Computed tomographic measurement of macroporosity in chisel-disk and no-tillage seedbeds

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Abstract

Methods for evaluating soil conditions as influenced by tillage are often limited to analysis of bulk samples. The application of medical computed tomography (CT) to the characterization of tillage effects on soil provides an alternative tool for measurement since it is at a more detailed scale. The objective of this study was to compare soils under conventional and no-tillage (NT) systems using X-ray CT. Chisel-disk-disk (CDD) conventional tillage and NT systems were compared for a Mexico silt loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs) soil. Five replicate soil cores (75 mm long by 75 mm diameter) were collected from each treatment. Two CT systems were used in this study: a medical CT scanner (MCT, 1 mm thick scans) and an ultra-high resolution CT scanner (UHCT, 0.1 mm thick scans). Significantly higher soil density was found for the NT treatment using the MCT scanner \( P = 0.05 \). Data from the UHCT scanner were used to compare the effects of scan thickness and to evaluate macropore characteristics. Macropore area was significantly higher \( P < 0.001 \) for CDD as compared to the NT treatment: 11 versus 5%. The number of macropores in the CDD treatment were twice those in NT; their perimeter was 62% longer; and their circularity was 94% of that for pores from the NT tillage treatment. The macropore box-counting fractal dimension \( D \) was significantly greater \( P < 0.001 \) for CDD \( D = 1.44 \) as compared to the NT treatment \( D = 1.26 \), reflecting the greater space-filling behavior of the CDD treatment. This study shows that the UHCT scanner can characterize differences in soil macroporosity more precisely than standard MCT scanners. The use of ultra-high resolution tomography can aid in the discrimination of differences between seedbeds created by different tillage systems. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Computed tomography; X-ray CT; Fractal analysis; No-tillage; Conventional tillage

1. Introduction

The rationale for tillage of soils is to improve their physical condition, to produce a more favorable environment for seed germination and plant growth. To improve means to do it in a better way, implying the difference between good and poor conditions is known (Kuipers, 1963). A major effect of tillage on the soil physical condition is to alter the soil structure. Soil structure has been defined by Dexter (1988) as “the spatial heterogeneity of the different components or properties of soil . . .”. Soil structure defines the framework of soil in which chemical, physical and biological reactions take place. Traditional methods for determining soil structure include measurements of soil bulk density, pore-size distribution, aggregate size distribution and the stability of aggregates and pores. These measurements are usually destructive
and do not provide information on the spatial heterogeneity of the different components which constitute soil structure. Questions such as how to till soil with the least damage to soil structure, and with the least cost are difficult to answer precisely with these traditional methods because of the complexity of soil structure.

One important feature of soil structure is the number and size of macropores (tillage-induced structure, wormholes, root channels, etc.). Macropores have a great influence on many soil properties, as shown by numerous investigations. Pore shape, size, orientation, and size distribution affect the rate of water flow and retention (Rasiah and Aylmore, 1998). However, differences in hydraulic conductivity under different tillage treatments tend to be inconsistent. It is sometimes thought that no-tillage (NT) promotes infiltration; however, some workers have found that lower conductivity values occur with NT versus conventional tillage (Gantzzer and Blake, 1978; Lindstrom and Onstad, 1984). This is attributed to decreased total porosity, and specifically macroporosity. Other workers have found that NT increases macroporosity compared to conventional tillage (Wu et al., 1992; Benjamin, 1993). Tollner et al. (1984) and Culley et al. (1987) found that differences between NT and conventional tillage treatments were not different. A tool to assist in better understanding these differing results is needed.

