CT-measured macropore parameters for estimating saturated hydraulic conductivity at four study sites

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Abstract
Saturated hydraulic conductivity is a critical physical parameter essential for predicting infiltration in soils as well as runoff. X-ray computed tomography (CT) has been used as a measurement tool for assessment of soil pore parameters important for water transport. The objective of this study was to use CT-measured soil pore data to predict saturated hydraulic conductivity from four study sites with multiple treatments and soil depths. Soil cores were removed from four study sites in Iowa and Missouri. Study sites included soils developed on deep loess as well as loess and glacial till. Treatments evaluated at the four sites include: row crop, stiff-stemmed grass hedges, agroforestry buffers, grass buffers, conservation reserve program (CRP) management, restored prairie and native prairie. All samples (76 mm diam. by 76 mm long) were scanned using a Siemens Somatom with a 0.19 by 0.19 by 0.5 mm resolution. Pore parameters estimated by CT included macroporosity (> 1000 µm diam.), coarse mesoporosity (200 to 1000 µm diam.), number of pores, circularity of pores, and fractal dimension of macroporosity. The best regression model for estimating the log-transformed saturated hydraulic conductivity was the logarithm of number of pores ($r^2 = 0.69$). This study illustrates the application of CT methods as a characterization tool of soil pores for prediction of hydraulic conductivity.

Key Words
Circularity, coarse mesoporosity, fractal dimension, macroporosity, saturated hydraulic conductivity, x-ray computed tomography

Introduction

Saturated hydraulic conductivity is an important soil parameter which is highly influenced by soil management (Udawatta et al. 2008). Perennial vegetative buffers have been shown to maintain or improve soil hydraulic properties (Rachman et al. 2005). These buffers include stiff-stemmed warm season grasses (Rachman et al. 2005), trees and grasses (Udawatta and Anderson 2008), and cool season grasses (Udawatta and Anderson 2008). The purpose of these buffer systems is to control surface runoff and sediment loss from land under row crop and grazing management practices. Since vegetation is perennial, soil under buffers may develop biologically produced macropores as a result of active growth of grass roots and associated fauna.

An important soil pore parameter for infiltrating water is the degree of macroporosity (Allaire-Leung et al. 2000). Macropores (relatively large soil pores > 1000 µm diameter) allow water to penetrate into the soil and, under ponded conditions at the soil surface, water flow in soils will be dominated by the macropore system. Water transport follows the path of least resistance through these macropores, while in contrast, water movement in soil without macropores occurs through smaller pores or voids between the grains or aggregates (Warner et al. 1989). For both macropore flow and matrix flow, the shape, size, orientation and distribution of soil pores influence the rate of water flow and retention in the soil (Rasiah and Aylmore 1998).

Porosity is often characterized using analysis of soil water characteristic curves, tension infiltrometer data, and soil bulk density data (Everts and Kanwar 1992). These are an indirect measure of porosity or pore size distribution, and do not include any detailed information on the nature of the pores or their spatial distribution (Gantzer and Anderson 2002). A recent measurement tool used by soil scientists to assess soil pores is X-ray computed tomography (CT; Perret et al. 2000; Gantzer and Anderson 2002) which can be used for *in situ*, nondestructive, and repetitive measurements at sub-millimeter scales. Detection of macropore features and their relative frequency has been done using CT methods to quantify macropore diameters as small as 0.15 mm (Gantzer and Anderson 2002). The objectives of this study were to characterize macropores of intact soil samples using CT methods from four study sites with selected land management treatments, and correlate saturated hydraulic conductivity with CT-measured macropore parameters.

Methods

Study sites and core samples

Data used for the current study were obtained from four study sites which compared CT-measured macropore parameters for selected soil management treatments (Kumar et al. 2010; Rachman et al. 2005; Udawatta and Anderson 2008; Udawatta et al. 2008). Rachman et al. (2005) compared CT-measured macropore properties within the 0 to 20 cm soil depth for stiff-stemmed grass hedge, row crop and deposition zone treatments (30 cores) on Monona silt loam (fine-silty, mixed, superactive, mesic Typic Hapludolls). CT-measured macropore properties were assessed within the 0 to 40 cm depth of Mexico silt loam (fine, smectitic, mesic Vertic Epiaqualfs) for four treatments (96 cores): row crop, native-undisturbed prairie, restored prairie, and conservation reserve program (CRP) treatments (Udawatta et al. 2008). Udawatta and Anderson (2008) evaluated macropores for agroforestry buffer, grass buffer and row crop treatments (90 cores) within the 0 to 50 cm depth of Putnam silt loam (fine, smectitic, mesic Vertic Albaqualf). Macropore properties were measured for continuously grazed pasture, rotationally grazed pasture, agroforestry buffer and grass buffer treatments (120 cores) within the upper 50 cm of Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalf; Kumar et al. 2010). A total of 336 core samples were used for this study. The Monona and Menfro soils formed on deep loess while the Mexico and Putnam soils (claypan soils) formed on loess and glacial till.

