sample while Table 3 shows the average values. The no-tillage treatment has an average value of 0.84 and rotational tillage a value of 1.11. This difference is significant at the 0.05 level and indicates that the no-tillage loses more water for the same amount of micropore shrinkage when compared to the rotational tillage treatment.

Table 4 shows the individual means for each tillage and depth combination. The no-tillage surface horizon has a value of 0.83 and the rotational tillage surface horizon a value of 1.14. Likewise, the no-tillage subsurface horizon has a value of 0.86 and the rotational tillage subsurface horizon a value of 1.16. These significant differences indicate that the no-tillage system is more strongly structured in the micropore region and less prone to shrinkage and swelling with wetting and drying cycles. The micropores are less susceptible to closing when the water content is high; causing the swelling of the primary peds, indicating that a higher amount of water can be stored in the micropores. This conclusion agrees with the results found for the pedostructure parameters $W_m$ and $K_{bs}$, which describe the soil–water behavior at the transition between the macropore and micropore regions.

However, when looking at the estimated $K_{bs}$ values, the significant difference due to tillage no longer occurs (Table 4). The estimated values of $K_{bs}$ for the no-till surface horizon, using measured and estimated soil properties were 0.88 and 1.12, respectively. In comparison the values for the rotational tillage surface horizon, using measured and estimated soil properties were 0.89 and 1.16, respectively. These similarities are largely due to the similar soil physical properties found at both tillage sites.

3.9. Variations in $V_o$ based on tillage method

$V_o$ is the measure of the specific volume of the soil when all the water has been removed from the system, leaving only the soil solids and air. Values of $V_o$ for each individual sample are listed in Table 2 and the average values are presented in Table 3. Individual values of $V_o$, regardless of the tillage method, ranged from 0.53 to 0.67. The average $V_o$ for the no-tillage treatment was 0.62, while the average for the rotational tillage was 0.56. This difference is significant at the 0.05 level. This suggests that even though rotational tillage creates more macropores to allow for greater water infiltration and greater root depth capabilities, no-tillage actually provides more open pore space for water storage and root growth. The no-tillage treatment therefore has a higher specific volume and consequently, lower bulk density, than the rotational tillage. When comparing the values for $V_o$ for depth, regardless of tillage, the difference is not significant. The surface horizon has a value of 0.60 and the subsurface horizon a value of 0.58. However, the interaction between tillage and depth was significant for $V_o$, with the subsurface horizon of the rotational tillage having a substantial lower value than the other three combinations (Table 4).

The no-tillage surface horizon has a value for $V_o$ of 0.60, while the value of $V_o$ for the surface horizon of the rotational tillage is 0.60. Therefore, the bulk density at the dry state of the no-tillage (1/0.604 = 1.66 kg dm$^{-3}$) is slightly less than the bulk density of the rotational tillage (1/0.60 = 1.67 kg dm$^{-3}$). Since these two soils have similar porosities, but different levels of micropore water contents ($W_m$), this shows that the rotational tillage has a higher percentage of micropores present in its structure. This difference in the pore size distribution is primarily due to the macropores being created by tillage, while the micropores are the result of wetting/drying cycles on the undisturbed soil matrix.

For the subsurface horizon, the no-tillage treatment had a $V_o$ value of 0.61, making it slightly less dense (1/0.61 = 1.65 kg dm$^{-3}$) at the dry state than the surface horizon. The largest change in $V_o$ can be seen in the rotational tillage subsurface horizon, with a value of 0.53. This large decrease in the specific volume, and thus a large increase in the bulk density (1/0.53 = 1.88 kg dm$^{-3}$), can be attributed to the presence of a plow pan after several cycles of tillage. As the soil aggregates in the surface horizon are destroyed to create macropores, the soil immediately beneath the implement is smeared by the
movement of the implement, closing pores to water movement and compacted by the weight of the implement. Therefore, the initial statistical results of a higher \( V_o \) in no-tillage compared to the rotational tillage may not be completely accurate as the interaction between tillage and depth is significant for the rotational tillage, subsurface horizon treatment.

As in estimating \( K_{bs} \), the estimated \( V_o \) values between the tillage schemes do not show the significant differences seen in the measured pedostructure parameters (Table 4). The no-till surface horizon had a value of 0.59 using the measured soil properties, while the rotational tillage had a value of 0.59. Using the estimations from estimated soil properties, the no-till surface horizon had a value of 0.65 and the rotational tillage had a value of 0.65. This indicates that the soil properties chosen for estimation in this study are not good indicators of \( V_o \).

## 4. Conclusions

The development of the pedostructure concept (Braudue and Mohtar, 2004, 2006; Braudeau et al., 2004) can lead to a better understanding of soil–water behaviors across spatial scales. While numerous studies have been undertaken to discover the effects of land management on common soil physical, biological, and chemical properties, no such studies have been done concerning the pedostructure concept. The purpose of this study was to determine the effect of differing land management schemes, in this case, different tillage treatments, on the pedostructure parameters. Replicates from two soil series, an Aeric Epiaquod under the rotational tillage and an Aquic Hapludalf under no-tillage from DeKalb County, Indiana were collected and the pedostructure parameters extracted using the procedure documented by Salahat (2006).

These results indicate that the no-tillage treatment has a higher percentage of micropores available for water storage throughout the profile. Also, no-tillage has a significantly higher specific volume at the dry state, \( V_{ds} \), meaning a lower bulk density for better water infiltration and root growth. However, this may not be completely accurate, as the interaction between tillage and depth was significant for the rotational tillage, subsurface horizon treatment. More experimentation is needed before a conclusive determination can be deduced. While none of the other parameters were significantly different in a statistical sense, \( E_{ma} \), \( \sigma \), and \( K_{m} \) were lower for the no-tillage treatment compared to the rotational tillage treatment. Higher \( E_{ma} \) and \( \sigma \) values for the rotational tillage treatment indicate a higher percent of surface area exposed to water, air, and chemical movement, while less negative values of \( K_{m} \) for the no-tillage treatment agree with the conclusion that no-tillage has more and better defined micropore space compared to the rotational tillage treatment. \( W_i \), the water content at saturation, was almost identical for all treatment combinations, indicating a higher amount of macropores present in the rotational tillage, as the micropore water content (\( W_{m} \)) in the no-tillage is higher. Additionally, none of the parameters was significantly different due to depth alone, regardless of tillage method.

These results signify a higher percentage of micropores in the no-tillage treatment along with a lower bulk density at all water contents. The results also show that the parameters involved in describing the interactions occurring near the primary pedds (such as \( \sigma \) and \( E_{ma} \)) show insignificant statistical differences between tillage methods, while the parameters describing the micropores (\( W_{m} \), \( K_{m} \)) do show significant differences between the two. Moreover, while the macropore parameters do not differ significantly between the tillage treatments, rotational tillage does have a higher percentage of macropores comprising the pore space.

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### References


