Center for Agroforestry
University of Missouri-Columbia

Department of Soil, Environmental
and Atmospheric Sciences and
The Center for Agroforestry
School of Natural Resources
University of Missouri-Columbia

Ranjith P. Udawatta
Associate Professor Research
203 Anheuser-Busch Natural
Resources Bldg.
Columbia, MO 65211
PHONE: 573-882-4347
FAX: 573-882-1977
EMAIL: UdawattaR@missouri.edu

April 14, 2016

Dr. Jan Vanderborght
Topical Editor
SOIL

Revised Manuscript "SOIL-2015-42- Synchrotron Microtomographic Quantification of Geometrical Soil Pore Characteristics Affected by Compaction."

Dear Dr. Vanderborght,

We would like to express our sincere appreciation to you for your constructive comments and suggestions to improve our manuscript.

I am submitting an Adobe PDF file containing the revised manuscript (**SOIL-2015-42 Synchrotron Microtomographic Quantification of Geometrical Soil Pore Characteristics Affected by Compaction**" for consideration for publication in the SOIL.

We have followed both suggestions to improve the manuscript. Our responses to comments are in bold face so you can evaluate how we addressed each comment.

Thanks again for your efforts in handling this manuscript.

Sincerely,

Ranjith Udawatta
Associate Professor, Agroforestry and
Watershed Research

Enc.

REPLY TO COMMENTS FROM THE EDITOR

Interactive comment on "Synchrotron microtomographic quantification of geometrical soil pore characteristics affected by compaction"
by R. P. Udawatta et al.
J. Vanderborght (Editor)
j.vanderborght@fz-juelich.de
Received and published: 7 October 2015
Synchrotron microtomographic quantification of geometrical soil pore characteristics affected by compaction

Referee comments:
The discussion paper is nicely written. Introduction is not comprehensive. It definitely overshadows some of the recent studies that investigated the effect of compaction on soil pore characteristics using X-ray CT. For example:

Schäffer, B., Stauber, M., MuÌ´Lller, R., Schulin, R., 2007. Changes in the macropore structure of restored soil caused by compaction beneath heavy agricultural machinery: A morphometric study. Eur. J. Soil Sci., 58, 1062-1073.
Lamandé, M., Wildenschild, D., Berisso, F.E., Garbout, A., Marsh, M., Moldrup, P., Keller, T., Hansen, S.B., de Jonge, L.W., Schjønning, P., 2013. X-ray CT and laboratory measurements on glacial till subsoil cores: Assessment of inherent and compaction affected soil structure characteristics. Soil Science, 178, 359-368
Kim, H., Anderson, S.H., Motavalli, P.P., Gantzer, C.J., 2010. Compaction effects on soil macropore geometry and related parameters for an arable field. Geoderma, 160, 244-251

Thank you very much for the references and suggestions to improve our paper. We have read the three papers and compared methods and results of those papers with ours.

The purpose of our paper was to explore the potential of using a 9-µm resolution for determining soil physical properties. A 9 µm pore diameter would correspond to pores that drain near field capacity, or -100 to -300 cm of soil water potential (-10 to -30 kPa). None of the papers mentioned used computer tomography at such a fine scale to examine pore parameters at different compaction levels.

Schäffer et al 2007 showed that macropores determined by water desorption and CT at a scale >100 µm resolution suggested that finer pores were not resolved. However, their results agrees with our study which used a much finer scale, where we were able to find significant differences in mean pore

radius and largest pore volume across compaction levels. Nevertheless, our purpose was to determine if the 9-µm resolution scans used could discriminate soil having 2-mm versus 0.5-mm aggregate size classes. We were not able to find significant differences in mean pore radius or largest pore class likely because many pores within the 2 mm aggregates are smaller than 9-µm making discrimination of these pores impossible, and thus discriminations of parameters ineffective as indicated in our ANOVA table.

Lamandé et al 2013 had scans acquired at 600-µm resolution for a Luvisol (Alfisol according to US soil taxonomy). Scans were acquired from 2 depths: 0.35 and 0.70 m and analyzed for total porosity and air-filled porosity (at -100 cm soil water potential, hPa). Despite coarse resolution, they were able to measure differences between surface and subsoils primarily because of *visualization* not because of *CT measured parameters*. In Figure 5, they were not able find significant differences between the compacted and the control treatment for porosity or air-filled porosity. Unlike their study, we were able to find significant differences (Table 1).

Kim et al 2010 paper was published in Geoderma. Anderson and Gantzer are co-authors of both Kim et al and the current paper under review. The images were acquired at much coarser scale (500-µm) using a medical scanner. Our purposes was to determine if the 9-µm resolution scans used could discriminate a soil having 2-mm versus 0.5-mm aggregate size classes and different compaction levels.

Even with the fine 9-µm resolution, discrimination of total pore volume and mean pore volume was not possible between aggregate and compaction because small pores were not detected individually.

Further I have some comments on the technicality of the paper as follow
1. Table 1; why there is a large standard deviation in case of mean pore radius, total pore volume, largest pore volume etc. as the used experimental system is very clean. Is there something wrong with the segmentation method or packing/pressing of the soil cores created some artifacts? You can evaluate porosity distribution along the height of soil column (porosity at each slice) to confirm the method of packing.

We have followed analysis procedure developed and explained by Venkatrangan et al 2000 (J Geophysical Research). Results from their analysis of 3DMA is similar to ours.

The larger variability associated with the different measures that were not significant was caused by natural varaiations between samples. This simply reflects the nature of the variables.

2. It is really hard to see any difference between the treatments in all of the figures presented. Can you find other ways to plot the data?

> **We have completed the analysis and the table shows some significant differences. We agree figures do not show differences. We believe that figures should be included so the reader could plan future studies accordingly.**

3. If the X-ray CT porosity decreased from 10.9 to 4.9% under compaction then why not the different morphological indices showed the proportional affect particularly coordination number and tortuosity. Is it possible for you to evaluate the Euler number, which is good measure of the pore connectivity?

