Quantifying the influence of tillage system on soil structural quality using X-ray computed tomography[1]

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ABSTRACT: This research was focused on quantifying the impact of tillage systems on the annual dynamics of soil microstructure. Intact soil cores were collected from long-term management plots in Ontario, Canada. Specific attention was given to zero-tillage, spring plow and spring tandem disk systems. X-ray CT scanning was used to obtain high-resolution 3D imagery of each core. Analysis of the Hounsfield-scale imagery revealed higher radio-densities for the whole soil and soil matrix in the zero-till plots, at post-planting. This corresponded with notably less soil porosity. Specialized plugins were used in ImageJ to segment resolvable pores, then to quantify their abundance and morphology in the binarized imagery. The dominant pore shapes were triaxial and prolate, with equant and oblate usually being present in lesser amounts. Changes in pore shape, during the growing season, could be explained by root extension and faunal activity, as well as drying and wetting. During the winter, the tendency to increase triaxial pores, could be related to the formation of ice lenses. Though there was a convergence of pore size distribution, in the tilled and zero-till soils, and both spring tillage systems increased the proportion of smaller pores, the spring-plowed soils showed the greatest increase in pore size over the winter. Considering interim results, in comparison with zero-till, spring tillage systems (especially plowing), not only directly altered soil structure, but also its response to natural factors during both the growing and winter seasons.

Indexation Terms: radio-density, porosity, temporal variability

INTRODUCTION

The impact of agricultural management systems on soil quality is an important issue globally. In order to sustain soils, efforts are being made to refine and develop best management practices. This requires a better understanding of the behavior of soils in relation to specific tillage systems.

Soils are very complex systems; studying their structure is one way to evaluate their diversity and also to understand why they are so important. Soil structure refers to the physical arrangement of voids and soil materials in the solid state with various sizes and shapes. Bulk density (defined as mass per unit volume of soil) is one of the most common measures of structure; it can be useful to determine how compaction has affected certain portions of the soil. Pore-size distribution is essential in understanding the factors and processes influencing structure. Macropores (those drained by gravity) tend to represent hydrological features, plant roots, small animals and movement of air; meanwhile, some micropores contain water that is not plant-available.

Soil quality can be defined from many perspectives, depending on the focus on the study, including biological activity, nutrients, organic matter etc. Several structural characteristics such as bulk-density, porosity, pore-size distribution and shape, can also be used as indicators of soil quality. In this regard it is important to recognize that these indicators of soil quality are not static. As per Li et al (2007), long-term conventional tillage results in poor structural quality and low productivity.

Multiple factors can influence the formation of soil pores, including roots, ice lenses, fauna burrowing, as well as swelling/shrinking due to water content. Four types of pore shapes can be distinguished (Zingg, 1935) equant, prolate, oblate and triaxial. Equant pores may result from packing grains and small aggregates. Prolate pores are tubular shapes, such as those formed by roots and burrowing fauna. Triaxial pores are flat with some thickness, which can be from shrinking or swelling fracture plains and ice lenses. Oblate pores can form from a pressure mechanism or fractures from wetting/drying.

Among the first users of X-ray CT for soil were Petrovic et al (1982), to study the bulk density. Subsequent developments in X-ray CT imaging technologies, and associated computerized processing (Cnuddle et al. 1997), offer the capacity to study soil structure from a full 3D perspective (Terribile et al. 1997). Most applications have focused on the microporosity, root systems, hydro-physical features and density of soils when using the X-ray CT technology (Taina et al. 2007). The most valuable aspect of this technology is that it is non-invasive and non-destructive.

The objective of this research is to evaluate the microstructure of the soil plow layer, in relation to tillage, at key times during the year. Specific attention was given to the variability of radio-density of the soil matrix phase, as well as morphometric quantification of resolvable pores, using high-resolution X-ray CT imagery of intact soil cores.

MATERIALS AND METHODS

This study was conducted on long-term tillage experimental area at the Elora Research Station, in Ontario, Canada ($43^0$64’10” N, $80^0$40’56” W). According to the Canadian System of Soil Classification (SCWG, 1998) the soils are classified as Orthic Grey-Brown Luvisol. Established in 1976, this area contains 10 different practices (replicated randomly in each of 4 rows) including conventional, zero-tillage and alternative methods (Scaiff, 2011). Individual plot measure 6 x 12 meters; they are planted to a common rotation of corn in even-numbered years (2012 was year of sampling) and soybean in odd-numbered years. The specific treatments included in this report are *Zero-Till*, *Spring Moldboard Plow plus Cultivate & Pack*, and *Spring Tandem Disc plus Cultivate & Pack*.

