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November 19, 2015

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,

R.P.Ud

Ranjith Udawatta
Associate Professor, Agroforestry and
Watershed Research

Enc.

<u>REPLY TO COMMENTS FROM THE TOPICAL EDITOR</u>

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).**

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 & recon- struction (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 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,

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

J. Vanderborght (Editor)
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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.

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 now removed figures that do not show differences.

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**.