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CT-MEASURED MACROPORES AS AFFECTED BY AGROFORESTRY AND GRASS BUFFERS FOR GRAZED PASTURE SYSTEMS

Sandeep Kumar[1], Stephen H. Anderson[1], and Ranjith P. Udawatta[1,2]

[1]Department of Soil, Environmental and Atmospheric Sciences, University of Missouri-Columbia
[2]Center for Agroforestry, University of Missouri-Columbia. Columbia, MO 65211, USA.
Contact: sk9fd@mizzou.edu

Abstract: Agroforestry and grass buffers have been proposed for improving water quality in watersheds. Buffer vegetation influences soil porosity, essential for water, gas and nutrient transport in soils. The objective of the study was to compare differences in CT-measured macropore (>1000-µm diam.) and coarse mesopore (200- to 1000-µm diam.) parameters within agroforestry (AgB) and grass buffer (GB) systems associated with rotationally grazed (RG) and continuously grazed (CG) pasture systems, and to examine relationships between CT-measured pore parameters and saturated hydraulic conductivity (K_{sat}). Soils at the site were Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalf). Six replicate intact soil cores, 76.2 mm diam. by 76.2 mm long, were collected using a core sampler from the four treatments at five soil depths (0-50 cm at 10-cm intervals). *Image-J* software was used to analyze the five equally spaced images from each core. CT-measured soil macroporosity (>1000 µm diam.) was 13 times higher (0.053 m^3m^3) for the buffer treatments compared to the pasture treatments (0.004 m^3m^3) for the surface 0-10 cm soil depth. Buffer treatments had greater macroporosity (0.020 m^3m^3) compared to pasture (0.0045 m^3m^3) treatments. The K_{sat} values for buffer treatments were five times higher and bulk density was 5.6% lower compared to pasture treatments. CT-measured pore parameters (except macropore circularity) were positively correlated with K_{sat}. This study illustrates the benefits of agroforestry and grass buffers for maintaining soil pore parameters critical for soil water and nutrient transport.

Abbreviations: AgB, agroforestry buffer; CG, continuously grazed pasture; CT, computed tomography; GB, grass buffer; K_{sat}, saturated hydraulic conductivity; NPSP, nonpoint source pollution; RG, rotationally grazed pasture

INTRODUCTION

Agroforestry buffers have been recently introduced to improve environmental quality and diversify farm income. Agroforestry and grass buffers help in reducing nonpoint source pollution (NPSP) from row crop areas by improving soil hydraulic properties and reducing surface runoff (Udawatta et al., 2002; Seobi et al., 2005). These buffers increase the soil porosity relative to row crop land management under tilled or no-till practices (Seobi et al., 2005). Establishment of buffers in pasture areas has been shown to decrease soil bulk density and increase soil porosity (Kumar et al., 2008).

Soil porosity is an important parameter related to transport and storage of water and nutrients in the soil. Water transmission and storage depend on the geometry and size distribution of soil pores (Eynard et al., 2004). Pore size distribution and connectivity of pores, is believed to control soil hydraulic properties (Pierret et al., 2002).

X-ray CT scanning has been shown by various researchers to be useful for measuring soil microstructure (Phillips and Lannutti, 1997; Alshibli et al., 2000). X-ray CT scanning has given promising results for measuring the shape, distribution, and arrangement of soil pores within the soil (Udawatta et al., 2008b). This technique also has been applied to characterize pore continuity and tortuosity (Udawatta et al., 2008b). According to Tollner et al. (1994), X-ray CT scanning can provide aggregate size data consistent with traditional testing.

CT procedures have advantages compared to traditional methods since these procedures provide a finer resolution on a mm- to micrometer-scale (Gantzer and Anderson, 2002). The non-destructive nature of CT scanning allows the same soil sample to be scanned at different times. Carlson et al. (2003) reported that the best advantage of CT is its ability to quickly and nondestructively image the interior of a three-dimensional object. CT techniques can give the three dimensional structure of soil pores. Another advantage of X-ray CT scanning is its ability to quantitatively measure soil bulk density and water content distributions in undisturbed soil samples (Heijs et al., 1995).

The objective of the study was to compare effects of agroforestry buffer (AgB) and grass buffer (GB) systems associated with rotationally grazed pasture (RG) and continuously grazed pasture (CG) systems on CT-measured macropore (>1000-µm diam.) and coarse mesopore (200- to 1000-µm diam.) parameters and to examine relationships between CT-measured pore parameters and saturated hydraulic conductivity (K_{sat}).

