EVALUATING SOIL TILLAGE PRACTICES USING X-RAY COMPUTED TOMOGRAPHY AND CONVENTIONAL LABORATORY METHODS

M. Ambert-Sanchez, S. K. Mickelson, S. I. Ahmed, J. N. Gray, D. Webber

ABSTRACT. *Using x-ray computed tomography (CT) for non-destructive 3-D imaging and analysis of soil physical properties has been investigated for over 30 years. However, applying this system in soil science has remained a specialized research area using primarily low-resolution medical-grade x-ray CT units that were not designed for soil analysis applications. The main research objectives were to characterize and compare physical properties of soil core samples from long-term chisel plow (CP) and no-till (NT) agricultural field management sites using a high-resolution industrial-grade x-ray CT unit and two conventional soil laboratory method (SLM) soil macroporosity analysis procedures. Field research activities during 1999 included collecting four soil columns for each CP and NT soil management practice at the Iowa State University Northeast Research and Demonstration Farm at Nashua, Iowa. Findings from this study indicate that percent macroporosity and soil bulk density values were significantly higher and lower, respectively, for annual CP rowcrop (corn and soybean) versus annual NT rowcrop systems. Since the soil structure of perennial NT vegetation (native grasses and trees) is similar to CP, rowcrop practices could explain inconsistent soil hydraulic conductivity values from NT cropping systems. These results underscore the potential of x-ray CT as an effective soil porosity analysis tool and suggest the development of an online database of x-ray CT 3-D soil core images based on soil type and tillage system. This readily available information could aid scientists in soil structural analysis applications, potentially avoiding the limitations of x-ray CT unit cost and system availability issues.*

Keywords. *Computed tomography, Conservation tillage practices, Soil analysis and quantification, Soil laboratory methods, Soil physical properties, X-ray CT scanner.*

The analysis and characterization of soil structure and the spatial configuration of mineral and organic constituents have evolved from a simple 2-D petrographic technique (Kubiena, 1938) to microscopic 3-D computerized image analysis that includes x-ray computed tomography (CT), which was initially developed as a medical diagnostic tool based on x-ray attenuation principles by Hounsfield (1973). Following the advent of this non-destructive 3-D imaging and analysis method, soil science researchers began applying x-ray CT technology to quantifying soil bulk density, root-related water absorption processes, soil water content, macropore characteristics, and water movement through the soil profile (Petrovic et al., 1982; Hainsworth and Aylmore, 1983; Crestana et al., 1985; Grevers et al., 1989; and Perret et al., 1997, respectively). Thorough overviews and syntheses of CT technology as applied to soil science were also presented by Duliu (1999), Ketcham and Carlson (2001), Mees et al. (2003), Cnudde et al. (2006), Taina et al. (2008), and Helliwell et al. (2013).

A valuable attribute of the qualitative and quantitative information provided by x-ray CT is that it can provide a good understanding of soil structural changes due to soil tillage and compaction (Taina et al., 2008). Consequently, several studies have documented these anthropogenic effects on soil physical properties using x-ray CT systems (Olsen and Børresen, 1997; Gantzer and Anderson, 2002; Munkholm et al., 2003; Papadopoulos et al., 2009; Garbout et al., 2013). Gantzer and Anderson (2002) indicated that important features of soil structure are the number and size of macropores, which include tillage-induced structures, wormholes, and root channels. Rasiah and Aylmore (1998) found via x-ray CT analysis that macropore physical properties affect water flow rate and retention.

Differences in hydraulic conductivity values, as a function of different tillage treatments, tended to be inconsistent based on results of some researchers' reporting that no-till (NT) promotes infiltration while others determined that NT decreased macroporosity and infiltration, and still other researchers found no significant infiltration differences

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between NT and conventional tillage practices (Gantzer and Anderson, 2002). Although variable soil types could have contributed to these inconsistent results, several other more recent studies also used x-ray CT technology to investigate soil core sample macroporosity characteristics as a function of the effects of agroforestry, native prairie, grass buffer, and no-till rowcrop vegetation systems (Rachman et al., 2005; Udawatta et al., 2006, 2008; Udawatta and Anderson, 2008; Kumar et al., 2010a, 2010b). All of these CT-applied soil structure analyses found that agroforestry and other perennial NT vegetation systems had significantly higher soil percent macroporosity and hydraulic conductivity values compared with annual NT rowcrops that included primarily corn, soybean, and corn-soybean rotation systems.