> **3DMA does not include Euler number. We believe that approximately 40% of the total porosity that was not resolved by the 9-µm voxel and does not allow capturing differences in morphological indices which may be apparent in these smaller pore sizes. Thus even at 9-µm resolution computer tomography was insufficient detecting these differences.**

4. Why mean pore radius is same for the both aggregate size classes? Is something wrong with the packing of soil or segmentation method?

> **We were able to obtain relationships of measured versus CT bulk density with coefficient of determination greater than 0.98. CT determined 2 mm aggregate class nearly perfectly. However, 0.5 mm aggregate class the relationship was much poorer likely because of unresolved porosity for pores < 9 µm.**

5. I am suggesting here two parameters that need to be investigated in such studies i. pore shape evolution under compaction and ii. Degree of anisotropy of the pore space.

> **The objective of the study was examine the effects of compaction using 9 µm resolution scanning and 3DMA image analysis. Pore shape evolution was beyond the scope of this study.**

6. Further it is good exercise to compare results using multiple segmentation methods. Locally adaptive segmentation methods may perform better here.

> **The objective of the study was examine how compaction changes pore parameters by using scanning and 3DMA. Comparison of various segmentation methods is beyond the scope of this study**.

***Interactive comment on* “Synchrotron microtomographic quantification of geometrical soil pore characteristics affected by compaction” *by* R. P. Udawatta et al.**

Anonymous Referee #2

Received and published: 17 August 2015

Overview:

Synchrotron-based X-ray tomography study enables detailed insights into the pore space architecture at μm resolution. The authors used this technique to analyze the changes in pore space features during compaction. The main finding is that soil com- paction leads to a significant reduction in macroporosity and that the reduction is pore size specific. More involved morphological features like coordination numbers and mean path lengths also exhibit characteristic differences. The analysis has no techni- cal flaws. However, the findings are not supported by accompanying laboratory mea- surements so the implications for functional properties are not backed by data and the conclusions are a bit weak. The manuscript can be improved quite a bit (see my comments below).

General comments:

1. The method description can be shortened considerably. Both the imaging & reconstruction (GSECARS and IDL) as well as the image processing methods (3DMA) have been published in detail elsewhere. It’s sufficient to refer to them and state the impor- tant facts (energy, spatial resolution, filtering and segmentation method and network extraction).
   Thank you for the constructive suggestion. We have shortened the manuscript and included relevant literature with similar previous work by our group and others. However, another reviewer has suggested that paper was well-developed and provided sufficient information to understand the methods and therefore we did not condense the methods section excessively.

2. The main message gets lost in too many details. Too often you just repeat in the main text what has already been presented in Table 1 or the figures.
   As suggested we have removed the requested information in the results section and shortened the Results and Discussion sections.

3. The stated objective of your study (p4l25-27) is a bit vague. One could interpret it as if you used X-ray tomography in combination with 3DMA just because it was available to you and you want to demonstrate its capabilities now by detecting soil compaction at the pore scale. This may sound a bit unfair and I’m sure this is not true, but you need to put more effort into convincing the reader that from your findings one can learn something about the processes that act on the pore space during compaction.
   Thank you for the comment. We have revised objectives as suggested.

4. Figures with 3D renderings or 2D sections of the pore space are required to get an idea about the expected differences.
   We have included two new figures in the revised manuscript as suggested.

5. The whole concept of coordination numbers and mean path length between adjacent nodes is well defined for rocks with distinct granular structure and clearly separable pore bodies and throats. For a soil with coherent structure and anisotropic macropores it might be somewhat ill-defined. I have to assume this, because you do not show images of the pore space. This may be the reason why you got unrealistically high coordination numbers, because it is not intuitive what a directly connected pore node is supposed to be in those cases (see comment below). It is therefore hard to judge for the reader how much the results for mean path lengths and coordination numbers depend on the parameters that you've set during network extraction.
   Thanks you for the comment. We have included a figure that shows differences between two densities. Since separation of solid and void is difficult using the raw images we agree that more sophisticated thresholding is required for these type analysis. However, we believe, indicator kriging method of the 3DMA Software is the best method to use. We believe that results from this study will help future research to be planned differently, since it shows the limits of the technique, and aid work for evaluation of these parameters to distinguish differences between in pore characteristics as influenced by soil management (tillage) practices.

6. In some occasions you refer to changes in functional properties due to soil compaction. However, you didn't measure those functional properties like water retention, air permeability penetration resistance etc. with accompanying laboratory measurements to support your findings. Therefore all implications are a bit speculative. The paper could be strengthened a lot, if you did this for the updated version of the draft (using the same sample preparation steps).
   Thank you for the good suggestion. We planned to conduct water retention and movement within those soils at those densities. However, we did not complete those analysis for this paper and are being conducted for a separate study.

Specific comments:

p4l1: missing comma before connectivity
Thanks, we have included a coma.

p5l5-7: What was the motivation to chose different size classes?
Two different aggregate size classes were evaluated to quantify the changes in geometrical pore parameters as influenced by compaction and to evaluate whether CT methods have sufficient resolution at 9 micron scale to explain changes in geometrical pore properties.

p5l22-25: Irrelevant information. It's better to cite an appropriate reference for the GSECARS beamline here.
Thanks for the suggestion we have edited this section as suggested.

p6l1-4: So you used a white beam setup with an energy range of 7-70keV and a spot size of 10-30μm. All other information is too complicated to understand for anyone who is not an expert in synchrotron X-ray tomography.
We believed that sufficient information must be provided for the reader to understand the methods.

p6l10-13: irrelevant information
Thanks for the suggestion we have deleted this section in the revised manuscript.

p6l24-25: unclear what the Riemann function does - better write: ... filtered back-projection with the IDL programming language (Rivers, 1998).
We have revised this section in the revised manuscript.

p7l19-21: These statements are hard to understand for someone who hasn't used IK before. Two threshold have to be set a priori; one for dark voxels that definitively belong to pores and one for bright voxels that definitively belong to solid space. The remaining voxels are assigned by the IK algorithm according to neighborhood statistics. These two thresholds were set manually at the histogram peaks for pores and the aluminium wall.
We have revised these sentences.

p8l3: ' ... pass so-called pore throats'
We have revised these sentences.

p9l18-l25: This paragraph can be omitted (or should be placed somewhere else.)
We have deleted this section as suggested.