One method for direct measurement of intact soil structure is the use of X-ray computed tomography (CT) scanners for determining the relative density of soil and its spatial arrangement in intact cores (Anderson et al., 1988). CT measures soil structure non-invasively and non-destructively and provides spatial information on pores and soil solids at less than millimeter scales. Soil macropores can be identified from the soil matrix with CT (Anderson et al., 1990; Peyton et al., 1992; Zeng et al., 1996; Olsen and Børresen, 1997; Asare et al., 1999). However, in nearly all studies, the volume element (voxel) resolution of medical CT scanners (hereafter referred to as MCT) is not uniformly scaled. Scans are usually thicker (1–4 mm) than the cross-sectional picture element (or pixel) dimensions (0.1 mm × 0.1 mm). This limits medical CT imaging resolution to detecting only “large” macropores (>1–2 mm). While high-energy synchrotron scanning is capable of spatial resolution on the order of a few micrometers, the small 1–2 mm sample size requirements limits its use for intact soil cores containing large aggregates and voids produced by tillage (Spanne et al., 1994).

Because voxel thickness of MCT scanners is relatively large, macropore detail is not well characterized with these systems. The goal of this research is to evaluate seedbed macroporosity using a high-resolution CT scanner to measure relative attenuation values (RAV) of intact soil samples from conventional tillage chisel-disk-disk (CDD) and NT seedbeds. The objectives are to estimate and compare CT-measured relative density and to estimate and compare CT-measured macropore characteristics from the CDD and NT treatments.

2. Materials and methods

2.1. Field experiment

The experimental site was located at the Bradford Research Center, 8 km east of Columbia, MO. The soil is a Mexico silt loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs). The Ap (0–178 mm) is very dark grayish brown (10YR 3/2, wet) or grayish brown color (10YR 5/2, dry) having an organic matter content of approximately 1.9%. It has a silt loam texture (clay ~20%, silt ~68%), with weak fine granular structure, and is very friable. The site had been in continuous NT corn (Zea mays), soybeans (Glycine max), and hairy vetch (Vicia villosa) production during the last 6 years. Hairy vetch was the most recent crop. The tractor used was a 96 hp John Deere 4020. Hairy vetch was planted with a Tye no-till drill. Corn and soybeans were planted with a Kinze no-till planter. The chisel-plow used for plot preparation was a Landroll with seven chisel tines spaced at 300 mm. The disk was a 470 International tandem disk with 560 mm blades. The same tractor and tillage equipment was used for all plot preparation.

Tillage was done in October 2000 less than 24 h before sampling. Two adjoining strips, 4 m wide by 10 m long, were prepared. One strip was left untouched for collection of NT samples. The other strip was prepared with a chisel-plow immediately followed by two diskings (CDD), a typical tillage practice for the region. Soil samples were collected
at an average field water content of 0.33 m$^3$/m$^3$ for the CDD and 0.37 m$^3$/m$^3$ for the NT treatment using a core type sampler (Blake and Hartge, 1986). To standardize water content, samples were later equilibrated to equal soil water potential in the lab. No significant compaction was observed during sampling. Soil cores 75 mm × 75 mm i.d. were collected in Plexiglas cylinders. Five intact soil cores were taken in the NT and CDD treatments at the 25–100 mm depth within the Ap-horizon. Cores were transported to the laboratory and stored at 4 °C. Sample cores were trimmed at both ends and covered with a fine nylon mesh to contain soil within the cylinders. Cores were allowed to slowly wet for 24 h with a slowly increasing head of water from a Mariotte bottle. They were then weighed, drained and equilibrated to −4 kPa using a glass-bead tension table, and weighed again before being transported to the CT scanners for measurement. After scanning, sample cores were dried and weighed to determine water content and bulk density. Oven-dry water contents were determined after placing sub-samples into an oven at 105 °C for 24 h. Bulk density was calculated with air-dry weights corrected using oven-dry water contents (Blake and Hartge, 1986). Total porosity was calculated from the bulk density values assuming a particle density of 2.65 Mg/m$^3$. Measured macroporosity was calculated by subtracting the water content at −4 kPa from that at 0 kPa.

2.2. CT scanning

Two different CT scanners were used. These scanners were a GE Genesis-Zeus medical CT scanner (MCT) and a Bio-imaging research “ultra-high resolution” CT (UHCT) scanner. The MCT scanner was used for scanning relative voxel densities in the soil cores. Ten soil cores were scanned. Cores were scanned with five consecutive slices located near the center of each sample. The slices for each core were contained in a volume of 75 mm i.d. by 5 mm in length. The scanner resolution was 0.19 mm × 0.19 mm × 1 mm, with a field of view or object reconstruction diameter of 96 mm (Ketcham and Carlson, 2001). The X-ray beam was set to 120 kV and a current of 100 mA (Table 1).