Soil core collection and scanning

Intact soil cores were collected, from the plow layers, using 64 mm diameter Lexan tubes. All steps were done so as to minimize impact, which would alter the microstructure. The adjacent soil material was excavated and the tube was gently pushed downward filling the first centimeter. This process was continued until the tube was nearly full of soil; cotton was then placed on the soil surface (to provide support) and the tube was capped and the core extracted. Sampling was done on three occasions: *Post-Planting* (June), *Pre-Winter* (December) and *Post-Winter* (April of following year). Upon arrival in the lab the soil cores were refrigerated (to inhibit biological activity), then slowly dried at 40^{o}C, until a constant weight was achieved.

The middle 3.5 cm of each soil core was then imaged using a GE MS8x-130 X- ray CT scanner, at a pixel size of 20 μm, using an excitation energy of 120kV and 155uA. Reconstruction of the 3D imagery was done at a voxel size of 40 μm, using GE eXplore Reconstruction Utility. The final image volume was 840 x 840 x 600, for a total of 423 million voxels.

3D image processing

In order to remove random noise, the raw 3D images were filtered using Gaussian smooth (with a radius of 1), function in GE Microview. The 3D volume files (in vff format) were then converted to stack of an unsigned 16-bit tiff images and imported into NIH Image J (Rasband, 2015). Finally the imagery was rescaled such that air=0 and water= 1000 Hounsfield Units (HU).

Radio-density histograms were generated for each of the 3D grey-scale (16-bit signed) images; these were average, from which clamping (max/min) values were selected, from the void and matrix peak positions (using Origin Pro), as input for image binary-segmentation (Jefferies et al, 2014). This procedure was followed by edge detection, using 3D Laplacian filter, followed by seeded region growing.

3D image analysis

The ‘Analyze Particles’ plug-in, in ImageJ, was used to measure the shape, size, and orientation of each resolvable (segmented), based fitting ellipsoids around each shape. Specifically, this analysis was performed on voids having volumes >8 voxels (or 0.0005 mm^3) and <100,000 (or 6.4 mm^3, corresponding to the interconnected, inter-aggregate porosity) Using the major, intermediate, and minor axis lengths, of the fitted ellipsoid, each pore was classified according to the Zingg (1935) criteria.

Using the histogram function, in ImageJ, radio-density (expressed in HU) histograms and mean radio-density values were generated for each greyscale image. Once the imagery had been binarized, a NAN (not-a-number) mask was applied to the resolvable pores to allow calculation of the radio-density of the non-pore soil matrix.

RESULTS AND DISCUSSION

Radio-density during the growing season

In general, there seems to be a loosening of the soil matrix during the growing season (**Figure 1**). Though the zero-till system was the densest, because it is not routinely tilled, is also showed a decrease that could be related to the development of roots and swelling/shrinking. Both tilled systems show an increase in bulk radio-density, reflecting further consolidation from the spring operations.

The soil matrix density showed more subtle change, during the growing season, than the whole soil. The highest values were found for zero-till, with decreases for spring-plow and spring-tandem.

Radio-density during the winter season

Over the winter season, the spring-plowed soil showed an increase in whole soil radio-density (**Figure 1**), whereas spring-tandem and zero-till show no major change. Apparently, only the spring-plowed soils experienced further consolidation.

The winter season further showed that the zero-till experience no big change in soil matrix radio-density, but the spring-plowed and spring-tandem disked soils both show an increased. The latter would result from ice lenses compressing the matrix.