Table 1: Total volume is hard to interpret. You should use porosities instead. There seems to be a footnote for Aggregate* compaction, but I couldn't find it. What are the units in the ANOVA lines? Sizes and volumes or probabilities
We have provided the sample size (5 mm long and 5mm diameter) and bulk density values in the methods section. Porosity can be estimated from those values. We also have provided CT resolved pore volume in Table 1 to estimate CT resolved porosity.

p10l1: Geometrically
Thanks for the suggestion. It was corrected.

p11l6-7: That's only the case, if the largest pore has connection to the surface.
This comment is true. However, our samples were uniformly packed and on seals were present that would prevent connections to the surface.

p11l7-8: Do you present the results of the Assouline model somewhere in you paper and compare them to measures values? Otherwise this statement is a bit speculative and should be changed accordingly.
Thanks for the suggestion. We have revised this section.

Figure 1: The differences between the sub-figures are hard to see. Also, why did you use selected replicates and not the the average pore size distribution of all three replicates. I suggest to plot treatment averages with for different line styles in one figure on a reduced x-range up to 400μm.
Treatment averages were provided in the table (1). Sample average was also included in each figure. We attempted to develop all replicates in a figure for each treatment, it was too crowded. Then we developed a figure using average values. It did not represent samples as those frequencies were not the same for all samples.

Figure 2: Same problem like Fig. 1. Why did you pick specific replicates and not treatment averages? All replicates seem to have virtually identical size distributions, which is in contrast to what you state in the text.
Treatment averages were provided in the table (1). Sample average was also included in each figure. We attempted to develop all replicates in a figure for treatment it was too crowded. Then we developed a figure using average values. It did not represent samples as those frequencies were not same for all samples.

p11l27-p8l3: ’Masked’ might be the wrong word here. Compaction is just less severe in a sand as compared to a silt loam with macropores.
We have edited this sentence in the revised manuscript.

p12l3-11: Your statements in this paragraph are not justified by your results, because you did not conduct a REV analysis. To do so you need to start with a small sub- volume, increase it in steps and look how porosity or any other property changes with sample volume. Only if the value stabilizes before you’ve reached the total sample size, is an REV truly reached. Also, your samples are very different from those in Wildenschild et al. Please do a correct REV analysis or omit this paragraph altogether.
We have deleted this paragraph as suggested.

p12l14: omit ’i.e. a good pore network.’
Thanks, revised as suggested.

p12l15: How can a pore node be directly connected to so many neighbouring nodes? Do up to 40 pores meet in one singular bond of the network? Even more than ten is hard to imagine. So what does the algorithm consider to be directly connected? The explanation in on page 9, l8-9 is not helpful.
The resolution was 9 micrometers and there are smaller pores that were detected by the method. The measurement is likely an artifact of the method.

Moreover the probability for these points is so small to be insignificant. Only large pore coordination number ≤ 20 was used to determine characteristics coordination numbers.

Fig 3: Same problem like figures before: Why not treatment averages and plotting all in one figure with different symbols? Otherwise the impact of different treatments is difficult to evaluate.
Treatment averages were provided in the table (1). Sample average was also included in each figure. We attempted to develop all replicates in a figure for treatment it was too crowded. Then we developed a figure using average values. It did not represent samples as those frequencies were not same for all samples.

p12l16-18: Leave out this sentence. It's just trivial that the probability has to decrease with increasing CN.
We have deleted this sentence in the revised manuscript.

p12l24-29: That information is explained in too much detail and dilutes the main mes- sage, which is that different initial aggregate sizes had no significant effect on CN (or Co).
Table 1 provides statistical differences and mean values for each treatment. We have revised this section.

p13l14: 'imply' is a to strong word here, because CN is a local property whereas air continuity is a global percolation property. They don't necessarily need to be corre- lated. Independent laboratory measurements with the same aggregate packing would be helpful.
Thanks for the suggestion. This is beyond the scope of the paper and we will not be able to conduct this additional work

p13l29-p14l1: This information is irrelevant.
We have deleted this sentence in the revised manuscript.

p14l11-23: The whole discussion would be easier to follow if you showed 2D section or 3D renderings of the pore space architecture for different treatments. After reading the draft the greater path lengths for smaller aggregates don't make much sense too me and the presented explanation is not convincing.
Thanks for the suggestion. We have included 2 figures as suggested.

p15l16-17: Be more specific. How do they agree with your results? Values like 1.20-1.21 are quite different from 1.46-1.74.
We have revised this statement.

p16l14-15: 'These results provide a picture ...' - To put it in a bit exaggerated terms, this study merely collected all results that 3DMA is able to compute and presented them in every detail. However, a general picture of what happens in the pore space during compaction is not given. It is somwhat obvious that

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macroporosity decreases and that big pores are more likely to be closed during compaction. Any further insights into pore-scale processes during compaction are not really obvious from the text, or at least not well discussed. They might be somewhere, but it’s just too many results and unrelated discussions which distract from that important message. You could shorten the result section and provide this discussion as the separate section in between the results and the conclusions.

We have included a section that address the above comment. This section summarizes the effects of mechanical compaction on CN, path length, and tourtuocity.

Interactive comment on SOIL Discuss., 2, 825,

REPLY TO COMMENTS FROM THE TOPICAL EDITOR

After a quick access review, I recommend the authors to include the spatial resolution of the microCT (not only the smallest pore volume but also the dimensions of the voxels).

> **We have included pixel size and slice thickness for voxel dimensions in the revised manuscript (Lines 148-150).**

In the statistical analyses, log transformations were used to compare the distributions. Were the variances of the distributions similar after transformation? Which averages of the distributions were actually compared: the geometrical or the arithmetic ones? I propose to include also the average of the logtransformed parameters and the standard deviation of these logtransformed parameters.