Due to cost, the UHCT was used to evaluate two cores from the CDD and two cores from the NT treatments for macropore amount, number, size-distribution, perimeter, circularity, and fractal dimension. These cores were selected based on data from the MCT scans, however, all cores within treatment were similar. The UHCT scanner was designed to complement medical scanners capable of spatial resolutions of a millimeter and synchrotron facilities capable of spatial resolutions of a few micrometers. The scanner has an “ultra-high resolution” subsystem for scanning small objects that can be penetrated by relatively low-energy X-rays. Ketcham and Carlson (2001) report the instrumentation and scanning techniques. Samples were scanned using a FeinFocus 200 kV microfocal X-ray source and Toshiba image intensifier as a detector, read by a 512 × 512 CCD video camera. X-ray settings were 180 kV and 0.133 mA, resulting in an X-ray focal spot of about 0.03 mm (Table 1). A wedge calibration, consisting of averaged detector readings with X-rays through a full rotation corresponding to scan conditions, was taken through a cylinder of fine glass beads (~40 μm) to correct for beam hardening. The samples were scanned in a 160% offset mode in order to permit a decrease in source to object distance and thus improve scan resolution. Reconstruction parameters were chosen to optimize the use of the 12-bit grayscale range available in the data image files. The 512 × 512 pixel scan field of view diameter was 75 mm, resulting in pixel dimensions of 0.148 mm × 0.148 mm with a thickness of 0.097 mm producing a voxel volume of 0.0021 mm$^3$ (Table 1).

2.3. Image analysis

ImageJ ver. 1.20 software was used for image analysis (Rasband, 2001). ImageJ is a public domain Java image-processing program that can calculate
area and pixel value statistics of user-defined selections. It can create density histograms and line profile plots. The threshold feature was used to interactively set the lower and upper threshold values, segmenting the image into pores and solids. The measure tool was then used to measure the porosity of the entire region of interest. The analyze particles tool was used to measure statistics of the individual pores. The zproject projection tool was used to project an image stack that displayed sequential related scans in a window along the z-axis perpendicular to the image plane. The sum slice feature of zproject was used to sum the slices in an ImageJ stack.

To develop a calibration procedure for MCT scans, a graph of frequency versus Hounsfield numbers was produced and correlated to a graph of frequency versus 8-bit grayscale values. (Hounsfield numbers \( H \) are defined with reference to water as follows: \( H = (\mu_s - \mu_w) \times 1000 / \mu_w \), where \( \mu_s \) and \( \mu_w \) are the soil solid and water linear attenuation coefficients; Anderson et al., 1988.) The correlation coefficient for this was 1.0. By definition, a Hounsfield number of zero is defined by pure water when the total voxel is filled with water. Hounsfield values below zero represent volumes with lower densities than water, such as air. Because of differences in X-ray characteristics, it is not possible to convert data from the UHCT into Hounsfield values. For purposes of this paper, these data will be referred to as a relative attenuation value (RAV). An RAV equal to zero corresponds to air and an RAV equal to 256 corresponds to the densest solid (for the soils, this corresponded to manganese concretions). Hounsfield values for the MCT were scaled to RAV to allow for comparison of data. The MCT resolution was at 1 mm thick scan slice, whereas the UHCT was set to a 0.1 mm scan thickness. For comparison of the differences between the slice thicknesses, only data obtained from the UHCT scanner were used to eliminate systematic differences between devices. This was done by summing each pixel location across the ten 0.1 mm slices to create one comparable 1.0 mm-thick slice.