Intact soil cores (76.2 mm diameter by 76.2 mm long) housed in Plexiglas cylinders with 4 mm wall thickness were collected from each site. A plastic cap was placed on each end of the soil core secured with masking tape. Cores were then placed in sealed plastic bags, transported to the laboratory, and stored in a refrigerator at 4° C.

The lower end of each core was covered with 2 layers of fine nylon mesh to contain soil within cylinders. Cores were slowly saturated from the bottom with water (6.24 g L^{-1} $CaCl_2$ and 1.49 g L^{-1} $MgCl_2$) using a Mariotte system. Samples were drained and equilibrated to –3.5 kPa using a glass-bead tension table. Samples were weighed and transported to the CT scanner for measurement. Two phantoms, distilled water in an aluminum tube and a solid copper wire, were attached to each core before scans were taken. Phantoms were to assure that data were comparable between scans for different treatments.

Scanning and image analysis

The CT scanner used for all studies was a Siemens Somatom Plus 4 Volume Zoom. The scan system parameters were set to 125 kV, 400 mA and 1.5-s scan time to provide detailed and low noise projections. The field of view, i.e. the cross sectional dimension, was 100 mm with 512 by 512 picture elements (pixels) giving a pixel size of 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. Five scan slices were taken in each core with a 10 mm distance between each scan. The first scan slice was taken at a 15 mm distance from the top of the soil core. After scanning, saturated hydraulic conductivity was measured using either the constant head method or falling head method. The soil cores were then dried to determine bulk density.

The scanned images were analyzed for macropore (>1000-µm diam.) and mesopore (200- to 1000-µm diam.) characteristics using the *ImageJ* version 1.27 computer software package (Rasband 2002). The macropore and mesopore characteristics analyzed included the number of pores, macroporosity, coarse mesoporosity, pore area, perimeter of pores, and macropore fractal dimension (fractal D). Pore circularity was estimated using pore area and perimeter of pores. Macroporosity and mesoporosity at each depth were calculated from the total area of all macropores and mesopores isolated in the image at a given depth divided by the cross sectional area of the selected region on the soil core image.

The *Region of Interest* (ROI) tool was used to select a circular region of 73-mm diam. in each image. This region was selected to exclude voids near the core walls and minimize the effects of beam hardening due to the Plexiglas cylinder. The *Clear Outside* tool was used to clear areas outside the selected region. The *Threshold* tool was used to partition pores from solids after converting the image into an 8-bit grayscale image. The threshold values selected to analyze all images were from zero to 40 grayscale (range is 0 to 255). These grayscale values are the relative attenuation values (RAV) that are related to porosity (Gantzer and Anderson 2002). The *Analyze Particles* tool was used to measure statistics of individual pores.

Fractal dimension values were analyzed within a 50-mm by 50-mm square image in the center of the core. The threshold values for estimating the fractal dimension of the macropores were from zero to 100 RAV or grayscale. The higher RAV (100) for fractal dimension analyses as compared to pore characteristic analyses (40) was used to increase data density.

Pearson correlation coefficients were estimated between saturated hydraulic conductivity and the CT-measured pore parameters. Regression analyses were performed between saturated hydraulic conductivity and CT-measured pore parameters. Log_{10}-transformations were conducted on K_{sat} and CT-measured number of pores, since these distributions were positively skewed. These transformations normalized the data.

Results

Correlation among CT-measured parameters and K_{sat}

Linear correlation coefficients among bulk core properties (bulk density and saturated hydraulic conductivity, K_{sat}) and CT-measured pore parameters are shown in Table 1. The parameter with the highest correlation with log(K_{sat}) was CT-measured number of pores (r = 0.830, P < 0.001). Fractal dimension of macroporosity was the parameter with the next highest correlation (r = 0.704, P < 0.001). These two CT-measured parameters (number of pores and fractal dimension) were also highly correlated (r = 0.781, P < 0.001).

