

# CT-measured macropores as affected by agroforestry and grass buffers for grazed pasture systems

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**Abstract** Agroforestry and grass buffers have been proposed for improving water quality in watersheds. Soil porosity can be significantly influenced by buffer vegetation which affects water transport and water quality. The objective of the study was to compare differences in computed tomography (CT)-measured macroporosity (>1,000- $\mu\text{m}$  diam.) and coarse mesoporosity (200- to 1,000- $\mu\text{m}$  diam.) parameters for agroforestry and grass buffer systems associated with rotationally grazed and continuously grazed pasture systems. 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). Images were acquired using a hospital CT scanner and subsequently soil bulk density and saturated hydraulic conductivity ( $K_{\text{sat}}$ ) were measured after scanning the cores. *Image-J* software was used to analyze five equally spaced images from each core. Bulk density was 5.9% higher and saturated hydraulic

conductivity ( $K_{\text{sat}}$ ) values were five times lower for pasture treatments relative to buffer treatments. For the 0–10 cm soil depth, CT-measured soil macroporosity (>1,000  $\mu\text{m}$  diam.) was 13 times higher for the buffer treatments compared to the pasture treatments. Buffer treatments had greater macroporosity ( $0.020 \text{ m}^3 \text{ m}^{-3}$ ) compared to pasture ( $0.0045 \text{ m}^3 \text{ m}^{-3}$ ) treatments. CT-measured pore parameters were positively correlated with  $K_{\text{sat}}$ . The project illustrates benefits of agroforestry and grass buffers for maintaining soil porosity critical for soil water and nutrient transport.

**Keywords** Agroforestry buffer (AgB) · Computed tomography (CT) · Continuously grazed pasture (CG) · Grass buffer (GB) · Macroporosity · Mesoporosity · Rotationally grazed pasture (RG)

## Abbreviations

$K_{\text{sat}}$  Saturated hydraulic conductivity  
NPSP Nonpoint source pollution

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## Introduction

Agroforestry and grass buffers improve soil hydraulic properties and reduce nonpoint source pollution (NPSP) from row crop areas (Udawatta et al. 2002; Seobi et al. 2005). Buffers increase soil porosity relative to row crop land management under tilled or no-till practices (Seobi

et al. 2005). Buffers in pasture areas have been shown to maintain soil bulk density and soil porosity whereas, grazed pasture areas increase density and decrease porosity of soils (Kumar et al. 2008).

Soil porosity is an essential parameter related to transport and storage of water and nutrients in the soil. Water transmission and storage depend on pore size distribution and their geometry (Eynard et al. 2004). Pore size distribution and connectivity of pores, is believed to control soil hydraulic properties (Pierret et al. 2002). Hence it becomes essential to quantify the pore parameters accurately. Different methods have been used to measure soil porosity, but X-ray CT scanning methods appear to provide more detailed results. This technique 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 been used effectively for measuring the shape, distribution, and arrangement of soil pores (Udawatta et al. 2008b). CT procedures provide a finer resolution of measurement, on a mm-to micrometer-scale (Gantzer and Anderson 2002). The non-destructive nature of CT scanning allows the same soil core sample to be scanned at different times. Other advantages of the CT technique over traditional methods are its ability to quickly and nondestructively image the interior of a three-dimensional object (Carlson et al. 2003), and to quantitatively measure soil bulk density and water content distributions in undisturbed soil samples (Heijs et al. 1995). These techniques also have been used to characterize pore continuity and tortuosity (Udawatta et al. 2008b).

The objective of the study was to compare effects of agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) systems on CT-measured porosity, macroporosity (>1,000- $\mu\text{m}$  diam.) and coarse mesoporosity (200- to 1,000- $\mu\text{m}$  diam.) and to examine relationships between CT-measured pore parameters and saturated hydraulic conductivity ( $K_{\text{sat}}$ ).