Although soil structural components that include macropores can be identified from the soil matrix using x-ray CT technology, nearly all studies reported by Gantzer and Anderson (2002) used low-resolution medical-grade CT systems that were not uniformly scaled regarding volume element (voxel) resolution. Since 2002, medical-grade CT scanners have been the predominant systems used in several CT-applied soil structure analysis studies included in this article. Moreover, these medical-grade CT systems are limited to image resolutions that only detect "large" macropores (>1 to 2 mm) and generally provide poorly characterized macroporosity results (Gantzer and Anderson, 2002). Consequently, Gantzer and Anderson (2002) employed both medical-grade and high-resolution industrial-grade x-ray CT systems to measure relative x-ray attenuation values of conventional chisel-disk-disk (CDD) tillage and NT intact soil samples, and they compared the estimates of macropore characteristics from these CDD and NT treatments. They concluded that the industrial-grade x-ray CT scanner can characterize differences in soil macroporosity more precisely than standard medical-grade CT systems. They also concluded that high-resolution tomography can aid in the discrimination of differences between seedbeds created by different tillage systems. While several reports over the last 30 years predicted that x-ray CT systems would become less expensive and more available, Cassel and Nielsen (1994) and Macedo et al. (2002) found that the major limiting factors against widespread adoption of x-ray CT technology for soil science investigations were cost and availability.

The main objectives of this research were to characterize and compare the physical properties of soil core samples taken from long-term chisel plow (CP) and no-till (NT) agricultural field management sites using an industrial-grade x-ray CT unit and two conventional soil laboratory method (SLM) porosity analysis procedures. Specific objectives of this study included comparing soil structure analysis results from the SLM and CT procedures to evaluate differences in percent macroporosity and macropore number distribution, addressing reported inconsistencies in soil hydraulic conductivity values based on CP and NT tillage systems, and suggesting the development of a database of x-ray CT 3-D soil core images based on soil type and tillage system. This soil core image database could be made available via the internet to soil scientists for laboratory soil structural image comparison and related nondestructive evaluation of soil characteristic and process analysis applications, potentially avoiding the substantial limitations of industrial-grade x-ray CT unit cost and system availability issues.

Materials and Methods

Research Site and Soil Description

The field plot soil core sampling component of this study was conducted at the Iowa State University Northeast Research and Demonstration Farm near Nashua, Iowa (42° 56.173′ N, 92° 34.196′ W). The predominant soil type at the research site is Kenyon loam, a fine loamy, mixed, mesic Typic Hapludolls in the Clyde-Kenyon-Floyd soil association. Lesser soil types at the site include Clyde loam, Floyd loam, and Readlyn loam. The soils are classified as deep, moderately well-drained, and moderately permeable with selected soil physical properties given in table 1 (Voy, 1995).

Soil Sampling Apparatus and Procedure

Sixteen soil sample columns (30.48 cm long × 7.72 cm diameter) were obtained from the research site in undisturbed condition during the 1999 continuous corn crop rotation season to evaluate the effects of macropores on eight CP and eight NT treatment samples at three soil depth ranges ("slice zones"): 0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm. The 16 soil cores were collected using a portable soil hammer apparatus that consisted of a slide arm and an unbolted (removable) base with dimensions of 76.2 cm in length and 7.62 cm in diameter. The removable base was designed to enable the Plexiglas cylinder to be placed inside the base, allowing attachment to the slide arm and hammer, which was placed onto the soil surface and struck repeatedly until a soil depth of 30.48 cm was reached. All 16 soil cores were then placed in freezer storage prior to soil core sample preparation. The 30.48 cm long soil core length was selected to provide the necessary slice zones for the soil tillage effects analysis and to determine the approximate depth for all 16 samples where soil core sampling compaction and pore space deformation effects started to occur (at 15.3 cm, below which the remaining 12.66 cm was cut and discarded). Likewise, the top (surface) 2.52 cm

Table 1. Selected soil descriptions and physical properties (maximum depth range = 0 to 53 cm) at the Iowa State University Northeast Iowa Research and Demonstration Farm site (Voy, 1995).

Soil Map Unit	Soil Series	Soil Description	Bulk Density ($g\ cm^{-3}$)	Clay (%)	Permeability ($cm\ h^{-1}$)
83	Kenyon	Fine-loamy, mixed, mesic Typic Hapludolls	1.40	18 to 26	1.5 to 5.1
84	Clyde	Fine-loamy, mixed, mesic Typic Haplaquolls	1.35	28 to 32	1.5 to 5.1
198	Floyd	Fine-loamy, mixed, mesic Aquic Hapludolls	1.35	20 to 26	1.5 to 5.1
399	Readlyn	Fine-loamy, mixed, mesic Aquic Hapludolls	1.35	18 to 24	1.5 to 5.1

section was cut and discarded to minimize the effects of air porosity encircled on the soil core sampler cylinder walls. This preparation process resulted in a 15.3 cm long soil core sample. After the 16 soil columns were prepared, they were again placed in freezer storage until SLM and x-ray CT analyses were conducted. Final selection of soil columns for analysis involved using a 3-D visualization program to choose structured soils from different plots with good soil details. This selection process, which incorporated quantification of soil properties (e.g., macroporosity), was conducted in the x-ray facility at the Center for Nondestructive Evaluation (CNDE), Ames, Iowa.