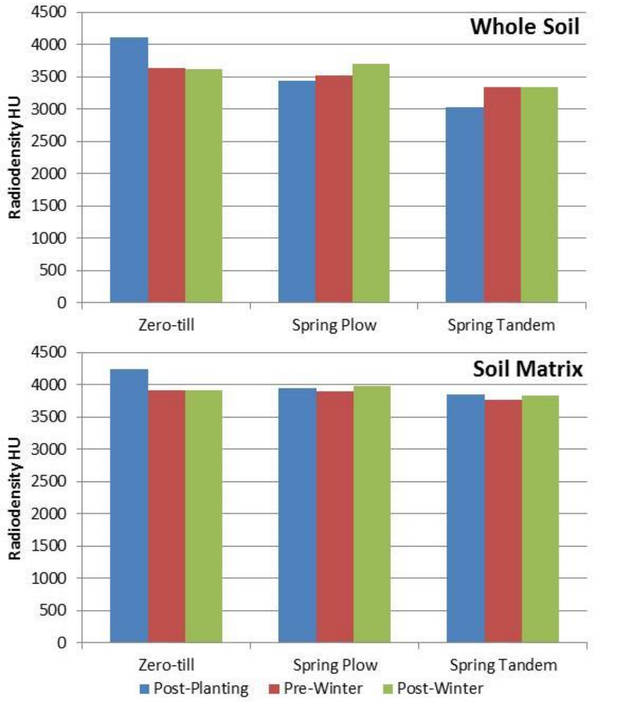

Figure 1 - Mean soil radio-density, expressed with (whole soil) and without (soil matrix) masking of resolvable pores.

Resolvable Porosity

Resolvable porosity, at post-planting, was notably lower in the zero-till soils, since they were not subject to any preparatory spring disturbance (**Figure 2**). Of the two tilled soils, spring-tandem disk resulted in greater porosity than spring-plow. During the growing season, zero-till increased, meanwhile the other two systems decreased in porosity; the latter suggests substantial consolidation. The winter season resulted in a slight increase in porosity in zero-till, but a notable decrease for the spring-plow system.

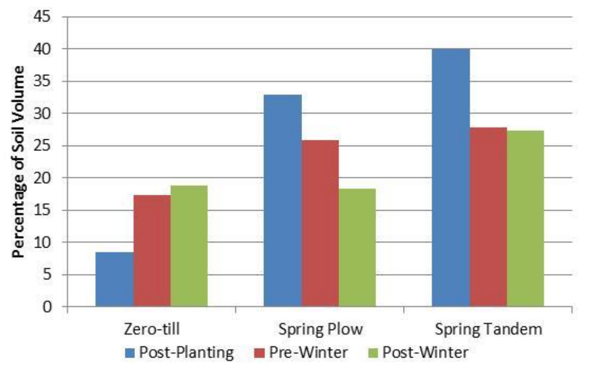

Figure 2 - Mean resolvable soil porosity.

A substantial proportion of the pores could not be classified, according to shape, because ImageJ was unable to return the appropriate parameters; these are labeled as 'unclassified' (**Figure 3**). There was an increase in the amount of unclassified pore shapes for all treatments, though zero-till had the most unclassified of the three systems. In general, the dominant void shapes were the triaxial (45^{+} %) and then prolate (20-30%); equant and oblate shapes followed (of which that can be classified), and represented in the rest of the pore space.

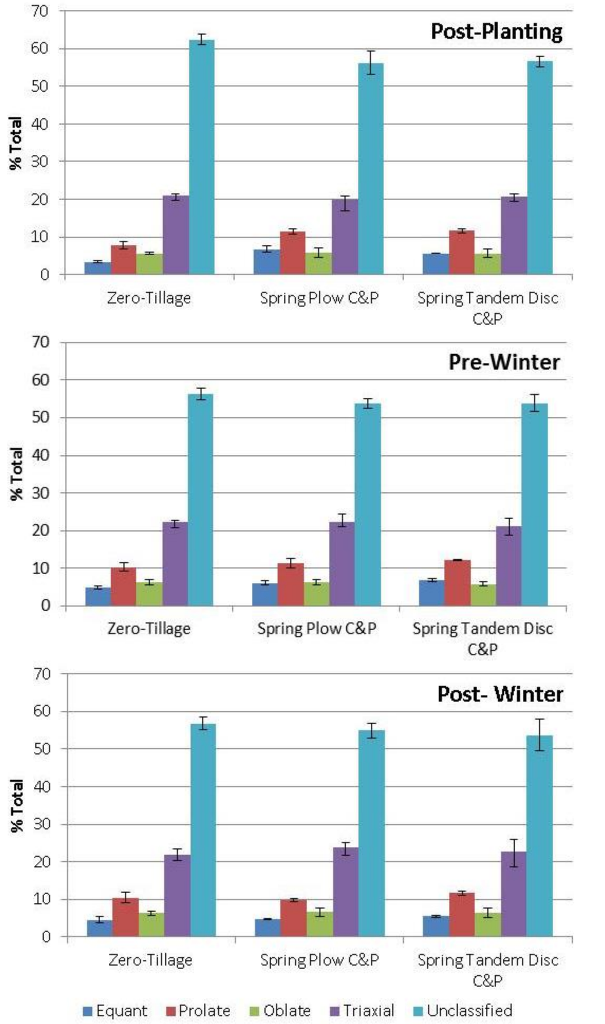

Figure 3 - Categorization of resolvable pores according to Zingg (1935) shape classes. Unclassified pores lacked valid measurements for one or more of the ellipsoid axes.