## Materials and methods

### Experimental site

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. The distance between the trees and the tree rows was three meters. 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 four treatments included agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) systems. The AgB and GB buffer treatments were fenced from the pasture areas preventing access by the cattle. The RG treatment was rotationally grazed with six equal sized fenced paddocks within the small watershed. The CG pasture treatment was continuously grazed by cattle.

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 1 month due to slow grass growth. The pasture treatment sites had been grazed for 3 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.

### Soil core samples

Intact soil cores were collected from the four treatments and five soil depths (0–50 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 AgB samples were taken from soil under six replicate trees; three samples each from two tree rows in the agroforestry buffer area. These core samples were taken at a distance of 20 cm away from the base of tree trunks. The GB samples were taken from six replicate grass buffer areas. The RG samples were taken from six replicate rotationally grazed areas and CG treatment samples were taken from six replicate continuously grazed areas. Soil cores were labeled, trimmed, and sealed in plastic bags and transported to the laboratory and stored at 4°C until measurements were taken.

### Scan analysis

Soil cores were saturated with a dilute salt solution ( $\text{CaCl}_2$ ;  $6.24 \text{ g L}^{-1}$  and  $\text{MgCl}_2$ ;  $1.49 \text{ g L}^{-1}$ ) 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  $>85 \mu\text{m}$  equivalent cylindrical diameter to enhance image contrast between air-filled pores and soil solids. The bottom of the each soil core was wrapped with two layers of fine nylon mesh to secure soil within the soil core. While moving the cores from saturation chamber to draining table, a small plastic petri dish was used to carry the cores. These soil cores were scanned using a Siemens Somatom Plus 4 Volume Zoom X-ray CT scanner to acquire CT scan images. Two phantoms, distilled water in an aluminum tube (outside and inside diam. 2.32 and 1.60 mm) and a solid copper wire (outside diam. 0.55 mm), were attached to the long axis of the Plexiglas cylinder for a standard comparison among scans (Udawatta et al. 2006). 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. A total of 600 images were analyzed from all the four treatments. 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  $0.018 \text{ mm}^3$ .

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 ( $>1,000\text{-}\mu\text{m}$  diam.), and coarse mesoporosity (200- to  $1,000\text{-}\mu\text{m}$  diam.). Macroporosity and coarse 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 ( $2,500 \text{ mm}^2$ ) of the selected region on the soil core image. The fractal dimension of macropores was also analyzed.

The threshold value selected to analyze all images was 40 (range is 0–255) and it was based on the intensity of water phantoms. 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. Rachman et al. (2005) and Udawatta et al. (2006) also used 40 as threshold value to compare buffer versus row crop scans. 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).

### Soil physical properties

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

### Statistical analysis

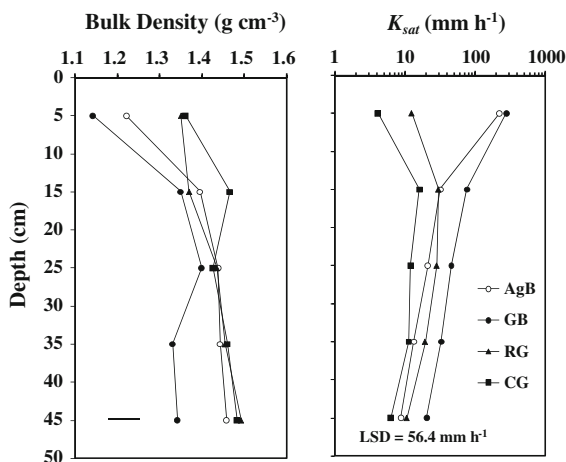
An evaluation of the sample data was conducted using analysis of variance. Single degree-of-freedom contrasts were determined and conducted as follows: *buffers versus pastures*, *GB versus AgB*, and *RG versus CG*. The differences in pore characteristics among scans along the soil core were statistically compared to evaluate depth and management influences using PROC MIXED (SAS Institute 1999). Statistical differences were declared significant at the  $\alpha = 0.05$  level.