X-Ray CT Scanning System and Image Data Acquisition Procedure

The CNDE industrial-grade x-ray CT scanning system used in this study was based on an IRT model IXRS-320/3200 x-ray tube at a maximum tube voltage of 320 kV and power of 3200 W with focal spot sizes of 0.12 and 0.3 cm and a 9° cone beam angle. This IRT scanner was used to conduct relative 3-D pixel (or "voxel") volume scans of eight randomly selected soil cores from the total of 16 CP and NT soil core samples. The 30 cm image intensifier consisted of an approximately 2.74 cm diameter output phosphor optically coupled with a lens to a Cohu model 4915 charge-coupled device (CCD) camera that included a 1.27 cm image format with RS-170 signal output. During an x-ray CT scan, the object was projected in increments of 1° over a rotation of 360°. The scanner image resolution was 0.6 mm × 0.6 mm × 1.275 mm (approx. voxel volume = 0.46 mm^3). The voltage and current settings used during the x-ray CT scanning process were 95.3 kV and 0.22 mA, respectively.

The x-ray CT image data acquisition process initially included adjusting x-ray energy levels during CT scanning to account for scatter and beam-hardening effects (Martz et al., 1989). During the CT scanning process, images were generated automatically by the CCD camera. The CT images were subsequently reconstructed using a filtered back-projection algorithm (RECON) program (Zhang, 2003). The software used to visualize the reconstructed images was the New X-ray Vision (NXrVision) program developed at CNDE (Zhang, 2003). The NXrVision program is the data collection program used to set up a CT scan. This software program collected CT data as radiographic images and fully controlled the system hardware motion stages and monitors. Macro-processing, system calibration, and image development were also managed by this program. There are several tools in the NXrVision program, one of which includes a process for viewing the reconstructed CT images. An additional software program (Xpert) was available to view the CT slices in a 3-D format (Fan, 2001). In this study, 40 image "slices" conducted on each of the three 5.1 cm soil segment depths (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm) were generated as sinograms in the *.sin format from the NXrVision program. A schematic of the CNDE x-ray CT scanner system with component descriptions is shown in figure 1.

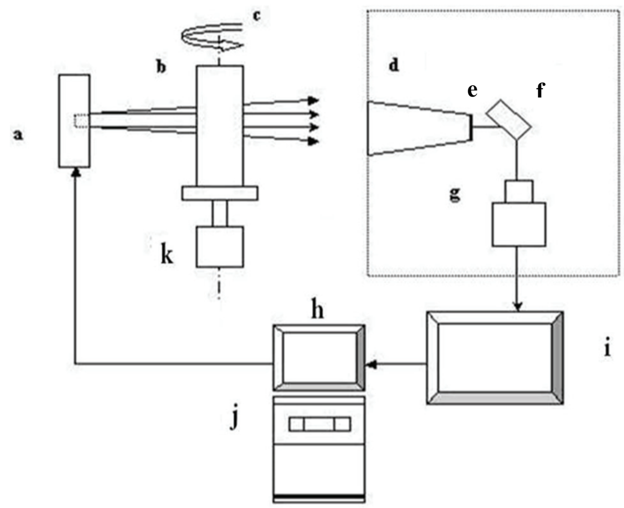

Figure 1. Schematic diagram of the x-ray CT scanner system: a = x-ray tube, b = fan beam, c = rotation axis, d = shutter and image intensifier, e = objective lens, f = mirror, g = camera, h = CPU, i = frame grabber, j = x-ray control panel, and k = platform positioner controller.

X-Ray CT Soil Macroporosity Analysis

Following x-ray CT soil core sample scanning and image reconstruction, the next step involved quantifying the soil macroporosity in undisturbed soil columns for CP and NT tillage practices. An important assumption of this study was to consider only pores larger than 1000 µm as macropores. Several studies have reported classifying soil macropores as an equivalent cylindrical pore diameter greater than 1000 µm (Perret et al., 1999; Rachman et al., 2005; Udawatta et al., 2006, 2008; Udawatta and Anderson, 2008; Kumar et al., 2010a, 2010b). Consequently, this study determined that pores larger than 1000 µm were considered macropores using the x-ray CT soil macroporosity analysis procedure.

The measurement of macropores was conducted using an analytical approach involving the measurement of macropore diameter and distance across the soil sample using the distance formula applied to cross-sectional images, as described by Sullivan (2002). The x-ray CT analysis procedure for measuring porosity was based on the difference in the CT gray-scale value between soil and pores. A simple threshold method was used in this analysis, and by counting the voxels with gray-scale values of porosity and those of soil, the percent porosity for the sample was calculated. The threshold was varied to ensure that the porosity measure was stable. Porosity in subregions of the soil was estimated by virtually sectioning the soil sample with the x-ray CT viewing software and repeating the process for the porosity measurement for the whole sample.