MCT and UHCT scan images were both adjusted for boundary effects and beam hardening by selecting a region of interest of 70 mm in diameter. MCT and UHCT scan images were converted with ImageJ to produce 8-bit grayscale images that were then evaluated. For this paper, threshold values from 0 to 60 grayscale, or RAV were used to represent macroporosity. These values were chosen based on analysis of histograms of grayscale values from large (>1 mm) well-defined macropores identified in the image. It is impossible to completely discriminate macropores perfectly due to attenuation, partial volume effects, and beam hardening. However, this technique provides much better resolution than bulk sample methods. Box-counting fractal dimensions of images were determined on a region of interest of 48 mm × 48 mm. This smaller square area was required by the computer program. Threshold values for this analysis were slightly different and set from 0 to 94 RAV. The reason for the higher upper threshold limit for the fractal analysis was to increase data density in the NT treatment, which was otherwise too sparse. Analyses of the images from the CDD and NT treatments consisted of a determination of the number of macropores, macropore area (mm²), macropore perimeter (the length of the pore/solid boundary), macropore circularity circularity = 4\( \pi \) (area/perimeter²), and macropore box-counting fractal dimension from the cross-sectional slices. Equivalent cylindrical diameter was calculated by assuming that pore areas were circular (equivalent cylindrical diameter = 2(area/\( \pi \))⁰.⁵).

3. Results

3.1. Bulk sample properties

Fig. 1 presents average RAV of the MCT scans for the replicate samples from the CDD and NT treatments. Mean RAV for the CDD samples was 99 ± 1.6 (mean ± standard error) and that for the NT was 134 ± 0.9. A two-sample t-test indicated these means were significantly different at the <0.001 probability level. These values correspond to wet bulk densities of 1.35 Mg/m³ ± 0.05 for the CDD and 1.80 Mg/m³ ± 0.03 for the NT samples (dry bulk densities were 1.1 Mg/m³ ± 0.04 and 1.44 Mg/m³ ± 0.04). Fig. 2a and Table 2 present additional information about the effects of the tillage treatments on bulk density. Since the RAV distributions are not perfectly normal, use of non-parametric statistics provides detailed information on the increase in density in the NT versus CDD treatments. For both scanners, the density values for the NT are significantly greater than for the CDD.
Fig. 1. Average RAV collected using the MCT scanner with a voxel size of 0.19 mm × 0.19 mm × 1 mm thick collected from CDD and NT seedbeds (n = 5 scans per replicate). Error bars represent 1 S.E.

Fig. 2. Frequency versus RAV collected with the UHCT scanner with a voxel size of 0.15 mm × 0.15 mm × 0.1 mm thick from CDD and NT seedbeds for (a) complete RAV range and (b) low RAV range with slice thicknesses of 0.1 and 1 mm. Data are for a representative slice from one core.
Table 2
Average RAV for critical histogram points from the UHCT scanner integrated over 1 mm for the CDD tillage and NT treatments \((n = 5)\)

<table>
<thead>
<tr>
<th>Critical points</th>
<th>CDD</th>
<th>NT</th>
<th>(P &gt; F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit</td>
<td>159</td>
<td>173</td>
<td>0.044*</td>
</tr>
<tr>
<td>Mid-point</td>
<td>131</td>
<td>144</td>
<td>0.019**</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability levels.
** Significant at the 0.01 probability levels.

Since samples were scanned wet \((-4 \text{kPa})\), the relevant density for comparison is the wet density since sample drying causes significant shrinkage for this soil \((\text{Anderson et al., 1988})\). Many researchers have reported that cultivated samples have reduced densities in the surface soil \((\text{Gantzer and Blake, 1978; Logsdon et al., 1990; Rhoton et al., 1993; Mahboubi et al., 1993})\). While these measurements detect increased porosity for the CDD treatment, they provide no information on the spatial heterogeneity of the constituents of soil structural units within the samples. To explore this aspect, it is necessary to use CT scanners.

