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Quantification of 3-D soil macropore networks in different soil types and land uses using computed tomography

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SUMMARY

The importance of soil macropores as preferential pathways for water, air, and chemical movement in different soils has long been recognized. However, quantification of complex macropore structures and their relationships to soil types and land uses remains elusive. The objectives of this study were to (1) quantify 3-D macropore networks in intact soil columns using an improved approach and (2) investigate the effects of soil type and land use on soil macropore characteristics. Two soils with contrasting textures and structures (Hagerstown silt loam and Morrison sand) from two land uses (row crop and pasture) were investigated. Intact soil columns, 102 mm in diameter and about 350 mm in length, were taken for each soil type-land use combination. The soil columns were scanned using X-ray computed tomography at a voxel resolution of 0.234 mm × 0.234 mm × 2.000 mm. After reconstruction, characteristics of macropore networks were quantified, including continuous macroporosity change along depth, macropore size distribution, network density, surface area, length density, length distribution, mean hydraulic radius, tortuosity, inclination (angle), and connectivity (path number and node density). The approach we developed provided an improved quantification of complex 3-D macropore networks. The analysis of variance indicated that soil type, land use, and their interaction significantly influenced macroporosity, network density, surface area, length density, node density, and mean angle. The interaction of soil type and land use also influenced mean tortuosity and hydraulic radius. Within the same soil type, the soils under pasture land use had greater macroporosity, length density, and node density than that under row crop, especially in the subsoil. This was due to greater organic matter content and more biota activities in the pasture. Within the same land use, the Morrison sand displayed lower overall macroporosity than the Hagerstown silt loam because of weaker structure and higher amount of rock fragments in the Morrison soil and thus less suited for biota activities. The results from this study provide improved quantitative evaluation of a suite of soil macropore features that have significant implications for non-equilibrium flow prediction and chemical transport modeling in field soils.

1. Introduction

The importance of macropores as preferential pathways of water, air, and chemicals in the soil has been widely recognized (Beven and Germann, 1982; Lin et al., 2005; Jarvis, 2007). The conductivity of macropores to water flow strongly depends on the 3-D geometry and topology of macropores. Macroporosity, number of macropores, pore length, pore size distribution, continuity, tortuosity, and connectivity are considered as significant characteristics that influence water flow and solute transport through macropores (Perret et al., 2000; Pierret et al., 2002; Bastardie et al., 2003; Peth et al., 2008; Luo et al., 2008). Different types of macropores have distinct geometries and therefore function differently (Lin et al., 1996; Luo et al., 2008). Soil type and land use are among the main factors influencing macropore characteristics (e.g., Gantzer and Anderson, 2002; Zhou et al., 2008; Udawatta et al., 2008; Mooney and Morris, 2008).

Reconstruction, visualization, and quantification of 3-D macropore networks are essential to correlating macropore characteristics to their physical, chemical, and biological functions and to predicting their dynamics under different land uses. The tradition methods, such as thin-sections, have limited ability to observe 3-D macropore geometry and topology. With advances in imaging techniques, X-ray computed tomography (CT) has become attractive for non-destructively observing soil structure including

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macropore networks (e.g., Anderson et al., 1990; Perret et al., 1999, 2000; Luo et al., 2008). Although CT investigations of 2-D macropore characteristics have provided useful information for enhanced understanding of complex soil pore space and related land use impacts (e.g., Gantzer and Anderson, 2002; Udawatta et al., 2008), quantifying macropore features in its true 3-D has been more limited.

Although 3-D visualization of macropores has been realized with algorithms that synthesize 2-D CT images (e.g., Heijs et al., 1995; Mooney and Morris, 2008), quantification of 3-D macropore networks remains a challenge. Various approaches have been used to quantify 3-D macropore geometry and topology. Mathematical morphology (Serra, 1982) has been used to quantify the characteristics of 3-D earthworm burrows using X-ray CT, including pore size distribution, length of each branch, connectivity, and branching intensity (Capowiez et al., 1998; Pierret et al., 2002; Bastardie et al., 2003). Perret et al. (1999) developed a 26-neighbor algorithm to reconstruct the 3-D images of soil macropores in intact soil columns and calculated the number of macropore network, length, tortuosity, hydraulic radius, numerical density of networks, and their connectivity. Lindquist (2002) developed a software package to calculate the 3-D pore size distribution, throat-area distribution, effective throat/pore radii ratios, and pore tortuosity of macropores.

The objectives of this study were to (1) introduce an improved protocol to quantify soil macropore networks based on 3-D X-ray CT images and (2) evaluate the effects of land use and soil type on 3-D soil macropore features. Improvements in our protocol include the length-based macropore parameters such as length density, length distribution, mean hydraulic radius, tortuosity, and angle, which were accurately calculated by skeletonizing 3-D macropores. In this study, macropore size was sorted by actual volume instead of classical assumed equivalent radius. Macropore connectivity was also characterized by quantifying both inter-connectivity (node density) and paths of macropores through the entire soil column (path number), which are more suitable for describing macropores at the column or larger scales, instead of more classical Euler number as an index of connectivity. The variety of 3-D macropore network parameters calculated from our improved protocol, especially when combined with soil functions (see our example application in Luo et al. (submitted for publication)), are essential to understanding macropore impacts on soil properties with different soil types and land uses.