The entire frozen 15.3 cm long prepared soil core sample was used in the CT analysis for generating cross-sectional images of the three 5.1 cm slice zones (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm). However, the top (surface) 2.52 cm and bottom 12.66 cm soil core sample segments of the original 30.48 cm soil core were cut and discarded during the preparation process. These soil core preparation steps were conducted to minimize the effects of sampling tube wall air porosity encirclement and soil core sampling compaction and deformation, respectively. For example, if the air volumes from the original 2.52 cm top (surface) and bottom 12.66 cm soil core segments were included in the quantification calculations, they could overestimate and underestimate the macroporosity analysis values, respectively.

The computer program used for macroporosity analysis was referred to as 3-D visualization software and was written in Microsoft Visual C++ program script (Fan, 2001). This 3-D image analysis software enabled the x-ray CT system user to observe details such as macropores and colors from specified regions of interest (ROI) in cross-sectional images and convert standard ASCII (*.asc) data files to 3D (*.vol) ROI images format files.

Soil Laboratory Methods (SLM) for Macroporosity Analysis

In addition to quantifying macroporosity and other soil physical properties using x-ray CT, two SLM soil structural analysis procedures were applied to soil core samples in this study to determine air-filled porosity at three different soil depth ranges (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm). The frozen soil cores that were pre-cut to 15.3 cm for the CT analysis were cut again into three slice zones of 0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm for the SLM analysis. The two SLM procedures involved saturating a soil core sample and allowing the pore water to drain under gravity conditions. The macroporosity analysis results generated by the computer programs used with the x-ray CT procedure were compared to the average of the two SLM analysis results to quantify soil macroporosity. The results of these SLM procedures were then analyzed and compared with the CP and NT soil tillage treatment data results.

Air-filled porosity measurements by the first SLM procedure (SLM1) involved wetting a soil sample 5.1 cm in height to saturate the sample with water from the bottom to the surface for 24 h. Immediately following the 24 h wetting period, the soil sample was removed from the water reservoir and allowed to drain freely for 2 min under gravity conditions. The drained water (effluent) from the large pores was captured in drain cups. This effluent represented the drained pore volume (or the air-filled pore volume) of the soil sample. Under normal gravity drainage conditions, the equilibrium matric potential would be 0 cm at the bottom of the column and -5.1 cm at the top of the column. These two matric potential measurements represented an average matric potential of -2.5 cm for the entire soil sample (Jury and Horton, 2004).

The second SLM soil pore analysis procedure (SLM2) used to determine air-filled porosity of the soil sample was conducted by computing the total porosity of the soil. The bulk density of the soil core sample was calculated by dividing the soil dry mass (g) by the total volume (cm^3) of the soil sample. In addition to the bulk density, the volumetric water content was determined by multiplying the soil bulk density ($g\ cm^{-3}$) by the gravimetric water content (g). The quantification of air-filled porosity was determined by subtracting the volumetric water content (cm^3) from the total pore volume (cm^3) (Hillel, 1980).

During the initial wetting of the soil core samples, a potential discrepancy in the SLM1 and SLM2 analysis procedures (caused by trapped air in some of the pores) could have resulted in soil samples reaching less than saturation conditions. Consequently, the volume of water in the soil core sample from the SLM1 procedure could have differed from a soil sample saturated in a water reservoir; or the soil sample may have been lifted from the water reservoir before it was placed over the effluent cup. Additionally, the process of lifting the soil sample from the water reservoir could have resulted in drainage from the largest pores that was not captured in the effluent cup. Therefore, the application of only the SLM1 procedure might underestimate the drained porosity, whereas the exclusive application of the SLM2 procedure (e.g., the sample was fully saturated from a water reservoir) could possibly overestimate the actual drained porosity. In these cases, small pores circled by water or entrapped air did not drain from the soil sample, and this approach to macroporosity quantification required taking a simple average of both the SLM1 and SLM2 results to obtain a more reasonable approximation of air-filled porosity values. Consequently, the average of the two SLM soil macroporosity analysis procedure values is indicated as a single analysis procedure (SLMX).

Macroporosity Distribution

Soil structure analysis data regarding the distribution of macropores can enhance understanding of fissure transport concepts and pore size and water flow distributions in undisturbed soil cores. Several studies have used modern laboratory methods and soil macroporosity data to determine the movement of water through the soil profile (Hopmans et al., 1992; Perret et al., 1997; Rasiah and Aylmore, 1998; Kasteel et al., 2000; Mooney, 2002; Wildenschild et al., 2005). In this study, soil macroporosity was quantified by applying x-ray CT scanning for soil core samples under CP and NT soil tillage treatments at three soil depth ranges (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm).