MATERIALS AND METHODS

Study Area and Management

The experimental site is located at the Horticulture and Agroforestry Research Center (HARC) in New Franklin, MO, USA (39°02’N, 92°46’W, 195 m above mean sea level). The study site was established in 2000 to compare the effects of grass and agroforestry buffers on runoff water quality (Kumar et al., 2008). The pasture areas and buffers were re-seeded with tall fescue (*Festuca arundinacea* Schreb) in 2000. The pastures were also seeded with red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) into the fescue in 2003. Four rows of eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) were planted into the fescue to create the agroforestry buffers in 2001. Trees were planted at 3 m intervals within and between rows. Additional information about the study site can be found in Kumar et al. (2008).

Soils at the site are Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalf). The annual precipitation of the experimental site for the last 50 years (1956-2006 year) is 967 mm; mean temperature in July is 25.6°C and mean temperature in January is -2.1°C. The treatments included agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) systems. The GB and AgB buffer treatments were fenced from the pasture areas preventing access by the cattle. The RG treatment was rotationally grazed with six fenced areas (paddocks) within the small watershed. The CG pasture treatment was continuously grazed by cattle with no rest.

Grazing was initiated at the site in late March or early April and discontinued in late October or early November each year. During late July or early August, cattle were removed for about one month due to poor grass growth. The pasture treatment sites had been grazed for three years prior to sampling. Each year, beef cows were introduced in the pasture area with average weight of 520 kg. The number of cattle for the small watershed (0.8 ha) was three. Eighty-five percent of the grazing area (0.64 ha) of the watershed was divided into six smaller rotationally grazed paddocks with a single wire electric fences for cattle management. The other 15% of the grazing area was continuously grazed. The cows were moved between paddocks on each Monday and Thursday with each paddock being grazed for 3.5 days and rested for 17.5 days.

Sample Collection

Intact soil cores were collected from the four treatments and five soil depths (0 to 50 cm in 10 cm increments) with six replications per treatment on 6 and 7 June, 2007. The Plexiglas rings were 76.2 mm long and 76.2 mm diam. The CG treatment samples were taken from six replicate continuously grazed areas and RG samples were taken from six replicate rotationally grazed areas. The AgB samples were taken from soil under six replicate trees, three each from two tree rows in the agroforestry buffer area. These samples were taken at a distance of 20 cm from the base of tree trunks in the agroforestry buffer. The GB samples were taken from six replicate grass buffer areas. Soil cores were labeled, trimmed, and sealed in plastic bags and transported to the laboratory and stored at 4^oC until measurements were taken.

Scanning and Image Analysis

Soil cores were saturated with a dilute salt solution **(**$CaCl_2$; 6.24 g L^{-1} and $MgCl_2$; 1.49 g L^{-1}) to retain soil structure. After 24 h, weights were recorded and samples were then drained at 35 cm tension for 24 h using a glass-bead tension table, which removed water from pores > 85 μm equivalent cylindrical diameter to enhance image contrast between air-filled pores and soil solids. These cores were scanned using a Siemens Somatom Plus 4 Volume Zoom X-ray CT scanner to acquire CT scan images. Five images were acquired from each core at the following scan depths from the core surface: 1.7, 2.8, 3.9, 5.0, and 6.1 cm. The pixel resolution was 0.19 by 0.19 mm. The width or "slice" thickness was 0.5 mm producing a volume element (voxel) size of 0.018 mm^3.

Images were analyzed using the *Image-J* ver. 1.27 software (Rasband, 2002) to examine the treatment effects on pore size distributions and pore characteristics.

The macropore and mesopore characteristics analyzed included porosity (macroporosity plus coarse mesoporosity), macroporosity (>1000-μm diam.), and coarse mesoporosity (200- to 1000-μm diam.). In addition, fractal dimension of macropores was analyzed. Macroporosity and mesoporosity at each scan 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 (2500 mm^2) of the selected region on the soil core image.

The threshold value selected to analyze all images was 40 (range is 0 to 255). The values lower than the threshold values were identified as the air-filled pores and the values greater than threshold value were identified as non-pore. The fractal dimension of macropores was determined with zero to 100 threshold values to better populate the low porosity samples with pores (Gantzer and Anderson, 2002).

Saturated Hydraulic Conductivity and Bulk Density

After scanning, saturated hydraulic conductivity and dry bulk density were determined on all 120 soil cores. Saturated hydraulic conductivity was measured using the constant head method (Klute and Dirksen, 1986). The same soil cores were used for determining bulk density as described by Blake and Hartge (1986).