Porosity during the growing season

In general, triaxial and prolate pores increased, during the growing season, which could be a consequence of root development and faunal burrowing (**Figure 3**). In zero-till soil, there was an increase of both equant and prolate pores, with a decrease in the triaxial. This suggests a transition of pore shapes from triaxial to equant and prolate over the growing season. Spring-plow also showed a decrease in equant, which could be reflecting a deformation to triaxial. In contrast, spring-tandem disk showed an increase in equant which could reflect a transition from triaxial pores.

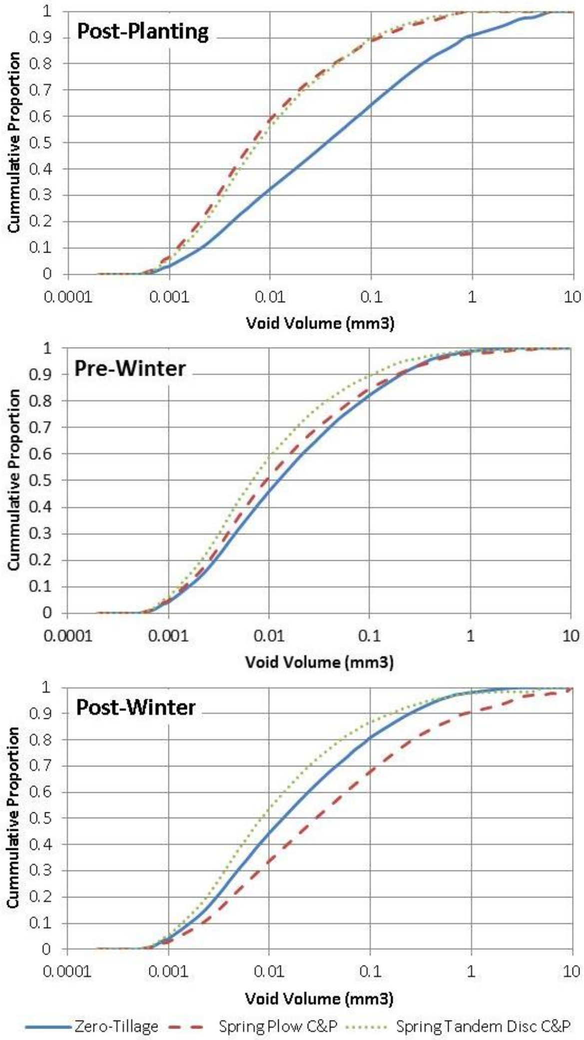

Figure 4 - Cumulative size distribution of resolvable pores, with volumes ranging from >8 to <100,000 voxels.

At post-planting, the two tilled systems presented similar pore size distributions, both exhibited smaller pore sizes than the zero-till **(Figure 4)**. Over the growing season there was a convergence of pore size distribution, reflecting similarity in crop and wetting/drying cycles. Of the three systems the spring-plow experienced the greatest changes.

Porosity during the winter season

No change of pore shape were seen in the zero-till during the winter (**Figure 3**), but spring-plow and tandem disk showed an increase in triaxial pores, which could be attributed to ice lens formation.

Over the winter season, the spring-plowed soils exhibited the greatest change in pore size distribution (**Figure 4**); the apparent increase in pore size can be attributed to expansion of freezing of water and ice lens growth. The pore size distribution for zero-till and spring-tandem disk did not behave noticeably different during the winter.

CONCLUSIONS

Based on these interim results, soil microstructure dynamics, as indicated by radio-density and pore shape/size parameters, is influenced by type of tillage system.

Changes in both the pore shape and pore size distribution could be related to biological activity and wetting/drying, during the growing season, and freezing, during the winter.

Of the three systems evaluated, the *spring plow with cultivate and pack*, exhibited the most dynamic behavior for the parameters measured.

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