Soil pore characteristics assessed from X-ray micro-CT derived images and correlations to soil friability

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Abstract

X-ray computed tomography (CT) scanning technology has, in recent decades, been shown to be a very powerful technique to visualize and quantify soil structure. The objective of this project was to quantify soil pore characteristics, on undisturbed field moist soil, using a high resolution X-ray CT scanner and link then these results to soil friability assessed using the drop shatter method. Minimally disturbed soil cores were taken from selected treatments in a long-term rotation and tillage treatment experiment located on a silt loam at the Elora Research Station near Elora, Ontario, Canada. Soil cores varied in porosity and pore characteristics. A drop shatter test was used as a reference procedure to quantify soil friability. The top 40 mm of the 80 mm high soil samples were scanned using a X-ray micro-CT scanner. The selected region of interest (36×36×36 mm) was reconstructed with a voxel size of 60 μm. Estimated surface area, produced from the drop-shatter test, varied between 0.2 and 1.62 m² kg⁻¹, and an average of 0.79 m² kg⁻¹. Total and air-filled porosity was determined on the soil cores using traditional methods. Total porosity ranged from 41 to 60 m³ 100 m⁻³, and an average of 49 m³ 100 m⁻³. The air-filled porosity, at sampling/testing, ranged between 5 and 32 m³ 100 m⁻³, with an average of 15 m³ 100 m⁻³. The porosity determined from CT imagery ranged between 1 and 31 m³ 100 m⁻³, with an average of 4.5 m³ 100 m⁻³. The number of branches, junctions and end points averaged 298, 117 and 198 per cm³, respectively. We found significant and strong correlations between the soil pore characteristics assessed on the whole soil cores and the characteristics of the air-filled pores determined using high-resolution X-ray computer tomography (CT). Our study confirmed a significant correlation between soil friability, expressed by surface area produced by standardized drop-shatter, and soil pore characteristics. The strongest correlations were found with porosity, surface area and number of junctions per cm³.

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1. Introduction

X-ray computed tomography (CT) scanning technology has, in recent decades, been shown to be a very powerful technique to visualize and quantify soil structure, as reviewed by Taina et al. (2008). The application was, in the early years after adoption in soil science, concentrated on describing macro-structures such as biopores (Capowiez et al., 2003; Gregory et al., 2003), tree roots (Pierret et al., 1999) and dense layers (Lipiec and Hatano, 2003). With the development of high-resolution micro-CT scanning over the last decade, the technique has also been applied to other aspects of soil micromorphology. It has especially been used to quantify soil pore space characteristics on images with voxel size of <50 μm (Elliot and Heck, 2007; Peth et al., 2010; Quinton et al., 2009; Schluter et al., 2011).

Soil pore characteristics are important for a large range of essential soil functions such as colloid, water and gas transport, habitat for soil organisms as well as soil mechanical properties such as soil friability. The latter is a key soil physical property, yielding valuable information on the ease of producing a favorable seed- and rooting bed during tillage operations (Munkholm, 2011). Soil friability is related to brittle fracture of soil as described by Braunack et al. (1979) and Dexter and Watts (2000). Brittle fracture results from the progressive development of fracture planes, resulting in a crack opening and a sudden loss in strength (Hatibu and Hettiarachchi, 1993). The propagation of cracks in an unconfined stressed soil depends on the frequency and the morphology (connectivity, orientation) of the air-filled pores as well as the strength at the crack tips as stressed by Hallett et al. (1995a,b). A strong link between soil fragmentation/soil friability and air-filled soil pore space was confirmed by Munkholm et al. (2002), and this suggest a strong correlation between soil friability and pore characteristics derived from 3D images of soil structure.
The objective of this project was to quantify soil pore characteristics on undisturbed field moist soil using a high-resolution X-ray CT scanner and then link these results to pore characteristics assessed using traditional methods and soil friability assessed using the drop shatter method. We hypothesized 1. Significant and strong correlations between soil pore characteristics assessed using traditional and X-ray CT methods and 2. Significant and strong correlations between soil pore characteristics of especially the air-filled macropores and soil friability. Samples were taken from selected treatments in a long-term rotation and tillage experiment. The experiment allowed us to test the hypotheses for a given soil type, on samples that varied in soil pore characteristics and friability. In this paper we do not focus on treatment effects per se; they are reported by Munkholm et al. (accepted for publication) together with other data from the experiment.