The quantification of macropores was determined by using the known size of a voxel. A simple calibration of the voxel size was done by measuring a known object in the CT scan and counting voxels across a feature. The coordinates of pore size were read directly from the computer screen and input into equation 1 (described by Sullivan, 2002):

$$d = \sqrt{(Y_2 - Y_1)^2 + (X_2 - X_1)^2} \quad (1)$$

where d is the distance measured across a pore equal to the square root of X_1, X_2, Y_1, and Y_2 spatial point coordinate values of the circumference of each macropore. Figure 2 shows x-ray CT radiographic images of macroporosity distribution throughout the entire 15.3 cm soil profile depth for a CP tillage treatment soil core sample.

The x-ray CT images in figure 2 illustrate a soil profile diagram divided into three soil depth ranges (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm) represented in three-dimensional (3-D, left view) and two-dimensional (2-D, right view) images obtained from the x-ray CT scan for a

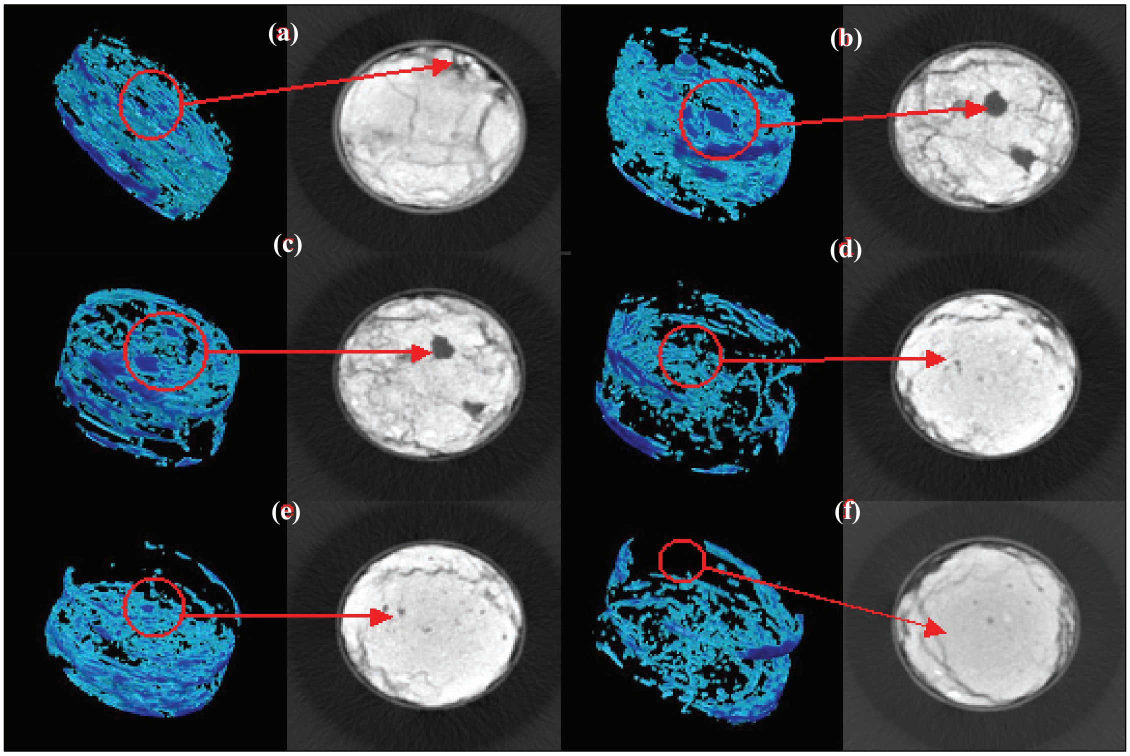

Figure 2. Macroporosity distribution in the top 15.3 cm soil profile for a chisel-plow (CP) tillage treatment using x-ray computed tomography (CT). Soil depth ranges of 0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm are depicted in images a-b, c-d, and e-f, respectively.

soil under the CP soil tillage treatment. The CT images are intended to enhance visualization and analysis potential for identifying and locating soil features such as macropores. For example, figures 2a and 2b (representing the top and bottom soil surfaces at 5.1 cm depth) show few pores at this depth, while figures 2c and 2d (representing a soil depth of 10.2 cm) show large pores at the top of the soil surface and few pores at the bottom. The soil core sections in figures 2e and 2f (representing a soil depth of 15.3 cm) show a very small number of visible macropores. The cracks and pores identified in this soil profile are suspected to have been made by earthworms (*Lumbricus terrestris*) and are similar to soil features measured by Jégou (1998) that included diameters and widths of 1 and 0.5 cm, respectively.