## Results and discussion

### Soil bulk density and saturated hydraulic conductivity

Soil bulk density (BD) was significantly different among the treatments ( $P < 0.01$ ; Fig. 1). Buffer treatments ( $1.35 \text{ g cm}^{-3}$ ) had 5.6% lower BD as compared to pasture treatments ( $1.43 \text{ g cm}^{-3}$ ). Soil depth zone (10 cm depth increments) also influenced the BD ( $P < 0.01$ ). Interactions between treatment by soil depth were also found to be significant ( $P < 0.01$ ; Fig. 1). The BD for the buffer treatments increased with soil depth, whereas BD for the CG treatment was almost unaffected because of the compaction effect. The current findings support the results reported for a similar experimental site (Kumar et al. 2008).

The saturated hydraulic conductivity ( $K_{\text{sat}}$ ) values were significantly different among the treatments ( $P < 0.01$ ; Fig. 1). The buffer treatments had the highest ( $75.8 \text{ mm h}^{-1}$ )  $K_{\text{sat}}$  and pasture treatments had the lowest  $K_{\text{sat}}$  ( $15 \text{ mm h}^{-1}$ ), averaged across the depths. The  $K_{\text{sat}}$  was about 31 times higher in the buffers as compared to grazed pasture systems for 0–10 cm soil depth zone. The  $K_{\text{sat}}$  values significantly



**Fig. 1** Soil bulk density and saturated hydraulic conductivity ( $K_{\text{sat}}$ ) for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments influenced by soil depth. The LSD (0.05) value for bulk density is indicated by the bar and for  $K_{\text{sat}}$  is listed on the graph due to the log scale

decreased with increasing soil depth zone (Fig. 1; Kumar et al. 2008).

### Macropores, porosity, macroporosity and coarse mesoporosity

The CT-measured macropores and porosity, the sum of macroporosity and coarse mesoporosity, were significantly different among the treatments ( $P < 0.01$ ; Table 1; Fig. 2). The macroporosity and coarse mesoporosity were also influenced by the four treatments ( $P < 0.01$ ; Table 1; Fig. 2). Significant differences were found for two contrasts: ‘buffers versus pastures’ and ‘GB versus AgB’ ( $P < 0.01$ ; Table 1). Interactions between treatment and soil depth zone were also found ( $P < 0.010$ ; Table 1; Fig. 2). Buffers had 3.2, 3.7, 4.3, and 2.4 times, respectively, higher macropores (19), porosity ( $0.026 \text{ m}^3 \text{ m}^{-3}$ ), macroporosity ( $0.0195 \text{ m}^3 \text{ m}^{-3}$ ), and coarse mesoporosity ( $0.006 \text{ m}^3 \text{ m}^{-3}$ ) as compared to pasture treatments (6, 0.007, 0.0045 and  $0.0025 \text{ m}^3 \text{ m}^{-3}$ , respectively). The GB treatment had the highest porosity, macroporosity and coarse mesoporosity among all the treatments.

Soil depth zones also influenced the macropores, porosity, macroporosity and coarse macroporosity (Table 1). Porosity, macroporosity and coarse mesoporosity decreased linearly with soil depth ( $r = -0.82$ ,  $-0.82$  and  $-0.82$ , respectively for all the three parameters).

A 77 and 57% decrease in the porosity values were observed from first to second depth zones for the AgB and GB treatments, respectively. In contrast, an increase in the values of porosity was observed in the RG (86%) and CG (100%) treatments for similar depth zones (Fig. 2). Similarly macroporosity (69%) and coarse mesoporosity (52%) decreased for buffers and increased for the pasture treatments (113 and 100%, respectively) from first to second depth zones. This was probably due to the compaction caused by cattle grazing on the grazed pasture treatments.

The macropores, porosity, macroporosity and coarse mesoporosity were higher for the buffer treatments which will enhance water infiltration and reduce runoff compared to grazed pasture treatments. The current findings supported previous results reported by Rachman et al. (2005) and Udawatta et al. (2006, 2008a).

