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CT-measured pore characteristics of surface and subsurface soils influenced by agroforestry and grass buffers

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ABSTRACT

Permanent vegetative buffers with grass and/or trees are expected to improve soil porosity compared to row crop management, yet little is known about the extent of changes in soil properties with depth and how rapidly these changes take place. The objective of this study was to compare the effects of agroforestry and grass buffers on computed tomography (CT)-measured macropore (diam. >1000 μm) and coarse mesopore (diam. 200–1000 μm) parameters within 0.50 m soil profiles and to examine relationships between CT-measured pore parameters and saturated hydraulic conductivity (K_{sat}). Undisturbed soil cores (76 mm diam. by 76 mm long) from a no-till corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr.; RC) rotation, grass buffer (GB), and agroforestry buffer (AB) treatments were collected with six replicates from the 0- to 0.50-m depth in 0.10-m increments on a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualf). Five CT images were acquired throughout each soil core using a medical CT scanner with 0.2 by 0.2 mm pixel resolution and 0.5 mm slice thickness. Soil pore parameters including number of pores, number of macropores, number of coarse mesopores, porosity, macroporosity, coarse mesoporosity, and fractal dimension were analyzed using *ImageJ* software. Treatment and depth effects were significant for all seven parameters. These seven pore parameters were different between row crop and buffer treatments as well as grass and agroforestry buffer treatments. The GB and AB treatments had 26 and 36 macropores per 2500-mm^2 area, respectively. These numbers were 2 and 2.6 times greater than 14 macropores in the RC treatment. No macropores were detected in the 40 to 50 cm depth of the RC treatment. The fractal dimension of macroporosity for the agroforestry treatment was 1.2 and 1.1 times greater than row crop and grass buffer treatments, respectively. Soil bulk density and saturated hydraulic conductivity were significantly different among the treatments. The fractal dimension accounted for 76% of the variability in K_{sat}. This study concludes that establishment of permanent vegetative buffers improves CT-measured soil parameters and these CT-measured parameters may be used to quantify the effects of management relative to environmental benefits and improved water transport and retention models.

1. Introduction

Permanent vegetative buffers such as agroforestry and grass buffers, grass filter strips, and riparian practices reduce non-point source pollution (NPSP) from agricultural lands (Gilliam, 1994; Udawatta et al., 2002). These environmental benefits are attributed to physical, biological, and chemical changes in the soil and vegetation. Improvements in soil porosity, water storage, and infiltration influence water movement within the soil and thereby affect NPSP losses from watersheds. Perennial vegetation such as pasture, grass buffers, or tree buffers increase soil porosity compared to row crop land under tilled or no-till management (Bharati et al., 2002; Seobi et al., 2005). Changes in soil bulk density and addition of organic matter probably contribute to better soil porosity. Perennial vegetation also promotes more vertical and horizontal roots that persist longer than roots of annual crops. This may result in larger and longer continuous pores extending to subsurface horizons.

Soil pores, especially macropores (diam. >1000 μm; Luxmoore, 1981) promote rapid soil water movement through the profile and allow air and water movement into the soil (Perret et al., 1999; Fox et al., 2004). Rapid flow in subsurface soil can by-pass the soil matrix and also transport chemicals and contaminants to deeper horizons (Tuller and Or, 2002). Wilson and Luxmoore (1988) stated that macropore flow contributed 73% and 85% of water movement under forested conditions within saturated and ponded soils, respectively. In addition, better water drainage and air transport can occur due to more continuous

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Abbreviations: AB, agroforestry buffer; CT, computed tomography; GB, grass buffer; K_{sat}, saturated hydraulic conductivity; NPSP, non-point source pollution; RC, row crop.

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pores which will improve plant growth. Literature shows increased macroporosity under permanent vegetation can reduce contaminant losses from NPSP (Edwards et al., 1988; Sklenicka et al., 2002).

Macropore characteristics such as shape, size, orientation, and size distribution affect the rate, flow, and retention of water (Rasiah and Alymore, 1998; Udawatta et al., 2006). Poiseuille's relationships show that conductivity of fluid is related to the effective pore radius and continuity of pores which cannot be measured by traditional water retention methods. In soils with high clay content and very low infiltration, the absence of macropores can lead to increased copious surface flow. Therefore, differences in porosity among soils need to be quantified to diagnose changes due to agricultural land management practices and to develop better conservation management practices (Pachepsky et al., 1996).

In recent years, more emphasis has been placed on quantifying the geometry and topology of macropore structure to understand macropore effects on water and gas movement in soils (Pierret et al., 2002). X-ray computed tomography (CT) procedures have received increased attention in recent years in soil and earth sciences, due to CT's ability to non-destructively evaluate properties at a finer resolution (mm- to μm-scale) compared to bulk core analysis (Gantzer and Anderson, 2002; Udawatta et al., 2008a). CT-measured properties have been found to have close agreement with water retention-derived estimates (Rachman et al., 2005). Research has shown that X-ray CT-measured pore parameters under stiff-stemmed grass hedges, grass buffers, agroforestry buffers, conservation reserve program (CRP), native prairie, and row crop management were well correlated with macropores estimated with water retention and saturated hydraulic conductivity (Rachman et al., 2005; Udawatta et al., 2006, 2008b). Furthermore, quantification of pore structure at mm- to μm-scales has been shown to be important in predicting micro-scale fluid flow properties (Prodanović et al., 2007).