> **We have included additional information about data with relevant references for the procedures. 3-DMA generates geometrical determined pore parameters and those were used for the statistical analyses (Lines 228-233). We also have included standard deviations for all mean values for each parameter and treatment (Table 1).**

Synchrotron Microtomographic Quantification of Geometrical Soil Pore Characteristics Affected by Compaction

Ranjith P. Udawatta*[1,2], Clark J. Gantzer[1] Stephen H. Anderson[1], and
Shmuel Assouline[3]
Dept. of Soil, Environmental and Atmospheric Sciences[1], The Center for Agroforestry[2]
School of Natural Resources, University of Missouri,
Columbia, MO 65211, USA and
Dept. of Environmental Physics and Irrigation, Agricultural Research Organization,
Volcani Center, Bet-Dagan, Israel[3].

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*Corresponding author's
Telephone number: 573-882-4347
Fax number: 573-882-1977
E-mail address: UdawattaR@Missouri.edu

Synchrotron Microtomographic Quantification of Geometrical Soil Pore Characteristics Affected by Compaction

Ranjith P. Udawatta*, Dept. of Soil, Environmental and Atmospheric Sciences[1], The Center for Agroforestry[2] , School of Natural Resources, University of Missouri, Columbia, MO 65211, USA

Clark J. Gantzer, Dept. of Soil, Environmental and Atmospheric Sciences, School of Natural Resources, University of Missouri, Columbia, MO 65211, USA

Stephen H. Anderson, Dept. of Soil, Environmental and Atmospheric Sciences, School of Natural Resources, University of Missouri, Columbia, MO 65211, USA

and

Shmuel Assouline, Dept. of Environmental Physics and Irrigation, Agricultural Research Organization, Volcani Center, Bet-Dagan, Israel.

*Corresponding author's

Telephone number:	573-882-4347
Fax number:	573-882-1977
E-mail address:	UdawattaR@Missouri.edu

Synchrotron Microtomographic Quantification of Geometrical Soil Pore Characteristics Affected by Compaction

ABSTRACT

Soil compaction degrades soil structure and affects water, heat, and gas exchange as well as root penetration and crop production. The objective of this study was to use X-ray computed microtomography (CMT) techniques to compare differences in geometrical soil pore parameters as influenced by compaction of two different aggregate size classes. Sieved (diam. < 2mm and < 0.5mm) and repacked (1.51 and 1.72 Mg m^{-3}) Hamra soil cores of 5- by 5-mm (average porosities were 0.44 and 0.35) were imaged at 9.6-micrometer resolution at the Argonne Advanced Photon Source (synchrotron facility) using X-ray computed microtomography. Images of 58.9 mm^3 volume were analyzed using 3-Dimensional Medial Axis (3DMA) software. Geometrical characteristics of the spatial distributions of pore structures (pore radii, volume, connectivity, path length, and tortuosity) were numerically investigated. Results show that the coordination number (CN) distribution and path length (PL) measured from the medial axis were reasonably fit by exponential relationships $P(CN)=10^{-CN/Co}$ and $P(PL)=10^{-PL/PLo}$, respectively, where Co and PLo are the corresponding characteristic constants. Compaction reduced porosity, average pore size, number of pores, and characteristic constants. The average pore radii (63.7 and 61 μm; $p<0.04$), largest pore volume (1.58 and 0.58 mm^3; $p=0.06$), number of pores (55 and 50; $p=0.09$), and characteristic coordination number (3.74 and 3.94; $p=0.02$) were significantly different between the low density than the high density treatment. Aggregate size also influenced measured geometrical pore parameters. This analytical technique provides a tool for assessing changes in soil pores that affect

hydraulic properties and thereby provides information to assist in assessment of soil management systems.

Abbreviations: 3-DMA, 3-Dimensional Medial Axis software; 3-D, three dimensional; CN, coordination number; Co, characteristic coordination number constant; CMT, computed microtomography; diam., diameter; PL, path length; PLo, characteristic path length constant.

INTRODUCTION

Degradation of soil structure is a serious worldwide problem (Schrader et al., 2007). Soil structure is important for crop production because it partly determines rooting depth, the amount of water that can be stored, and movement of air, water, nutrients, and soil microfauna (Brussaard and van Faassen, 1994; Whalley et al., 1995). During soil compaction, soil structure is degraded and soil aggregates are consolidated decreasing soil porosity; and subsequently these changes alter water, heat, and gas transport as well as root penetration and soil productivity (Kim et al., 2010). Assessment of soil compaction is a fundamental way to evaluate environmental impacts of agricultural operations on soils.

Researchers have been evaluating soil compaction due to natural and anthropogenic activities (Soane and van Ouwerkerk, 1995; Assouline et al., 1997; Marsili et al., 1998; Green et al., 2003). Differences in porosity among dissimilar soils and treatments are often quantified using bulk density estimated with soil cores, changes in soil thickness, and changes in penetrometer resistance. Porosity determined by traditional methods often lacks detailed information on spatial variability in geometrical pore characteristics. In addition, porosity is often estimated by indirect procedures which do not contain information on the spatial distribution of pores and most measurements are based on observations in two-dimensions (Beven and Germann, 1982; Gantzer and Anderson, 2002; Mooney, 2002).

Soil scientists are working to examine microstructure of the soil system to better predict water and gas movement, to assess the effects of management on soil pore parameters and microbial habitats, as well as to evaluate treatment effects on root development. Microstructure governs the flow of resources through the pore space of the soil media and creates spatial and temporal differences in the media (Young and Crawford, 2004; Zhang et al., 2005). Research suggests that understanding of geometrical pore parameters is critically important to issues related to movement of microfauna, water, solute, and gases as well as root development. These pore parameters include: pore dimension, pore size distribution, connectivity, shape factor, and tortuosity as well as distributions or probabilities of these parameters (Ioannidis and Chatzis, 1993; Tollner et al., 1995; Ioannidis and Chatzis, 2000; Lindquist et al., 2000).