Statistical Analysis

A test for homogeneity of variance was conducted to evaluate the variability within the different treatments due to the systematic arrangement of treatments. Single degree-of-freedom contrasts were also determined and were conducted as follows: *buffers vs. pastures*, *grass buffer vs. agroforestry buffer*, and *rotationally grazed pasture vs. continuously grazed pasture*. The differences in pore characteristics among scans along the soil core were statistically compared to evaluate depth and management influences using PROC MIXED (SAS Inst., 1999). Statistical differences were declared significant at the $\alpha = 0.05$ level.

RESULTS AND DISCUSSION

CT-Measured Porosity, Macroporosity and Coarse Mesoporosity

CT-measured porosity (macroporosity plus coarse mesoporosity), macroporosity and coarse mesoporosity were significantly influenced by the AgB, GB, RG, and CG treatments ($P<0.01$, Table 1, Fig. 1). Significant differences were found for two contrasts: ‘buffers vs. pastures’ and ‘grass buffer vs. agroforestry buffer’ ($P<0.01$; Table 1). Buffers had higher porosity (271%), macroporosity (322%), and coarse mesoporosity (140%) as compared to pasture treatments. All three parameters were found to be the highest for the GB treatment.

Soil depth zones (10 cm increment depths) also influenced porosity, macroporosity and coarse macroporosity (Table 1). Porosity decreased linearly with soil depth ($r = -0.82$). Similar trends were found with macroporosity ($r = -0.82$) and coarse mesoporosity ($r = -0.83$). The greatest differences among depth zones for porosity, macroporosity and coarse mesoporosity were observed between the 0-10 and 10-20 cm depth zone.

Porosity, macroporosity, and coarse mesoporosity values decreased from the first to second depth zones for the AgB (77, 79, 82%, respectively) and GB (57, 63, 25%, respectively) treatments; whereas, an increase in the values of these parameters was observed in the RG (86, 150, 50%) and CG (100, 75, and 200%) treatments for similar depth zones (Fig. 1). This was probably caused by cattle grazing on the pasture treatments. Interactions between treatment and soil depth zone were also found ($P<0.010$; Table 1; Fig. 1).

Previous studies in Iowa and Missouri showed that grass, tree and native prairie improved CT-measured porosity and macroporosity (Rachman et al., 2005; Udawatta et al., 2006, 2008a). The data from the current study showed that the CG treatment had the lowest porosity and macroporosity which will probably contribute to more surface runoff

Table 1. Average CT-measured porosity (porosity, macroporosity, and coarse mesoporosity) and fractal dimension of macropores as influenced by agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) treatments and soil depth along with the analysis of variance.

	Porosity	Macro-porosity	Coarse Mesoporosity	Fractal Dimension
Treatment means	m^3 m^3	m^3 m^3	m^3 m^3	
Agroforestry buffer (AgB)	0.018^b	0.013^b	0.004^b	1.21^b
Grass buffer (GB)	0.034^a	0.026^a	0.008^a	1.41^a
Rotationally grazed (RG)	0.008^c	0.005^c	0.003^c	1.14^b
Continuously grazed (CG)	0.006^c	0.004^c	0.002^c	1.08^b
Depth means				
0- to 10-cm	0.035^a	0.035^a	0.029^a	1.33^a
10- to 20-cm	0.017^b	0.017^b	0.013^b	1.21^b
20- to 30-cm	0.010^c	0.010^{bc}	0.007^{bc}	1.15^c
30- to 40-cm	0.009^c	0.009^c	0.005^c	1.14^c
40- to 50-cm	0.011^c	0.011^{bc}	0.007^{bc}	1.13^c
	Analysis of Variance, P > F			
Treatment	<0.01	<0.01	<0.01	<0.01
Buffers vs. Pastures	<0.01	<0.01	<0.01	<0.01
GB vs. AgB	<0.01	<0.01	<0.01	<0.01
RG vs. CG	0.63	0.78	0.10	0.10
Depth	<0.01	<0.01	<0.01	<0.01
Treatment by Depth	<0.01	<0.01	<0.01	<0.01

The ANOVA table represents significance levels among treatments and depths for the measured parameters.

from this area. In contrast, the buffer treatments had higher porosity and macroporosity values which will allow better infiltration of water and hence less runoff.