Regression relationships for K_{sat}

Regression parameters for estimating log(K_{sat}) using log(CT-measured number of pores) for the four study sites are included in Table 2. Coefficients of determination ranged from 0.50 to 0.76. The lowest intercept value was found for the Rachman et al. (2005) study site while the highest value occurred with the Kumar et al. (2010) study. The Rachman et al. (2005) study site had the highest slope (1.84) while the Kumar et al. (2010) study site had the lowest slope value (1.28).

Table 1. Correlation matrix of CT-measured macropore pararameters and log(saturated hydraulic conductivity, K_{sat}).

	Macro-f† (cm^3 cm^{-3})	Coarse Meso-f† (cm^3 cm^{-3})	Log (Number of Pores)	Pore Circularity	Fractal Dimension of Macro-f	Bulk Density (g cm^{-3})	Log(K_{sat}) [log(mm hr^{-1})]
Macro-f	1.000	0.458‡	0.618	-0.088	0.768	-0.514	0.572
Coarse Meso-f		1.000	0.435	-0.052	0.480	-0.280	0.380
Log(Number of Pores)			1.000	0.301	0.781	-0.144	0.830
Pore Circularity				1.000	-0.033	0.324	0.180
Fractal D of Macro-f					1.000	-0.509	0.704
Bulk Density						1.000	-0.173
Log(K_{sat})							1.000

†Macro-f = macroporosity, Meso-f=mesoporosity.
‡Correlation values higher than 0.175 or lower than -0.175 correspond to P < 0.001.

Table 2. Regression parameters and coefficients of determination for predicting log(Ksat) from log(number of pores) at four study sites.

Study Site	Intercept	Slope	r^2	n
Rachman et al. (2005)	-1.74	1.84	0.62	30
Udawatta et al. (2008)	-1.12	1.44	0.69	96
Udawatta/Anderson (2008)	-1.50	1.77	0.76	90
Kumar et al. (2010)	-0.76	1.28	0.50	120

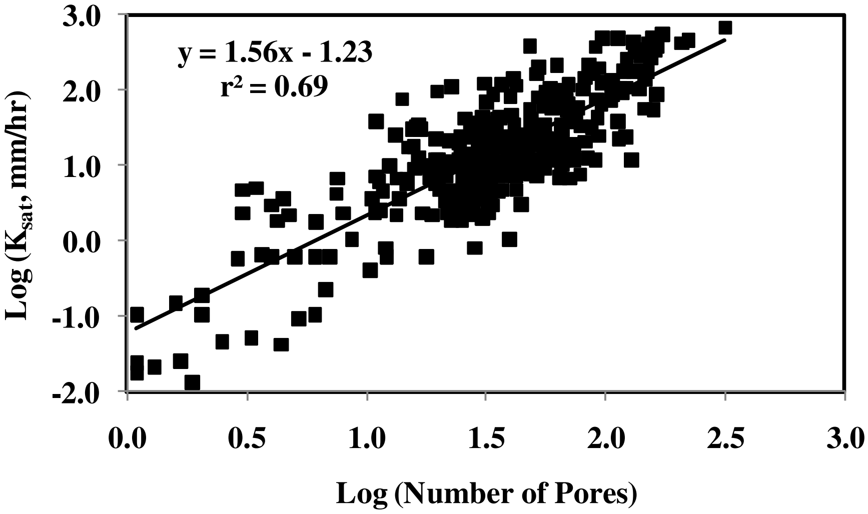

Figure 1. Regression relationship between saturated hydraulic conductivity [log(K_{sat})] and CT-measured number of pores [log(number of pores)].

The overall regression relationship between log(K_{sat}) and log(CT-measured number of pores) is shown in Figure 1. Adding the fractal dimension of macroporosity into the regression relationship increased the r^2 value from 0.69 to 0.70. Including additional parameters did not improve the coefficient of determination.

Conclusion

A study was conducted to compare how well CT-measured pore parameters performed in estimating saturated hydraulic conductivity from four study sites in Iowa and Missouri. CT-measured pore parameters included number of pores, macroporosity, coarse mesoporosity, pore circularity, and fractal dimension of macroporosity. The best regression model for estimating log(saturated hydraulic conductivity) was log(number of pores) with a coefficient of determination of 0.69. Results of the study indicate that CT methods may be very useful for characterizing pores from multiple sites with several land management treatments and can potentially estimate saturated hydraulic conductivity.

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