2. Materials and methods

2.1. Soil sampling

Minimally disturbed soil cores (Ø= 6.4 cm, height = 8.0 cm) were taken from the long-term rotation and tillage trial (initiated in 1980) located at the University of Guelph’s Elora Research Station near Elora, Ontario, Canada (43°39’ N, 80°25’ W). The soil is mapped as a Woolwich silt loam and classified as a Grey Brown Luvisol (CSSC, 1998) or Albic Luvisol (WRB, 2006). The particulate size distribution is on average: 16, 44, 40 and 2.13 g 100 g−1 of clay, silt, sand and organic carbon, respectively. Thirty-year average rainfall (1970–2000) is reported at 920 mm and it is distributed relatively uniformly over the twelve months. The average monthly temperatures for January, April and July are −7.6, 5.9 and 19.7°C, respectively (Meteorological Services Canada, 2010).

The experimental design is a randomized block split plot with four replicates. The main plot treatment is rotation and the plot treatment is tillage. Seven 4-course rotations are included in the trial. Samples were taken from Rotation 1 (R1), designated C–C–C–C, which is continuous corn (Zea mays L.) and Rotation 6 (R6), designated C–C–O(RC)–B(RC), which is corn, corn, oats (Avena fatua L.) and spring barley (Hordeum vulgare L.). Red clover (Trifolium pretense L.), designated (RC), was used as an under seeded cover crop in oats and spring barley. In 2010, first-year corn was grown in R6. The tillage treatments included no tillage (NT) and conventional tillage with moldboard plowing (MP). Moldboard plowing (to 20 cm depth) was last carried out on November 18, 2009. Secondary tillage, in association with MP, consisted of two passes by a field cultivator and packer within 1 day prior to crop seeding in the spring. The tillage plots are 7 × 17 m; and 8 rows of corn were sown in each of the studied plots on May 7 2010.

On May 28, 2010, two samples were taken from the 10–20 cm depth in each of the 16 plots included in this study. One sample was taken between rows 2 and 3 and another between rows 6 and 7. These rows had not been trafficked in relation to crop establishment. The samples were taken in the center of the plots. Immediately after sampling, the samples were stored in a refrigerator at 5 °C until CT scanning as well as between CT scanning and the drop-shatter test. The CT images from two samples were lost and data analyses were, therefore, carried out on in total 30 samples.

2.2. CT scanning

The top 40 mm of the soil samples were scanned using an EVS (now GE Medical, London, Canada) micro-CT scanner, model MS8X-130. The samples were scanned at 120 kV, 170 mA and 3500 ms exposure generating an axial sequence of X-ray attenuation imagery. A high-pass copper filter was utilized, between the tube and the sample, to minimize the hardening of artifacts and maximize the contrast between sample phases. The individual scans took 3.5 h. Software from GE Healthcare (GE Reconstruction Utility), specifically written for the unique instrumental design, was used to reconstruct the 16 bit axial image into a 3D image model. The resulting 3D imagery had a voxel size of 20 μm. To reduce uncorrelated noise from the CT image, a 3D low-pass Gaussian filter was applied in Micro View (GE Healthcare, 2006), as described by Tarquis et al. (2009). For each soil sample, a region of interest (ROI) of 36 mm × 36 mm × 36 mm was generated in Micro View. The ROI was located in the center of the sample. The file size was large and we were, due to computing constraints, not able to make subsequent analysis on the entire dataset. We choose to reduce resolution instead of volume as we were mainly interested in the largest air-filled macropores. These pores we assumed to be of strongest importance in relation to soil