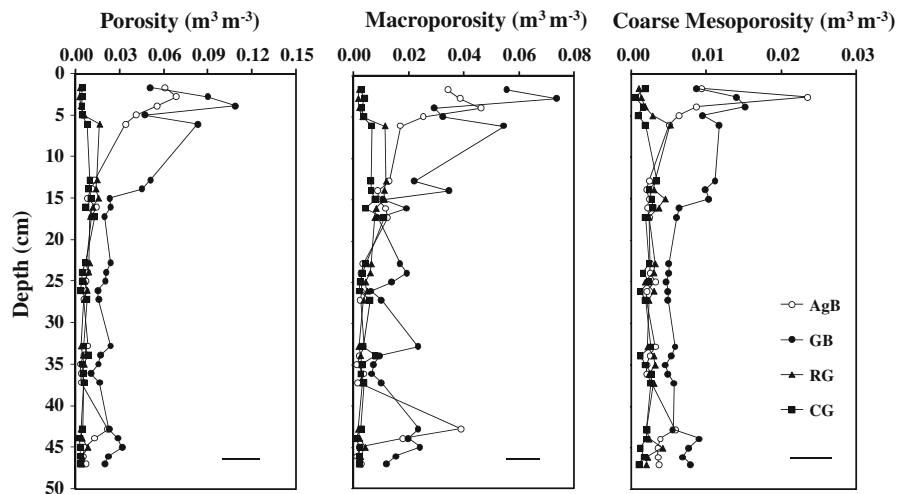
**Table 1** Analysis of variance and CT-measured macropores, porosity (porosity, macroporosity, and coarse mesoporosity) and fractal dimension of macropores for the agroforestry buffer

(AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) treatments and soil depths

	Number of Macropores	Porosity			Fractal dimension
		Porosity $m^3 m^{-3}$	Macroporosity $m^3 m^{-3}$	Coarse mesoporosity $m^3 m^{-3}$	
<b>Treatment means</b>					
Agroforestry buffer (AgB)	13 <sup>b</sup>	0.018 <sup>b</sup>	0.013 <sup>b</sup>	0.004 <sup>b</sup>	1.21 <sup>b</sup>
Grass buffer (GB)	25 <sup>a</sup>	0.034 <sup>a</sup>	0.026 <sup>a</sup>	0.008 <sup>a</sup>	1.41 <sup>a</sup>
Rotationally grazed (RG)	6 <sup>c</sup>	0.008 <sup>c</sup>	0.005 <sup>c</sup>	0.003 <sup>c</sup>	1.14 <sup>b</sup>
Continuously grazed (CG)	5 <sup>c</sup>	0.006 <sup>c</sup>	0.004 <sup>c</sup>	0.002 <sup>c</sup>	1.08 <sup>b</sup>
<b>Depth means</b>					
0- to 10-cm	23 <sup>a</sup>	0.035 <sup>a</sup>	0.029 <sup>a</sup>	0.007 <sup>a</sup>	1.33 <sup>a</sup>
10- to 20-cm	13 <sup>b</sup>	0.017 <sup>b</sup>	0.012 <sup>b</sup>	0.004 <sup>b</sup>	1.21 <sup>b</sup>
20- to 30-cm	9 <sup>c</sup>	0.010 <sup>c</sup>	0.008 <sup>bc</sup>	0.004 <sup>bc</sup>	1.15 <sup>c</sup>
30- to 40-cm	8 <sup>c</sup>	0.009 <sup>c</sup>	0.007 <sup>c</sup>	0.003 <sup>c</sup>	1.14 <sup>c</sup>
40- to 50-cm	8 <sup>c</sup>	0.011 <sup>c</sup>	0.005 <sup>bc</sup>	0.003 <sup>bc</sup>	1.13 <sup>c</sup>
<b>Analysis of variance, <math>P &gt; F</math></b>					
Treatment	<0.01	<0.01	<0.01	<0.01	<0.01
Buffers vs. Pastures	<0.01	<0.01	<0.01	<0.01	<0.01
GB vs. AgB	<0.01	<0.01	<0.01	<0.01	<0.01
RG vs. CG	0.52	0.63	0.78	0.10	0.10
Depth	<0.01	<0.01	<0.01	<0.01	<0.01
Treatment by depth	<0.01	<0.01	<0.01	<0.01	<0.01