CT-Measured Fractal Dimension of Macropores

Fractal dimension of macropores was significantly affected among the four treatments (P<0.01; Table 1). The fractal dimension of macropores ranged from 1.08 (CG treatment) to 1.41 (GB treatment). Significant differences were found for two contrasts: 'buffers vs. pastures' and 'grass buffer vs. agroforestry buffer' (Table 1). The higher fractal dimension values for the surface 0-10 cm depth observed in the AgB (1.53) and GB (1.62) treatments may suggest more macroporosity and hence a higher probability of preferential water flow due to large and more elongated pores compared to the RG and CG treatments. The fractal dimension of macropores increased from the first to second depth zone (1.08 to 1.21; 1.06 to 1.08, respectively, for RG and CG treatments); with further depths, the values decreased.

The continuous grazing treatment lowered the fractal dimension for the first depth zone; hence values for this treatment increased from the first to second depth. Soil depth zone also influenced the fractal dimension of macropores ($P<0.01$). Fractal dimension decreased with soil depth (Table 1) as did macroporosity.

Correlation of Pore Parameters and Saturated Hydraulic Conductivity

An evaluation of soil bulk density and saturated hydraulic conductivity is presented prior to correlation analysis of properties. Soil bulk density was different among the treatments ($P<0.01$; Fig. 2). Buffer treatments (1.35 g cm^{-3}) had 5.6% lower soil bulk density than pasture treatments (1.43 g cm^{-3}). Soil bulk density changed with soil depth zone ($P<0.01$). Bulk density generally increased with soil depth for the buffer treatments whereas for the CG treatment bulk density was unaffected after the second soil depth zone (Fig. 2). Interactions between treatment and soil depth were also found ($P<0.01$; Fig. 2). The current study supports findings reported in previous research (Kumar et al., 2008).

The K_{sat} values were found to be different among the treatments. The buffer treatments had the highest (75.8 mm h^{-1}) K_{sat}, averaged across depths while the two grazed pasture treatments had the lowest K_{sat} (15 mm h^{-1}). The K_{sat} was about 31 times higher in the buffers as compared to grazed pasture systems for 0-10 cm soil depth zone. The K_{sat} values significantly decreased with increasing soil depth zone (Fig. 2).

For correlation analysis, averages of the five scan depths per core were used as core parameters for each property. Nine CT-measured pore parameters (number of pores, number of macropores, number of coarse mesopores, porosity, macroporosity, coarse mesoporosity, area of largest pore, circularity of macroporosity, and fractal dimension of macropores) along with bulk density were regressed with saturated hydraulic conductivity (Table 2).

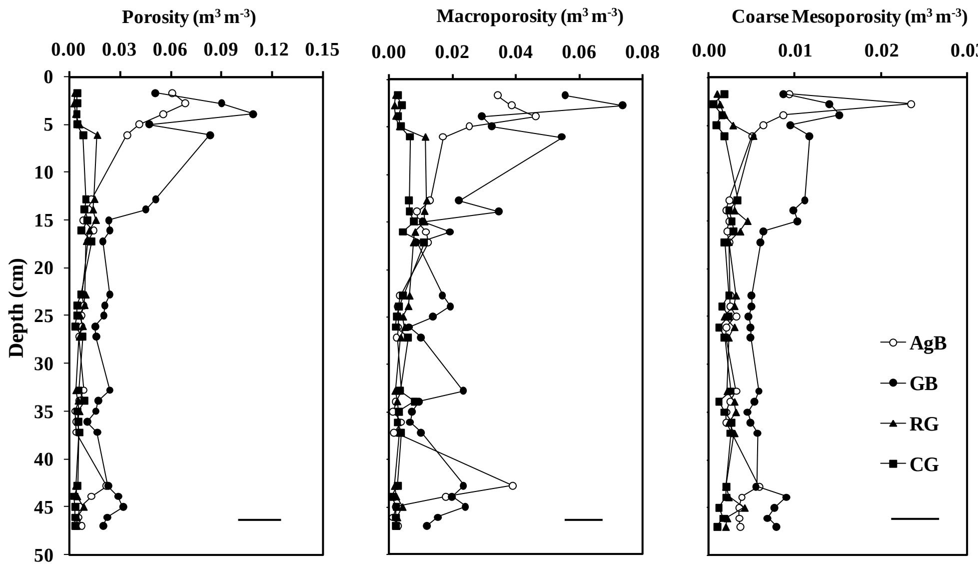

Figure 1. CT-measured porosity, macroporosity, and coarse mesoporosity for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments influenced by soil depth. The bar indicates the LSD (0.05) values.