### Table 1

<table>
<thead>
<tr>
<th>No. cm−3</th>
<th>1 cm2 cm−3</th>
<th>100 m−3</th>
<th>mg m−3</th>
<th>g 100 g−1</th>
<th>MWD</th>
<th>cm3 100 m−3</th>
<th>SA noises</th>
<th>cm2 cm−3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.36</td>
<td>48.6</td>
<td>15.3</td>
<td>33.3</td>
<td>24.5</td>
<td>15.3</td>
<td>0.79</td>
<td>10.4</td>
</tr>
<tr>
<td>St. dev.</td>
<td>0.13</td>
<td>5.1</td>
<td>7.0</td>
<td>3.5</td>
<td>3.0</td>
<td>5.6</td>
<td>0.34</td>
<td>3.7</td>
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<tr>
<td>High</td>
<td>1.57</td>
<td>59.5</td>
<td>32.2</td>
<td>38.1</td>
<td>30.2</td>
<td>28.7</td>
<td>1.62</td>
<td>17.4</td>
</tr>
<tr>
<td>Low</td>
<td>1.07</td>
<td>40.7</td>
<td>5.2</td>
<td>25.5</td>
<td>17.9</td>
<td>8.0</td>
<td>0.20</td>
<td>3.1</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>No. pores</th>
<th>1 cm2 cm−3</th>
<th>100 m−3</th>
<th>% of eCT</th>
<th>1 cm2 cm−3</th>
<th>% of SA CT</th>
<th>SA largest</th>
<th>Branches</th>
<th>Junctions</th>
<th>End points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>94</td>
<td>4.5</td>
<td>61</td>
<td>37</td>
<td>2.3</td>
<td>56</td>
<td>279</td>
<td>117</td>
<td>199</td>
</tr>
<tr>
<td>S.D.</td>
<td>74 (0.37)</td>
<td>27</td>
<td>25</td>
<td>74 (0.3)</td>
<td>26</td>
<td>12.9</td>
<td>2142</td>
<td>1036</td>
<td>922</td>
</tr>
<tr>
<td>High</td>
<td>277</td>
<td>30.7</td>
<td>99</td>
<td>114</td>
<td>12.9</td>
<td>96</td>
<td>2142</td>
<td>1036</td>
<td>922</td>
</tr>
<tr>
<td>Low</td>
<td>15</td>
<td>1.1</td>
<td>22</td>
<td>11</td>
<td>0.6</td>
<td>17</td>
<td>76</td>
<td>33</td>
<td>53</td>
</tr>
</tbody>
</table>

a Geometric means.
b S.D. for log10-transformed data.
fragmentation. The ROI was reconstructed with a voxel size of 60 μm to create a manageable file size.

2.3. Binary thresholding

CT imagery of soil typically contains a large proportion of mixed voxels, i.e. voxels containing more than one of the major constituents: air, water and solid; this is due, in part, to the existence of particles and pores smaller than the voxel size. Therefore, thresholding is of utmost importance and the selected way of thresholding has traditionally been highly user dependent (Baveye et al., 2010). In this paper, we modified the standardized and automated thresholding procedure developed by Elliot and Heck (2007) and further described by Tarquis et al. (2009). The open source software program ImageJ was used for binary thresholding and image analysis (Rasband, 2005). Each image “slice” had a depth of 60 μm and a length and width of 36 mm. A standard deviation (SD) variance plug-in was applied to the stack of images and this created a modified stack of low variance (LV) voxels. The threshold limit was user set at an upper value of 1.10 and a lower value of 0.90 standard deviations. Voxels that had variance above 10% from the surrounding voxels neighboring 124 voxels (5 × 5 × 5 unit volume) were deemed too heterogeneous and were given a zero value, and the remaining areas of low variance kept their original values; the zeros were changed to become Not-A-Number (NAN). A vast majority of the voxels exhibited variances larger than 10% and this will obscure the threshold value. By removing these voxels from the calculation, the peaks of the specific phases will be solely represented. The multi-threshold plug-in was used for thresholding the images, specifically employing the threshold algorithm created by Huang and Wang (1995). The resulting threshold value was then applied when thresholding the original stack of CT images.