Computed microtomography can be viewed as a technique in soil studies that enables examination of local variation (micrometer scale), whereas conventional tomography enables examination at a millimeter scale (Macedo et al., 1998). CMT has been used in examination of pores in sealing materials for nuclear waste and in rock and soil media as well as evaluation of fluid transport; in addition pore dynamics, and bacterial and root studies have been reported (Coles et al., 1998; Kozaki et al., 2001; Lindquist, 2002; Gregory et al., 2003; Thieme et al., 2003; Udawatta et al., 2008; Peth et al., 2010). However, these procedures require images at μm resolution to accurately describe changes within the media. Better resolution in tomography requires a smaller sample size. Advantages of CMT procedures include repeated examination of interior structural features of samples at micrometer-scale resolution within three dimensions, measurement of connectivity and tortuosity, nondestructive evaluation of sample interiors retaining connectivity and spatial variation in pores, as well as enabling examination of dynamic soil processes and quantification of pore geometry (Asseng et al., 2000; Al-Raoush, 2002; Mooney, 2002; Pierret et al, 2002; Carlson et al., 2003; Udawatta et al., 2008).

Quantitative information of soil structure is required to improve understanding of infiltration, contaminant movement through porous media, and quantification of model parameters associated with fluid and gas movement (Pachepsky et al., 1996; Perret et al., 1999; Ioannidis and Chatzis, 2000; Wildenschild et al., 2002; Fox et al., 2004; Assouline, 2004). However, CMT, volume rendering and three-dimensional (3-D) image analysis studies focusing on soil compaction are rare. The objective of this study was to use synchrotron X-ray computed microtomography to quantify the influence of mechanical compaction on geometrical soil pore characteristics of two soil aggregate classes.

MATERIALS AND METHODS

Soil and Sample Preparation

The soil used for this study was a loamy sand (Typic Rhodoxeralf) collected from the 0-100 mm depth of an experimental field at Bet-Dagan, Central Israel (32° 12`N and 35° 25` E). The soil contains 87% sand, 2% silt, and 11% clay (mainly smectite). Air-dry soil was sieved through 2.0 and 0.5 mm mesh sieves to separate into two aggregate size classes: < 2 mm and < 0.5 mm. Soil was packed in 5 mm long by 5 mm diameter aluminum cores with 1.0 mm wall thickness, in three replicates for each treatment. Soil cores from each aggregate class were compacted with a small press to obtain pre-determined bulk density values of 1.51 and 1.72 Mg m^{-3}. The selected two values represent the range in bulk densities commonly found with these soils and site conditions. The open ends of the soil core were covered with aluminum plates and sealed with tape to secure soil materials inside the core. Samples were stored at room temperature before scanning.

Image Acquisition and Tomographic Reconstruction

Air-dry soil cores were transported to the GeoSoilEnviroCARS (GSECARS) sector at the Argonne Advanced Photon Source for image acquisition at the X-ray computed microtomography facility (https://gsecars.uchicago.edu/). Soil cores were imaged at a 9.6 μm resolution using the bending magnet beam line 13-BM-D, which provides a parallel beam of high-brilliance radiation with a vertical beam size of about 5 mm. Specific synchrotron tomographic procedures and additional details can be found in Kinney and Nichols (1992).

The data processing consisted of three main steps: preprocessing, sinogram creation, and reconstruction. Since there is a constant digitization offset (~ 50 counts) this value was subtracted from each pixel. The second step was to remove "zingers", these are bright pixels caused by scattered X-rays striking the CCD chip. The third step of the preprocessing was completed to normalize each data frame to the field image and to correct for drift.

The first step of sinogram creation was to take the logarithm of the data relative to air. Centering the rotation axis of the projection was completed by fitting a sinusoid to the center-of-gravity of each row in the sinogram. Ring artifacts were removed by detecting and correcting anomalous columns in the sinogram. Tomographic reconstruction was completed using filtered back projection with the IDL programming language (Rivers, 1998). The raw data used for tomographic reconstruction were 12-bit images with a total of 360 images collected as the sample was rotated twice from 0 to 180° in 0.5° steps. The data were piped to massive parallel SGI computers to view real time data before image acquisition was completed.

Image Analysis

The 3-Dimentional Medial Axis (3-DMA) computer software was used to examine differences in geometrical pore characteristics among the treatments (Lindquist and Venkatarangan, 1999) using a 1.7 GHz Linux computer with 2 GB of memory. Pore characteristics were analyzed at $9.2\text{x}10^2$ μm^3 voxel size (1 pixel=9.61 μm and 1 slice=10 μm; voxel size=9.61x9.61x10). Images were cropped into a 3.7 by 3.7 by 4.3 mm rectangular array block to remove artifacts. Spatial distributions for nodal pore volume, coordination numbers, pore path length, and tortuosity, were obtained for 58.9 mm^3 volumes. The six main analysis steps in 3-DMA were completed by a number of imbedded algorithms: segmentation of image, extraction and modification of the medial axis of pore paths, throat construction using the medial axis, pore surface construction, assembly of pore throat network, and geometrical characterization of pore throat network (http://www.ams.sunysb.edu/~lindquis/3dma/3dma_rock/3dma_rock.html accessed June 2012).

The grey-scale intensity of each CT-image voxel is an integer value from 0-255 (2^8 bit scale). Simple thresholding and indicator kriging (IK; Oh and Lindquist, 1999) separated the voxels into two populations using intensity values and voxels having intermediate intensities by using the maximum likelihood estimate of the population set, respectively (Fig. 1). Indicator kriging requires sub-populations of voxels for each phase (pore and solid) to be positively identified. The remaining voxels were assigned by the IK algorithm according to neighborhood statistics. This was satisfied by using grey-scale intensity values for air and aluminum as threshold cutoff values. These two thresholds were set manually on histograms to separate populations.

The *Medial Axis* of a digitized sample is a 26-connected centrally-located skeleton of voids which preserves the topology and geometry of the object (Sirjani and Cross, 1991). An erosion-based algorithm is used to extract and modify the medial axis of the pore space (Lee et al., 1994). Spurious paths, which are not significant descriptors of the object, and all dead-end paths were removed (trimmed) from the volume. A filter was used to minimize misidentification of segmentation artifacts such as small isolated pores/clusters. The process resulted in the medial axis, ‘backbone’.