The ANOVA table represents significance levels among treatments and depths for the measured parameters. Within columns, values followed by the same letter for the treatments or the depths are not significantly different at the 0.05 probability level

**Fig. 2** Porosity, macroporosity, and coarse mesoporosity measured by CT for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments influenced by soil depth. The LSD (0.05) values are indicated by bars



Fractal dimension of macropores

The fractal dimension of macropores ( $D$ ) was significantly different among the four treatments

( $P < 0.01$ ; Table 1). Significant differences were found for two contrasts: ‘buffers versus pastures’ and ‘GB versus AgB’ (Table 1). Higher fractal dimension values were found for the surface

**Table 2** Single and two parameter relationships between CT-measured pore parameters with saturated hydraulic conductivity ( $K_{\text{sat}}$ )

Relationship	Coefficient of determination	Significance level
Single parameter		
$K_{\text{sat}} = -0.36 + 3,743.88 \times \text{macroporosity}$	0.580	0.001
$K_{\text{sat}} = -6.51 + 3,166.25 \times \text{porosity}$	0.579	0.001
Two parameters		
$K_{\text{sat}} = 4.59 - 5.93 \times \text{macropores}^a + 6,825.76 \times \text{porosity}$	0.635	0.001
$K_{\text{sat}} = 10.9 - 3.54 \times \text{macropores} + 6,292.15 \times \text{macroporosity}$	0.607	0.001

<sup>a</sup> Macropores = number of macropores

0–10 cm depth in the AgB ( $D = 1.53$ ) and GB ( $D = 1.62$ ) treatments compared to RG ( $D = 1.08$ ) and CG ( $D = 1.06$ ) treatments. For surface depths, Rachman et al. (2005) reported similar values of fractal dimension ( $D = 1.70$ ) for the grass hedge position compared to the grass buffer treatments in the current study. Buffers ( $D = 1.31$ ) had higher values of fractal dimension compared to pasture ( $D = 1.11$ ) treatments which may suggest more macroporosity and hence a higher probability of preferential water flow due to large and more elongated pores in the buffers relative to pasture treatments (Udawatta et al. 2008b).

For pastures, the fractal dimension of macropores increased from the first to second depth zone and then decreased for further depths. This was due to the compaction effect which occurs in the surface depths. 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 saturated hydraulic conductivity and pore parameters

For correlation analysis, an average of the five scan depths per core was used to estimate core parameters for each property. All CT-measured pore parameters (macropores, porosity, macroporosity, coarse mesoporosity, and fractal dimension of macropores) along with bulk density were regressed with saturated hydraulic conductivity (Table 2).

All five CT-measured pore parameters were positively correlated with  $K_{\text{sat}}$ . Among all the 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 64% of the variation in  $K_{\text{sat}}$ . 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. Increased porosity and macroporosity values as observed in the buffer areas in the current study should increase the water infiltration and reduce sediment transport capacity of the runoff water. Similar results were reported by Dosskey et al. (2007).

#### Conclusions

The current study evaluated CT-measured pore parameters as affected by buffers managed under grazed pasture systems. Buffers had higher macropores, 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  $K_{\text{sat}}$  for the buffer treatments was 31 times higher compared to pasture treatments within the upper 0–10 cm depth.

All five pore parameters in the 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. This was due to the compaction caused by the cattle grazing. The grazing was not allowed in the buffers hence improved soil parameters were found for these treatments compared to pasture treatments. All five CT-measured pore parameters were positively

correlated with  $K_{\text{sat}}$ . Buffers had higher pore parameters which were attributed partially to differences in root growth. Increased macroporosity in the buffers will probably increase soil water infiltration, increase gas exchange, and reduce runoff and nonpoint source pollution. The current study finds that for improved water infiltration into the soil and to reduce the runoff, buffer zones should be managed to prevent cattle traffic for better maintenance of soil pore characteristics.

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