The statistical results were obtained using SAS version 8.2 (SAS, 1985). Significant differences among CP and NT soil tillage practices and SLMX and CT analysis methods were determined by applying SAS general linear model (GLM), analysis of variance (ANOVA), and Student's t-test paired comparisons at the 5% probability level ($p \leq 0.05$).

Results and Discussion

This agricultural field and laboratory study investigated the effects of long-term soil tillage practices on soil structural characteristics in continuous corn crop research plots in north-central Iowa. The study also sought to determine significant differences ($p \leq 0.05$) between SLMX and x-ray CT soil structure analysis procedures and quantify soil core sample percent macroporosity, macropore number, and macropore distribution in the soil profile under CP and NT soil tillage treatments.

X-Ray CT and SLMX Macroporosity Analyses

The results from Student's t-test paired comparisons of SLMX and CT soil analysis values of eight total observations, averaged to four observations of the mean for percent macroporosity, indicate no significant difference between SLMX and CT treatment paired values (df = 3, t = 1.77, p = 0.17). Although the sample size ($N = 4$) for this paired comparisons t-test is rather small and has been cautioned against by some methodologists, de Winter (2013) found that a paired t-test is feasible with extremely small sample sizes and concluded that there are no principal objections to using a t-test with sample sizes as small as $N = 2$. Table 2 shows the ANOVA results of 24 total observations, averaged to eight observations of the mean percent macroporosity values,

Table 2. Percent macroporosity analysis results averaged among the three soil depth ranges (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm) for eight observations of the mean values of comparisons made between soil laboratory methods (SLMX) and x-ray computed tomography (CT) and chisel-plow (CP) and no-till (NT) soil tillage treatments.

Tillage Treatment	Macroporosity Analysis[a]	
	SLMX[b]	CT
CP	9.81 a (3.61)	8.00 a (4.93)
NT	8.39 a (2.71)	5.87 b (3.79)

[a] Means followed by different lowercase letters are significantly different ($p \leq 0.05$). Values in parentheses indicate soil tillage treatment standard deviations. Means are combined ($n = 8$) for SLM and CT methods and CP and NT soil tillage treatments.

[b] Values are based on the average (SLMX) of soil laboratory methods: SLM1 = Sample saturated and then oven dried at 105°C. SLM2 = Sample saturated and then drained for 1 h.

Table 3. Percent macroporosity analysis results at the three soil depth ranges (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm) for 12 observations of the mean values of comparisons made between soil laboratory methods (SLMX) and x-ray computed tomography (CT) and chisel-plow (CP) and no-till (NT) soil tillage treatments.

Depth (cm)	Tillage Treatment	Macroporosity Analysis[a] SLMX[b]	CT
0 to 5.1	CP	13.1 ac (4.65)	12.8 ac (4.78)
	NT	9.81 a (0.83)	10.1 ac (3.33)
5.1 to 10.2	CP	8.34 a (1.75)	5.87 a (3.85)
	NT	7.11 a (0.91)	3.87 b (0.84)
10.2 to 15.3	CP	7.95 a (0.96)	5.34 a (2.27)
	NT	8.26 a (4.52)	3.64 b (2.26)

[a] Means followed by different lowercase letters are significantly different ($p \leq 0.05$) within and among soil depths (b and c, respectively). Values in parentheses indicate soil tillage treatment standard deviations. Means are combined (*n* = 12) for SLM and CT methods and CP and NT soil tillage treatments.

[b] Values are based on the average (SLMX) of soil laboratory methods:
SLM1 = Sample saturated and then oven dried at 105°C.
SLM2 = Sample saturated and then drained for 1 h.

of multiple comparisons between the SLMX and x-ray CT methods and CP and NT tillage treatments averaged among the three soil core sampling depth ranges (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm). Although these results indicate no significant differences ($p \leq 0.05$) for percent macroporosity between the CP and NT soil tillage treatments when using the SLMX procedures, the NT treatment had significantly lower ($p \leq 0.05$) percent macroporosity compared with the CP treatment when using the CT method.