3DMA uses throat finding algorithms (Venkatarangan, 2000; Shin, 2002) to determine the location of minimal area cross-sectional surfaces where one or more void paths pass, called pore-throats (Kwiecien et al., 1990). The throat region is defined by the voxel sets through which each triangulated throat surface pass, and throat surface areas are determined as triangulated interfaces.

The next step is to determine the network of pore paths (a connected curve of voxels) and vertices (a cluster of one or more voxels where three or more paths intersect). Throat surfaces separate pore spaces and determine network of pores. Pores are cross-indexed with their connecting throats and adjoining pores while throats are cross-indexed with the pores they connect. The algorithm also computes a center of mass, principal directions for each pore, and the diameter passing through the center of mass in each principal direction. An effective pore radius can be computed using the sphere of equivalent volume. The analysis generated distributions of the principal diameters and the effective radius values for the pores and throats.

Path length (the distance between the centers of any two adjacent nodal pores along the mid line of the connecting path) is determined by the distance measure algorithm (Lindquist, 2002). Dijkstra's algorithm (Cormen et al., 1990) embedded as part of the 3DMA software determined path tortuosity. The algorithm uses a gamma distribution for tortuosity probability distribution (Lindquist et al., 1996) and generated tortuosity of each pore and, and average and cumulative tortuosity values for each sample. The software generated an assembly of pore networks and geometrical characteristics of pore networks. The following information generated by the 3DMA was analyzed as outlined in Lindquist et al. (2005): effective radius, pore volume, coordination number, path length, and path tortuosity along with their corresponding probability density relationships.

The coordination number (CN) is measured by directly counting the distribution of medial axis vertex sets. Coordination numbers between 3 and 20 were used to develop exponential distribution relationships [$P(CN) = 10^{-CN/Co}$] between coordination numbers and probability density values to determine characteristic coordination number constants (Co) for each sample. A similar approach was used to determine characteristic path length constants (PLo), fitting an exponential distribution [$P(PL) = 10^{-PL/PLo}$] of path length (PL) and probability density. Pore radii (μm), pore volume (mm^3), coordination number, path length, and tortuosity differences were compared among treatments. A selected replicate for each treatment was used to show the distributions of above properties in figures.

Statistical Analysis

Geometrically determined pore parameters were analyzed to examine differences and similarities among treatments for: pore radius, volume, porosity, mean pore volume, number of pores, coordination number, path length, and tortuosity as described by Lindquist et al. (2000). Bulk averaged variables have become the “historical operational descriptors” in theoretical description of porous media microstructure. Therefore, the averaged values are given in Table 1 with respective standard deviations. Four treatments in factorial design (two factors of density and aggregate size; two levels) were compared: two aggregate size classes (<2.0 and <0.5 mm diam. referred to as H2 and H5, respectively) and two compaction levels identified as low (L) and high (H) representing two bulk density values (1.51 and 1.72 Mg m^{-3}, respectively) with three replicates. Analysis of variance was conducted with SAS using the GLM procedure to test differences between treatments (SAS Institute, 1999). Least square means were calculated to find significant differences between treatments for each measured parameter. Statistical tests included normality of data distribution and significant differences among treatments.

RESULTS AND DISCUSSION

Effective Pore Radii and Volume

Since effective pore radii were not normally-distributed, log-transformed effective pore radii values were used in the statistical analysis. Effective pore radii were 63.75 and 61.18 μm for 1.51 and 1.72 Mg m^{-3} treatments (averaged for both aggregate sizes), respectively (Table 1, Fig. 2) and the compaction was significant ($p=0.04$). As expected, pore radius decreased with increasing density. However, aggregate particle size had no significant effect on measured pore radii. Mean pore radii were 62.64 and 62.29 μm for 0.5 and 2.0 mm aggregate sizes (averaged for both densities), respectively.

Similar to effective pore-radii, log-transformed pore volumes were used for analysis. Table 1 shows that total pore volume, largest pore size, mean pore volume, and number of pores decreased with increasing compaction for the high density samples compared to low density. The largest pore volume and number of pores were different ($p<0.10$, Fig. 3). However, the largest pore size was 2.7 times larger in the less compacted treatment as compared to the high-density treatment. The average pore volumes were 7.1×10^5 and 6.6×10^5 μm^3 for 1.51 and 1.72 Mg m^{-3} bulk density treatments (averaged for both aggregate sizes), respectively. CMT-measured porosity values were 10.9% and 4.9% for the high and low-density treatments, respectively. Note that the CMT-measured porosity is lower than the core-estimated porosity due to the limited resolution of the scanner. Total core porosity was 1.2 times smaller and CMT-measured pore volume was 2.2 times smaller in the high-density treatment as compared to the low-density treatment. This result is consistent with the fact that the soil porosity should decrease when moving from low to high bulk density; although the range in values will be smaller for the bulk core properties. The aggregate size-class containing finer aggregates (H5) had 1.7 times more pore volume, 2.1 times greater largest pore volume, and more pores than the aggregate class including larger aggregates (H2). In terms of the effect of compaction on pore size distribution, Figures 1 and 2 show that compaction preferentially affected the larger pores, reducing them in size (radius and volume) in both aggregate categories. This is in agreement with the estimated effect of compaction on the pore size distribution derived from changes in the water retention curve (Assouline, 2006a).

The results observed in this study agree with findings between soil porosity and pore size distribution relationships in previously published data (Lindquist et al., 2000; Seright et al., 2001; Udawatta et al., 2008). Although differences in pore volume and radii may exist among treatments, the effects may be somewhat less dominant due to fewer aggregates (due to sandy texture) and/or few inter-aggregate spaces (due to sandy texture).