We hypothesized that agroforestry and grass buffer practices improve soil porosity by altering pore characteristics within the soil profile. The objectives of this study were to: (1) evaluate differences in CT-measured macropore and coarse mesopore characteristics (number of pores, number of macropores, number of coarse mesopores, porosity, macroporosity, coarse mesoporosity, and fractal dimension) among treatments, and (2) correlate CT-measured pore parameters with saturated hydraulic conductivity (K_{sat}).

2. Materials and methods

2.1. Study area

The agroforestry watershed with grass legume and tree buffers at the University of Missouri-Greenley Memorial Research Center (40° 01′ N, 92° 11′ W), Novelty, Missouri was selected to investigate buffer effects on CT-measured soil pore parameters. A detailed description of the watershed, management, soils, climate, grass legume buffers, and agroforestry buffers can be found elsewhere (Udawatta et al., 2002, 2006). In brief, the 4.44-ha watershed was managed with a corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation since 1991 with no-till land preparation and planting on the contours. During the sampling year, soybeans were planted on June 19, and yields averaged 2939 kg ha^{-1}. Redtop (*Agrostis gigantean* Roth), brome grass (*Bromus inermis* Leyss.), and birdsfoot trefoil (*Lotus corniculatus* L.) grass - legume buffer strips (4.5 m wide) at 17 to 36-m spacing were established in June 1997. Pin oak (*Quercus palustris* Muenchh.), swamp white oak (*Q. bicolor* Wild.), and bur oak (*Q. macrocarpa* Michx.) seedlings were planted at 3-m intervals in the center of the grass legume strips in November 1997. The average tree height was 3.5 m at the end of the 2005 growing season.

The parent materials for the soils in the watershed are glacial till and wind-blown Peorian loess. Soils in the sampling area in the watershed are mapped as Putnam silt loam (fine, smectitic, mesic Vertic Albaqualf). Typically, the top 50 cm includes four horizons. The Ap horizon is 7 cm thick (0–7 cm), AE horizon 15 cm thick (7–22 cm), E horizon 16 cm thick (22–38) cm, and Bt_1 horizon 12 cm thick (38–50 cm).

2.2. Treatments, sampling, and sample preparation

The three treatments were: agroforestry buffers (AB), grass buffers (GB), and row crop (RC) areas. Undisturbed soil cores from the surface 0- to 50-cm depth were collected at 10-cm increments (from the same hole) with six replicates from 27 May to 3 June 2005 using a core sampler. Dimensions of sampling Plexiglas rings were 76.2 mm long and 76.2 mm diam. with a 3.2 mm thick wall. Samples for the AB treatment were taken 15 cm from the base of six pin oak trees. Samples for the GB treatment were taken between two trees (1.5 m from trees). For the row crop treatment, six locations were sampled within the crop areas midway between buffers. Two plastic caps and masking tape were used to secure soil inside the cylinders. The soil cylinders were labeled, placed in plastic bags, sealed, and stored in a refrigerator at 4 °C until analyses were conducted.

Soil cores were prepared for saturation by replacing the bottom plastic cover with two layers of fine nylon mesh to secure soils within the cylinder and removing the top plastic cover. Soil cores were placed in a 15-cm deep plastic tray and slowly saturated from the bottom with a solution containing calcium chloride ($\mathrm{CaCl_2}$; 6.24 g L^{-1}) and magnesium chloride ($\mathrm{MgCl_2}$; 1.49 g L^{-1}) using a Marriotte system. After saturation, wet weights were recorded and samples were placed on a 3.5 kPa glass-bead tension table for 24-h for draining. This procedure removed water from macropores and coarse mesopores to allow better image contrast. Samples were re-weighed and two plastic end caps were secured with masking tape. A distilled water phantom (water in an aluminum tube, outside and inside diam. 2.32 and 1.60 mm) and a solid copper phantom (outside diam. 0.55 mm) were attached to the long axis of the Plexiglas cylinder as standards to compare values among scans. The constant head method or falling head method (for samples with low flow) was used to determine K_{sat} after scanning. A syringe was used to apply a bentonite slurry to seal the samples along the core walls to remove boundary flow along the core wall (Blanco-Canqui et al., 2002). Bulk density was also measured.

2.3. Scanning and image analysis

A Siemens Somatom Plus 4 Volume Zoom X-ray CT scanner at the University of Missouri Hospital and Clinics was used for CT image acquisition. The scan system parameters were set to 125 kV, 400 mAs, and 1.5 s scan time to provide detailed and low noise projections. The pixel resolution was 0.19 by 0.19 mm. The X-ray beam width or “slice” thickness was 0.5 mm producing a volume element (voxel) size of 0.018 mm^3. The scanner resolution limits the size of a smallest pore (~200 μm diam.) that can be detected with this procedure and therefore, porosity estimated by this procedure may not represent total porosity of a soil sample. It is noted that CT estimates of porosity near the lower resolution of the scanner will have a partial volume effect and have less precision. Soil cores were positioned horizontally on the scanner stage so that the X-ray beam was perpendicular to the longitudinal axis. Scan depths within a core were 15, 26, 37, 48, and 59 mm from the top of the soil core.

Pore characteristics of scanned images were analyzed with public domain software *ImageJ* version 1.27 (Rasband, 2002). A 2500-mm^2 square area (50 mm×50 mm) was demarcated as the Region of Interest and then the exterior area was deleted to exclude voids near the core walls and to minimize beam hardening interference (Fig. 1). The region adjacent to the interior wall may have had higher porosity due to discrepancy between the radii of the curvature between the soil particles and the Plexiglas wall (Al-Raoush, 2002). More details on the image analysis can be found in Udawatta et al. (2006).