Table 3 reports the ANOVA results of 24 total observations averaged to 12 observations of the mean values of percent macroporosity comparing the two laboratory (x-ray CT and SLM) methods and two soil tillage (CP and NT) treatments at the three soil core depth ranges. The results indicate no significant differences ($p \leq 0.05$) in percent macroporosity between soil tillage treatments at each of the three soil core depths for the averaged SLMX laboratory procedure values and at the shallowest soil core depth range (0 to 5.1 cm) for the x-ray CT method. However, under the CT analysis, the NT soil tillage treatment had significantly lower ($p \leq 0.05$) percent macroporosity compared to the CP treatment for the two deeper soil core depth ranges (5.1 to 10.2 cm and 10.2 to 15.3 cm, respectively). A macroporosity study using the CT analysis method conducted by Perret et al. (1997) for an uncultivated field for no-till treatment produced a percent macroporosity value of 7.0% for undisturbed soil columns 15 cm in length. In contrast, the percent macroporosity value obtained using the x-ray CT method in this study was approximately 5.9% for soil columns of approximately 15.3 cm in length. However, a study by Vermeul et al. (1993) that developed an improved SLM procedure for quantifying soil macroporosity reported percent macroporosity values of 8.0% and 0.3% for CP and NT soil tillage treatments, respectively, versus average values of 10% and 8.0%, which were obtained in this study that used similar soil tillage treatments.

X-Ray CT and SLMX Macropore Number Distribution Analyses

The results of applying the x-ray CT method in conducting macropore number analysis of 24 observations for CP and NT soil tillage treatments averaged among the three soil core depths indicated no significant differences ($p \leq 0.05$) in average macropore number between the CP and NT soil tillage treatments for the x-ray CT method. However, there was a variation in average macropore number in the CP tillage treatment, as indicated by a greater than 100% increase in the standard deviation for the CP treatment as compared to the NT treatment.

Figure 3 shows results of the macropore number distribution experiment using x-ray CT. From these results, there

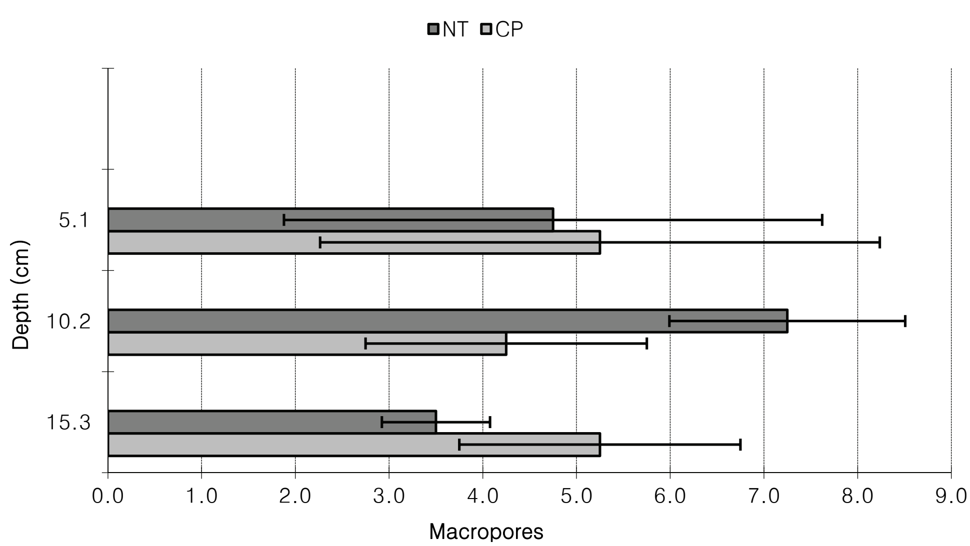

Figure 3. Average macropore number distribution as a function of three soil core sampling depths (5.1, 10.2, and 15.3 cm) and two soil tillage treatments, no-till (NT) and chisel-plow (CP), using x-ray computed tomography (CT). Error bars indicate ±1 standard deviation of the mean.

was a significantly lower ($p \leq 0.05$) average macropore number for the NT soil tillage treatment than for the CP treatment at the deepest soil core sampling depth (15.3 cm). There also was considerably more variation in the average macropore number for the CP treatment than for the NT treatment at the 10.2 and 15.3 cm soil core sampling depths.

X-RAY CT AND SLMX SOIL TILLAGE PRACTICE COMPARISON ANALYSIS

Soil core samples from two conservation tillage practice treatments (CP and NT) were collected and analyzed for characterizing and quantifying soil physical properties using SLMX and x-ray CT soil structural analysis methods. Statistical analysis also was used to determine significant differences ($p \leq 0.05$) between CP and NT soil tillage treatments and SLMX and CT laboratory analysis methods. Another experiment was conducted using the x-ray CT method to determine the number and distribution of macropores observed in the three soil core sample depth profiles (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm).

The results from this study showed that while the SLMX and x-ray CT procedures are notably different approaches to conducting a soil core sample structural analysis, similar results were obtained by using average values in multiple statistically based comparisons. This indicates that both the SLMX and x-ray CT methods could effectively analyze and quantify soil macroporosity at different soil depths for soils under CP and NT tillage treatments. Significantly higher ($p \leq 0.05$) soil macroporosity percentage values in the first soil depth range (0 to 5.1 cm; table 3) may be due in part to higher biological activity caused by earthworms or root growth (Logsdon and Linden, 1992) prior to soil core sample collection. These higher macroporosity values could also be a function of chisel-blade cutting in the first 20.3 cm of soil depth (Kay and VandenBygaart, 2002; Sasal et al., 2006), possibly resulting in more pores in the subsurface soil profile.