2.4. Image analysis

General pore characteristics in the 3D images were generated for each ROI using the ImageJ plug-in 3D object counter plug-in (Bolte and Cordelières, 2006). This plug-in were used to count the number of unconnected pores and determine characteristic such as volume and surface area for the individual pores. The algorithm used the nearest neighbor approach to separate objects. Based on the individual pore results, we calculated the total pore volume and surface area. The In this study, a minimum pore volume filter of 3 voxels was used in 3D object counter, this is to reduce the possibility of interpreting noise as an indication of a pore. A skeleton reconstruction was also performed for each sample to determine pore branching of the pores, average length of the pores and maximum pore length. In this study the plug-in provided by BoneJ (Doube et al., 2010) is used to achieve these results. Firstly, the binary stack undergoes a 3D thinning algorithm in the plug-in skeletonize 3D. The thinning algorithm utilizes the 3D erosion function in ImageJ, which erodes the pores surface until only the skeleton remains. Erosion was performed symmetrically in order to guarantee medial position of the skeleton lines and such that the connectedness of the object is preserved (Lee et al., 1994). This skeletonized binary stack is then put through the analyze skeleton algorithm within the BoneJ plug-in, which

\[ \varepsilon_{CT} = 3.8 \, m^3 \, 100 m^{-3} \; ; \; SADS = 0.82 \, m^2 \, kg^{-1} \]

\[ \varepsilon_{CT} = 2.8 \, m^3 \, 100 m^{-3} \; ; \; SADS = 0.43 \, m^2 \, kg^{-1} \]

\[ \varepsilon_{CT} = 3.0 \, m^3 \, 100 m^{-3} \; ; \; SADS = 0.96 \, m^2 \, kg^{-1} \]

\[ \varepsilon_{CT} = 2.1 \, m^3 \, 100 m^{-3} \; ; \; SADS = 0.56 \, m^2 \, kg^{-1} \]

Fig. 1. Visualization of pore structure from the X-ray CT imagery of four different samples (598 × 598 × 560 voxels total volume).
provides a summary of number, length (mean, maximum and total) and junction of branches in each ROI. Visualization of the 3D images was carried out using the binary stack the plug-in 3D image viewer in ImageJ. This plug-in generates a 3D representation of the stack and allows for visual assessment of the ROI.

2.5. Drop shatter test

Soil fragmentation behavior was evaluated in the field by a drop shatter test modified from the methods described by Hadas and Wolf (1984) and Schjønning et al. (2002). Once the CT imaging was completed, the undisturbed cores were gently pressed out of the tubes and then dropped from 2.0 m depth onto a concrete floor. The soil was subsequently air-dried and passed through a nest of sieves with the openings of 19, 9.2, 4, 2 and 1 mm. The amount of material in each size class was recorded. Based on the results, the mean weight diameter (MWD) and the approximate specific surface area (m² kg⁻¹) of the samples were calculated according to Hadas and Wolf (1983). These parameters have been used as indices of soil friability as reviewed by Munkholm (2011).

2.6. Standard soil core measurements

All soil samples were weighed before CT scanning and drop-shatter test, (field moist) condition, in air-dry condition after drop-shatter and in oven dry condition (105 °C, 24 h) after sieving. This allowed us to calculate total porosity and air-filled porosity at sampling as well as bulk density when assuming a particle density of 2.65 g cm⁻³.

2.7. Statistical analysis

All statistical analyses were carried out using SAS (Version 9.2, SAS Institute, Cary, NC) (SAS Institute, 2005). We used PROC INSIGHT to test data for normality. The pore characteristics derived from CT imagery were log-transformed to yield normality. We used PROC GLM to test interaction between soil friability and pore characteristics. There was no significant effect of management observed on the relationships between soil friability and pore characteristics.

3. Results and discussion

3.1. Standard soil characteristics

The rotation and tillage experiment allowed us to test the hypotheses on samples with a wide range in basic soil pore characteristics for a given soil type. Total porosity ranged from 41 to 60 m³ 100 m⁻³ with an average of 49 m³ 100 m⁻³ (Table 1). These values are in correspondence with previous measurements from the experiment (e.g. Mueller et al., 2009). The air-filled porosity at sampling/testing displayed an even larger relative variation, i.e. from 5 to 32 m³ 100 m⁻³. The water content at sampling was, on average, 24 g 100 g⁻¹. This indicates a matric potential around −333 hPa, at sampling, according to water retention data from the Elora site (Parkin, unpublished data). Thus the soil could be considered within the range for optimum friability (−300 to −1000 hPa) according to Utomo and Dexter (1981) as well as Munkholm and Kay (2002).