Coordination Number

Higher pore coordination numbers (CN) imply greater connectivity developing between nodal pore sites that are well connected and extended; a good pore network. Coordination numbers varied between 3 and 40 and ≤ 20 were used to develop relationships (Fig. 4). Coefficients of determination for the CN and probability relationships were > 0.99 for all treatments. The coordination number constant (Co) values varied between 3.44 and 4.29 with a mean of 3.91±0.27 for all samples. Coordination number constants was significantly different between low and high density treatments (Table 1; $p<0.02$). The low-density treatment had 6% greater probability for pore connectivity than the high-density treatment. The same trend was observed for both aggregate categories of low-density treatments as compared to the high-density (Table 1). The mean Co values were 3.72 and 3.97 for 0.5 and 2.0 mm diameter aggregate treatments, respectively ($p<0.10$).

The range of Co values observed in this study were similar compared to values observed for heterogeneous soil material (Udawatta et al., 2008). In Udawatta et al. (2008), larger soil cores were analyzed at 84 μm resolution and Co values ranged between 3.30 and 5.14. The selected 3 to 20 coordination number range for the current study resulted in a straight line as compared to the ranges used by Lindquist et al. (2000) and Udawatta et al. (2008) in their relationships. Lindquist et al. (2000) imaged rock material at 6-μm resolution, as compared to 9.6-μm resolution in this study. Both Lindquist et al. (2000) and Udawatta et al. (2008) reported significant differences in Co values among treatments. We speculate that soil material with more uniform size particles and lack of aggregates may have caused small differences among treatments. In addition, treatments examined in this study further segregated soil particles by creating aggregate size classes as a treatment and thereby forming more homogeneous samples. This also suggests that these soils with more uniform larger grain size lose more pore connectivity than small particles during compaction. Results may indicate that the rate of air and liquid flow may be reduced by compaction due to a lower number of connected pores. Another reason for the observed Co values could be that compaction preferentially affected larger pores reducing them in size while smaller pores maintained the same connectivity (Fig. 1, 2, and 3). This pattern has been observed by soil water retention studies as influenced by compaction (Or et al., 2000; Assouline, 2006a; Kumar et al., 2008).

Path Length

Path lengths (PL) measured in this study ranged from 3 to 597 μm (Fig. 5). Path lengths between 100 and 400 μm were selected for the development of exponential relationships [$P(PL) \sim 10^{-Pl/PLo}$] between path length and probability density. The selected range exhibited a linear relationship with coefficients of determination ranging from 0.96 to 0.98 with a mean of 0.97. Characteristic path length constants (PLo) ranged from 157.7 to 219.3 with a mean of 179.5. Mean PLo values for the low density and high-density treatments were 179 and 180, respectively, and the difference was not significant (Table 1). The greater PLo values imply a greater probability of occurrence of a given path length than in the high-density treatment. Between the two aggregate size classes, 0.5 mm aggregates had a larger PLo (185) as compared to the larger aggregates (174; not significantly different). This high PLo is an indication of greater probability of paths in a soil with small aggregates.

Researchers have used differences in path lengths imaged by varying resolutions to compare porosity in sandstone and conservation management effects on path lengths. Lindquist et al. (2000) observed differences in PLo values in sandstone with porosities varying from 7 to 22%. Udawatta et al. (2008) showed that PLo was significantly higher for buffer treatments as compared to row-crop management. Similar to other studies, the differences in PLo values as influenced by compaction and aggregate size were significant between treatments in the current study. According to Wu et al. (2006), path length was higher for smaller particles. The greater path lengths in smaller particle media have been attributed to larger pore spaces among larger particles that reduced the distance due to relatively easier corners in the media. They also noticed that relative path lengths were higher through pores as compared to over the grains in their scanning electron microscope study with cubic sodium chloride.

Path Tortuosity

Figure 6 shows that probability decreased with increasing path tortuosity and tortuosity values ranged from 1 to 3.7. The highest probability occurred at a path tortuosity of 1.12. In general, the probability was less than 0.05% for path tortuosity values greater than two and the distribution of data points were more scattered for tortuosity values > 2.5, greater deviation from a linear distribution with probability.

Although tortuosity of the pore network depends on the grains in the media (Friedman and Robinson, 2002), the aggregate treatment was not significant in the current study (p=0.13; Table 1). Slightly greater tortuosity for smaller particles could be due to image analysis techniques as larger particles create larger spaces between particles thus reducing the tortuousness of paths. In contrast, tortuosity increased linearly with increasing particle size and the gas diffusion coefficient decreased in a plant growth media study with 1 to 16 mm size bark materials (Knongolo and Caron 2006). Higher tortuosity values due to compaction, aggregate size, or management affect water, solute, and gas movement through the media and higher tortuosity imposes greater resistance.

Mean tortuosity values were 1.20 and 1.21 for 1.51 and 1.72 Mg m^{-3} bulk density treatments, respectively (Table 1). Pore paths were 0.8% more tortuous for the higher compaction as compared to the lower compaction (not significantly different). In addition, the probability was slightly higher for tortuosity > 2.5 for more compacted soils than the 1.51 g cm^{-3} bulk density soil.

Average tortuosity values between 1.46 and 1.74 were observed among crop and buffer soils (Udawatta et al., 2008). The mean tortuosity value was 2.7 with a 1.5 to 4.5 range in a fluid transport study, using synchrotron CMT (Coles et al., 1998). Path tortuosity values observed in this study and the Udawatta et al. (2008) were less than 1.75 while Perret et al. (1999) observed values as high as 2.4. The difference can be attributed to image resolution and image analysis software.

Imaging techniques are capable of estimating tortuosity in X, Y, and Z directions (Wu et al., 2006). Such measurements are important for materials with anisotropic pore structure that have preferential pore directions. For example, clay soils with restrictive horizons may promote lateral flow above the restrictive horizons. In contrast, compaction may occur in three dimensions and pore structure may not always form a continuous network; could be an isolated entity. At this time, it is not clear whether tortuosity data measured in all cardinal directions and locations will be useful in predicting transport. Future studies are needed to examine how water, solute, and gas movement are affected by anisotropic tortuosity among porous media with heterogeneous particles.

Pore characteristics of (Co) and (PLo) as influenced by aggregate-size and compaction.

Conventional methods for determination of porosity document that aggregate size and compaction significantly decrease pore-size. Our results show that these changes are relatively small making it difficult to discriminate among soils of differing aggregate-size and compaction.