The results from comparing the CP and NT soil tillage treatments and SLMX and x-ray CT laboratory analysis methods indicated that the analysis methodology was not the same for both SLMX and CT when quantifying the percent macroporosity for the NT treatment. However, both laboratory analysis methods could be used to quantify the percent macroporosity for a particular soil type under the CP treatment.

From the comparisons made for the CP and NT treatments for macropore numbers counted using the x-ray CT method at the three soil profile depths (5.1, 10.2, and 15.3 cm), it is apparent that more variation in the number of macropores was found for both soil tillage treatments at the 5.1 cm soil depth. Alternatively, the number of macropores for the NT treatment showed significantly less variation at the deepest soil core depths (10.2 and 15.3 cm). In essence, this research shows that x-ray CT is an effective method to enumerate pores and visualize the distribution of pores in a soil column.

SUMMARY AND CONCLUSIONS

The use of x-ray CT for analysis of soil structural properties has been investigated for almost 35 years. Consequently, this primarily research-based application of x-ray CT technology has provided important visual and numerical soil structure information and data not readily obtained using conventional SLM protocols. However, several reports over the past 30 years predicted that CT systems would become increasingly available, accessible, and less expensive as an effective non-destructive 3-D soil structural analysis tool. Although a substantial increase in CT system computing power and user efficiency during this period has significantly improved CT image resolution and analysis capabilities, widespread use of this technology has not been the case, since CT applications in soil science have essentially remained a specialized research area using primarily low-resolution medical-grade CT systems that were not designed for soil analysis applications.

The overall findings of this study demonstrate that a higher-resolution industrial-grade x-ray CT scanning system is a more effective tool for conducting qualitative and quantitative soil porosity analyses of soil core samples from various soil tillage practices, as compared to the lower-resolution medical-grade x-ray CT systems used in other similar investigations. Specific conclusions from these findings include the following results and suggestions for future soil structural analysis research applications:

- The comparison of percent macroporosity values between CP and NT soil tillage treatments for the CT analysis method averaged among all three soil core sampling depth ranges (0 to 5.1 cm, 5.1 to 10.2 cm, and 10.2 to 15.3 cm) indicated that the NT treatment had significantly lower percent macroporosity than the CP treatment.
- While the comparison between the CP and NT treatments for both the SLMX and CT analysis methods at each of the three soil core depths showed elevated percent macroporosity values at the shallowest depth (0 to 5.1 cm), the SLMX and CT results indicated that the NT treatment had significantly higher bulk density and lower percent macroporosity than the CP treatment at the two deeper depth ranges (5.1 to 10.2 cm and 10.2 to 15.3 cm) of the soil profiles.
- Although the comparison of macropore number between the CP and NT treatments using the CT method indicated no significant differences when averaged among the three soil core sampling depths, the macropore number distribution analysis determined that the NT treatment had a significantly lower average macropore number than the CP treatment in the deepest soil core depth (15.3 cm). There also was significantly more variation in macropore number in the 10.2 and 15.3 cm soil core depths for the CP treatment than for the NT treatment.
- While variability in the soil types selected for many studies of soil tillage practices could have contributed to the reported inconsistent hydraulic conductivity and percent macroporosity values, the findings from this investigation indicate that percent macroporosity

values were significantly higher for annual CP rowcrop vegetation systems compared to annual NT rowcrop systems. These findings compare with perennial NT vegetation systems (agroforestry, native prairie, and grass buffers) that had significantly higher percent macroporosity and hydraulic conductivity values than annual NT rowcrop systems, revealing a possible source of the conflicting reports regarding inconsistent soil hydraulic conductivity values for NT systems.

The overall results from this study underscore the potential of an industrial-grade x-ray CT system as an effective soil structural analysis tool. These results also suggest that an online database of x-ray CT soil core 3-D images based on soil type and tillage system could aid soil scientists in laboratory soil structural image comparison and related non-destructive evaluation of soil characteristics and process analysis applications, potentially avoiding the substantial limitations of industrial-grade x-ray CT unit cost and system availability issues.

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NOMENCLATURE

2D = two-dimensional
3D = three-dimensional
ANOVA = analysis of variance
CNDE = Center for Nondestructive Evaluation
CP = chisel plow
CT = computed tomography
GLM = general linear model
NT = no tillage
NXrVision = New X-ray Vision
p = probability
ROI = region of interest
SLM = soil laboratory method
SLM1 = SLM procedure 1
SLM2 = SLM procedure 2
SLMX = soil laboratory methods average