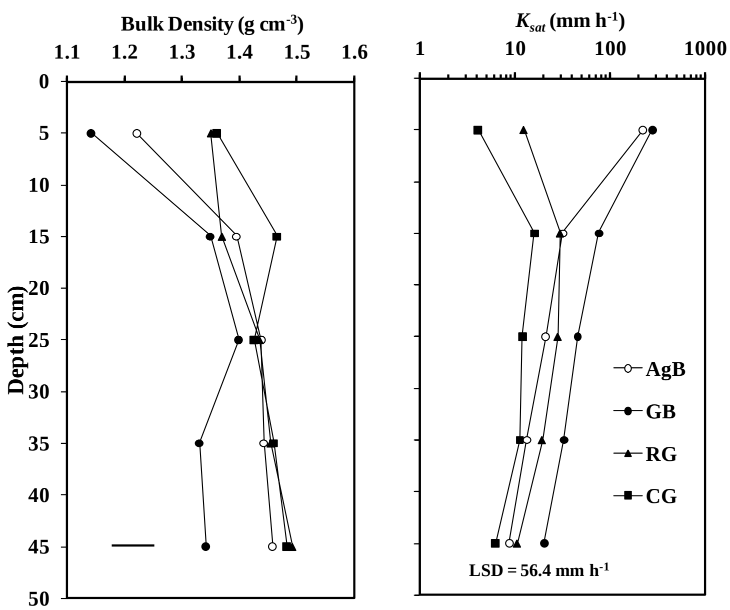

Figure 2. Mean soil bulk density and saturated hydraulic conductivity (K_{sat}) for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments influenced by soil depth. The bar indicates the LSD (0.05) value for bulk density. The LSD (0.05) value for K_{sat} is listed on the graph due to log scale.

All CT-measured pore parameters except circularity were positively correlated with K_{sat}. Circularity was negatively correlated due to more circular pores being present among the pasture treatments which had lower K_{sat}. Among the nine CT-measured pore parameters, macroporosity explained 58% of the variation in saturated hydraulic conductivity (Table 2).

Number of macropores with porosity was the best two parameter combination and accounted for 63% of the variation in K_{sat}. The number of macropores with macroporosity was the second best two parameter combination (Table 2). Regression analysis showed that macroporosity and porosity ranked the best when evaluating single parameters. Dosskey et al. (2007) reported that increased macroporosity should increase infiltration and reduce sediment transport capacity of the runoff water. Our findings imply that the buffers which had higher porosity and macroporosity will infiltrate more water and allow less runoff.

Table 2. Relationships between CT-measured pore parameters with saturated hydraulic conductivity.

Relationship	Coefficient of Determination	Significance Level
Single parameter		
K_{sat} = -0.36 + 3743.88*macroporosity	0.580	0.001
K_{sat} = -6.51 + 3166.25*porosity	0.579	0.001
K_{sat} = -30.84 + 1.58*pores[†]	0.517	0.001
Two parameters		
K_{sat} = 4.59 - 5.93*macropores[†] + 6825.76*porosity	0.635	0.001
K_{sat} = 10.9 - 3.54*macropores + 6292.15*macroporosity	0.607	0.001

[†]Pores = number of pores, macropores = number of macropores.

CONCLUSIONS

This study evaluated the hypothesis that buffers would influence CT-measured soil pore parameters in pasture systems. Agroforestry and grass buffer treatments had higher porosity, macroporosity, coarse mesoporosity, and fractal dimension of macropores compared to grazed pasture treatments. Buffer treatments also had lower soil bulk density (5.6 %) and higher saturated hydraulic conductivity (5 times higher) compared to pasture treatments. The K_{sat} for the buffer treatments was 31 times higher compared to pasture treatments within the upper 0-10 cm depth.

Most CT-measured pore parameters within buffer treatments usually decreased significantly between the first and second depth zones (0-10 and 10-20 cm) while values in these depth zones either increased slightly or stayed the same for the pasture treatments. All CT-measured pore parameters except circularity were positively correlated with K_{sat}. Increased macroporosity in buffer areas will probably increase soil water infiltration, increase gas exchange, and reduce runoff and nonpoint source pollution. Differences in pore parameters were attributed in part to differences in root growth and development among the treatments. For improved infiltration, buffer zones should be managed to prevent cattle traffic for better maintenance of soil pore characteristics.

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