3.2. Drop shatter test

The average mean weight diameter (MWD) was 15.3 mm, but it ranged from 8.0 to 28.7 mm (Table 1). The surface area produced...
from the drop-shatter test varied between 0.2 and 1.62 m² kg⁻¹, with an average of 0.79 m² kg⁻¹. This is comparable to the values reported for a drop shatter test on a sandy loam reported by Munkholm et al. (2002). The lowest degree of fragmentation was found for high density samples. The surface area produced decreased significantly and linearly with increasing BD (R² = 0.62).

3.3. CT scanning data

The average number of pores for the ROIs was 89 per cm³. However, only a few inter-aggregate pores dominated the pore volume detected from the CT imagery. The pore volume of the largest pore accounted for between 11 and 99% of the total ε_CT volume. The pore volume, ε_CT, displayed a geometric mean of 4.6 m³ 100 m⁻³ and ranged between 0.9 and 30.7 m³ 100 m⁻³ (Table 2). Examples of the pore network for four samples are shown in Fig. 1.

Essentially, the image analysis separated air-filled volume from solid and water and, therefore, the ε_CT values can be compared with the air-filled pore space value (ε_a) from the standard core measurements. On average we were able to indentify 37% of the air-filled macropores. In one case, ε_CT was larger than ε_a. This is likely due to the fact that ROI accounted for only about 25% of the total sample volume. The surface area showed a geometric mean of 2.3 cm cm⁻³, with values ranging between 0.6 and 12.9 cm². The results from the skeletonized procedure further showed a geometric mean number (per cm³) of 279, 117 and 198, respectively for branches, junctions and end points. The range between lowest and largest was large, e.g. 76 to 2142 for the number of branches per cm³. Examples of skeletonized pore network for four samples are shown in Fig. 2. Skeletonization of 3D soil pore network has previously been shown to provide valuable information on earthworm burrows network (Capowiez et al., 1998, 2003) and pore network in aggregates (Peth et al., 2008).

3.4. Correlation between soil pore characteristics

Significant linear and positive correlations were found between most of the different soil pore characteristics (Fig. 3). Strongest correlations were found between parameters assessed at similar level of observation. That is, the correlations were high between parameters determined on the whole samples, i.e. ε_T and ε_a, (R² = 0.78), the
parameters assessed from the X-ray CT imagery, i.e. log \( \varepsilon_{CT} \) and log SACT, \( \varepsilon_{CT} \), \( R^2 = 0.82 \) and the parameters assessed from the skeletonized images \( R^2 > 0.72 \) for any of the combinations of log branches, log junctions and log end points. Total and air-filled porosity was rather strongly correlated to porosity and surface area assessed from the X-ray CT imagery, \( R^2 = 0.51 \)–\( 0.64 \) but weakly correlated to the parameters measured on the skeletonized images \( R^2 < 0.33 \). Porosity and surface area assessed from the X-ray CT imagery, also correlated rather strongly to parameters assessed from the skeletonized images, especially with log branches \( R^2 = 0.44 \)–\( 0.60 \) and log junctions \( R^2 = 0.52 \)–\( 0.68 \). Log \( SACT \) correlated typically better to these properties than log \( \varepsilon_{CT} \).

3.5. Correlation between soil friability and pore characteristics

In general, the surface area parameter, \( SAD 

\text{Surface area, m}^2 \text{ kg}^{-1}

Porosity, \( \varepsilon_T \), m$^3$ 100m$^{-3}$ Surface area,CT, m$^2$ cm$^{-3}$

\begin{align*}
\text{SA}_{DS} &= 0.58 + 0.67 \log_{10}(\text{SA}_{CT}) \quad R^2 = 0.40^{**} \\
\text{SA}_{DS} &= 0.39 + 0.62 \log_{10}(\text{Por}_\text{CT}) \quad R^2 = 0.40^{**}
\end{align*}

Fig. 4. Relationship between pore characteristics on whole soil cores and friability assessed by drop shatter. *** indicates significant difference at \( P < 0.001 \) level.