3.2. CT-scan thickness

Fig. 2a presents UHCT data on the frequency versus RAV for 0.1 mm slices collected from the CDD and NT treatments. Fig. 2b expands the scale of this information over the RAV range from 0 to 100. Fig. 2b also presents information for 1 mm thick slice calculated by summing ten 0.1 mm thick scans. As can be seen, there are significant differences in the frequency values for specific RAVs for both tillage treatments and scan thicknesses. The CDD treatment has a greater increase in frequency in the low RAV range compared to the NT treatment \((\text{Fig. 2b})\) that is due to the lower density of this treatment. The 1.0 mm thick slice data for both treatments generally indicates a lower frequency for specific RAVs in the lower range compared to the 0.1 mm thick scans. This is probably due to the decreased resolution of the 1.0 mm thick slices. However, the decrease in the frequency for the CDD treatment 1.0 mm thick slices is about twice that for the NT treatment. This is probably due to the fact that there is a lower frequency of CT-detectable small macropores in the NT treatment compared to the CDD treatment, and thus the measurement is less influenced by the change in CT-scanner resolution. It may also be a result of an increase in tortuosity in the macropores for the CDD treatment compared to the NT treatment.

The effects of slice thickness on the standard deviation of the RAV within a slice for the tillage treatments are shown in Fig. 3. The standard deviation of the RAVs reduces as slice thickness increases. Specifically, the standard deviation of the 1.0 mm thick slice for the CDD treatment is reduced by 25% compared to that of the 0.1 mm thick slice. The reduction in the standard deviation for the NT treatment was 37%. This confirms the idea that higher resolution scanning...
provides additional details in RAVs. Moreover, it points out that relatively more information is lost in samples with smaller-sized macropores such as the CDD treatment samples. Quantitative data on the effects of scan thickness are presented in Table 3. The number of pores for the CDD and NT treatments are significantly reduced for the 1.0 mm thick slices compared to the 0.1 mm thick scans.

3.3. Macroporosity and macropore characteristics

Frequency data as a function of equivalent cylindrical diameter for the CDD and NT tillage treatments are shown in Fig. 4. Results of the effects of slice thickness are also illustrated. The benefit of using a higher resolution scanner is in the detection of pores with less than 1 mm diameters. The variable curve behavior for the CDD treatment is due to the selection of the discrete histogram categories of equivalent cylindrical diameters. Thus, the 1.0 mm thick slices are characterized by detecting significantly fewer pores especially with equivalent cylindrical diameters ranging from 0.2 to 1 mm in size.

These findings are similar to those of Asare et al. (1999). The values of macroporosity for this study were in the order of 11% for the CDD and 5% for the NT tillage treatments (Table 3), while those of the Asare et al. (1999) who used a scanner similar to the UHCT were 4% for a NT tillage treatment.

Results of macropore parameters for the tillage treatments for 0.1 and 1.0 mm thick slices are presented in Table 3. The number of macropores is significantly affected by tillage treatment. The 1 mm thick slices have fewer detectable pores compared to the 0.1 mm

<table>
<thead>
<tr>
<th></th>
<th>CDD</th>
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<tbody>
<tr>
<td></td>
<td>No. (#)</td>
<td>Area (mm²/mm²)</td>
<td>Perimeter (mm)</td>
<td>Circularity a</td>
<td>Fractal D</td>
<td>No. (#)</td>
<td>Area (mm²/mm²)</td>
<td>Perimeter (mm)</td>
<td>Circularity a</td>
<td>Fractal D</td>
<td></td>
<td></td>
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<tr>
<td>1 mm slice summed</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Average</td>
<td>221</td>
<td>0.086</td>
<td>5.97</td>
<td>0.94</td>
<td>1.40</td>
<td>51</td>
<td>0.033</td>
<td>5.31</td>
<td>0.98</td>
<td>1.08</td>
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<tr>
<td>S.D. (n = 5)</td>
<td>18</td>
<td>0.012</td>
<td>0.86</td>
<td>0.07</td>
<td>0.04</td>
<td>6</td>
<td>0.004</td>
<td>0.49</td>
<td>0.08</td>
<td>0.08</td>
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<tr>
<td>0.1 mm thick scan</td>
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</tr>
<tr>
<td>Average</td>
<td>351</td>
<td>0.114</td>
<td>5.24</td>
<td>0.91</td>
<td>1.44</td>
<td>151</td>
<td>0.049</td>
<td>3.24</td>
<td>0.97</td>
<td>1.26</td>
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<td></td>
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<tr>
<td>S.D. (n = 10)</td>
<td>12</td>
<td>0.004</td>
<td>0.26</td>
<td>0.02</td>
<td>0.02</td>
<td>25</td>
<td>0.004</td>
<td>0.16</td>
<td>0.03</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Circularity = 4π(area/perimeter²).