Using CMT methods, determination of the network of pore paths (Co) and the path length of pores (PLo) is possible. Results show much greater change in these characteristics compared to pore-size. Change in Co from 2- to 0.5-mm aggregates averaged over density reduced the connections 4%, while change in Co from 1.51- to 1.72 - Mg m^{-3} reduced the pores connections 6.4%, a much greater reduction than the reduction in pore radius. Values for PLo reflecting the tortuous nature of path lengths show the greatest discrimination among the aggregate-size and compaction treatments. Not surprisingly, change in PLo from 2- to 0.5-mm aggregates averaged over density increased path tortuosity by 4.3% as smaller aggregates reduced the probability of direct pore paths. In contrast, change in PLo from 1.51- to 1.72 - Mg m^{-3} decreasing PLo by 10.5%, demonstrated the greatest ability to discriminate among treatments.

Our results suggest that inclusion of CMT pore characteristics allow a better description of soil structure that can discriminate differences in pore characteristics of soil.

CONCLUSIONS

This study provides insight into the effects of compaction of two aggregate-size classes on soil structure parameters through the application of computed microtomography technology at a 9µm scale using a nondestructive and 3-dimensional rendering microtomography of a loamy sand soil. Two compaction levels on pore radius, largest average pore volume, number of pores, characteristic coordination number, and path length were investigated. The results provide a picture of how the pore space changes as the porosity decreased with compaction. These results can improve quantification and the ability to model soil structure. This method should aid with the development of tools to better assess soil structure and the measure the benefits of soil management to improve soil quality.

The study approach detected significant differences in certain measured parameters. The study results also show that differences in tortuosity were not clearly detected by the microtomography method used in this study. This could possibly be because of the imaging resolution and image analysis procedures used in the study.

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Table 1. Geometrical pore parameters (pore radius, pore volume, number of pores, characteristic coordination number, characteristic path length, and tortuosity) as influenced by aggregate size and compaction treatments and the ANOVA. Soil cores were scanned at the GeoSoilEnviroCARS (GSECARS) sector at the Argonne Advanced Photon Source X-ray computed microtomography facility. Values in parenthesis indicate standard deviations).

Treatment	Mean Pore radius	Total Pore volume	Largest Pore volume	Mean pore volume
	μm	mm^{3}	mm^{3}	μm^{3}
Aggregate Treatment means				
0.5 mm	62.64	5.87	1.47	6.8x10^{5}
2.0 mm	62.29	3.45	0.69	6.9x10^{5}
Compaction Treatment means				
1.51 Mg m^{-3}	63.75	6.45	1.58	7.1x10^{5}
1.72 Mg m^{-3}	61.18	2.87	0.58	6.6x10^{5}
Average	62.46	4.66	1.08	6.6x10^{5}
Standard error	0.76	1.86	0.33	2.6x10^{5}
Analysis of variance				
Treatment	0.183	0.478	0.129	0.640
Aggregate (0.5 vs. 2.0 mm)	0.753	0.384	0.127	0.790
Compaction (1.51 vs 1.72 Mg m^{-3})	**0.044**	0.212	0.063	0.286
Aggregate * compaction	0.533	0.852	0.773	0.556

Treatment	Number of pores	Characteristic coordination number (Co)	Characteristic path length number (PLo)	Tortuosity
Aggregate Treatment means				
0.5 mm	54	3.72	185	1.21
2.0 mm	50	3.97	174	1.20
Compaction Treatment means				
1.51 Mg m^{-3}	55	3.74	179	1.20
1.72 Mg m^{-3}	50	3.94	180	1.21
Average	52	3.84	179	1.20
Standard error	1.8	0.05	7.7	0.004
Analysis of variance				
Treatment	0.184	**0.007**	0.654	0.341
Aggregate (0.5 vs. 2.0 mm)	0.193	**0.010**	0.390	0.134
Compaction (1.51 vs 1.72 Mg m^{-3})	0.089	**0.029**	0.901	0.346
Aggregate * compaction	0.537	**0.025**	0.372	0.747

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Figure 1. Cross sectional and three dimensional images of soil core samples for bulk density 1.51 Mg m^{-3} (left) and 1.72 Mg m^{-3} (right).

Figure 2. Probability density distributions versus pore radii for Hamra 2.0 and 0.5 mm aggregate treatments (H2 and H5) and Low and High compaction treatments (L and H). Selected replicates are shown in the figure (last number in treatment name is replicate). The number within parentheses is the sample mean pore radius in μm. The circle represents the average pore radii and the horizontal line indicates the standard deviation of the mean.

Figure 3. Probability density distributions versus pore volume for Hamra 2.0 and 0.5 mm aggregate treatments (H2 and H5) and Low and High compaction treatments (L and H). Selected replicates are shown in the figure (last number in treatment name is replicate). The number within parentheses is the sample mean pore volume in μm^3. The circle represents the average pore volume and the horizontal line indicates the standard deviation of the mean.

Figure 4. Probability density distributions versus coordination number for Hamra 2.0 and 0.5 mm aggregate treatments (H2 and H5) and Low and High compaction treatments (L and H). Selected replicates are shown in the figure (last number in treatment name is replicate). Coordination number (CN) is number of curve segments meeting at the vertex and Co is the characteristic coordination number constant which is the value in each equation.

Figure 5. Probability density distributions versus pore path length for Hamra 2.0 and 0.5 mm aggregate treatments (H2 and H5) and Lowand High compaction treatments (Land H). Selected replicates are shown in the figure (last number in treatment name is replicate). Path

length (PL) is the length of the path between adjacent connected nodal pores and PLo is the characteristic path length constant which is the value in each equation.

Figure 6. Probability density (solid points) versus path tortuosity and cumulative probability density (solid line) versus path tortuosity for Hamra 0.5 and 2.0 mm aggregate treatments (H0.5 and H2.0) and Low and High compaction treatments (Land H). Selected replicates are shown in the figure (last number in treatment name is replicate). The vertical line and the number within parenthesis is the sample mean tortuosity.