between the surface area produced by the drop shatter test and total porosity, \( \varepsilon_T \), and air-filled pore space, \( \varepsilon_a \) (Fig. 4). Surprisingly, the correlation to total porosity was stronger than to \( \varepsilon_a \), i.e. \( R^2 = 0.66 \) compared with 0.52. We had expected a stronger correlation to \( \varepsilon_a \), as the air-filled pores are expected to play a key role in brittle fracture as described earlier. However, fracture not only depends on the abundance and characteristics of the air-filled pore space but also on the strength at the crack tips. Total porosity yields information on the average density and thus the packing of soil elements. Thus, \( \varepsilon_T \) may to a larger extent than air-filled porosity, reflect both key issues of brittle fracture (i.e. stress concentration at crack tips and strength at crack tips).

The pore characteristics from the CT imagery displayed positive and significant correlations to soil friability. The correlation to the pore volume, specifically \( \log \varepsilon_{CT} \), was weaker than to \( \varepsilon_a \) \( R^2 = 0.40 \) and 0.52, respectively) (Fig. 5b and a). It is possible that we may have been able to improve the fit to the drop shatter data if we had been able to quantify a larger proportion of the air-filled pore space. Remember, that pores with diameter in the range between 10 and
60 μm were not expected to be included in εCT and, therefore, we only detected in average 37% of εb with the described scanning and image analysis procedure. The correlation to surface area of the pore space, SACT was at the same level as for the pore volume, εCT.

Significant correlations were found between SADS and the log to the number of branches, junctions and end points per cm3 (R² = 0.35, 0.44, and 0.15, respectively) (Fig. 6a, b, c). This means that number of branches and junctions explained variation in SADS as good as log (εCT) and log (SADS). Good correlation between fragmentation and density of branches and junctions corresponded with what we had expected. A high density of branches and junctions signifies an extensive, well-connected and complex pore network, which implies a high probability of crack propagation and interaction. Given a random crack orientation, there will be a high chance of crack propagation irrespective of the orientation of the applied force. The high density of branches means short distances between individual branches and thus a high chance of crack interact according to Hallett et al. (1995b). There was a tendency to improved fit by combining log (εCT) and log (No. of junctions per cm⁻³) (R² = 0.48). We also found significantly improved fit when combining air-filled pore space (εb) with log (No. of junctions per cm⁻³) (R² = 0.62). This indicates that the morphology of the air-filled pore space play significant role in relation to soil friability.

3.6. Potential for improved fitting to drop shatter data?

The pore characteristics derived for high resolution CT scanning explained, at best, 48% of the variation in friability as expressed by SADS. Better correlation may have been achieved if we had scanned the whole 80 mm long sample and not just the top 40 mm. However, a much improved correlation cannot be expected from increasing the volume scanned. The selected (36·36·36 mm = 46,656 mm³ or 47 cm³) was around 10 times larger than the representative volume (REV) value of 3–5 cm³ for porosity and specific surface area estimated by Elliot et al. (2010) in another X-ray microCT imagery study. Improved fit to drop shatter data may also have been achieved by obtaining more detailed information on the air-filled pore space, i.e. finer spatial resolution and more sophisticated information on pore morphology. Information on the density and variation in density of the solid material may also be useful in improving fit to drop shatter data. This may add valuable information on the strength of the soil at the crack tips. General indices reflecting connectivity and entropy such as Eulers number (Vogel and Roth, 2001) and fractal dimension (Tarquis et al., 2008, 2009) derived from CT imagery may also be helpful in improving fits to experimental friability data.

4. Conclusions

We found significant and rather strong correlations between the soil pore characteristics assessed on the whole soil cores and the characteristics of the air-filled pores determined using high-resolution X-ray computer tomography (CT). Our study revealed a significant correlation between soil friability, expressed by surface area produced by standardized drop-shatter, and soil pore characteristics. The strongest correlations were found with pore volume, surface area and number of junctions per cm³. At best, the CT pore characteristics explained 48% of the variation which was at the same level as for bulk soil air-filled porosity but poorer than for total porosity (R² = 0.66). There is a need for further studies to improve the correlations between CT soil characteristics and soil friability. This study only included a soil from one soil type and at a single water content. More studies are needed to validate our findings for other soil types and for a range of water contents.

Acknowledgments

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