Fig. 4. Frequency versus equivalent cylindrical diameter of macropores measured using 0.1 and 1 mm thick slices collected with the UHCT scanner with a voxel size of 0.15 mm × 0.15 mm × 0.1 mm thick from CDD and NT seedbeds.
thick scans. The number for the NT treatment was 43% of the number in the CDD treatment (0.1 mm). The slice thickness also significantly affected the number of macropores; the number detected by the 0.1 mm scan thickness was significantly higher than the number detected by the 1.0 mm slice thickness. The macropore area measured by the UHCT scanner was 57% lower for the NT treatment compared to the CDD treatment (0.1 mm). The total porosity of NT is smaller than CDD. NT has large macropores, but few smaller macropores that are large enough to be detected by either the MCT or the UHCT. Comparable results to the number of macropores were found for the macropore area for the 0.1 and 1.0 mm thick slices.

The perimeter of macropores for the 0.1 mm thick scans was significantly less (38%) for the NT treatment compared to the CDD treatment. The 0.1 mm thick scans significantly increased the perimeter distance compared to the 1.0 mm thick slices. The CDD treatment was only 14% higher, while the NT treatment was 64% higher. Circularity of macropores is also presented in Table 3. This is a measure of the shape of the macropores. Macropores from the NT tillage treatment are 7% more circular than macropores from the CDD treatment (0.1 mm). Results indicate that there was a 3% increase for the 1.0 mm slice thickness compared to the 0.1 mm scan thickness for the CDD treatment, relative to only a 1% increase for the NT treatment as a function of scan thickness. This increase is probably due to the smoothing of the macropore RAV for the 1.0 mm thick slice compared to the 0.1 mm thick scan.

Fig. 5 presents UHCT grayscale images and associated binary images for the two tillage treatments.

Fig. 5. Grayscale and binary images from soil cores from CDD and NT seedbeds. (a) Grayscale for CDD, (b) grayscale for NT, (c) binary for CDD, and (d) binary for NT.
The CDD treatment images had a wider range of pore sizes. In contrast, the NT treatment images had fewer total pores and were characterized mainly by a few large pores. Table 4 presents UHCT measured macropore characteristics and directly measured macropore amount, as well as marginal tests of significance. The UHCT measured macroporosity corresponds very closely the amount of macropores measured directly by desorption over the entire core. In contrast, the 1 mm slice significantly underestimates macroporosity (Table 3). The percent macroporosity and number of UHCT macropores in NT was just 43% that found in CDD. This agrees generally with research findings showing that NT is of higher density and lower macroporosity. It also agrees with the MCT measured macropore findings of Olsen and Børresen (1997). However, unlike their findings, our graphs of frequency versus RA V do not show a marked low value spike but rather a small subtle increase in the low value RA V area.

Estimates of the macroporosity fractal dimension ($D$) for the two tillage treatments are shown in Table 4. The box-counting fractal dimension of the slices estimated from the UHCT images for the CDD treatment ($D = 1.44$) was significantly higher (13%) compared to the dimension estimated for the NT treatment ($D = 1.26$). This indicates that there was a significant reduction for the NT treatment compared to the CDD treatment in the space-filling nature of the macropores as shown in Fig. 5. It is likely that this is partly related to the total amount of macropores in the NT treatment. These results are similar to results from natural cores measured by Peyton et al. (1994) and Zeng et al. (1996) which showed that fractal $D$ was positively correlated with the amount of macropores. These results are also in agreement with Rasiah and Ayllmore (1998) showing that the CT-measured fractal $D$ is sensitive to structural differences in soils.