2. Materials and methods

2.1. Soils studied and their sampling

Two soil series with contrasting textures and structures – Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalfs) and Morrison sand (fine-loamy, mixed, active, mesic Ultic Hapludalfs) – were selected for this study. Both soils are typical in the Ridge and Valley Physiographic Region of Pennsylvania. The sandstone-derived Morrison soils had greater sand content and much higher rock fragments but lower silt and clay contents than the limestone-derived Hagerstown series (Table 1). Two common land uses – cropland and pasture – were selected for each soil series to investigate the impacts by land use. Both cropland sites had conventional tillage and rotation cropping of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) *Merr.*]. Both pasture sites were grazed by animals (cows and horses). Thus, there were four combinations investigated in this study: Hagerstown-cropland (H-C), Hagerstown-pasture (H-P), Morrison-cropland (M-C), and Morrison-pasture (M-P).

Five intact soil columns, 102 mm in diameter and about 350 mm in length, were randomly sampled from each site of the soil series-land use combinations in July 2007. A backhoe was used to carefully push polyvinyl chloride (PVC) pipe (with downward edge sharpened) vertically and gradually into the soil. Three soil horizons were contained in each sampled soil column (Table 1). Detailed procedures of our sampling protocol are described in Luo et al. (2008). Besides the large intact soil columns, three intact small soil cores, 55 mm in diameter and 60 mm in length, were also taken from each soil horizon to measure soil bulk density and saturated hydraulic conductivity in the laboratory. Disturbed soil samples were also taken from each horizon to determine particle size distribution and organic matter content (Table 1). During the soil sampling, each soil profile was also fully described according to standard soil survey procedures.

2.2. X-ray CT scanning

A HD250 Medical Scanner (Universal System, Inc., Solon, Ohio), a 4th-generation system of CT, was used to scan all the soil columns at an energy level of 130 kV and 100 mA. The 512 × 512 images with a voxel size of 0.234 mm × 0.234 mm × 2.000 mm

Table 1
Soil profile description and basic soil properties. The number in parentheses is one standard error ($n = 3$).

Soil and land use (symbol)	Soil horizon	Depth (cm)	Pedality (structure)[a]	Roots[b]	K_{sat}[c] (cm min^{-1})	Bulk density (g cm^{-3})	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Rock fragment[d] (%)	Total porosity[e] (cm^3 cm^{-3})
Cropped Hagerstown (H-C)	Ap1	0–15	2 f–m sbk	3 vf–f	0.051 (0.019)	1.34 (0.02)	19	65	16	4.5	1	0.49
	Ap2	15–31	2 m pl parting to 2 m sbk	3 f	0.045 (0.066)	1.35 (0.03)	17	68	15	3.5	2	0.49
	Bt1	31–36+	2 m sbk	2 f	0.035 (0.024)	1.46 (0.02)	23	52	25	1.9	2	0.45
Pastured Hagerstown (H-P)	A1	0–15	3 f–m gr	3 vf–m	0.206 (0.353)	1.16 (0.01)	24	62	13	7.5	1	0.56
	A2	15–32	3 m sbk	3 f	0.363 (0.549)	1.27 (0.00)	24	59	16	3.6	3	0.52
	Bt1	32–36+	2 m sbk	2 f	0.074 (0.010)	1.37 (0.04)	18	62	21	2.0	2	0.48
Cropped Morrison (M-C)	Ap1	0–10	1 f–m sbk	3 vf–f	0.367 (0.461)	1.53 (0.06)	87	9	4	2.0	20	0.42
	Ap2	10–20	1 m sbk	2 f	0.228 (0.034)	1.74 (0.03)	88	9	3	1.3	25	0.34
	Bt1	20–31+	1 m sbk	1 f	0.126 (0.193)	1.77 (0.04)	84	8	9	0.5	25	0.33
Pastured Morrison (M-P)	A1	0–10	1 f–m sbk	3 vf–m	0.357 (0.104)	1.41 (0.04)	73	18	9	4.3	1	0.47
	A2	10–20	1 m sbk	2 f	0.159 (0.084)	1.68 (0.03)	76	14	10	1.2	5	0.37
	Bt1	20–31+	1 m sbk	2 f	0.249 (0.380)	1.69 (0.04)	75	13	12	1.1	5	0.36

[a] Pedality is described using ped grade, ped size and ped shape: 1, 2, 3 for weak, moderate, and strong ped grades, respectively; vf, f, m and c for very fine, fine, medium and coarse ped sizes, respectively; sbk, gr, and pl for subangular blocky, granular and platy ped shapes, respectively.
[b] Roots are described using the quantity and size: 1, 2, 3 for few, common and many, respectively; vf, f, m, c, and vc for very fine, fine, medium, coarse and very coarse root sizes.
[c] Saturated hydraulic conductivity was determined using small soil cores in the lab using constant head method.
[d] Rock fragment (>2 mm in size) content estimated from the computed tomography images.
[e] The porosity was calculated from mean bulk density value (assuming a particle density of 2.65 g cm^{-3}).