The MCT-scanner detected only about 60% of the macropores measured by the UHCT scanner. The advantage of MCT scanners is that they are available at many hospitals in developed countries. The UHCT is currently less accessible and more expensive per scan. The cost is less for the MCT scanner, but it is unable to detect finer-scale resolution porosity differences between tillage treatments. The UHCT can measure most macropores and is able to detect finer-scale resolution porosity differences between tillage treatments.

### 4. Discussion and conclusions

This study shows that use of a UHCT scanner improves the resolution for measurement of macropore characteristics compared to an MCT scanner because of reduced voxel size. Continued work is necessary to improve UHCT scanner techniques. First is the development of improved methods to calibrate the instrument for specific soil samples and to better adjust scanner results for beam hardening and partial volume artifacts. Work is also necessary to more accurately measure the spatial heterogeneity of different soil components by developing measures for pore shape, continuity, and tortuosity. While measures of macropore numbers, macropore area, perimeter, circularity, and box-counting fractal dimension appear to be useful, they have limited capability to describe

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Treatment</th>
<th>$F^a$</th>
<th>Ratio (NT/CDD)</th>
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<tbody>
<tr>
<td>CT macropores (mm$^2$/mm$^2$)</td>
<td>0.11 0.05</td>
<td>1157</td>
<td>0.43</td>
</tr>
<tr>
<td>Measured macropores (v/v)</td>
<td>0.11 0.06</td>
<td>38</td>
<td>0.55</td>
</tr>
<tr>
<td>Number of pores</td>
<td>351 151</td>
<td>524</td>
<td>0.43</td>
</tr>
<tr>
<td>Perimeter (mm)</td>
<td>5.2 3.2</td>
<td>420</td>
<td>0.53</td>
</tr>
<tr>
<td>Macropore fractal $D$</td>
<td>1.44 1.26</td>
<td>82</td>
<td>0.87</td>
</tr>
<tr>
<td>Circularity</td>
<td>0.91 0.97</td>
<td>23</td>
<td>1.06</td>
</tr>
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</table>

$^a$ Degrees of freedom for $F(1, 18)$. All comparisons $(P > F) <0.001$.

$^b$ Measured over the entire core by desorption.

Table 4
Average macropore characteristics for ten 0.1 mm thick scans from the UHCT scanner for the CDD and NT treatments.
the systematic behavior of an assemblage of scans reconstructed as a volume. Analysis to describe the interrelationships and interdependence among measurements will be beneficial for developing simple, yet effective discriminators of tillage effects on soil properties.

Realization of these goals will allow for better discrimination of similar, but subtle differences in tillage-induced soil conditions such as seedbeds that are important for plant growth and development. Development of thresholds is necessary to identify important soil conditions that will better describe aspects of soil quality and more accurately parameterize the soil physical condition. This effort is necessary to advance development of 3D computer modeling of soil structure and to provide for a better understanding of the effects of soil structures on soil physical, chemical and biological processes.

UHCT tomography will advance discrimination of subtle differences in soil structure produced by tillage. In this study, samples from the CDD tillage treatment had significantly lower density than samples from the NT tillage treatment. When threshold values were chosen segmenting CT-images into macropores, comparison of 0.1 versus 1.0 mm thick scans measured significantly different numbers of macropores. The 0.1 mm thick slices measured a greater number of pores than the 1.0 mm thick slices (i.e. 59 and 196% greater in the CDD and NT treatments, respectively). The 0.1 mm thick scans had significantly greater macropore area compared to 1.0 mm thick slices; however, the 0.1 mm thick scans had reduced macropore perimeters and circularities. Statistics for the 0.1 mm thick scans showed that macropore area was significantly lower ($P < 0.001$) for the NT treatment (5%) versus the CDD treatment (11%). The number of macropores found in the CDD treatment was twice that found in the NT treatment; their perimeter was 62% higher; however, their circularity was only 94% that of pores from the NT tillage treatment. The macropore box-counting fractal $D$ was significantly greater ($P < 0.001$) for the CDD versus the NT treatment reflecting the greater space-filling behavior and wider range of pore sizes of the CDD treatment. The UHCT scanner can characterize tillage-induced differences in soil macroporosity more precisely than MCT scanners.

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